CascEff

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Methodology for creating a model of an incident with cascading effects for future threats

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Executive summary

Cascading effects modelling aims at understanding and modelling of dynamically spreading disturbances between dependent systems within a given territory. The main goal of this deliverable is to provide methodological support on cascading effects modelling to emergency responders, competent authorities, critical infrastructures operators, and others needing to determine dependencies, vulnerabilities and the risk for cascading effects. The methodology should be used for both anticipating and managing cascading effects of small and large scale incidents in a specified territory (case area).
The methodological framework is divided into six steps:

(1) set the case area and the individual systems in a given territory: all the systems are described in terms of functionality/provision services, vulnerability and potential outgoing effects;
(2) identify dependencies between systems: dependencies are identified in regards to systems' proximity and functionality,
(3) propagate the effects between systems: an initiating event is set in the case area, threatening the systems which can be impacted and which can impact, through cascading effects, other dependent systems,
(4) determine temporal aspects: buffer time, time-delay and overviews of timeline and tree-view are assessed in order to evaluate the potential time interval emergency responders have for mitigating effects,
(5) assess the impacts: social, human, economic, environmental and infrastructure impacts are evaluated for each impacted system in order for the emergency responder to compare impacts of cascading effects,
(6) Identify the key decision points: the combined assessment of timeline (step 4) and impacts (step 5) help the emergency responders to prioritize mitigation actions.

The methodological framework is exemplified using a demonstration case: the flooding of the French Seine river impacting roads and an industrial chemical plant in the vicinity of a Primary school. The framework is applied also to two other cases: (a) a wildfire near the Swedish city Gothenburg threatening telecommunication systems, lakes Stora and Lilla Deljsön, transportation, and a hospital, and (b) a power blackout in The Netherlands and Belgium affecting power supply, telecommunication, health care, public, main road transport axes (A58 and A12), rail transport, Marine transport of Antwerpen Port, air transport, water supply, BASF industrial plant and emergency response.

This methodology is currently the basis for the development of an incident evolution tool aimed at being used by emergency responders, critical infrastructure operators and other stakeholders involved during crisis preparation and management. The tool itself is described elsewhere.

1 Introduction

Cascading effects modelling aims at dynamically spreading disturbances between dependent systems within a given territory (Pescaroli and Alexander, 2015). The main goal of this document is to provide methodological support to emergency responders and critical infrastructures operators for both anticipating and managing cascading effects of small and large scale incidents in a specified territory.

The focus is, as shown on Figure 1 which presents the main concepts of cascading effects, on determining the systems with potential cascading effects, the dependencies between those systems, the results of systems being affected by the incident, allowing a final approach to find the key moments to influence the cascade, by either stopping it, either limiting the consequences.

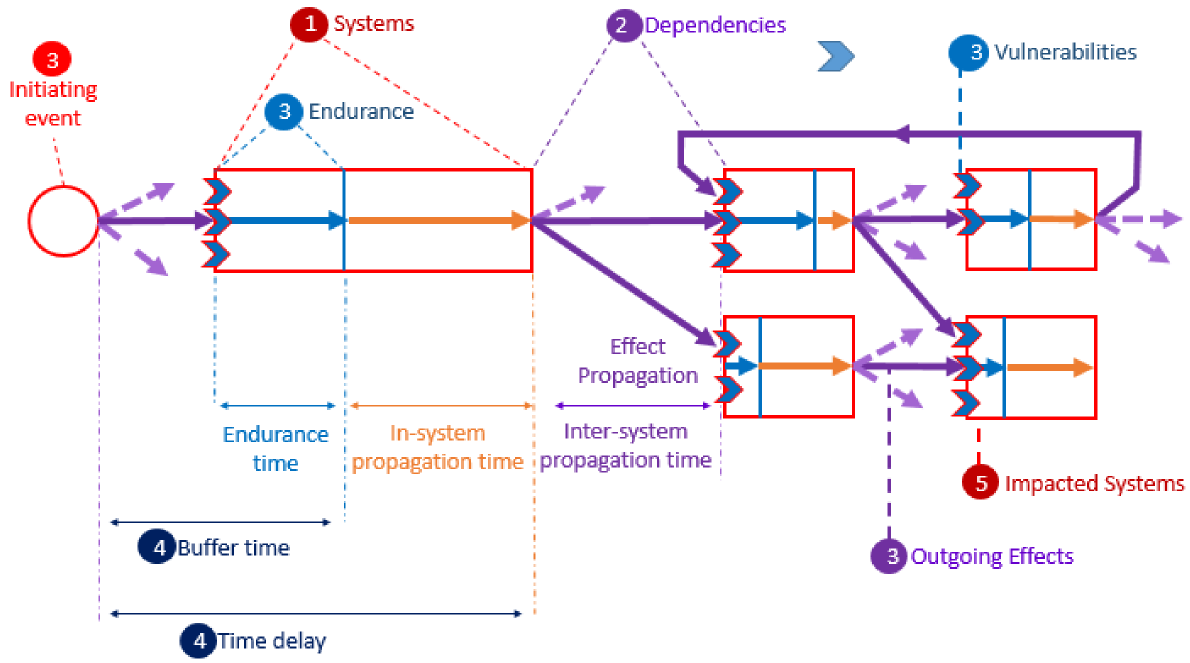

Figure 1 Conceptual figure specifying the terminology and the sections where the different terms are explained. The numbers in the Figure refer to the different steps of the methodology, explained further in Chapter 3.

The terms represented in Figure 1-1 are already defined in D1.6. We recall their definitions below. The potential way to assess them are specified in Chapter 3.

Buffer time: The time between the start of an outgoing effect in the originating system and the time before a cascading effect occurs in a dependent system, i.e. when the performance of the dependent system starts to degrade.

Dependency: Mechanism whereby a state change in one system can affect the state of another system.

Effect (propagation): (Propagation of) result of a cause in the presence of a hazardous situation (ISO 22559:2014)

Endurance time: Time a system can resist incoming effects before they start to create impact on the system.

Impacted system: A system that is negatively affected by either an initiating event or an originating system.

Initiating event: The first in a sequence of natural (e.g. flood), accidental (e.g. fire) or intentional (e.g. bombing) events that may affect one or several systems.

In-system propagation (time): (time of) propagation of effects between sub-systems within the same system.

Inter-system propagation time: Propagation of effects between two different systems.

Originating system: A system in which a failure propagates to another system.

Propagation time: The time it takes for the effects from the initiating event or an output of a system to propagate and reach the borders of a dependent system. The concept can be used to understand how fast effects spread, irrespectively of systems abilities to tolerate disturbances. Some effects can be seen as having zero propagation time (i.e. infinite spreading rate), e.g. power outage.

System: A distinct societal unit (such as a sector, operational activity, infrastructure, human community or natural resource) where a regularly interacting or interdependent group of items forming a unified whole.

Time delay: The time until when the output of a specific system is affected in relation to when the initiating event starts or the output of a system it depends upon is firstly affected. Time delay is hence the sum of the Buffer time and the Latent period. The concept can be used to signal “windows of opportunities” for breaking chains of cascading effects.

Vulnerability: Intrinsic properties of something resulting in susceptibility to a risk source that can lead to an event with a consequence. (EN ISO 22300, 2014)

2 Methodological approach

2.1 State of the Art

Cascading effects modelling is an emerging field of scientific research. Recent worldwide events such as the World Trade Centre terrorist attacks (2001), the Indian Ocean tsunami (2004), the Hurricane Katrina (2005), the London bombings (2005), the eruption of Eyjafjallajökull volcano (2010), the Tohoku earthquake and tsunami (2011) have significantly raised the attention on cascading effects. This encouraged the development of several cascading effects modelling methodologies or tools.

Existing cascading effects modelling methodologies (including frameworks and tools) focused mainly on critical infrastructures of different systems (power supply, water supply, telecommunications, etc.) rather than integrating also human aspects (societal behaviour, human coping capacity like sheltering/shielding, resilience, etc.). The reason is that critical infrastructures are considered as central elements through which failures or disturbances are spread. These methodologies are elaborated to cater the own interests of their developers for research or business purposes or to respond to the needs of critical infrastructures’ stakeholders. For example, specific current power supply methodologies comprise the models of the SEMPOC (Simulation Exercise to Manage POwer cut Crises) project, the "Consequence Calculation Model" applied in the DOMINO (Domino effects modelling infrastructure collapse) project, etc.

The limitation of the scope of these sector specific methodologies may lead to a good understanding of the disturbances spreading within the considered critical sectors. However, this leads very often to the difficulty, moreover, the impossibility, of their combination for a broader/holistic view of cascading effects within a given territory. This thus hinders a comprehensive understanding of the cascading effects within many critical sectors. There are currently few methodologies that consider simultaneously several types of critical sectors. Amongst them:

- The CRISADMIN[1] (CRitical Infrastructure Simulation of ADvanced Models on Interconnected Networks resilience) DG HOME project which aims at simulating the interdependencies between electricity, transportation and telecommunication networks while stressed by critical events, without considering cascading effects (Armenia et al., 2014);
- The PREDICT[2] (PREparing for the Domino effect in Crisis siTuations) framework project which aims at providing a comprehensive solution for dealing with cascading effect in multi-sectorial crisis situations covering aspects of critical infrastructures (Cahuzac-Soave and de Maupeou, 2016);
- The FORTRESS[3] (Foresight Tools for Responding to cascading effects in a crisis) Framework Project which aims at identifying and understanding cascading effects of a crisis by using evidence-based information from a range of previous crisis situations (Hagen et al., 2014);
- The CIPRNet[4] (Critical Infrastructures Preparedness and Resilience Research Network) Framework Project aiming at creating new advanced capabilities for multinational-emergency management, critical infrastructure operators, policymaker's stakeholders and the society through the use of modelling, simulation and analysis for Critical Infrastructure protection (Xie et al., 2016);
- The SNOWBALL[5] (Lower the impact of aggravating factors in crisis situations thanks to adaptive foresight and decision-support tools) Framework project aiming at lowering the impact of aggravating factors in crisis situation thanks to adaptive foresight and decision-support tools (Palumbo et al., 2016).

All of these methodologies highlight the needs to consider:

- The vulnerability and criticalities of the systems,
- Their potential impacts,
- The propagation effects and the propagation timeline.

Some methodologies need high level of data (CIPRNET), some use probability-based approach (PREDICT), others are more deterministic (FORTRESS, SNOWBALL). Some are based on visualisation tool for facilitating knowledge sharing amongst stakeholders involved in crisis preparation or management (PREDICT and FORTRESS).

Our approach aims at providing:

- a pragmatic approach totally end-user compliant by focusing on a total setup to fine-tune and find the key decision points;
- a generic modelling methodological approach able to handle both small and large-scale incidents with both low and high level of details on all sectors of societal life as well as

[1] http://www.crisadmin.eu/
[2] http://www.predict-project.eu/
[3] http://fortress-project.eu/
[4] https://www.ciprnet.eu/
[5] http://snowball-project.eu/

human aspects are taken into account by using both the deterministic and probabilistic approaches;
- a flexible modelling approach able integrate dynamic dependencies and allowing an advice on the unforeseen dependency

This approach should also allow modelling the cumulative cascading effects due to the combination of several disturbances of any hazard type.

2.2 How to address the challenges and gaps / general overview

The developed methodology is a step by step approach in 6 steps, described in the following sections. It allows a systematic approach on both small and large scale incidents.

The purpose is to develop a framework for assessing cascading effect modelling within a case area.

The focus is on determining the systems that can be cascading in a case area, the dependencies between those systems, the effect propagation between and within systems when a case area is affected by an initiating event in preparation phase or during an incident. This approach allows to determine temporal aspects and potential impacts of cascading effects and to assess the key moments that influence the cascade. The methodology thus depends on a thorough knowledge of systems and their components. In fact, the more accurate the input data and the more well-known the system's characteristics, the more precise the method can be in predicting cascading effects. However, even a lack of information does not prevent a user from following the method to the end. The user will simply obtain a more detailed information on foreseeable cascading effects.

The methodology was built in the perspective where crisis managers do not have access to complete and detailed database on the systems and their capacity to propagate and mitigate the effects. The proposed methodology is then framed to the condition where assessment of the systems' capacity to propagate effects is done once known the risk conditions. The methodology is then a top-down approach for which information grain size is decreasing from initial steps to the end.

The Figure 2-1 illustrates the different steps of the methodology.

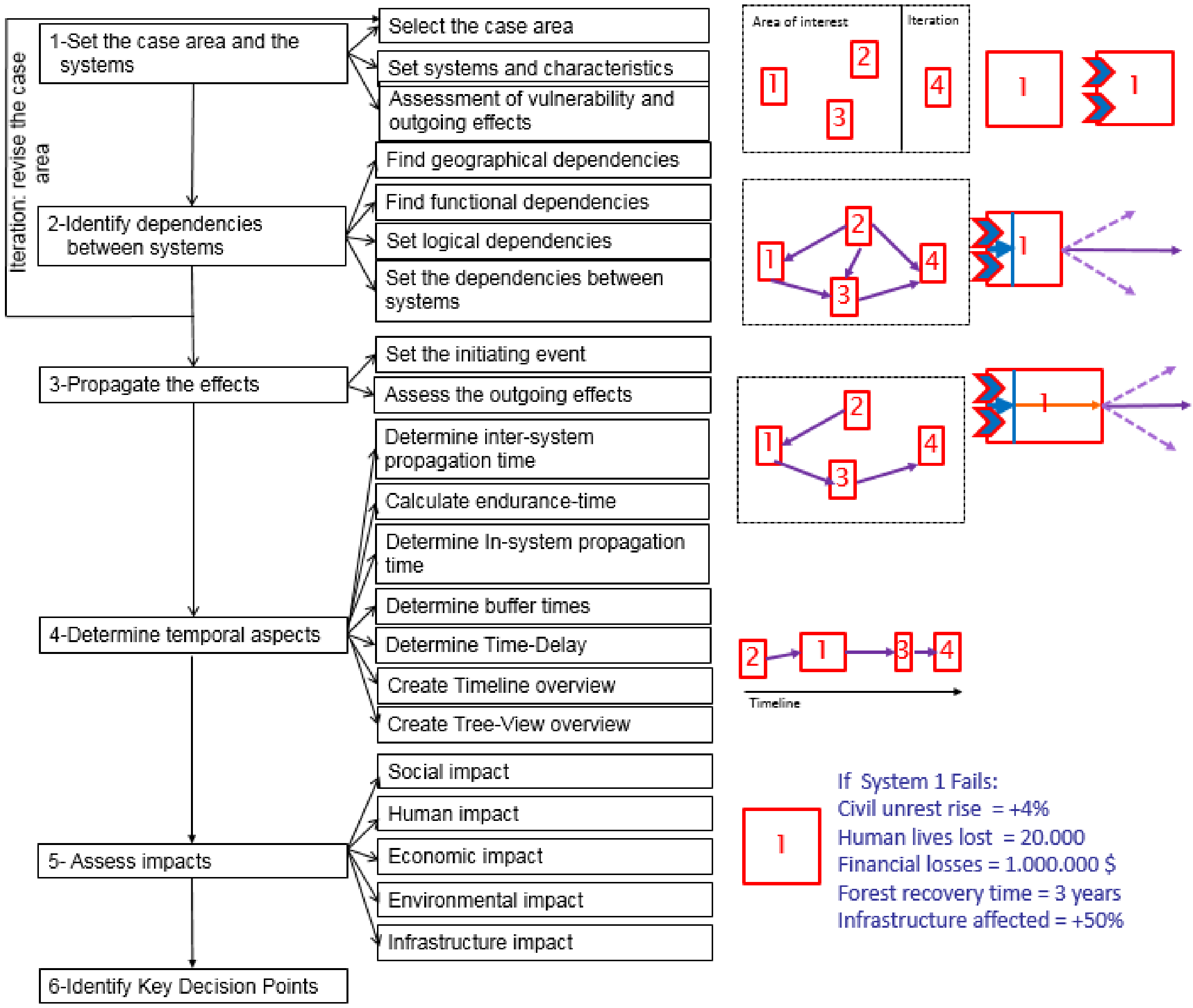

Figure 2-1 General overview of the methodology. The numbered boxes refer to systems included within the selected case area.

The steps presented in Figure 2-1 are described in the following sections.

(1) **Step 1**: Set the **Case area and the Systems** (Section 3.1)
- (1.1) Select the **Case area**
- (1.2) Set the systems and their **characteristics**
- (1.3) Assessment of **vulnerability** and **outgoing effects**

(2) **Step 2**: Identify **dependencies** between systems (Section 3.2)
- (2.1) **Geographical dependencies** between systems
- (2.2) **Functional dependencies** between systems
- (2.3) **Logical dependencies** between systems
- (2.4) Set the **dependencies** between systems
- (2.5) Revise the **case area**

(3) **Step 3**: **Propagate the effects** between systems under known risk conditions (Section 3.3)
- (3.1) Set the **initiating event**
- (3.2) Assess the **risk conditions** and **outgoing effects** of impacted systems

(4) **Step 4**: Determine the **temporal aspects** of the dependencies (Section 3.4)
- (4.1) Determine the **Inter-system propagation time**
- (4.2) Calculate the **endurance-time** of each system
- (4.3) Determine the **In-system propagation time**

(4.4) Determine the **Buffer Time**
(4.5) Determine the **Time Delay**
(4.6) Create the **Timeline** overview
(4.7) Create the **Tree-View** overview
(5) **Step 5**: Assess the i**mpacts: consequences system by system** (Section 3.5)
(5.1) The list of impacts and metrics
(5.2) The scorecard of impacts
(6) **Step 6**: Find the **key decision points** of the Cascade (Section 3.6)
(6.1) Compare impacts between systems
(6.2) Consider the time-delay

In the sections below, each step is described in more detail including reasoning why the steps are needed and examples on the results from each step.

3 Detailed description of the Incident Evolution methodology

As previously mentioned, the methodology aims at being a framework which can be easily customizable so that it can be applied whenever needed. The methodological steps, previously evoked, are described in this section and exemplified by one unique demonstration case so that to facilitate the understanding of users. The demonstration case is also supported by Annex 2 where different models available for determining vulnerabilities are described. It should, however, be emphasized that the methodology can be used also with other means than the detailed modelling. The steps are also illustrated with two shorter examples in Chapter 4.

3.1 Step 1: Set the Case area and the Systems

3.1.1 Select the Case area

Incidents happen everywhere. Providing the required information for everywhere is a task too big to complete. Hence the first step is to limit the scope to what is required to look at. This scope will largely define the amount of work required to completely go through this methodology.

To limit the scope, one needs to know where the focus is. Is it a certain region of interest, is it a specific object of interest, is it a training setup or perhaps a historical scenario to review. Depending on the geographical size of the scope one can draw that up as the Case Area. Case by case the area can be of different sizes as they have different scopes.

For ease of reference we recommend drawing an outline of the Case Area on a map (as shown in Figure 3-1). We also recommend starting small. Later steps allow you to iterate if necessary, in which case the Case Area can be enlarged to encompass the required additional space (cf. Section 3.2.5).

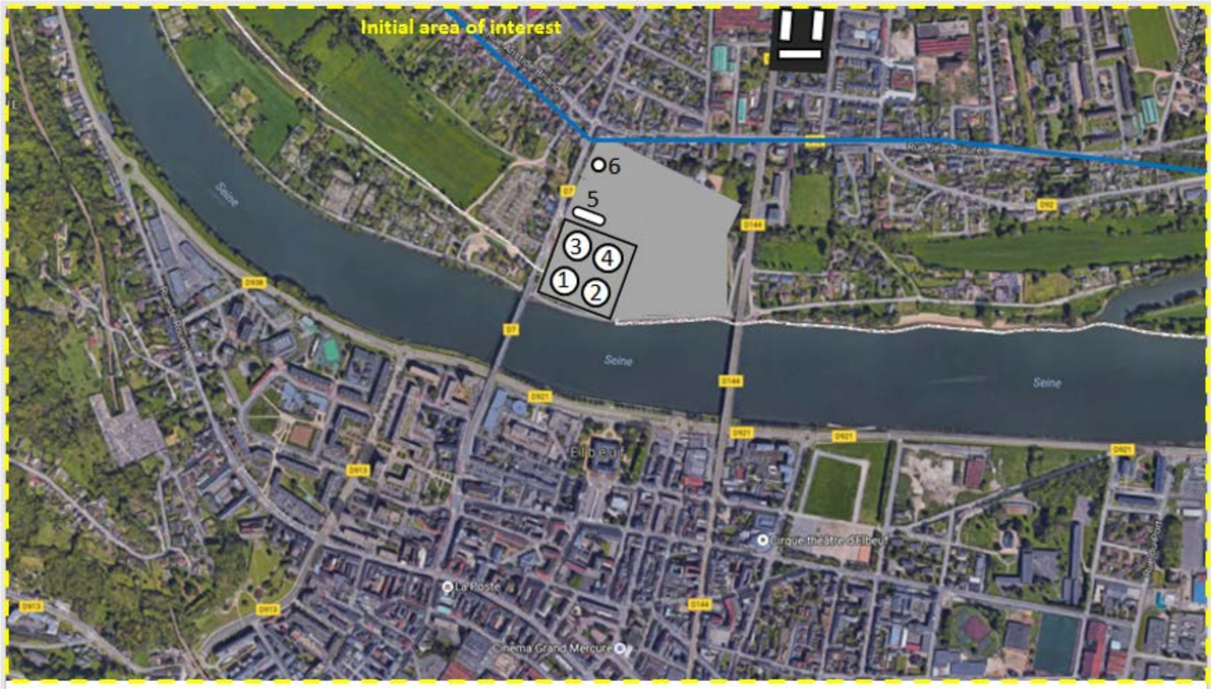

Figure 3-1 Case area outline of the demonstration case.

Figure 3-1 presents the description of a French case area crossed by the Seine river. This example, called afterwards "Demonstration case", will be used all along the description of the methodology for illustrating the different steps.
It contains not only industrial facilities but also civil housings (dwellings), leisure places and other providing service systems described in the next section.

3.1.2 Set the systems and their characteristics

Characterizing the systems allows forecasting the potential dependencies (developed in Step 2) within a case area.

A system can be made of several sub-systems or **components (**cf. Figure 3-2 **Illustration of the system's components)**.

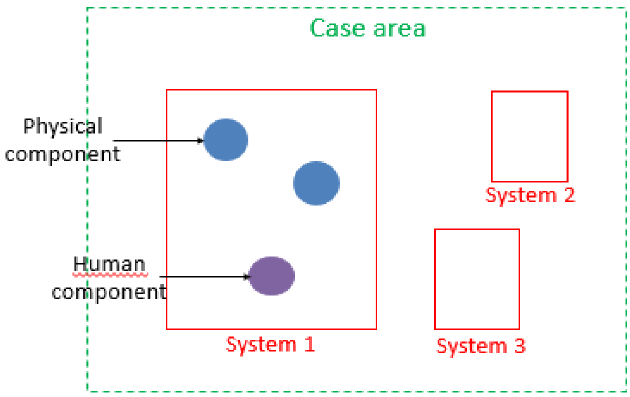

Figure 3-2 Illustration of the system's components.

The physical components are infrastructures, machines, tanks, or pipe/cables connecting one component to another one. The human and organisational components deal with organisational services, legislation framework impacting the organisation of the system and human behaviours and interactions within the system.

Each system is then described according to:

- its geographical location and altitude;
- its size or shape in regards to the case area;
- its components, i.e. the physical and human assets (see Figure 3-3) which allow the system to operate;
- the required services necessary to function;
- the provided services (functions); the added benefit of listing the systems functions is that those with the same function are likely to share the same or similar characteristics and setup of later steps. This will thus greatly reduce the amount of work required to specify the systems.

There is no rule of thumb to state on determining the appropriate detail level of system characterisation as it greatly depends on the chosen scope, the cascading event itself and desired end results. We thus recommend to keep in mind the stated scope and to use the map outline of the case area. To assist in this system determination, we created a non-exhaustive list of 22 System Categories derived from analysing 44 historical scenarios and listing the various systems impacted in the cascades (see D2.2 and D2.3). The 22 system categories are listed in Table 3-1 The 22 system categories.

Table 3-1 The 22 system categories.

System category
Power supply
Telecommunication
Water supply
Sewage supply
Oil and Gas
District heating
Healthcare
Education
Road transportation
Rail transportation
Air transportation
Sea transportation
Agriculture
Business and industry
Media
Financial system
Governmental system
Emergency response
The public
Environmental
Political system
Food supply

The more detailed the system's description, the more accurate the cascading effect modelling. In order to help the user, there were 114 system subcategories specified. This description is presented in Appendix 1 of D2.1.

For each system, we recommend do create a database, such as an Excel sheet where the components determining the vulnerabilities and/or outgoing effects of the system are described. Sometimes, the components of a system can be treated as separate systems where different types of hazards (outgoing effects) can lead to cascading effects between them and to other systems. This is exemplified in the following demonstration case.

Demonstration case:

The Figure 3-3 presents the different systems of the French case area.

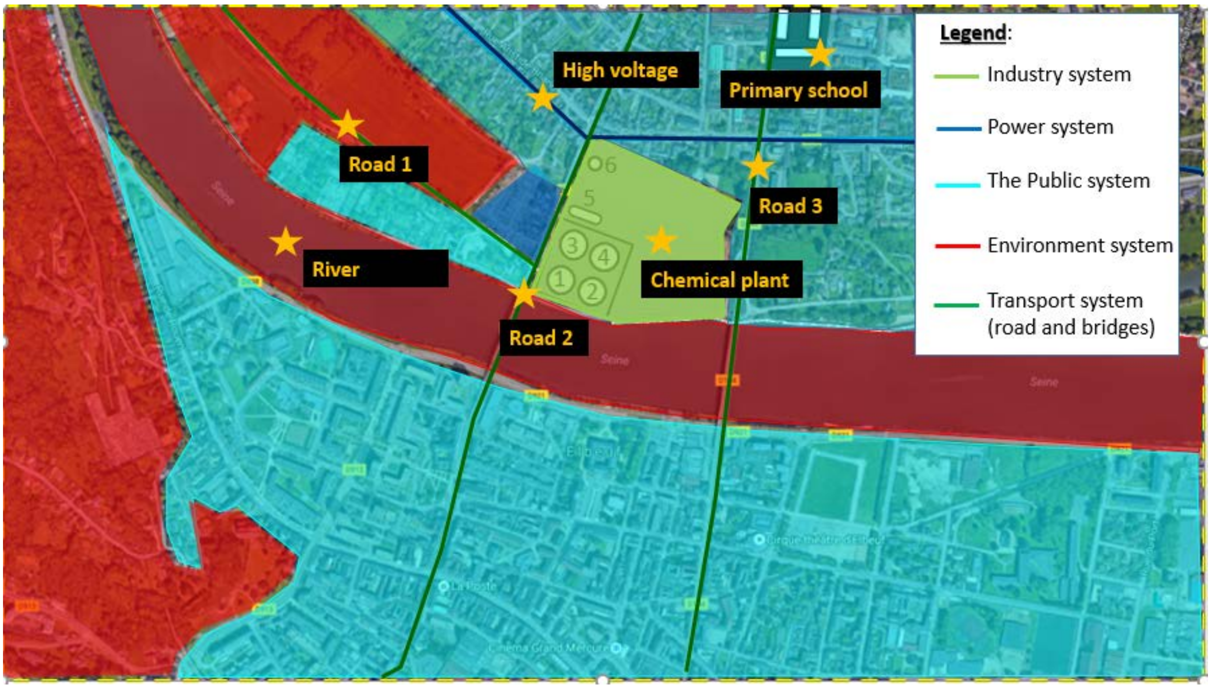

Figure 3-3 The identified systems of the French case area (the stars show the subsystems on which the characterization focus is made).

There are 5 types of systems: Industry, Power, The Public, the Environment and Transport systems.

For sake of simplicity, only the high voltage line (Transmission subcategory of Power supply system category), the chemical plant (subcategory of business and Industry system category), the river, the primary school (subcategory of Education system category) and the roads (subcategory of transport system category) are described below. Furthermore, only the physical components of these systems are described. The human components and their potential cascading effects are mainly described in WP3. We then invite the reader to look at document D2.3 for assessing vulnerability due to human components.

High voltage line

Some characteristics of the overhead high-voltage line are needed in order to assess the vulnerability to mechanical effects (climatic phenomena, blast wave...)

Table 3-2 Overhead high-voltage line characteristics.

Characteristics	Attribute
Height	45 m
Wire diameter	12 mm
Wire length between 2 piles	220 m
Material	Steel wire
Number of users	300.000

Chemical plant

The chemical plant is composed of 6 tanks (cf. Figure 3-3) described according to a set of characteristics useful to predict cascading effects.

Table 3-3 Component characteristics of the chemical plant.

Characteristics	Fuel tank N°1	Fuel tank N°2	Fuel tank N°3	Fuel tank N°4	LPG tank N°5	HCl tank N°6	Whole system
Product	Fuel	Fuel	Fuel	Fuel	Propane	Hydrochloric acid (aqueous solution 29%)	
Height (m)	10	10	19	19	5.5 (length)	10	
Radius (m)	7	7	10	10	1.15	6.5	
Shell thickness (m) (min/max)	0.005/0.01	0.005/0.01	0.007/0.015	0.007/0.015	0.009	0.004 ebonite steel	
Filling rate	20 %	20 %	20 %	20 %	20 %	35 %	
Number of workers	NA	NA	NA	NA	NA	NA	150 persons

Filling rates in Table 3-3 have been chosen considering two factors:

- Storage conditions
- Optimal filling rate to provide maximum outgoing effects

Primary school

The characteristics of this system are defined according to the number of persons present on the property, the presence of a containment room and if applicable, the time needed to evacuate to a local shelter.

Table 3-4 Primary school characteristics.

Characteristics during working hours	
Number of persons	60
Containment premises	No
Time needed to Secure the Confinement Premises (if there are containment premises)	-

River

The Seine river characteristics are described in Table 3-5.

Table 3-5 Seine river characteristics.

Characteristics	
Length	777 km
Basin area	79,000 km^2
Average flow rate	563 m^3/s
Maximum flooding height	4 m

Roads

The 3 roads highlighted in Figure 3-2 are very close to the river, the chemical plant and the primary school. Road 1 intersects with Road 2. Both of them insure the liaison between the chemical plant and other major transport axes. Road 3 insures the liaison to Primary school and is located in the neighbourhood of the chemical plant. Road 3 and Road 2 cross the river.

Table 3-6 Characteristics of roads 1, 2 and 3.

Characteristics during working hours	
Road 1- Number of cars / hour	5000
Road 1 - Length	2 km
Road 2- Number of cars / hour	10000
Road 2 - Length	50 km
Road 3- Number of cars / hour	15000
Road 3 - Length	100 km

These characteristics associated to their location, can be recorded in a database. They are inputs for assessing the overall vulnerability of the system, described in the following sections.

3.1.3 Assessment of vulnerability and outgoing effects

3.1.3.1 Assessment of vulnerability of each system

The vulnerability, illustrated in Figure 3-4 with arrows, is the susceptibility degree of a system to collapse or degrade under certain types of effects listed in Table 3-7 (indicated also with the metrics).

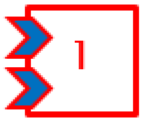

Figure 3-4 Illustration of a system's vulnerability.

The vulnerability should then be assessed for each component (physical and human) and for each type of effect. Knowing the vulnerability allows to predict a risk of effect propagation to other systems. That's why this step is very important.

Table 3-7 List of effects which can affect a system and their associated metrics.

Effect categories	Effects sub-categories	Code	Metric	Possible Units
Natural	Flood / Water	WA	Height AND Velocity	[m] AND [m/s]
	Epidemics	EP	Percentage of diseased AND Severity	[%] [low, medium, High]
	Wild fire	FI	Distance AND speed of Propagation	[m] AND [m/s]
	Landslide, ground movement, earthquake	GM	Acceleration OR Displacement	[m^2/s] [mm/m]
	Storm	WS	Wind Speed AND Precipitations	[m/s], Beaufort scale [mm]
	Tsunami	TS	Wave height	[m]
Accidental	Blast	PRI	Pressure value OR Pressure Variation AND Distance	[mbar] [mbar] [m]
	Projectile	MI	Distance AND Energy	[m] AND [kJ]
	Fire/Thermal radiation	TH	Distance AND Thermal radiation	[m] AND [kW/m^2]
	Emission of toxic release/dumping	TO	Concentration AND Distance	[mg/m^3] [m]
Functional	Communication Service Degradation	CS	Percentage	[%]
	Water Service Degradation	WS	Percentage	[%]
	Workforce Service Degradation	WS	Percentage	[%]
	Energy Service Degradation	ES	Percentage	[%]

Effect categories	Effects sub-categories	Code	Metric	Possible Units
	Food Supply Degradation	FS	Percentage	[%]
	Transport Service Degradation	TS	Percentage	[%]
Intentional	Bombing	PRI	Pressure value OR Pressure Variation AND Distance	[mbar] [mbar] [m]
	Social rumour / effect	SO	Severity	[low, medium, High]
	Hostage taking	HO	Number of people taken	[number]
	Shooting	SH	Number of people shot	[number]
	Fire	TH	Distance AND Thermal radiation	[m] AND [kW/m²]

As said previously, the vulnerability should be assessed according to these types of effects. Prioritizing one effect on others allow to **build scenarios** of cascading effects. Usually the effects considered in priority are those for which the vulnerability is maximal.

The way to assess the vulnerability of the systems for each effect subcategory can be through:

- the use of **deterministic models** on system components' behaviour as it is the case for soil erodibility assessed as a function of soil texture, structure, organic matter and permeability;
- the use of **experimental approach** where different system parameters are tested according to effect conditions. The vulnerability of tanks in energy systems can be assessed through types of material, thickness, shape/radius size under different pressures. Usually, **vulnerability thresholds** are the outcomes of experimental approaches.
- the **monitoring** of system conditions involved in the vulnerability assessment. The monitoring is done by using sensors adapted to risk conditions. For ground monitoring, geophysical sensors can measure ground movement, thermal sensors gas emissions, radar sensors roughness. Some examples on this topic are detailed in D2.4.

Scientific literature, models and databases usually gather information on or give access to systems' vulnerability. Experience of experts and responsible personnel will also be important in these analyses.

<u>**Demonstration case**</u>

Regarding the demonstration case, the effects which can affect the 7 systems belonging to 5 different system categories are the overall list but tsunami and volcano. Although volcano and tsunami cannot happen in the area, they can indirectly affect the system from good transport disruption (as it was the case with the Eyjafjallajökull volcano in 2010).

The way to assess the vulnerability of the systems to all effects can be:

- for chemical plant, the tanks are tested experimentally under different pressures/intensity levels of effects from which deterministic models can be derived. These models are usually used to assess regulatory safety thresholds which are then considered in systems' design. Vulnerability of the case area chemical plant components is better described in Step 3 (under flooding condition);

- for high voltage line as for chemical plant, cable vulnerability is also experimentally tested leading to deterministic models and safety thresholds considered for designing the infrastructure.
- for primary school and more generally buildings, vulnerability will be assessed using deterministic approach combining factors such as level of visibility, criticality of site to jurisdiction, impact of site outside of jurisdiction, accessibility of the site to the public, height of the building, type of construction (built underground, protected by earth berms and embankments, reinforced concrete, steel beams, masonry, steel studs, wood..), population capacity of the site, potential for collateral mass casualties (Kemp, 2007). It can be done also by in-situ or remote sensing monitoring (Mück et al., 2013);
- for roads, vulnerability is related to exposure (giving access to potential flooding, industrial accidents, wild fires, earthquakes…) and to the traffic.
- for river, vulnerability depends on the geomorphological, climatic and anthropogenic conditions where the river is such as distance to watershed head (and sometimes to the sea), degree of connectivity to other rivers, valley embedment, climatic conditions (high intensity frequency of rain events) and neighbouring soil sealing intensity which can hamper soil water filtration.

3.1.3.2 Assessment of outgoing effects

The outgoing effects of the systems and how far it can reach (outgoing effect distance) allows to determine geographically which and where impacted systems can be, due to outgoing effects of originating systems. This distance thus allows to assess the geographical dependencies between systems (cf. Step 2). This distance is illustrated in Figure 3-5.

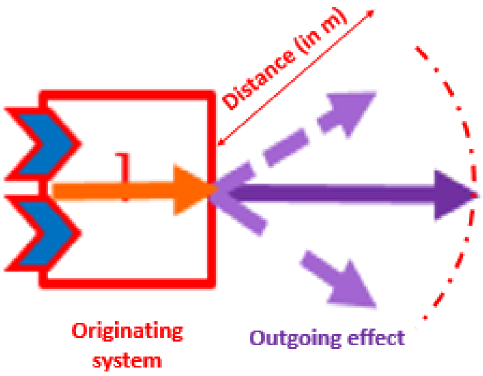

Figure 3-5 Illustration of outgoing effects distance.

When a system is reached by an incoming effect (outgoing effect from another system), which it is vulnerable to it can be affected. The system producing the outgoing effect becomes then an originating system which can lead to cascading effects.
The outgoing effect distance of an originating system can be calculated for each type of outgoing effect which list is the same as in Table 3-7 without intentional effects. Distances can be evaluated by using, as for vulnerability, experimental and deterministic approaches and scientific and regulatory databases.

As previously explained, it is important to note that the more the user will have specific descriptive data, the less it will be necessary to perform computing operations in the following steps 2, 3 and 4.

In Step 3, the outgoing effects are evaluated under specific risk conditions resulting from the initiating event.

Demonstration case

- For industrial and power supply systems like refineries and transmission cables, the maximum effect distance is provided through:
  - The regulatory safety distance;
  - Descriptive map of energy distribution networks;
  - Other data giving detail description of system propagation risk conditions.
- For Seine river, flooding distance can be assessed from historical databases regarding flooding in the same area. It can also be assessed by using remotely sensed data on topography, geology combined to weather data.
- For roads, effect distance is related to their degree of connectivity to other transport axes and to the transport purposes and traffic intensity.
- For public primary school, the outgoing effect is supposed to be null.

The Figure 3-6 illustrates potential outgoing effect distances (of the river and the chemical plant).

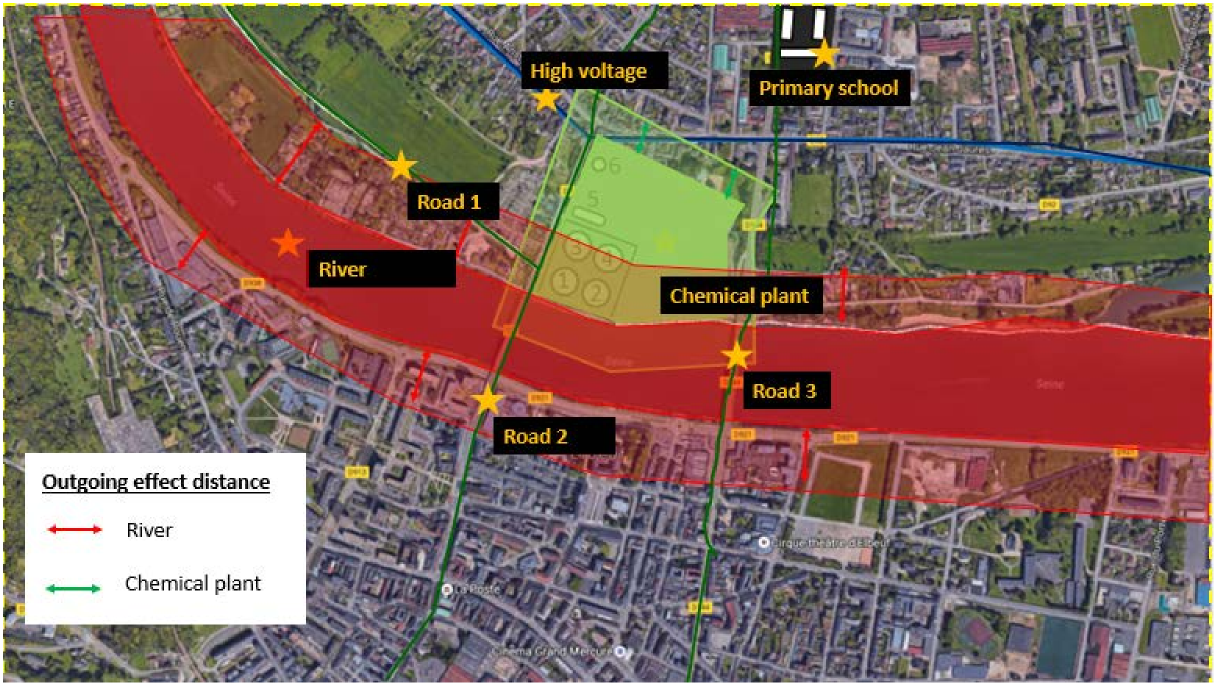

Figure 3-6 Illustration of potential outgoing effect distances (for the river, in red and the chemical plant, in green).

Interpretation of Figure 3-6 is done in the next section, related to dependencies.

3.2 Step 2: Identify dependencies between systems

Within a case area, systems, more specifically the components of the systems, are interacting through dependencies. These dependencies permit to predict which systems can be affected by other systems disruption or collapse.

Three types of dependencies can be distinguished: geographical, functional and logical. They are explained and illustrated in the following sections.

3.2.1 Definition and examples of geographical dependencies

The geographical dependencies are when systems that are located in the same area and where change in local environment can create state changes in all or some of them (i.e. a fire in a specific location can affect other systems in the vicinity, a flood can affect the system implanted in the floodplain, etc.).

For the geographical dependencies, since the effect area might change over time, it should not be limited to one single area or shape but should be defined in 3D Shape.

For ease of distinguishing dependencies on a geographical basis, any system that has its location or area partly covered by an outgoing effect area, which it is vulnerable to, is said to be affected.

<u>**Demonstration case**</u>

Regarding the French case area, Figure 3-6 Figure 3-6 Illustration of potential outgoing effect distances (for the river, in red and the chemical plantillustrates potential outgoing effect distance of the river and the chemical plant systems. From this Figure, it is easy to detect that river system has geographical dependencies with chemical plant, roads 1, 2 and 3, since a flooding can affect these systems.

The chemical plant has also geographical dependencies with the river (since toxic release of the chemical plant can induce river pollution), with roads 1, 2 and 3 (from industrial accidents), the primary school and the high voltage transmission line. River and chemical plant are then geographically interdependent.

Chemical plant geographically depends on Roads 1 and 2 for service and good provisions. Chemical plant and Roads 1 and 2 are interdependent although not for the same purpose.

Primary school geographically depends mainly on Road 3.

3.2.2 Definition and examples of functional dependencies

The functional dependencies are when the state of a system is dependent on the output(s) of another system (e.g. a public heating system is dependent on the gas network transportation to work).

The recommendation for finding functional dependencies is to ask “what does this system need to function?” or ask “what needs to be missing for this system to degrade?”. Then apply the answers for each of the case area systems. When having set the system characteristics in a database, the service required for functioning has been specified.

We recommend doing this system by system, to be able to keep a focus on all the outgoing or incoming service needs (service being provided by specific systems).

Examples of functional dependencies are presented in Figure 3-7.

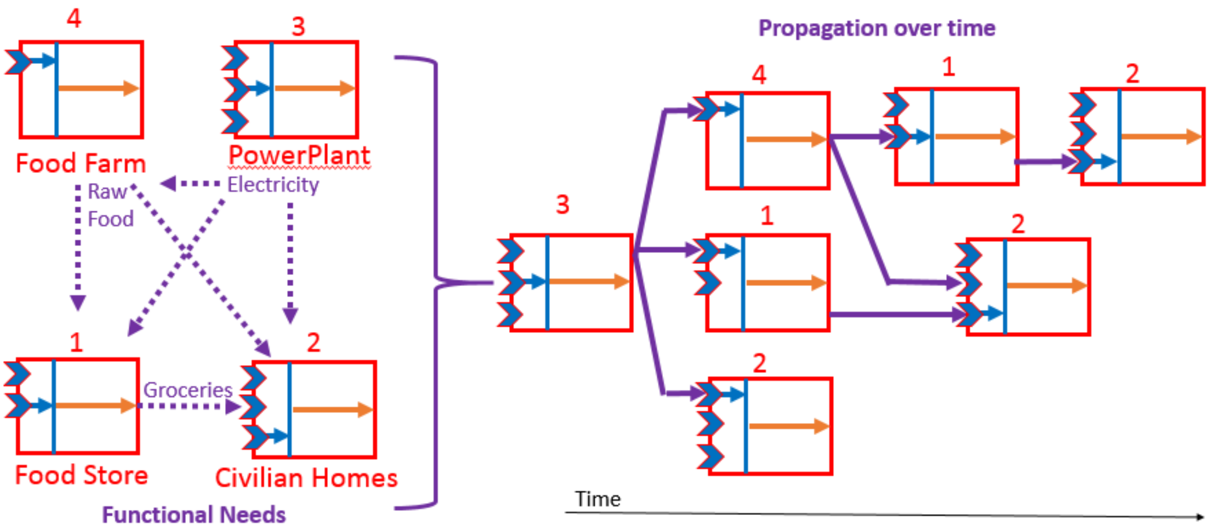

Figure 3-7 Representation of functional dependencies.

Food farm needs electricity to function, such as civilian homes and food stores which require also raw food from food farm to function. If the power plant system (system 3) is disrupted, there will be outgoing effects on food farm (system 4), food store (system 1) and civilian homes (system 2). Food farm (system 4) being affected, it can have impacts on food store (system 1) and civilian homes (system 2). Food store being affected can have impacts on civilian homes (system 2).

Demonstration case

Regarding the case area, the functioning of chemical plant depends on Roads 1 and 2 for incoming and outgoing service and good provisions.

Primary school is mainly depending on Road 3 for student transportation.

3.2.3 Definition and examples of logical dependencies

A logical dependency is/occurs when a state change in one system results in a state change in another, without a geographical or functional dependency causing this change.

The logical dependencies are related to the human components of the systems, both organisational, or individuals, etc. They usually consist of, or arise from, management processes, regulations, quality processes, choices and evaluations, and in general any component presenting human decisions and human actions. They are aspects of cognition and social life or dynamics, and they can affect any of the actors involved in incidents. As a consequence, these logical dependencies potentially concern all systems, including the Emergency response system, which can then cause other effect propagation. The logical dependency is as such a free dependency that can be added in creating a model of an incident with cascading effects when human decisions and actions create a new dependency across systems.

For these same reasons, it is also difficult to identify and much more difficult to predict them. They are best identified and investigated, by using a qualitative approach to social dynamics and effects, as described in Deliverable D2.3, whereas the geographical and functional dependencies are tackled by using deterministic and probabilistic approaches. To help in determining if there are logical dependencies involved, one can ask the question “is there anything else than geographical and functional dependencies that would cause this system to degrade?”

While their nature makes their prediction very difficult, it is possible to assess them and develop flexible policies and strategies in case logical dependencies arise during crises.

The assessment of logical dependencies should take into account the elements that are at the centre of the analysis provided in D3.2. These elements can be summarised for the purposes of this methodology as:
a) the centrality of the role of human behaviour and communication dynamics in crisis situations (i.e. their latent potential connection with all other systems);
b) their nature (flows of information, processes of negotiation), complexity, and their ephemeral directionality (incoming or outgoing direction of effects can change according to new dynamics of information flows, new interpretations, and event, artefact, and actor can affect each other, also from the micro to the macro level);
c) the role of specific temporal (including past) and spatial, information-rich, contexts on the impact that mediated information and decision making have on other systems during a crisis.

Logical dependencies do not behave in ways that allow calculation and modelling of cascading effects as the geographical and functional dependencies, but require contextualised approaches for each crisis, which also take into account the specific elements summarised above. The review of models, case studies, analysis, and guidelines presented in WP3 provides guidance that allow for logical dependencies to be tackled by policies strategies for planning, preventing and managing cascading effects. A successful management of many of the aspects of the logical dependencies is indeed best achieved by relying on those flexible models and strategies, and taking into account lesson learnt from past experiences, in order to adapt planning, response, and recovery management to the specific context of each new crisis.

<u>Demonstration case</u>
Regarding the French case area, let's imagine the flooding of the river which affect (through geographical dependencies) not only the chemical plant, but also the primary school. Although, the chemical plant and the primary school do not have neither geographical, neither functional dependency with the high voltage transmission line, evacuation of chemical plant or primary school can lead the workers or children to climb the overhead transmission cable pillar to avoid being drowned, resulting on a disruption of the power supply system. This human behaviour creates a logical dependency between the chemical plant and the transmission line and between the primary school and the transmission line, but it will not be taken into account in the following steps.

3.2.4 Set the possible dependencies

Now that the different types of dependencies are explained, the systems can be linked together within the case area. As said previously, in the following steps, the focus will be on geographical and functional dependencies only. For more information on logical dependencies, see Deliverable D2.3.

The dependencies between systems can be set up:
- From the knowledge of the case area system, built from field survey, as it was done for the demonstration case (It is the main approach we take in the following);
- From the globally analysis of past incidents linking originating to impacted systems (this analysis takes into account at the same time geographical and functional dependencies) as presented in Section 3.2.4.1;
- From the analysis of incoming effects the systems are vulnerable to and outgoing effects the systems can propagate both through geographical and functional dependencies (Section 3.2.4.2);

3.2.4.1 List of dependent systems from past incident analysis and probability of the dependencies

One can refer to this list when considering a large scale case area containing a lot of systems where access to detailed component description is rather difficult. This section, followed by probability analysis can help the user to build **a probabilistic approach**.

The global analysis of dependencies between systems acting either as originating either as impacted system has been made and presented in D2.3. The results of the analysis are summarized in Figure 3-8.

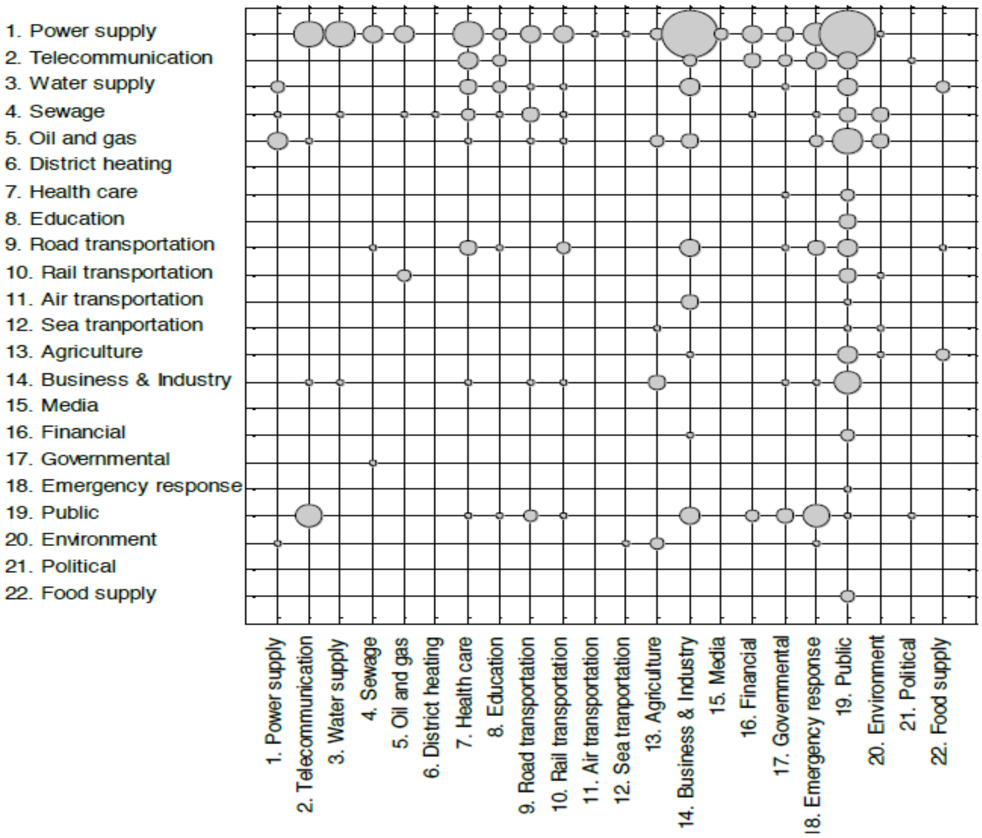

Figure 3-8 Number of OD-pairs with originators (i.e. initiating events or originating systems) on the y-axis and the dependences (i.e. impacted systems) on the x-axis. A large circle represents a frequent OD-pair, while a small circle represents an infrequent OD-pair (cf. Figure 5.1 of D2.3).

It appears that power supply is the most frequent originator, i.e. acting as initiating event or originating system of outgoing effects mainly on Industry and business, Public, Communication, Water supply and Education systems.

Based on the number of events used in D2.3, the occurrence rates of cascading effects in each system category in respect to the category of system where the originating effect occurs has been extracted. The results are shown in Figure 3-9.

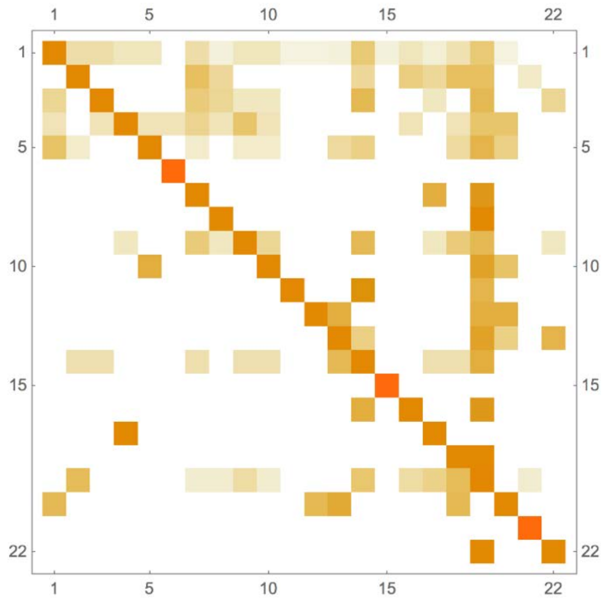

Figure 3-9 Occurrence rates of cascading effects in categories of system (X-axis) depending on the originating category of system (Y-axis).

Figure 3-9 shows the occurrence rates of the 22 system categories (numbered from 1 for "Power Supply" to 22 for "Food supply"). Because on one hand, the database of studied events is not enough statistically representative for placing a high confidence level on the occurrence rates, and on the other hand, the process whereby systems impact each other during these historical events is not precisely understood, the value of the calculated occurrence rates was not presented. Only their relative importance (in terms of dependence probability level) was illustrated using colour gradient. The darker the colour, the higher the rate.

A Markov chain process was used to estimate the probability of a system category to be impacted by an originating system category. The probability should be considered as the likelihood of a category to be impacted by incoming effects of a given category. Even if a high confidence level could not be placed in the results (due to the above-mentioned limitations), the probability provides an indication on the priority order of analysing dependencies and effect spreading between categories located within the case area since without any consideration of functional or geographical dependencies.

The Figure 3-10 (a) shows the probability of categories with "Power supply" (n° 1 on the Y-axis) as the originating category.

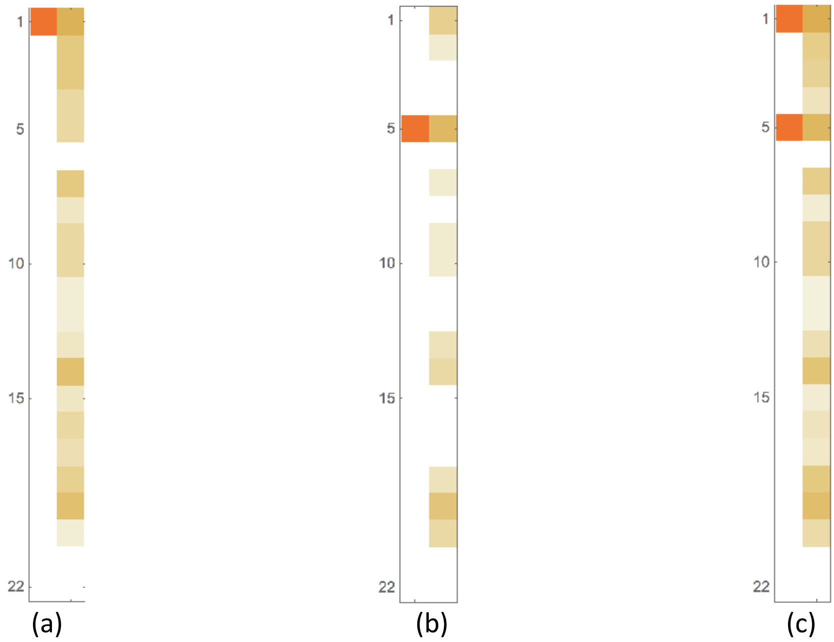

Figure 3-10 Dependence probability of system categories “Power supply” (a), “Oil and Gas” (b) and “Power supply” + “Oil and Gas” (c) as the originating categories.

It appears that almost all of categories can potentially be impacted by effects from “Power supply” (higher probability for the originating category). The “District heating” (n° 6), “Political” (n° 21) and “Food supply” (n° 22) categories have lower probability.

To ease the use of probability, the results are listed as a decreasing priority order ranking and presented in Annex 1.

3.2.4.2 List of dependent systems from the incoming and outgoing effects

Another way to identify and set up the dependencies between systems of the case area is to consider systems which can be either vulnerable to incoming effects or originator of outgoing effects. They are listed in

Table 3-8 for geographical dependencies and in Table 3-9 for functional dependencies.

Table 3-8 Systems which can be either vulnerable to incoming effects (V) or originator of outgoing effects (O) for geographical dependencies.

Legend/ V: system vulnerable to incoming effects, O: system producing outgoing effects	Epidemic (EP)	Fire (FI)	Ground movement (GM)	Humidity (HU)	Projectile effect (MI)	Industrial accident pressure (PR)	Wind pressure (PRW)	Radiation (RA)	Toxic effect (To)	Transport service degradation (TS)	Water / Flood (WA)	Temperature (TE)
Systems	**Effects**											
Power Supply		OV	V		OV	OV	V	OV		OV	V	O
Telecommunication		V	V			V	V	V			V	
Water supply	O		V						O		OV	V
Sewage	O		V								OV	
Oil and Gas		OV	V		OV	OV	V	V	OV	OV	V	
District heating		OV	V		OV	OV	V			V	V	V
Health care	OV		V		V	V	V		V		V	V
Education	V		V		V	V	V		V		V	V
Road transportation			V		O	OV	V		OV	OV	V	V
Rail transportation		V	V		O	OV	V		O	OV	V	V
Air transportation		OV	V		O	V	V			OV	V	V
Marine transportation	O	OV	V		O	OV	V		OV	O		
Agriculture	O	V	V				V	V	O		V	V
Business and Industry	O	OV	V		OV	OV	V	V	OV	V	V	V
Media												
Financial												
Governmental												
Emergency response	O											
The public	V	V	V		V	V	V	V	V	V	V	V
Environment	O	V				V	V		OV			V

Legend/ V: system vulnerable to incoming effects, O: system producing outgoing effects	Epidemic (EP)	Fire (FI)	Ground movement (GM)	Humidity (HU)	Projectile effect (MI)	Industrial accident pressure (PR)	Wind pressure (PRW)	Radiation (RA)	Toxic effect (To)	Transport service degradation (TS)	Water / Flood (WA)	Temperature (TE)
Systems	**Effects**											
Political												
Food supply	O							V				V

When a system is both originator and vulnerable, it can be considered as central node of effect propagation. In some way, it is a critical system. It is mainly the case for business and industry, transportation, power supply, oil and gas. The Public and Education systems are mainly vulnerable systems, acting then as impacted systems, more than originating system.

Table 3-9 Systems which can be either vulnerable to incoming effects (V) or originator of outgoing effects (O) for functional dependencies.

Legend/ V: system vulnerable to incoming effects, O: system producing outgoing effects to	Communication Service degradation (CS)	Energy Service degradation (ES)	Food supply degradation (FS)	Public health deterioration (PB)	Social effect (SO)	Transport service degradation (TS)	Workforce degradation (WFS)	Water Service degradation (WS)
Systems	**Effects**							
Power Supply		OV			V	O	V	V
Telecommunication	OV	V			OV			
Water supply		O	O	O	V		O	O
Sewage			O		O			
Oil and Gas	V	OV			V	VO	V	
District heating	V	OV		O	OV	V	V	
Health care				OV			OV	
Education				V	OV		V	
Road transportation			O		OV	OV	OV	
Rail transportation			O		OV	OV	OV	
Air transportation					OV	OV	V	
Marine transportation			O	O		O		
Agriculture			O	O	O	V	O	V
Business and Industry				O	OV	V	O	V
Media	V				O			

Legend/ V: system vulnerable to incoming effects, O: system producing outgoing effects to	Communication Service degradation (CS)	Energy Service degradation (ES)	Food supply degradation (FS)	Public health deterioration (PB)	Social effect (SO)	Transport service degradation (TS)	Workforce degradation (WFS)	Water Service degradation (WS)
Systems	**Effects**							
Financial	V				OV			
Government	V	V	V	V	V			V
Emergency response	V			O	V	V	V	
The public	V	V	V	V	VO	V	V	V
Environment			O	O	O			V
Political					VO			
Food supply			O	O	O		OV	

For functional dependencies, agriculture, water supply and food supply are acting mainly as originating system although incoming effects can also impact them. Government and the Public are mainly impacted systems.

These analyses allow for helping the user to classify the systems into vulnerable (impacted system) or originator system.

Demonstration case

The case area extent being not so big, we used the knowledge on the area we have, thus privileging common sense (Section 3.2.4.2) and field survey rather than existing database (Section 3.2.4.1). In the previous sections, we illustrated the geographical and functional dependencies between the 5 subcategories of systems found in the case area. Figure 3-11 maps the dependencies.

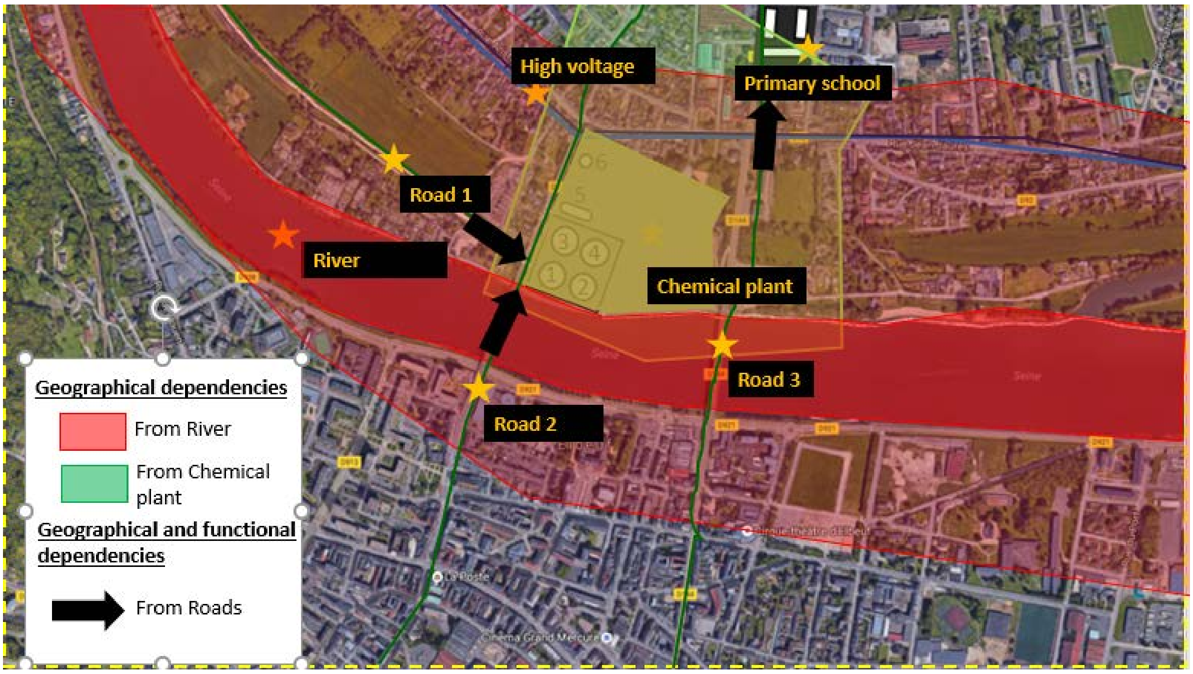

Figure 3-11 Map of the dependencies between the systems of the case area.

This map, which recalls the analysis done in Sections 3.2.1 and 3.2.2 allows to build the following dependency matrix (Table 3-11)

Table 3-10 Matrix of dependencies between the system of the case area (F: functional dependency, G: geographical dependency).

	Originating systems						
	River	Road 1	Road 2	Road 3	Chemical plant	High voltage	Primary school
Depend systems							
River					G		
Road 1	G		G/F		G/F		
Road 2	G	G/F			G/F		
Road 3	G				G/F		
Chemical Plant	G	G/F	G/F				
High voltage					G		
Primary school	G			G/F	G		

Table 3-10 allows to imagine high level impacts of an industrial accident and a flooding on the case area, since most of the systems are depending on chemical plant and river.

3.2.5 Revise the case area to consider

Assessment of the dependencies between systems can lead to identification of other dependencies with systems not located in the initial case area. An extension of the case area is then necessary, leading to an increase of the systems to consider as presented in Figure 3-12.

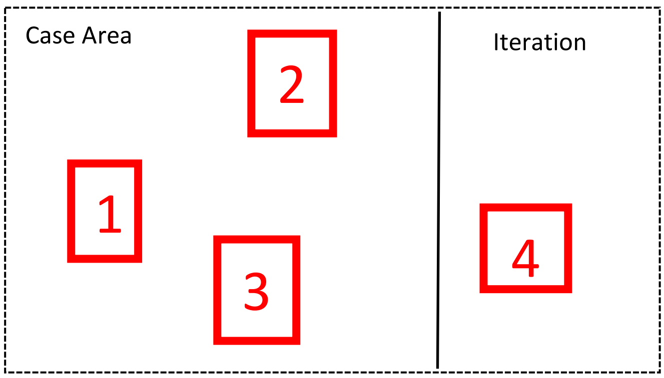

Figure 3-12 Extension of the case area after iterating Step 2.

<u>Demonstration case</u>

It would be possible to enlarge the area due to other geographical dependencies of the river with other systems (in that case all the systems which can be found along the 777 km of the river) or the downstream services of the high voltage transmission line with other systems outside the area. For sake of simplicity, we conserve the spatial extent of the case area, having in mind that for industrial accidents and flooding, other cascading effects may happen outside the area.

3.3 Step 3: Propagate the effects under known risk conditions

3.3.1 Set the initiating event

The initiating event is necessary to be able to provide the risk conditions of the potential cascading effects, i.e. the effect intensity and the system vulnerability, and then to assess, from the previously identified dependencies, the ones that will actually lead to cascading effects.

Table 3-7 provides the list of potential initiating events which can affect the systems.

Demonstration case: the initiating event is the flooding of the Seine river.

3.3.2 Assessment of the outgoing effects for each system

Once the initiating event is set, by following techniques presented in Step 2, it is possible to assess the outgoing effects of impacted vulnerable systems and to propagate the effects in cascading order. The list of outgoing effects is the same as the one presented in Table 3-7 without intentional effects, storm, tsunami and volcano which are usually not the consequence of 1st order effects.

As said previously, impacted system will lead to outgoing effects when they are vulnerable to a specific incoming effect intensity threshold due either to the initiating event (for 1st order cascading effect), either to originating systems (for other cascading orders). For functional dependencies, the threshold depends on the number of redundant functional dependencies which increase the threshold up to the redundancy number time the initial set up threshold). The redundancies of dependencies permit the system to function on degraded mode and to avoid cascading effect.

Demonstration case

The initiating event of the case area is set up as being **flooding of the river during working time hours**. The **effect propagation time** of flooding is set up to be **30 min**. The effect intensities have been set up to be between 4 m nearby the river (indicated in red and yellow in the Figure 3-13).

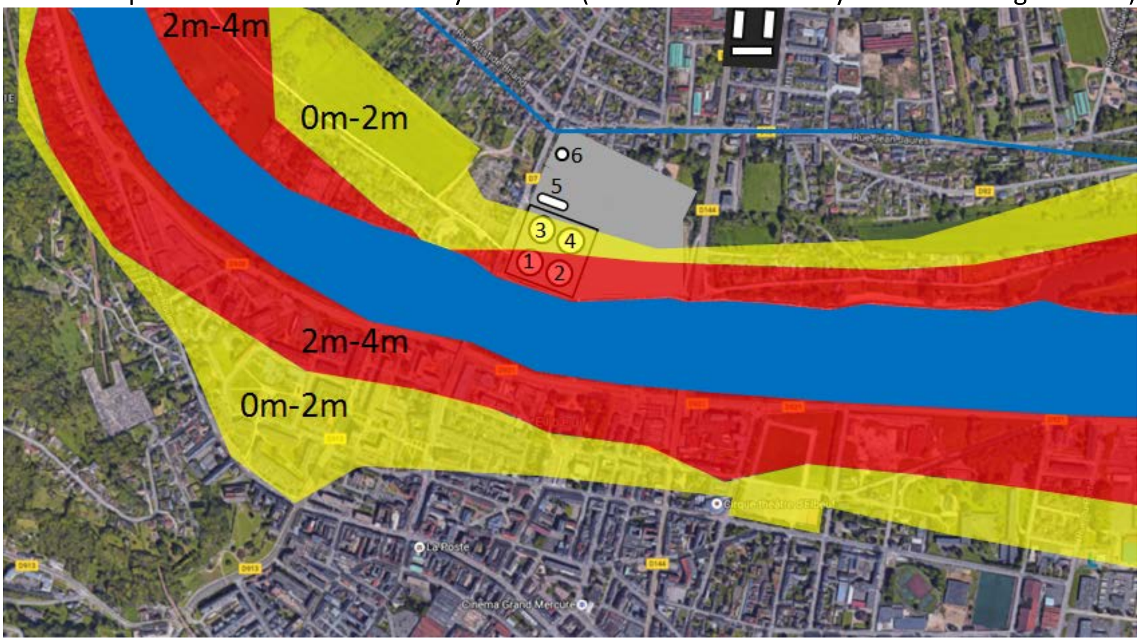

Figure 3-13 Mapping of the river water height (in m) along the river.

The water flow velocity has been set up to 2 m/s homogeneously in the river bed.

Considering the flooding of the Seine river shown in Figure 3-13, the 1st order cascading effects will be on roads 1, 2 and 3 and part of the chemical plant considered as the sum of the 6 tanks/components. The flood will impact Tanks 1, 2, 3 and 4 (see Figure 3-13).

Figure 3-14 represents the 1st order cascading effect.

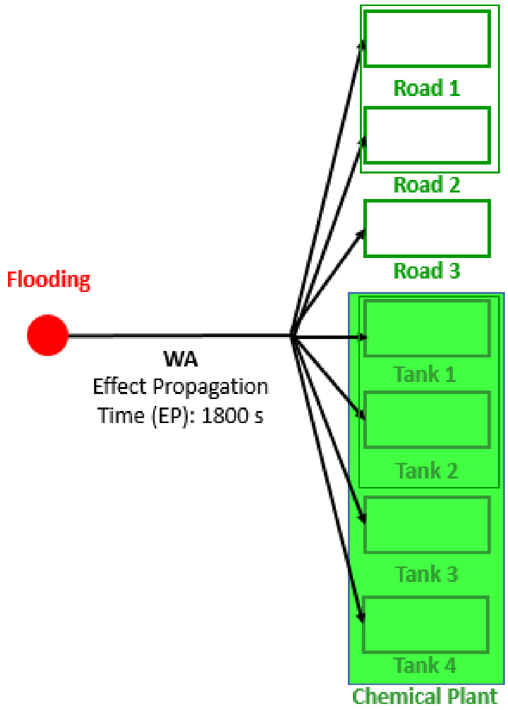

Figure 3-14 1st order cascading effect of the case area due flooding initiating event.

In order to assess the 2nd order cascading, vulnerability of roads and tanks to water height and velocity is assessed.

For the chemical plant tanks, the thresholds of water level height and water flow velocity for which the tanks become vulnerable are assessed by using deterministic predictive models illustrated in Figure 3-15. The detailed calculation of vulnerability is presented in Annex 2.

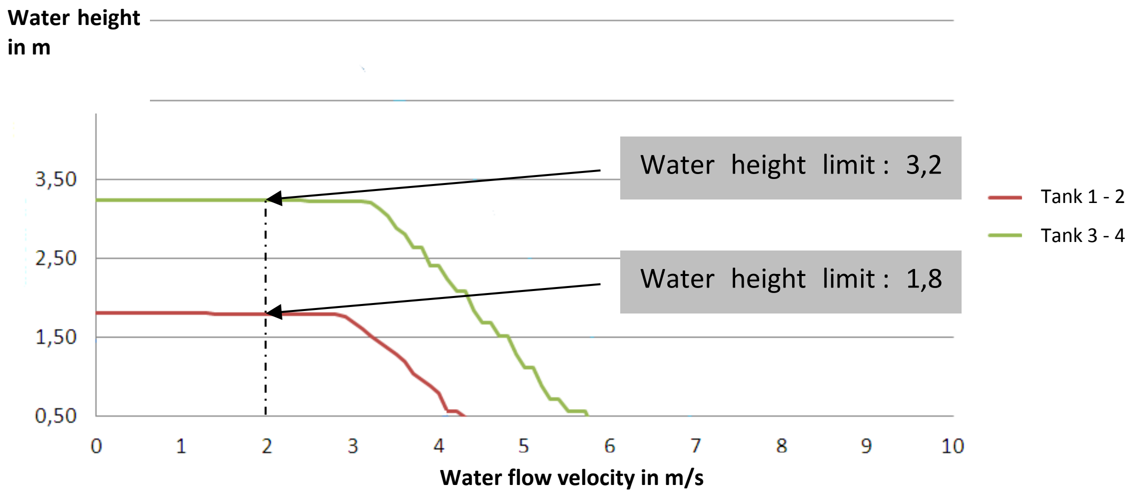

Figure 3-15 Permissible water level for anchored tanks with filling rate of 20 %.

Figure 3-15 shows that Tanks 1 and 2 are vulnerable to water height of 1.8 m and water flow velocity of 3 m/s. Tanks 3 and 4 are vulnerable to water height of 3.2 m and water flow velocity of 3 m/s. The conditions being:

- Tanks 1 and 2 are affected by water height of 4 m and water flow velocity of 2 m/s, so Tanks 1 and 2 are vulnerable and will propagate effects;
- Tanks 3 and 4 are affected by water height of 2 m and water flow velocity of 2 m/s, so Tanks 3 and 4 are not vulnerable and will not propagate effects;

As a consequence of Tanks 1 and 2 vulnerabilities, outgoing effects of these 2 systems will be:

- Fuel oil spill into the water (TO) i.e. into the river;
- Major fire (FI)
- Service Disruption of Transport (SI)
- Potential Workforce Degradation (WFS)

To assess the 2nd order cascading effects, one should now assess the vulnerability of Tanks 3, 4, 5 and 6 to fire. To this aim, effect distance of thermal radiation of Tanks 1 and 2 should be mapped for different intensity of thermal radiation.

Given the projected flooding height and the geomorphology of the case area, the fire will be confined to the retention basin surrounding the tanks. Thus, Tanks 3 and 4 will be impacted by the fire initiated on Tanks 1 and 2. The distances of the thermal effects for 3 overall thresholds of **thermal radiation** intensity are calculated for a retention basin with dimensions of 40 x 40 m². They are represented in Figure 3-17.

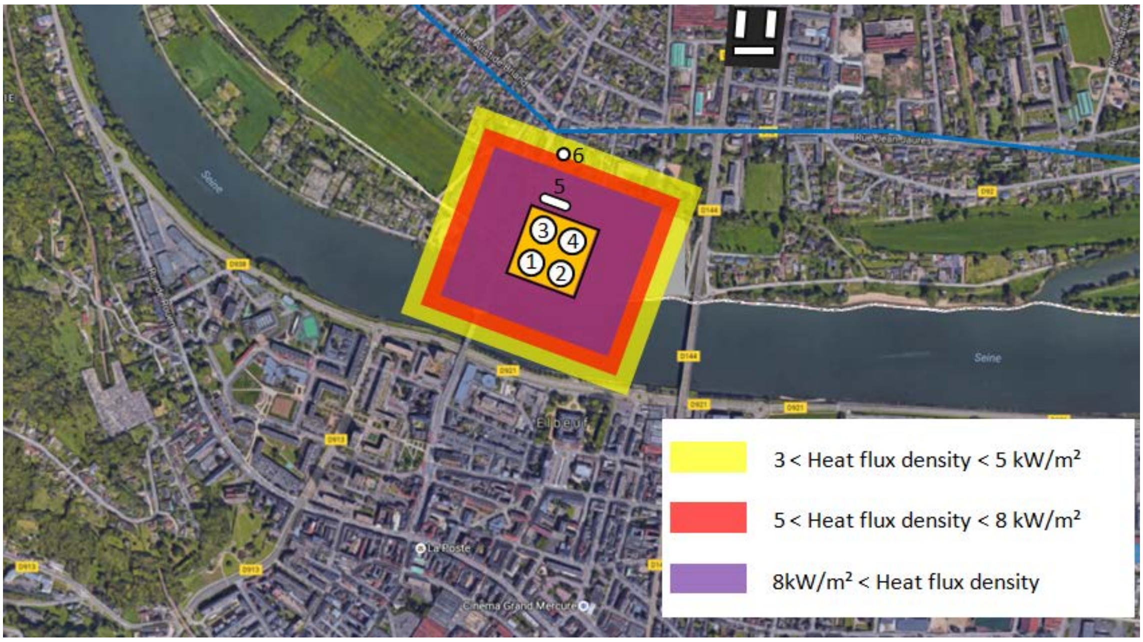

Figure 3-16 Thermal radiation effects distances calculated for the fire at Tanks 1 and 2.

Figure 3-16 shows that:

- Tanks 3 and 4 being in the neighbour of Tanks 1 and 2, will be directly impacted by the flames of the fire;
- Tank 5 is located at a distance of 4 m and Tank 6 at a distance of 40 m from the flame front.
- Roads 1 and 2 are within heat flux density lower than 5kW/m², they will be then impacted by Tanks 1 and 2 fire.

To evaluate vulnerability of Tanks 5 and 6 to the thermal radiation, the heat flow density is evaluated as a function of the distance by using a deterministic approach. Results are shown in Figure 3-17.

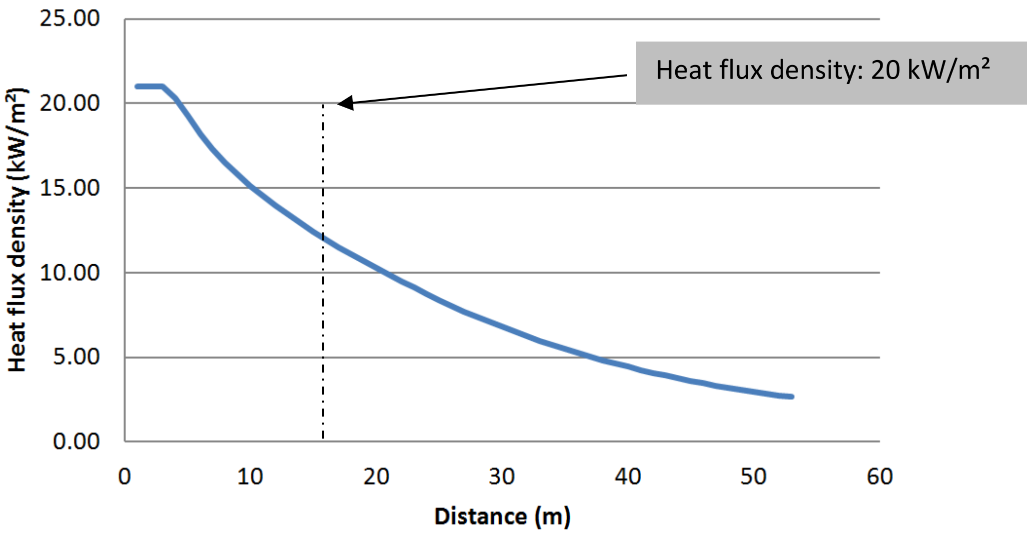

Figure 3-17 Heat flux density changes over distance.

From Figure 3-16 and Figure 3-17, it appears that LPG storage Tank 5 is impacted by 20 kW/m² heat flux density. The hydrochloric acid Tank 6 is impacted by a radiative heat flux density lower than 5 kW/m². In this case, the effect threshold for which the system is vulnerable (leading then to cascading effects) is 8 kW/m². So **LPG Tank 5** can be considered as **vulnerable** and **Tank 6** as **non-**

vulnerable. The other systems, which are the high-voltage line and the primary school are not impacted by the effects of the fire.

Regarding the flooding effects on roads 1 and 2, transport service will be interrupted in the vicinity of the chemical plant. The flooding effects on road 3 will impact the functioning of Primary school (incoming and outgoing of children particularly for those living on the other side of the river).

The second cascading order is shown in the Figure 3-18.

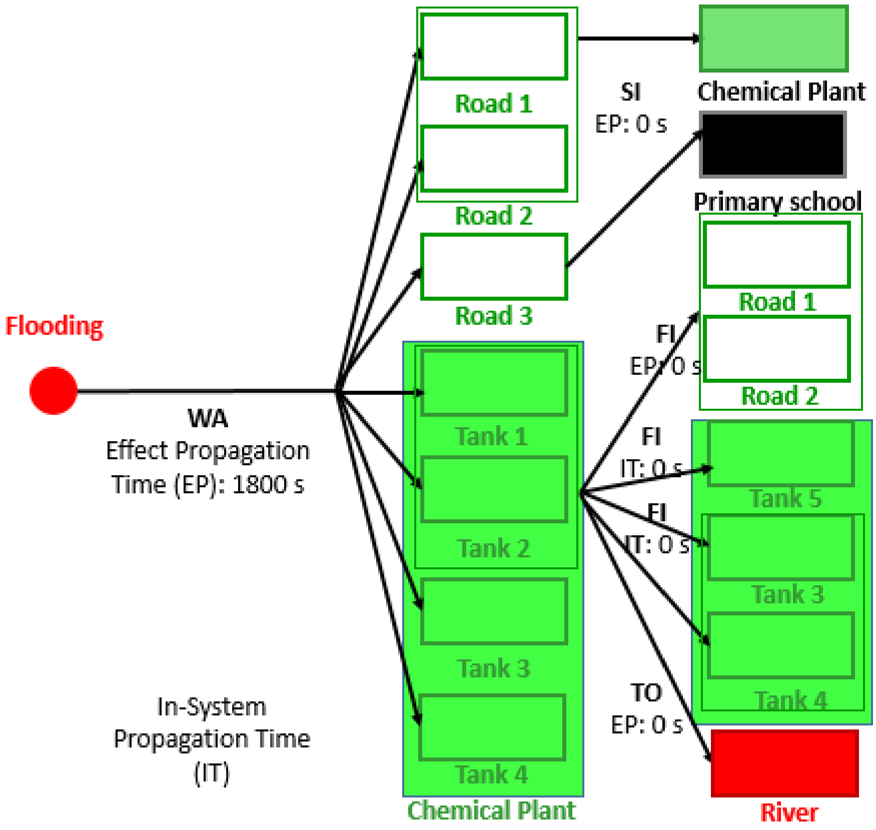

Figure 3-18 The second cascading order impact systems.

The fire on Tanks 3 and 4 will lead, as for Tank 1 and Tank 2 fire of the 1st cascading order, to hydrocarbons toxic release in the river (TO). Containing LPG, Tank 5 is able to develop BLEVE meaning thermal and pressure effects. The BLEVE-related overpressure effects of Tank 5 are calculated using the models and tools presented in Annex 2. The mapping of the calculated pressure effects is presented in Figure 3-19.

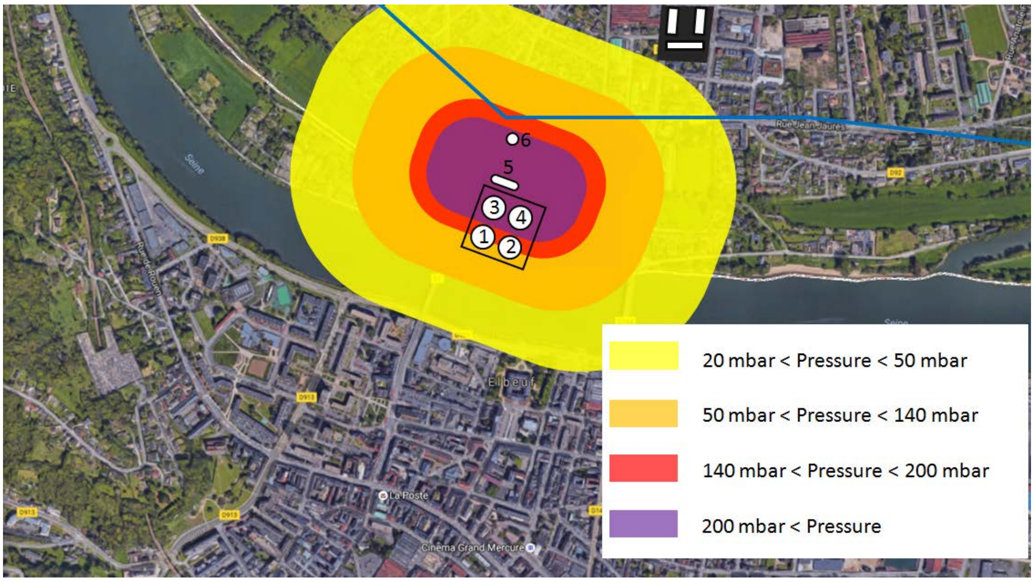

Figure 3-19 Mapping of the BLEVE-related overpressure effects of Tank 5.

Because of a pressure greater than 200 mbar at Tank 6 and greater than 140 mbar at High Voltage Transmission cable location, BLEVE of Tank 5 will affect the hydrochloric acid Tank 6 as well as the high-voltage line (possible structural failure if pressure level >140 mbar) and roads 1, 2 and 3 whereas the primary school will not be affected.

This leads to a Third cascading order impacted system illustrated in Figure 3-20.

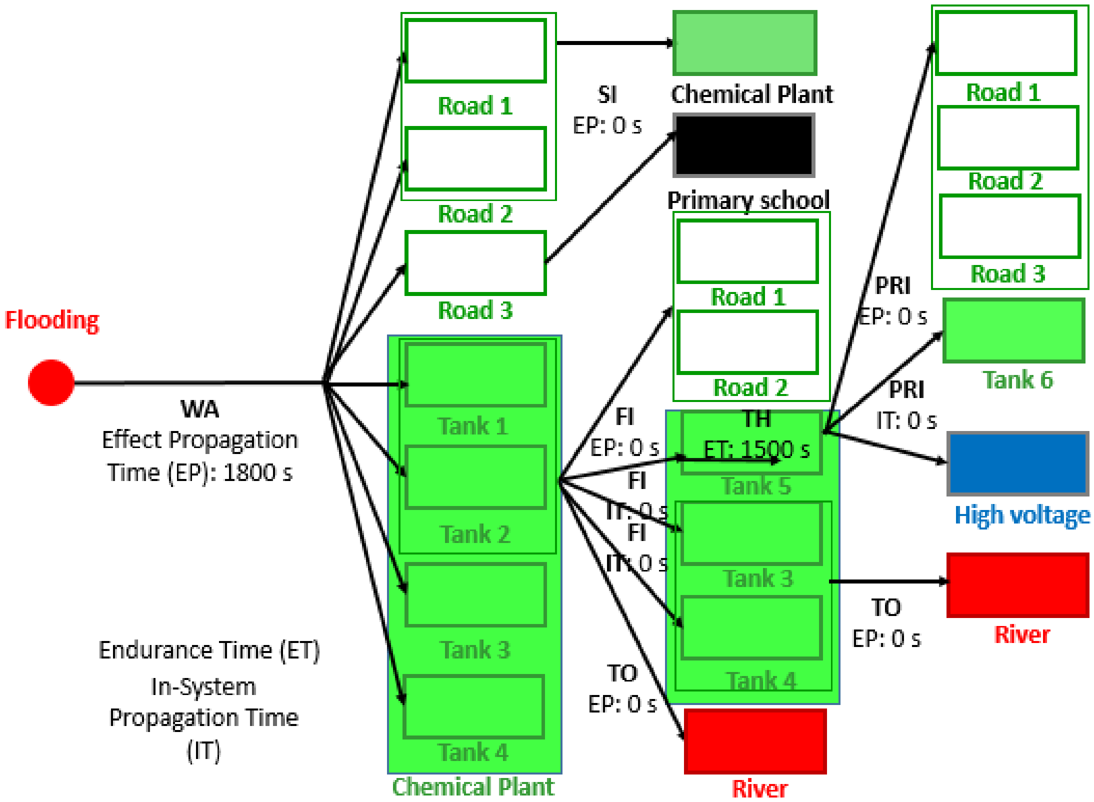

Figure 3-20 The 3rd cascading effect impacted systems.

The BLEVE effects of Tank 5 on the high voltage line will result in downstream impacts through functional dependencies. As previously mentioned, this effect is not developed here.
The collapse of the HCl Tank 6 will result in the formation of a toxic cloud (TO) that can affect all the systems open to the public like the Primary school. This is studied by considering the distances of the toxic effects for 3 thresholds calculated and shown in Figure 3-21.

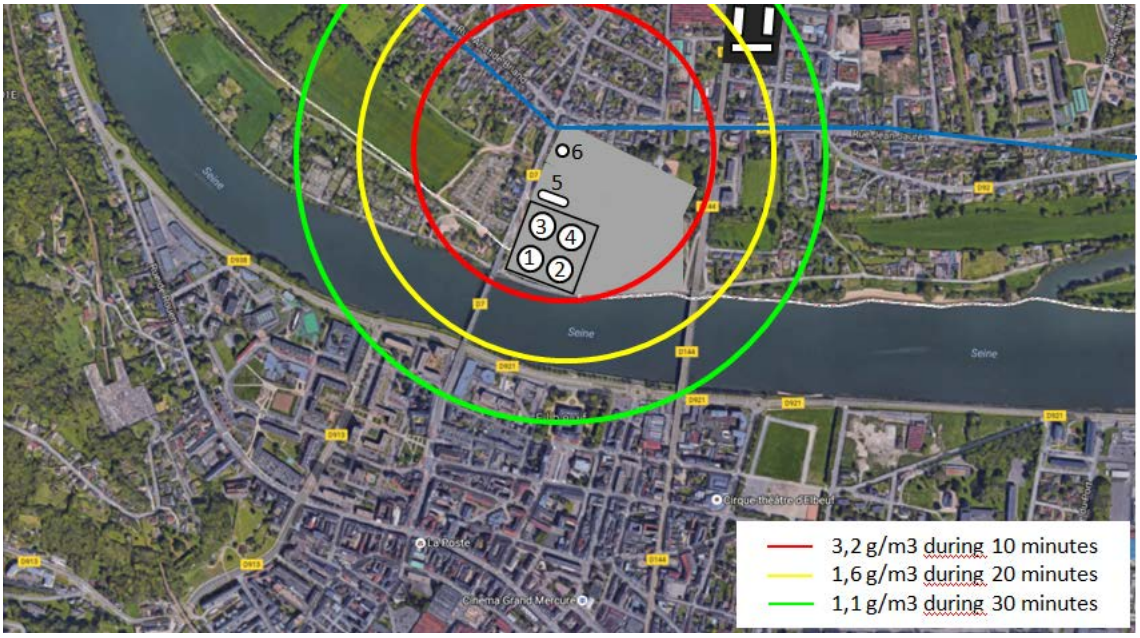

Figure 3-21 Mapping of the toxic thresholds for Serious Lethal Effects i.e. 5% lethality (and toxic release duration of 10, 20 and 30 minutes).

The toxic gas concentration being greater than 1.6 g/m^3, as shown in Figure 3-22, the primary school system will be impacted by outgoing effects from the HCl Tank for leak duration time of 20 and 30 minutes.

The fourth cascading order impact systems are shown in **Figure 3-22**.

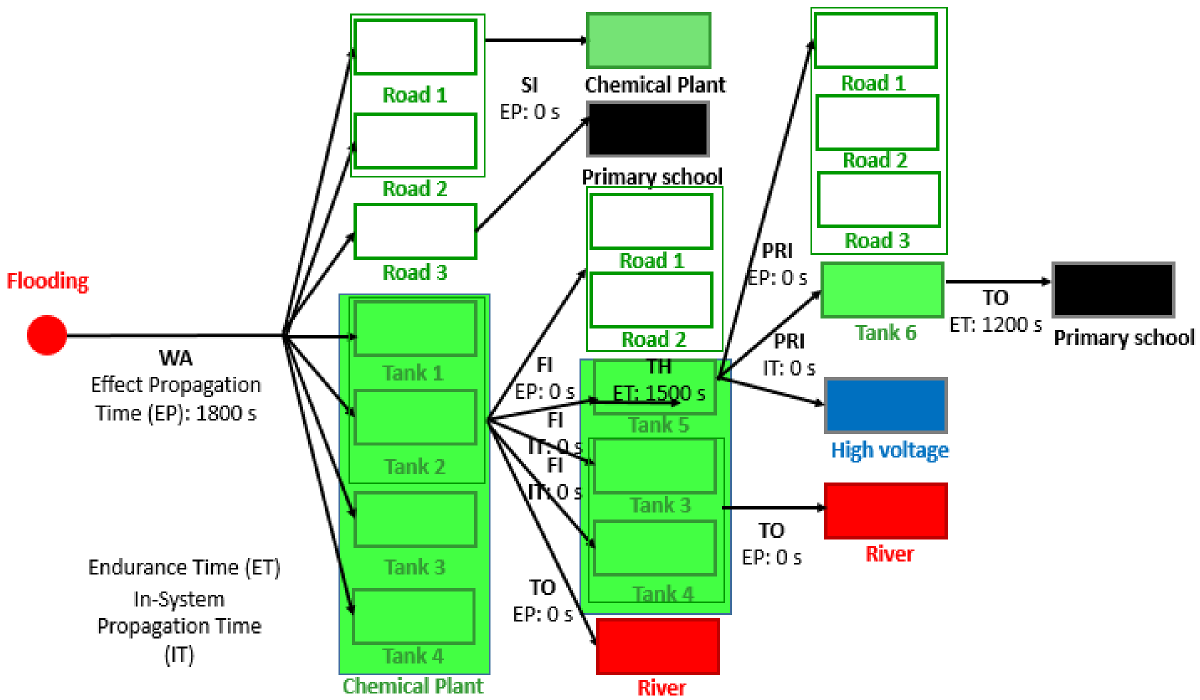

Figure 3-22 The final cascading effect tree (4th order cascading effect).

The effects of toxic release on Primary school is not followed by other cascading effects.

3.4 Step 4: Determination of temporal aspects outside the systems

3.4.1 Determine the inter-system propagation time

The concept of inter-system propagation time can be used to understand how fast effects spread, irrespectively of systems abilities to tolerate disturbances. Some effects can be seen as having zero propagation time (i.e. infinite spreading rate), e.g. power outage. It is illustrated in Figure 3-23.

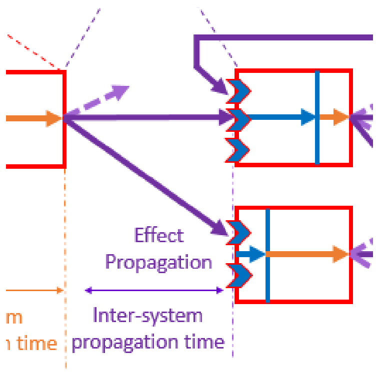

Figure 3-23 Illustration of inter-system propagation time.

The inter-system propagation time depends on the effects involved in the propagation:

- If the effect is due to a physical phenomenon like blast, radiation level, information transfer via internet, etc. the propagation time can be more or less instantaneous,

- If the effect is due to chemical phenomenon like pollution or contamination, the propagation time will depend on the chemical and the ability of transport media (air, water, soil) to diffuse the chemical. Regarding a wildfire, the dynamics depends on type of trees involved, field topography, level of humidity, direction and speed of wind, etc.

Demonstration case

As shown in Figure 3-22, the 1st order effect propagation, concerning flooding lasted **1800 s**. For the 2nd cascading order, when fire occurs in Tanks 1 and 2, thermal radiation propagation (TH) to roads and toxic release (TO) to river are instantaneous (**0 s**). Service Interruption (SI) on roads has also instantaneous effect on chemical plant and primary school. The inter-system propagation effect was of 2nd order cascading effects was then **0 s**. For the 3rd cascading order, once tank 5 blasted, the effect propagation to road and high voltage was instantaneous. The fire of tanks 3 and 4 provoked toxic release on river instantaneously. The effect propagation time of the 3rd cascading order is also 0. The 4th cascading order led to toxic cloud formation from tank 6 to primary school during **1200 s**. The whole inter-system effect propagation time is then **3000 s**.

3.4.2 Determination of endurance time

The **Endurance Time** is very important for emergency responder to know the potential time they have for putting in place crisis mitigation actions. The endurance time is illustrated in Figure 3-24.

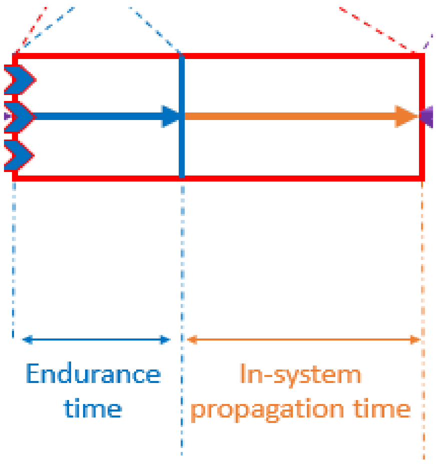

Figure 3-24 Illustration of Endurance-Time. In -system propagation time is defined in Section 3.3.4.

The endurance time is a function of the intrinsic/building characteristics of impacted components. The calculation of endurance time can then be obtained at the **component level**.

In case of geographical dependency, the endurance is a function only of the intrinsic characteristics of the impacted components. For example, in case of a tank impacted by thermal radiation, the endurance time may depend on its building material (a concrete tank is likely to have a higher resistance than a steel tank). This same reservoir, if it is equipped with a cooling system may have, depending on the severity of the incoming effect, a higher endurance-time increasing the possibility to put in place adequate countermeasures.

In case of functional dependency, the endurance time depends on the intrinsic characteristics of the systems to maintain provisioned services (as for geographical dependencies) but also on the functional dependency redundancy. For example, in case of a district heating system, a rupture of gas supply can be offset by the use of oil as long as the site has oil provision.

The calculation of endurance-time of system components is generally done combining experimental approaches and deterministic models.

<u>Demonstration case</u>
Tank No. 5 is subject to a heat flow of 20 kW/m². The endurance time was calculated using experimental approach combined with deterministic models to predict, according to time, the tank behaviour curve (with filling rate of 20 %) under applied pressure on internal shell tank correlatively to steel resistance (collapse stress), as shown in Figure 3-25.

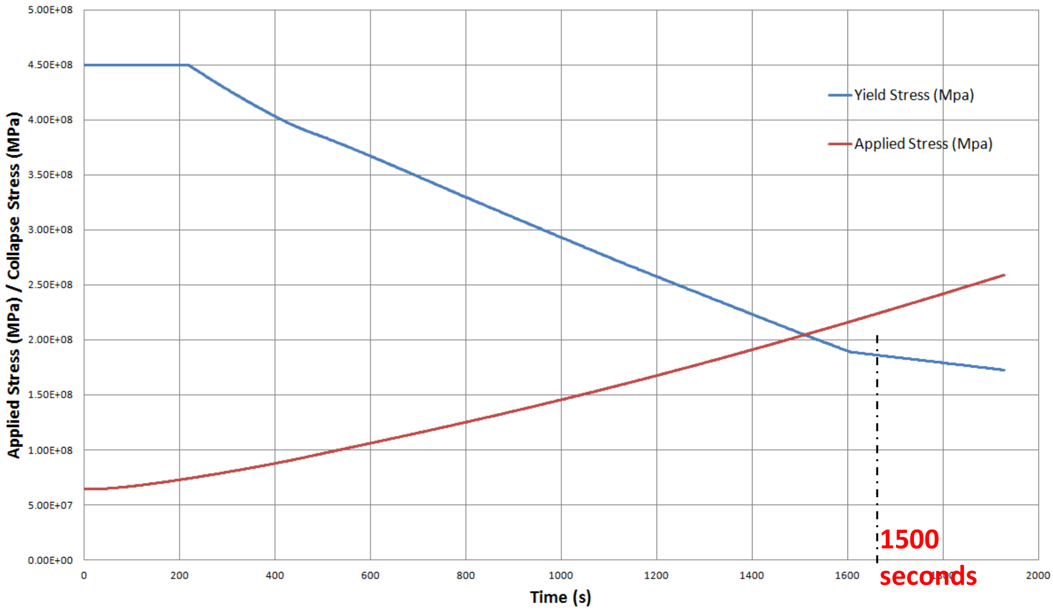

Figure 3-25 Tank Behaviour curve (filling rate: 20 %).

In that case the endurance time of the LPG tank will be around 25 min. Meaning that the overall endurance time for the "chemical plant" system will be around 25 min (conservative approach). Tanks 1, 2, 3, 4 and 6 have, regarding the incoming effects, endurance-time equal to 0. The **endurance-time of the chemical plant is then 25 min**.
Once flooded, segment of roads 1, 2 and 3 have also an endurance-time equal to 0. The same for high voltage line under pressure, primary school under toxic effect and transport service disruption and river under toxic release.

3.4.3 Determine the In-system propagation time

The assessment of the **In-system propagation time** is the same as conducting the assessment of Inter-system propagation-time but in that case, the systems are the systems' components. In this case, it may be interesting to take into account the internal capacity of response of the system to highlight new ways to stop cascade effects.

In-system propagation time is then usually assessed by using experimental approaches combined with deterministic models.

<u>Demonstration case</u>
In the previous example, the chemical plant was split in several components (the tanks). To ease the calculation, each component was evaluated as a system.
Looking at **Figure 3-22**, in-system effect propagation concern:

- Fire between Tanks 1 and 2 and Tanks 3 and 4: thermal effects propagation on tanks 3 and 4 was instantaneous;

- Fire between Tanks 1 and 2 and Tank 5: it took 1500 s for the thermal effect on tank 5 to turn into blast phenomenon due to endurance of tank 5 but the thermal effect propagation between Tanks 1 and 2 and tank 5 was also instantaneous;
- BLEVE effects on Tank 5 to Tank 6: effects of Tank 5 BLEVE to Tank 6 were instantaneous.

The in-system propagation time of the chemical plant is then 0 s.
The other systems were not decomposed into components. The in-system propagation time is considered to be 0.

3.4.4 Determine the Buffer Time

The buffer-time is the sum of the Inter-system propagation time and the endurance time, as illustrated in Figure 3-26. The buffer-time is the time emergency responders have for **avoiding in-system effect propagation**.

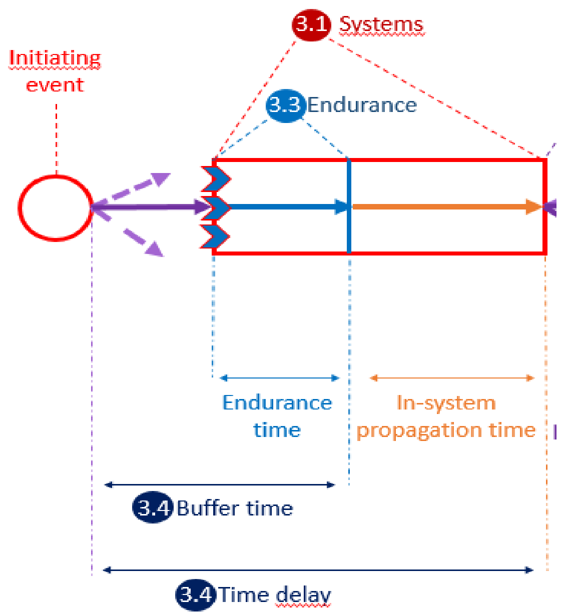

Figure 3-26 Illustration of Buffer Time and Time Delay.

<u>Demonstration case</u>
Considering **Figure 3-22** and the Section 3.3.3, the buffer-time of the 1st cascading order is 1800 s, whereas the one of the 4th cascading order is 1200 s. The 2nd and 3rd cascading orders have buffer-time equal to 0.

3.4.5 Determine the Time Delay

Time delay as the sum of the Buffer time and the in-system propagation time, allows the emergency responder to know the potential time they have to mitigate effects between two systems avoiding then another system to collapse. The concept can be used to signal “windows of opportunities” for breaking chains of cascading effects, as illustrated in Figure 3-26.

Demonstration case

Considering **Figure 3-22** and Section 3.4.2, the Time delay of the 1st cascading order is 1800 s, whereas the one of the 4th cascading order is 1200 s. The 2nd and 3rd cascading orders have Time delay equal to 0.

3.4.6 Creating the Timeline overview

The timeline overview should enable the emergency responders to evaluate the buffer time and time delay between systems in a chronological order so that the emergency responder knows the potential available time he/she has for coping the cascade as shown in Figure 3-27, where incident is represented according to time. This representation allows to detect the longest time periods where emergency responders can potentially mitigate the effects.

The way the timeline representation is used for analysing the key decision to take is explained in Step 6 (cf. Key Decision Points).

Demonstration case

From **Figure 3-22** represented time, it is possible to represent the timeline of the incident, shown in Figure 3-27.

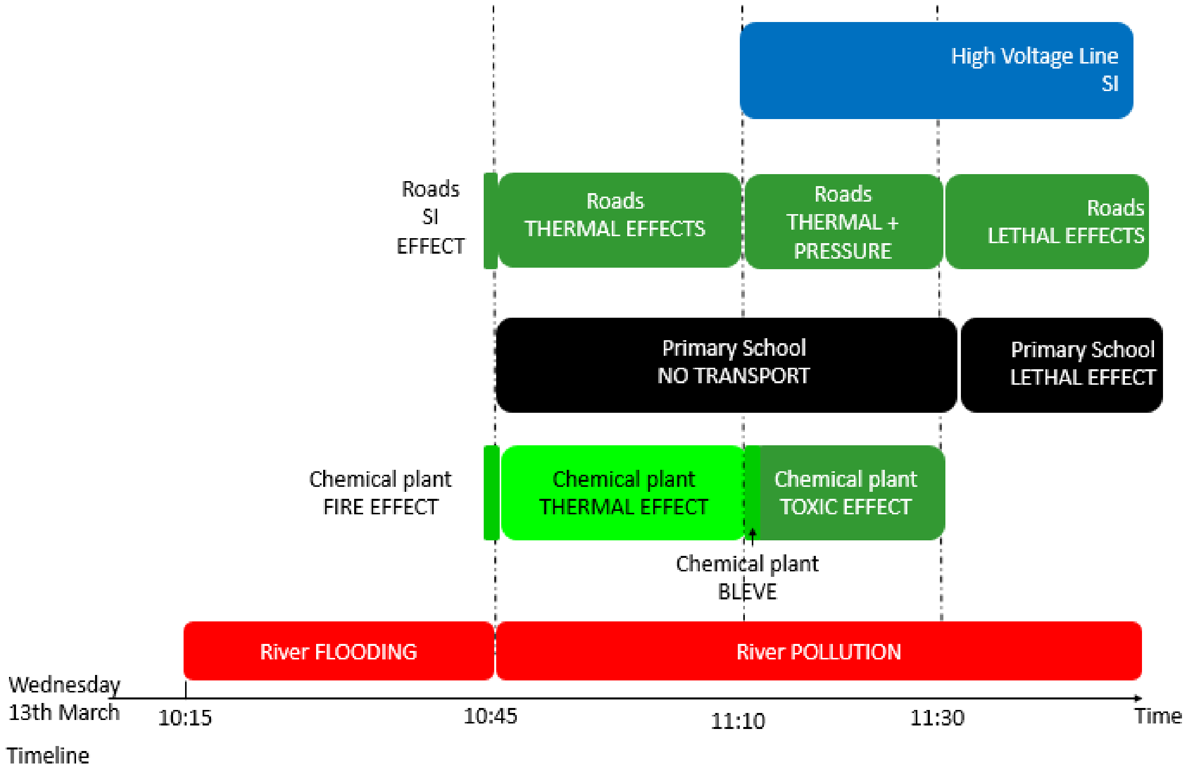

Figure 3-27 The timeline of the case area cascading effects.

As it is shown, the incident evolution of the case area is in a very short period meaning that emergency responders do not have possibility to mitigate the effects. This is more developed in Step 6 Section.

3.4.7 Creating the Tree-view

The Tree view consists in representing from the left to the right the earliest impacted system, using arrows to represent the (inter-)dependencies. By so doing, it is then possible to analyse the **propagation mode of the cascading effects** and to detect which system has the highest contribution to the total impacts within a certain impact subcategory (see section 3.5). This system is the most critical one.

G. Reniers and V. Cozzani (2013) distinguished 3 different propagation modes:

- *Simple propagation*: a primary single impacted system triggering a second single impacted system.
- *Multilevel domino chain*: a first scenario triggering a second accident scenario, the second accident scenario triggering a third one, and so on.
- *Multilevel propagation*: the propagation of the primary accident resulting in several simultaneous secondary scenarios triggered by the first primary accident. For example, the case of the 1984 Mexico City accident.

Another categorization was proposed by Reniers (2010) for the classification of domino events into the various types (internal, external, direct, indirect, temporal, spatial, serial, parallel).
These categorizations, applied to the CascEff project context, lead us to distinguish 3 types of propagation modes (see following Figure 3-28):

(a) the chain propagation, frequent for functional dependencies propagated by specific networks,
(b) parallel propagation, frequent for geographical dependencies multi-directionally affecting neighbouring systems and for functional dependencies where several systems depend on the same service like power plant,
(c) recursive propagation.

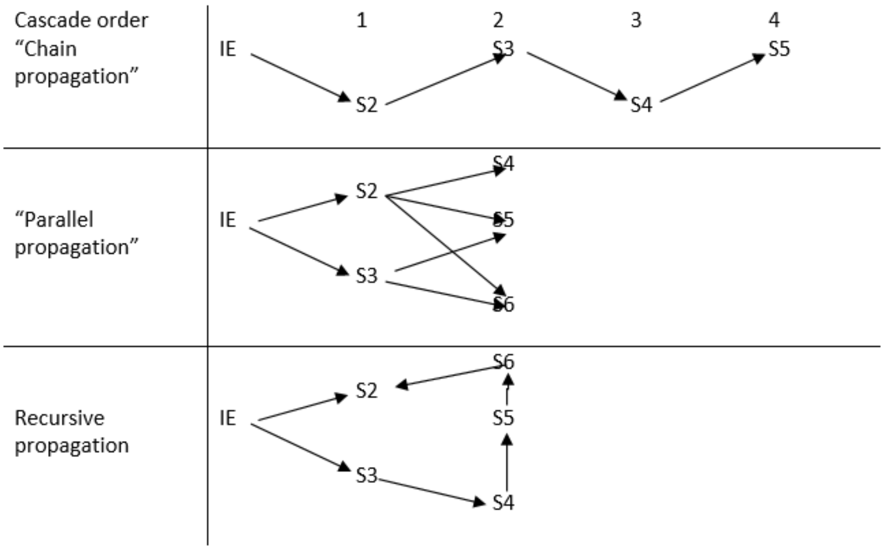

Figure 3-28 Types of propagation of cascading effects.

As shown in Figure 3-31, the parallel propagation is more likely to develop multiple incoming effects on a single impacted system and, as previously mentioned, multiple impacted systems at more or less the same time. In that case, coping the effect propagation is more complex to manage than for chain propagation. It is also the case for multiple incoming events impacting different locations at the same time.

The management issue related to chain propagation more likely induced by functional dependencies is that the geographical extent/area of the potential impacts can be very large, conversely to geographical dependencies. Communication with other emergency responders from other administrative areas should then be optimized.

Demonstration case

The Tree-View has been set up for the case area. It is shown in Figure 3-29.

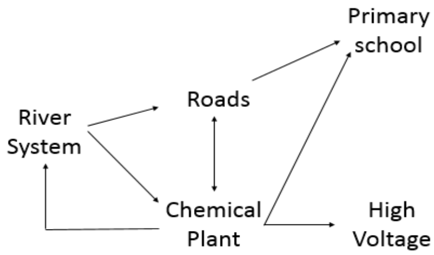

Figure 3-29 Time-Tree of the case area.

Figure 3-32 shows that river, roads and chemical plants are as much involved as each other in the cascading effects, acting then as originators. High voltage and primary school are impacted systems, not originating systems. These systems could affect also other systems, but those cascades are not included in the demonstration case included as an example.
The shape of propagation is a mix between parallel and recursive modes, meaning that it is very complex incident to manage.

3.5 Step 5: Assessment of the total impacts of a cascading effect

3.5.1 List of impacts and metrics

Evaluating the impact allows the emergency responders to prioritize their mitigation actions on the different systems based on impact categories. Five impact categories are identified, as shown in Table 3-11. For each category, different sub-categories are listed, along with corresponding units for evaluating damages.

Table 3-11 Description of categories and subcategories impact.

Impact categories	Impact sub-categories	Unit
Social	People affected by social unrest	Number
	People mistrusting authorities	Number
Human	Fatalities	number of employees, external rescue workers, public people
	Injuries (hospitalisation >24 h)	number of employees, external rescue workers, public people
	Homeless	Number
	Evacuated or confined residents >2h	Number
	Mental health injuries	Number
	People that has lost critical services	Number

Impact categories	Impact sub-categories	Unit
Economic	Direct and indirect economic costs	cost (€)
Environmental	Polluted land	area (m²)
	Polluted forest	area (m²)
	Polluted sea /water	area (m²), volume (m³)
	Dead animals	affected species, quantity
Infrastructure (infrastructure downtime)	Number of users	Number
	Available makeup capacity	Expressed according to system service efficiency like number of cars/hour for road transport, kW/hour for energy production system
	Time expected for repair	intervals of months
	Cost expected for repair	intervals of cost (€)

Due to the very different characteristics and values of the different categories, the impacts will be calculated and presented per subcategory of impact, and they will not be summed up to a single aggregated impact level. The choice to do differently can be based on political decisions or specific guidelines. It should in such cases, however, be noted that such calculations are not all straight forward and suffer from ethical issues.

Demonstration case

Each subcategory of impacts was assessed for each system. The results are listed in Table 3-12.

Table 3-12 Results of the impact subcategories for the 5 systems of the case area.

Impact categories	Impact sub-categories	High Voltage	Primary School	Chemical Plant	Roads	River
Human	1-Fatalities	0	5	150	150	0
	2-Injuries	0	55	0	300	0
	3-Evacuated or confined residents >2h	0	55	0	1,000	0
	4-Mental health injuries	0	55	0	1,300	0
	5-People that has lost critical services	30,000	60	0	3,000	0
Economic	6-Direct and indirect economic costs (€)	1,000,000	50,000	2,000,000	1,000,000	10,000,000
Environmental	7-Polluted land (km)	0	0	0	0	30

Impact categories	Impact sub-categories	High Voltage	Primary School	Chemical Plant	Roads	River
	8-Polluted sea /water (km)	0	0	0	0	777
	9-Dead animals	0	0	0	0	10,000
Infrastructure (infrastructure downtime)	10-Number of users	300,000	60	30,000	20,000	50,000
	11-Lost makeup capacity	100% of 300 kV	100% of 60 students	80% of 800L	80% of 20.000 cars/day	0%
	12-Time expected for repair (in mont)	0.25	6	30	0.25	1,200
	13-Cost expected for repair (in €)	50,000	100,000	300,000,000	100,000	0

The fatalities and injuries number are quite high, particularly for road and chemical industries where there are the most severe intensities of effects. Economic costs can be very high for environmental damage. For a better legibility, the results were standardised within each impact category and then compared (see Section 3.5.2).

3.5.2 Scorecard of impacts

The scorecard of impacts should allow to compare all the impact categories of the impacted systems as illustrated in Figure 3-30 for the demonstration case. This illustration combined with the timeline overview gives the prioritization keys of mitigation options. They are main results of the methodology.

Demonstration case

Figure 3-33 presents the standardised impact subcategory units for each system. It is then possible to compare more easily the impact intensities for all categories within the same graph.

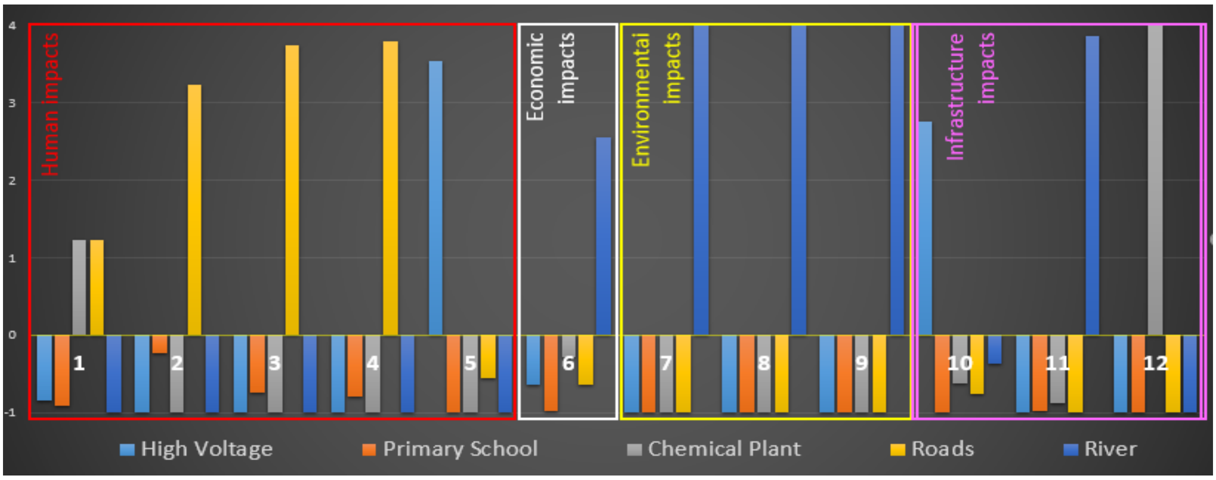

Figure 3-30 Standardized impact subcategory units for each system (the impact category number is 1-Fatalities, 2-Injuries, 3-Evacuated or confined residents >2h, 4-Mental health injuries, 5-People that has lost critical services, 6-Direct and indirect economic costs (€), 7-Polluted land (km), 8-Polluted sea /water (km), 9-Dead animals, 10-Number of users, 11-Time expected for repair, 12-Cost expected for repair).

Roads appear to lead to the highest injuries and fatalities (human health impacts), river leading to most of environmental impacts (this is not surprising), chemical plants one of the highest economic impacts and high voltage transmission line, the most connected users.
Primary school does not appear to be so critical although children are very vulnerable and should be protected first. This is discussed in the next section (Key Decision Points).

3.6 Step 6: Key decision points

The goal of this step is to determine times (points in the cascade tree) where decisions can be taken allowing to prevent, break and stop the cascade. This involves:

- The identification of the critical effect to be stopped or prevented;
- The determination of the anticipated available timeframe to stop the cascade order (temporal aspect).

These two points are the 'key decision points' of the Incident Evolution Methodology.

These points allow to answer the following questions:

(1) Which ongoing or expected future outgoing effect can I (still) stop or prevent?
(2) Which system has the highest impact within a sub-category compared to the others?
(3) How will the impacts be influenced if I stop or prevent an outgoing effect?
(4) How much time do I have to take a decision followed by an action?

The key decision points require two stages: the comparison of impact subcategories of one system on the others allowing to detect the most critical system (stage 1) and the assessment of the corresponding buffer time (stage 2).

3.6.1 Stage 1: compare impacts between systems

The decision-maker compares the impacts between systems by assessing a scorecard, as the one previously assessed in Section 3.5.2, having this time, vectors of impacts on dependent systems.
The scorecard allows for visualising the calculated impact sub-category of each originating system on each dependent system if no protective or mitigation measures are taken.

Demonstration case

For sake of pedagogy, the scorecard has been calculated for human fatalities, direct and indirect economic costs (in €), polluted land and sea (in km), lost makeup capacity (in%), cost expected for repair at infrastructure level (in €). Table 3-13 presents the impacts of river on the other systems, Table 3-14 is for the impacts of chemical plant on the other systems. The colours used for each impact category are those used in Step 5.

Table 3-13 Impacts of river on the other systems.

		Impact of river on			
Impact categories	**Impact sub-categories**	**High Voltage**	**Primary School**	**Chemical Plant**	**Roads**
Human	1-Fatalities	0	5	150	40
Economic	2-Direct and indirect economic costs (€)	1000000	50000	2000000	1000000
Environmental	3-Polluted land and sea (km)	0	0	0	0
Infrastructure	4-Lost makeup capacity	0	0	20%	20%
	5-Cost expected for repair (in €)	50000	100000	300000000	100000

Table 3-14 Impacts of chemical plant on the other systems.

		Impact of chemical plant on			
Impact categories	**Impact sub-categories**	**High Voltage**	**Primary School**	**Roads**	**River**
Human	1-Fatalities	0	5	150	0
Economic	2-Direct and indirect economic costs (€)	1000000	50000	1000000	10000000
Environmental	3-Polluted land and sea (km)	0	0	0	377
Infrastructure	4-Lost makeup capacity	100%	100%	20%	0%
	5-Cost expected for repair (in €)	50000	100000	100000	0

The standardized score of the system impacts on the others can also be visualised on the Tree-View map using the same colour (see Figure 3-31). The visualisation mode then eases the interpretation of dependencies between systems, impacts and timeline.

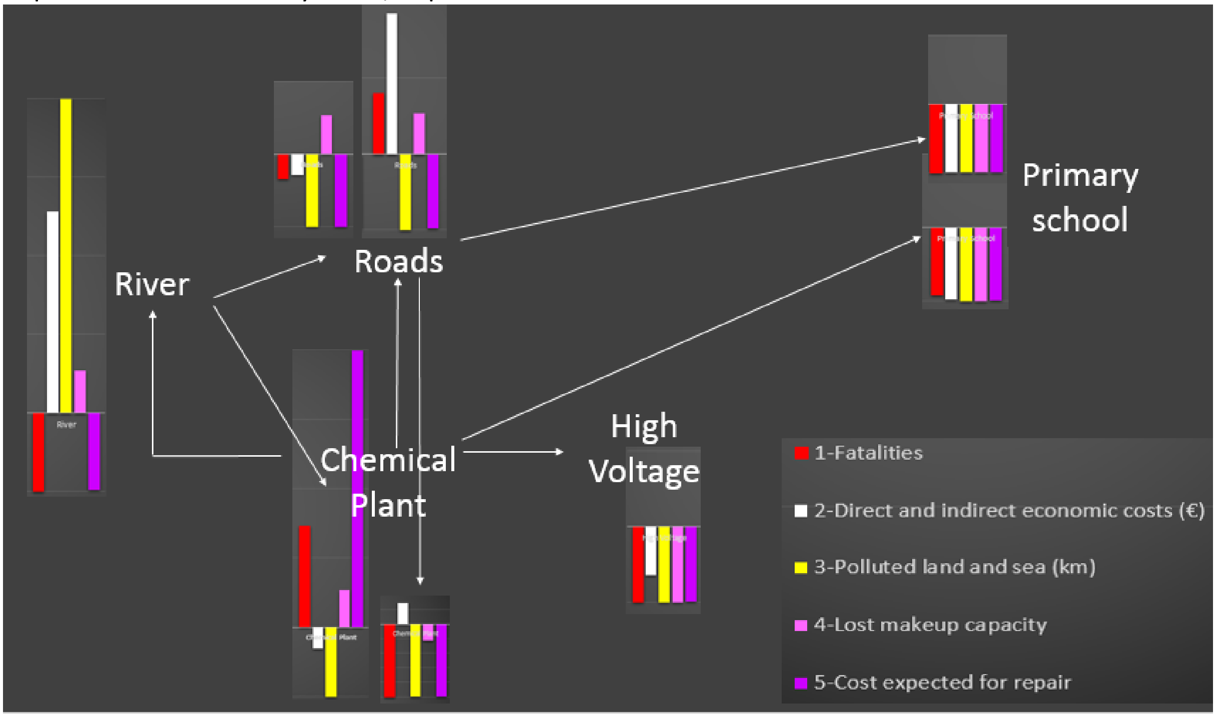

Figure 3-31 Tree-view of the scorecard of the system impacts on the other systems.

Figure 3-31 shows that river, if no measure is taken for preventing river flooding, has for all categories higher impacts on chemical plants than on roads. Chemical plant has higher impacts on primary school than roads (although the impacts are not so high) and it has higher impacts on roads than river. It has also very high environmental and economic impacts on river. Roads has lower impacts on chemical plant than river.
Figure 3-31 highlights then than river and chemical plant are the most critical systems influencing cascading effect, whereas school and high voltage line are the most vulnerable ones.

In order to take action, the emergency responder can make evaluate the following parameters:

- Experience and knowledge about the scenario and mitigating measures taken in the past (subjective decision). It will be based upon the identification of the type of impacted systems. For instance, in this case, schools is a critical system to protect.
- Recommendations from the existing pre-made incident management plans.
- Classification or prioritization. The decision-maker has to determine which of the impact sub-categories, is more important than another given the type and location of the incident. For instance, the decision-maker can decide that the first priority is to avoid casualties as many as possible instead of an impact on the environment. Another possibility is that the decision-maker wants to avoid the highest number in any impact sub-category. For instance, in Figure 3-31, it can be seen that if the cascade order increases, the values of the impact sub-categories decrease.
- Identification of the system that produces the critical effect: if the system can be isolated or if the incoming effect(s) on that system can be avoided/prevented/decreased in intensity, then the cascade will be stopped. In the case area, river and chemical plants are the most critical systems.
- Protect or deactivate the system with the potential of producing the most severe effects.

- Accepted level of consequences of a decision/action taken at a given time.
- Feasibility of the decision/action taken: availability and deployment of resources in a timely manner.
- Legal issues or policy concerns.

3.6.2 Stage 2: consider the time-delay

The temporal aspect is important for the support in the identification of key decision points:

- How much time does the decision-maker have to take a decision?
- What is the latest time that a decision must be taken and have an effect?

This comparison of impacts between systems needs thus to be connected with the time delay in order to know the maximum available timeframe for within a decision must be taken and action must be done. Basically, it comes down to defining if a decision is realistic/makes sense or not. It is clear that if the measure or mitigation is not put in place within the buffer time, the system will be affected.

The time to put mitigation measures in place will also depend on complex aspects such as availability of the correct type, amount and quality of resources, expertise. This time needs to be known to the decision-maker in order to assess the feasibility of the key decision point.

Combing the scorecard of impacts and the timeline induces another figure than the Tree-view more compliant with the timeline overview (see Figure 3-32).

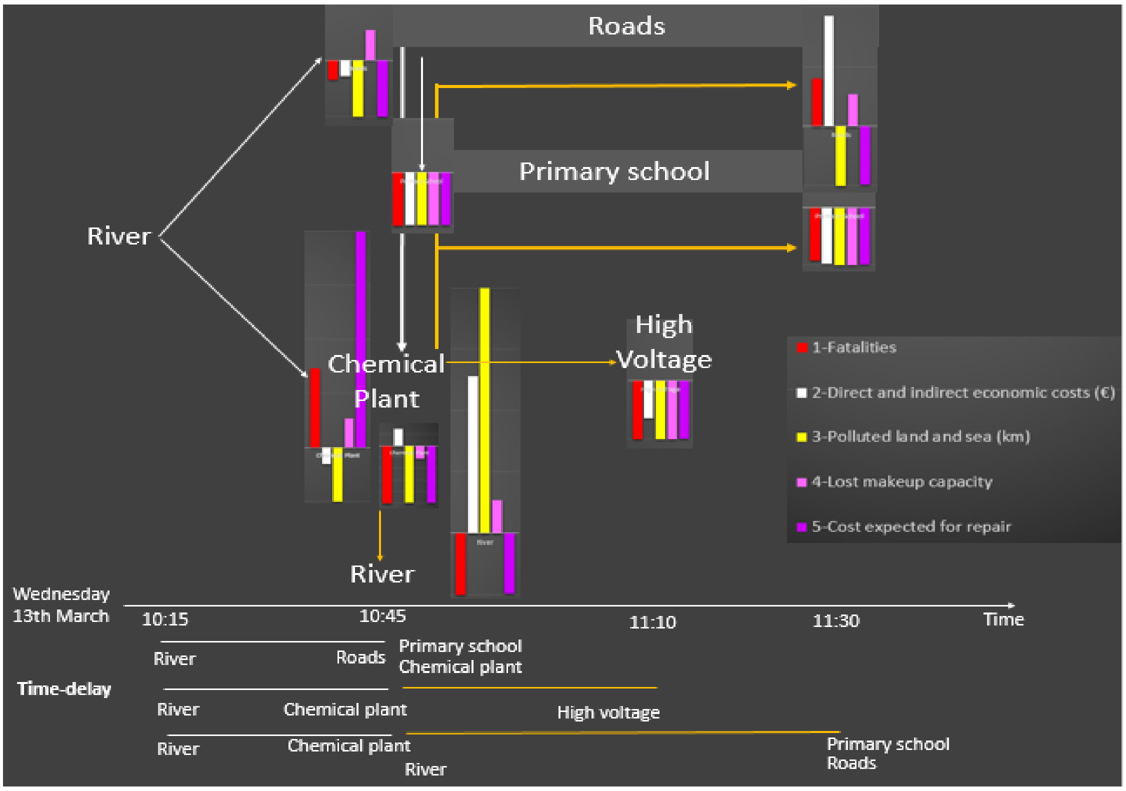

Figure 3-32 Illustration of 2 key decision points.

Figure 3-32 shows that the main impacts of the cascading effect will be within the first half an hour, when the river floods. If no protection can be set up on roads and on chemical plant within this timeframe, three quarters of hour are necessary to protect the primary school and people on the roads who need to be evacuated. Emergency response will have then to consider that children of the primary school can be evacuated only in the Northern part since the Southern part is flooded and is the closest to chemical plant.

Based on this combined assessment, a sequence of measures can be taken to limit, or even stop, one or several cascading effects. The decision-maker can thus add barriers and observe how they change the impacts. These barriers can be prioritized based on efficiency: giving higher priority to reducing global impact rather than impact on individual sub-systems.

4 Exemplification/illustration of the IE methodology

In this chapter a few short examples have been included to further illustrate the methodology. The methodology is not worked through in detail for these examples, but the most important parts of each step are discussed. This means that each step of the methodology is included, but the steps, systems, vulnerabilities, etc. are not analysed in detail.

4.1 Wildfire impacting other systems

The illustration below is based on a real event, occurring outside Gothenburg in Sweden. Many of the suggested cascading effects were avoided and did not occur, but could have happened, with other weather conditions, other strategies, etc. The real event started as a fire in the Skatås forest caused by children playing with matches. The scenario is described further also in D5.1.

4.1.1 Step 1: Set the Case area and the Systems

The case was created starting from the real incident, i.e. the forest (Skatås forest) where the fire started and the systems directly affected or threatened during the real fire, i.e. the Telecommunication mast, the lakes (Stora och lilla Delsjön), and the hospital Östra sjukhuset.

Figure 4-1 The Skatås forest to the east of the city of Gothenburg and around the lakes Stora and Lilla Delsjön.

Then other systems were added, plausible to be affected if the incident would escalate and cascade. Table 4-1 presents a summary of the included systems in the example. The system category and subcategory for each system are also included.

Table 4-1 Summary of the system included in the wildfire example. The corresponding categories and subcategories are also given.

Categories of systems	Sub-categories of systems	Systems
Environment	Forests	Skatås forest
Environment	Lakes	lakes: Stora and Lilla Delsjön
Telecommunication	Radio communication	Telecommunication mast
Water supply	Distribution	Drinking water
Power supply	Transmission	Underground electric cables
Health care	Hospitals	Hospital Östra Sjukhuset
Public		Residential area Kålltorp/Sävedalen
Road transport	National network	Road Riksväg 27
Road transport	National network	Road E20
Air transport	Airports	Landvetter airport
Business & Industry	Not specified	
Emergency response	Rescue services	Local fire and rescue service
Emergency response	Emergency health care	Local ambulance

4.1.2 Step 2: Identify dependencies between systems

Several of the systems are (or risk to be) geographically dependent, especially via fire or toxic smoke. The main source is of course the Skatås forest, but if the fire would spread there would be also other dependencies. This is exemplified in

Table 4-2. In the table is also included some identified functional dependencies.

Table 4-2 Examples of geographical (G) and functional (F) dependencies.

	Originating systems							
Dependent systems	Skatås forest	lakes: Stora and Lilla Delsjön	Telecommunication mast	Underground electric cables	Hospital Östra Sjukhuset	Road Riksväg 27	Residential area Kålltorp/Sävedalen	Landvetter airport
Skatås forest								
lakes: Stora and Lilla Delsjön	G							
Telecommunication mast	G			F				
Underground electric cables	G							
Hospital Östra Sjukhuset	G	F					G	
Road Riksväg 27	G						G	
Residential area Kålltorp/Sävedalen	G							
Landvetter airport	G					F		
The Public	G	F	F		F	F		F
Emergency response			F			F		

The dependencies are illustrated in Figure 4-3 below. There is also information given on what type of effect that is involved (see descriptions in section 4.1.3).

4.1.3 Step 3: Propagate the effects under known risk conditions

In this step the initiating event is set. For the case in question, the initiating event was a fire: children’s play with fire. The location of the initiating event (fire) is marked in Figure 4-2.

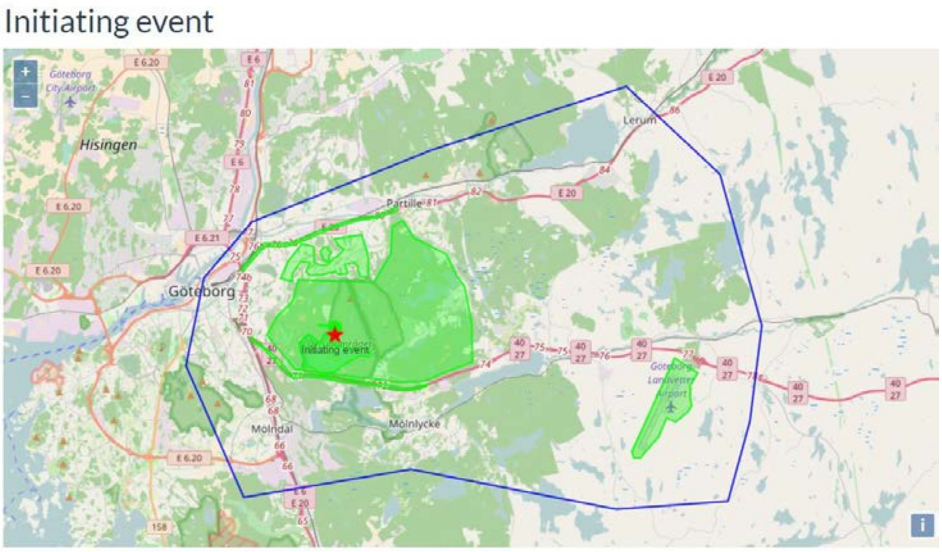

Figure 4-2 Illustration of the initiating event (red star) in relation to the case border (blue line) and different system (green areas).

In Figure 4-3, the different dependencies between system and cascading effects are illustrated. Please note that if a system can be affected by several different systems, there are more than one instance of the system, both vertically on the same order of cascading effects and horizontally in different orders of cascading effects.

The systems and dependencies included in the figure should be seen as examples. If one studies the risk for the spread of the fire from the forest, there can be also other cascading effects and consequences. In the given example the fire affects directly the telecommunication mast, the underground electric cables and a residential area, while the other included effects by the fire relates to toxic effects of the smoke from the fire.

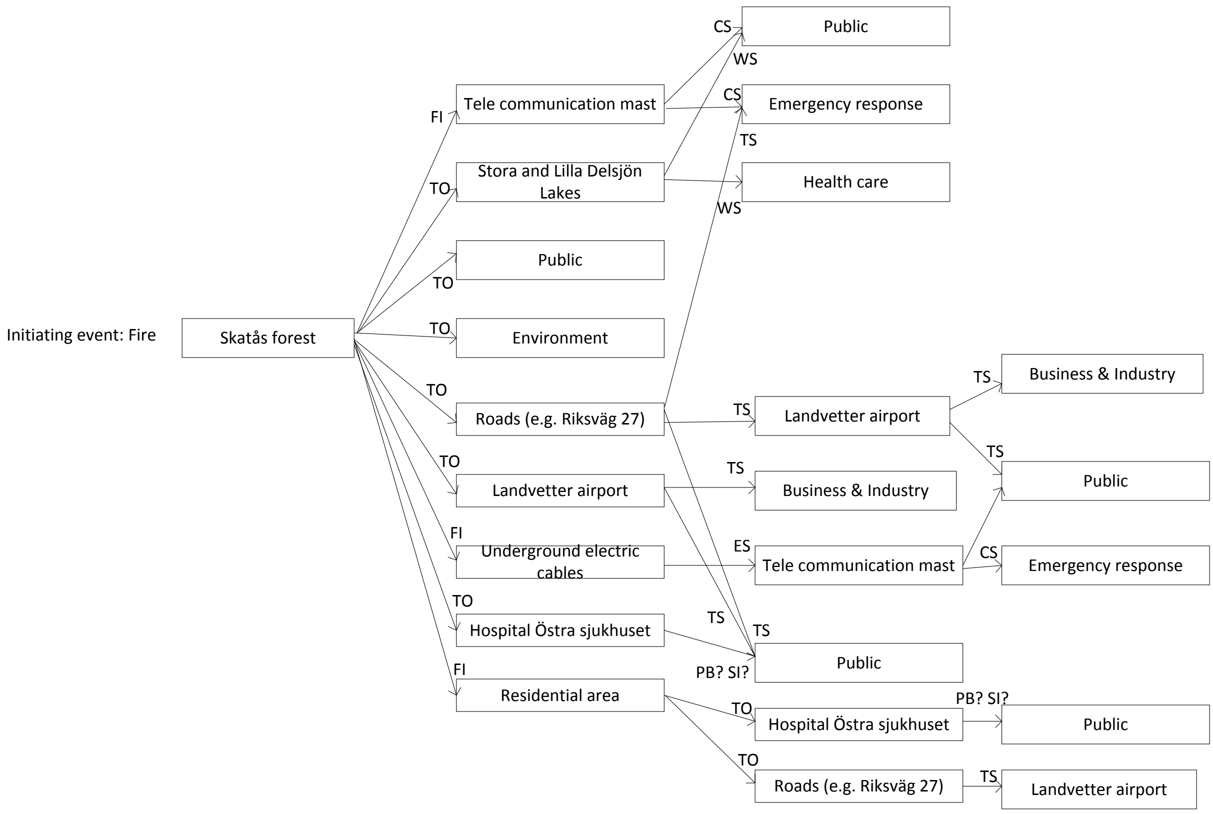

Figure 4-3 Illustration of the dependencies and possible cascading effects in the wildfire scenario.

4.1.4 Step 4: Determination of temporal aspects

The temporal aspects of the Skatås wildfire incident is illustrated in Figure 4-4 where the first part of each coloured box represent the propagation time (here a sum of in-system and inter-system propagation times), and the second part of each box represent the endurance time.
In this step also endurance times and in-system propagation times are set. These are not elaborated on in detail here, but are exemplified together with the inter-system propagation time (given as a total propagation time).

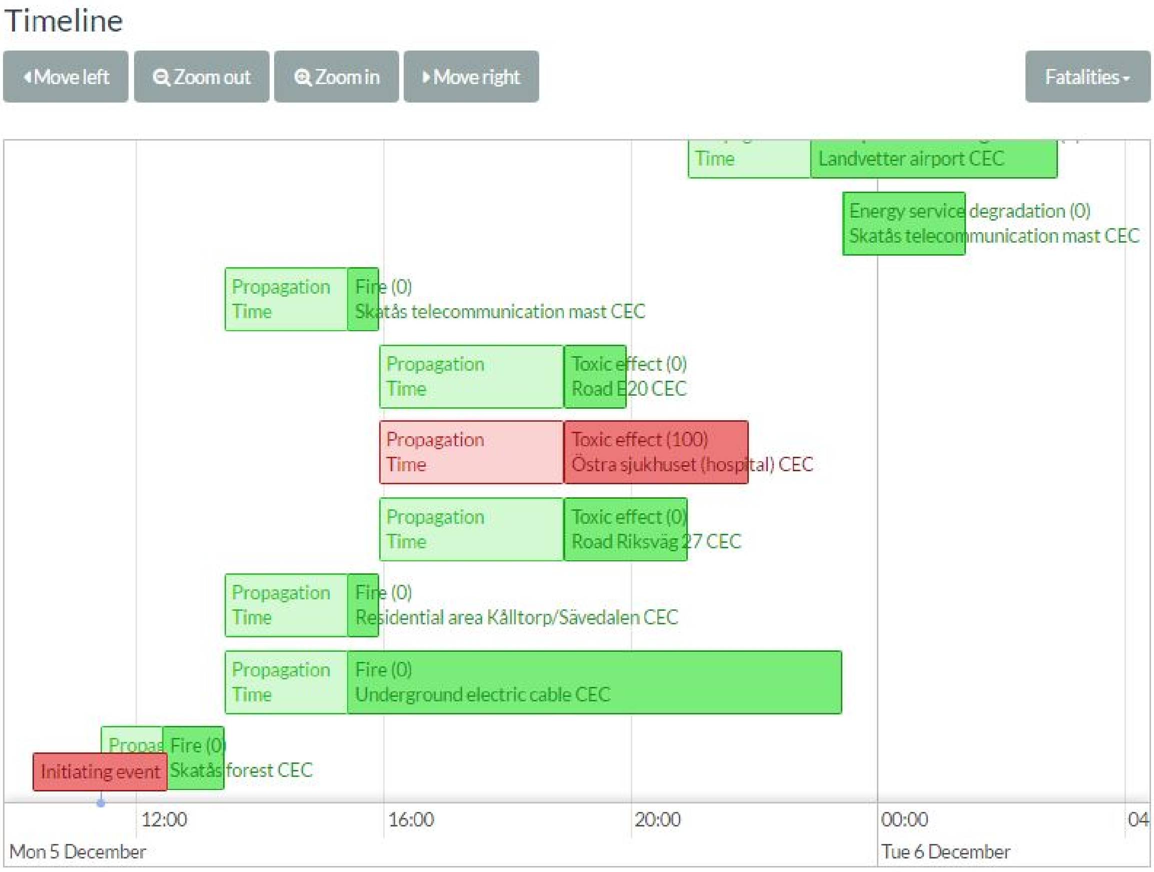

Figure 4-4 Timeline for the main systems in the Skatås wildfire incident.

4.1.5 Step 5: Assessment of the total impacts of a cascading effect

The impacts of each system were not analysed in detail in this example, but some assumed values have been used for illustration. In Figure 4-5 the different systems affected have been marked with different colours: red for fully affected, orange for partly affected and green for not affected. In the timeline in Figure 4-4 the systems were colour-coded based on the total fatalities for each system to mark the different system with the highest impacts. This is done per impact sub-category (in this case fatalities).

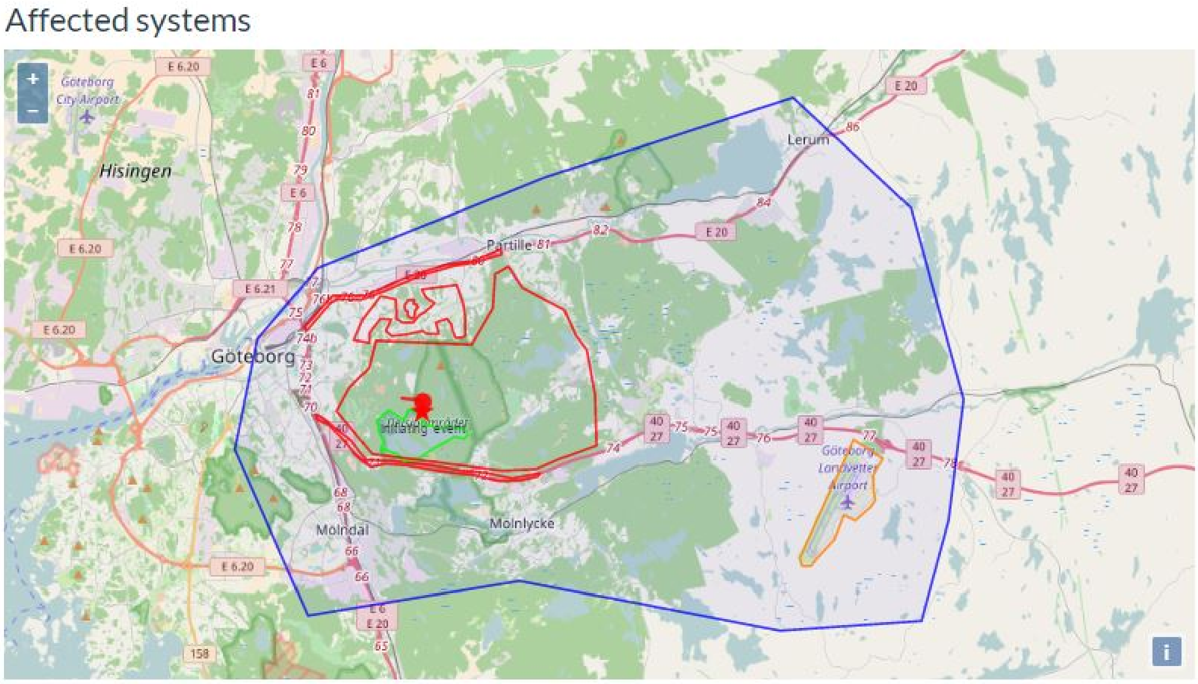

Figure 4-5 Illustration of affected systems in the wildfire scenario.

The impacts (per impact sub-category) can also be listed per system in a table. Such a list is exemplified in Table 4-3 for a few selected systems.

Table 4-3 Examples of impacts per impact sub-categories for a few selected systems.

Total impact

Select systems (5/9)

	Östra sjukhuset (hospital) CEC	Underground electric cable CEC	Skatås forest CEC
ECONOMICAL			
Direct economic cost	1,000,000 € 27%	10,000 € <1%	1,000,000 € 27%
SOCIAL			
People affected by social unrest	0	0	0
People mistrusting authority	0	0	0
INFRASTRUCTURE			
Number of users	0 0%	0 0%	0 0%
Available make up capacity	0 % 0%	25 % 100%	0 % 0%
Expected repair time	0 months 0%	0 months 0%	0 months 0%
Expected repair cost	0 € 0%	10,000 € <1%	0 € 0%
Life/property losses	0	0	0
ENVIRONMETAL			
Polluted land	0 km²	0 km²	0 km²
Polluted forest	0 km² 0%	0 km² 0%	5 km² 100%
Polluted sea	0 km² 0%	0 km² 0%	1 km² 100%
Dead animals	0	0	0
HUMAN			
Fatalities	100 100%	0 0%	0 0%
Injuries	1,000 >99%	0 0%	2 <1%
People that has lost critical services	0 0%	15 100%	0 0%
Mental health injuries	0	0	0
Evacuated	2,000 >99%	0 0%	10 <1%
Homeless	0	0	0

4.1.6 Step 6: Key decision points

Following the example presented in the different steps above, one can see that the fire in the Skatås forest can affect many different systems, both via fire spread and via the spread of toxic smoke and key decisions will relate to how far the fire can be let to spread before the risk for significant cascading effects become too large. The wind direction and wind speed will have a significant influence both on the risks and on the decisions needed to be taken. An aggravating circumstance is the proximity to the lakes which constitutes a water reservoir for drinking water, which means that the runoff water reaching the lakes must be limited. This affects the decisions on the firefighting tactics.

In the example above a key decision is also to decide whether and when the hospital should be evacuated. The risk for high impacts if the hospital is affected is illustrated by the red box in Figure 4-4. By in this way study the impacts belonging to certain impact sub-categories for the included system, key decision points can be found.

4.2 Black-out impacting other systems

The scenario involves a power black-out in The Netherlands and in Belgium. The power distribution station in Kreekrak (The Netherlands) and in Zandvliet (Belgium) connect the Dutch power grid with the Belgian power grid, as can be seen in Figure 4-6. The breaking down of both the power distribution stations result in a severe black-out, causing further cascading effects in power supply, heating problems, degradation of communication services, shutdown of businesses and industry, traffic problems etc.

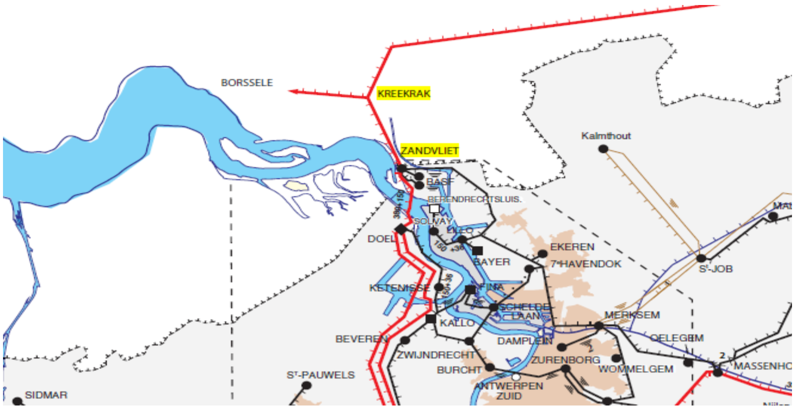

Figure 4-6 The 380 kV power grid around transmission stations Kreekrak and Zandvliet, north of Antwerp, Belgium.

This cross-border scenario is fictive, but the potential impacts are based on real-life large power outages in Europe in recent years (Italy-2003 and Turkey-2015).

4.2.1 Step 1: Set the Case Area and the Systems

The **Case Area** involves a severe power black-out in the south-west part of The Netherlands and the north-west part of Belgium.

Figure 4-7 Location of the 2 power distribution stations, situated in the north of the Port of Antwerp.

Figure 4-7 presents a summary of the included **Systems** in the example. The system category and subcategory for each system are also included

Table 4-4 Summary of the included Systems in the example. The system category and subcategory for each system are also included.

Categories of systems	Sub-categories of systems	Systems
Power supply	Transmission	Underground electric cables Distributed infrastructures
Telecommunication	Telephone landlines	Telecommunication mast
Health care	Hospitals	Hospital Antwerp, Goes
Public	Municipalities	Borssele, Bergen-op-Zoom, Goes, Zandvliet, Berendrecht, Ekeren, Kappellen
Road transport	National network	A58, A12/R2
Rail transport	Railway network	Railway Antwerp-Breda
Marine transport	Ports	Port of Antwerp, Port of Rotterdam
Air transport	Airports	Airport Deurne
Water Supply	Distribution	Water treatment plant Antwerp
Business & Industry	Chemistry & Petrochemistry	BASF Antwerp, Inovyn, IBR, Monsanto, Vesta Terminal, Oiltanking Antwerp
Business & Industry	Manufacturing	PSA Terminal
Emergency response	Rescue services	Local fire and rescue service

4.2.2 Step 2: Identify dependencies between systems

Several of the systems are (or risk to be) functional and geographical dependent, especially via the direct power supply connection and propagation of fire, smoke and toxic clouds. The main source is of course the power distribution stations Kreekrak and Zandvliet. This is exemplified in

Table **4-5**.

Table 4-5 Examples of functional (F) and geographical (G) dependencies.

	Originating systems										
Dependent systems	Power distribution station	Telecommunication mast	Underground electric cables	Hospital Goes, Antwerp	Port Antwerp, Rotterdam	Road A58/ A12	Water treatment plant Antwerp	Chemical Industry BASF Antwerp	Airport Deurne	Municipality Goes, Antwerp	Emergency Response
Power distribution station		G	G	G	G	G	G	G	G	G	G
Telecommunication mast	G		F		G						
Underground electric cables	G							F	F	F	
Hospital Goes, Antwerp	G									G	
Port Antwerp, Rotterdam	G	G					G	F			
Road A58/A12	G									G	F
Water treatment plant Antwerp	G				F			G			
Chemical Industry BASF Antwerp	G	F			F						
Airport Deurne	G				G	F				G	
Municipality Goes, Antwerp	G	F		F		F			F		
Emergency response	G	F				F					

The different dependencies between systems and cascading effects are illustrated in Figure 4-8 below. The illustration also involves a description of incoming and outgoing effects for each of the identified systems (see descriptions in section 3.3.2). As can been seen in Figure 4-8, there are more than one instance of the system, both vertically on the same order of cascading effects and horizontally in different orders of cascading effects. The systems and dependencies included in Figure 4-8, should be seen as examples. In the given example the black-out affects directly the telecommunication mast, the underground electric cables etc., while the other included effects by the black-out relates to degradation of transportation, communication services, social effects, etc.

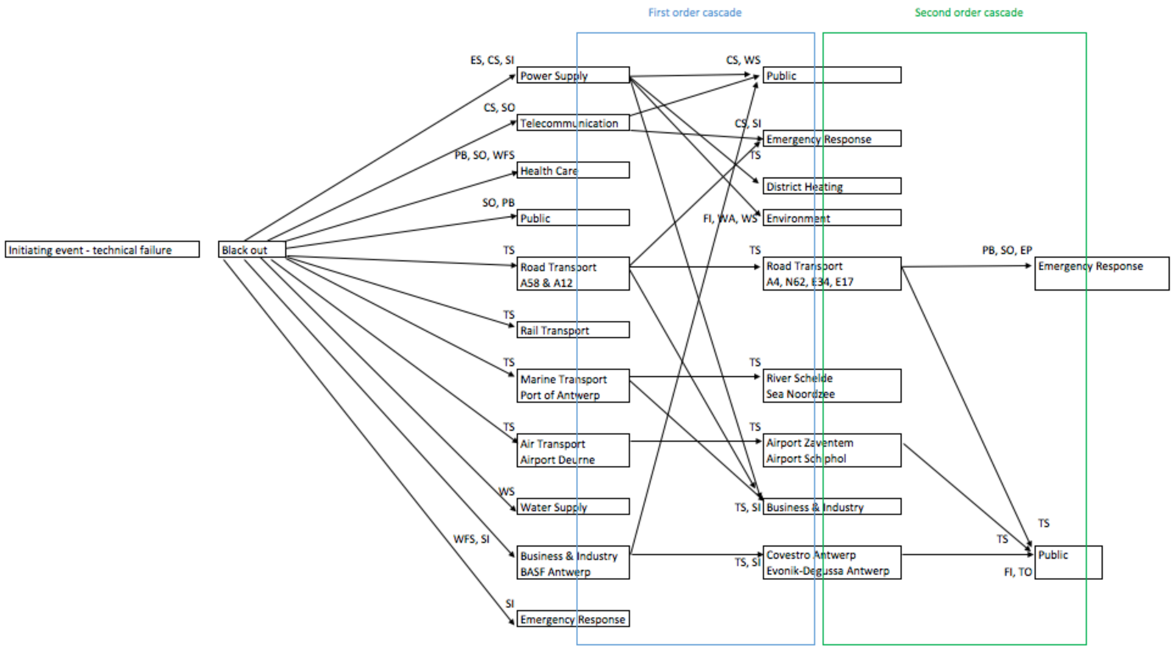

Figure 4-8 Illustration of the dependencies and possible cascading effects in the power black-out scenario.

4.2.3 Step 3: Propagate the effects under known risk conditions

In this step the **initiating event** is set. The initiating event was an energy services degradation: a failure of a critical component at a power distribution station Kreekrak in The Netherlands during severe winter weather. The location of the initiating event (black-out) is marked in Figure 4-9 below.

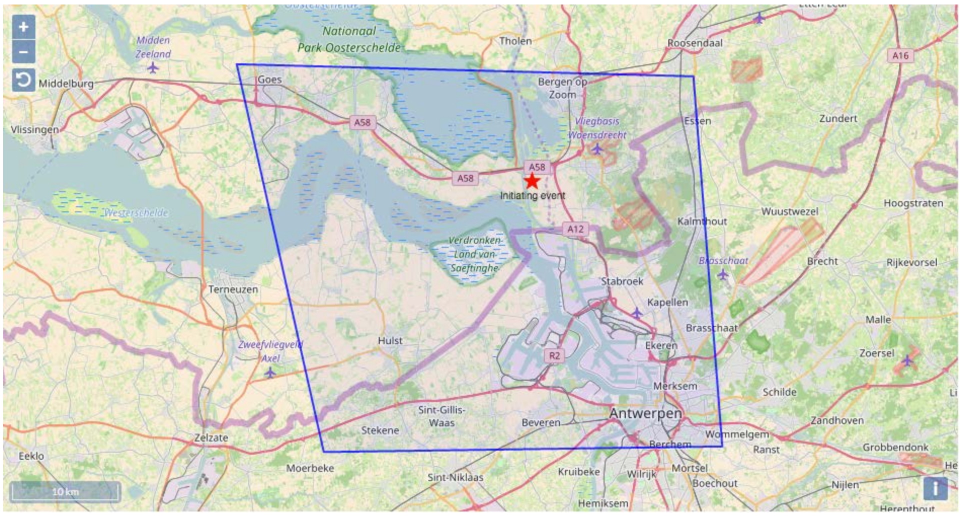

Figure 4-9 Illustration of the initiating event (red star) in relation to the case border (blue line) and different systems (ports, roads, airport, municipalities, business and industry etc.).

4.2.4 Step 4: Determination of temporal aspects

The temporal aspects of the black-out is illustrated in Table 4-6 where the first part of each coloured box represent the propagation time (here a sum of in-system and inter-system propagation times), and the second part of each box represent the endurance time.

In this step also endurance times and in-system propagation times are set. These are not elaborated on in detail here, but are exemplified together with the inter-system propagation time (given as a total propagation time).

Table 4-6 Timeline for the main systems in the black-out scenario

	Propagation Time	CS Telecommunication Mast				Propagation Time	WFS, SI BASF Antwerp	
		Propagation Time	SI Port of Antwerp					
		Propagation Time	TS Airport Deurne					
		Propagation Time	TS Roads A58/A12					
	Propagation Time	ES Underground electric cable						
Initiating event								
15:42	16:00	18:00			20:00	23:00		00:00
Tuesday 18 Dec								Wednesday 19 Dec

4.2.5 Step 5: Assessment of the total impacts of a cascading effect

The impacts (per impact sub-category) can also be listed per system in a table. Such a list is exemplified in Table 4-7 for a few selected systems.

Table 4-7 Examples of impacts per impact sub-categories for a few selected systems.

Impact sub-category	Port of Antwerp	Road A58/A12	Municipality Antwerp
Economical			
Direct economic cost	100.000.000 €	3.000.000 €	25.000.000 €
Social			
People affected by social unrest	500	3.700	220.000
Infrastructure			
Number of users	5%	2%	12%
Expected repair time	1 month	1 month	2 months
Expected repair cost	164.000 €	75.000 €	890.000 €
Human			
Fatalities	20	10	90
Injuries	10	80	680
People that have lost critical services	5	2	110.000
Evacuated	0	100	7.500
Homeless	0	0	0

4.2.6 Step 6: Key decision points

Following the example presented in the different steps above, one can see that the power black-out in the south-west part of The Netherlands and the north-west part of Belgium with its' high concentration of municipalities, transportation infrastructure, businesses and industries can affect many different systems, via the spread of the degradation of energy services, communication and transportation services and key decisions will relate to how far the black-out can be let to spread before the risk for significant cascading effects become too large. Since a lot of systems are interconnected (dependent) on power supply, one key decision shall deal with the isolation of the spread of the black out. An aggravating circumstance is the proximity of the Port of Antwerp, the 2nd largest petrochemical cluster in the world, which means that power isn't restored as quickly as possible that a lot of businesses and industries will be forced to shut down. This affects the decisions on the emergency response and mitigation tactics.

In the example above a key decision is also to decide whether and when the largest cities (Antwerp, Goes) and critical infrastructures for the public (hospitals) should be connected to the back-up power generators. By in this way study the impacts belonging to certain impact sub-categories for the included system, key decision points can be found.

5 Conclusions and perspectives

A generic framework has been developed for modelling dependencies and cascading effects for preparing crisis or to be used during crisis management. The methodology, which is a 6 steps approach, requires detailed information on the system, which most of the case, is difficult to obtain. So to avoid issues of lack of data, some steps refer to historical database analysis allowing to fill missing data gap. The methodology as such can, however, be used also if not all detailed data is available to study different options and scenarios.

The methodology has been exemplified by three case tests to illustrate the usability. The usefulness, the added-value and the adaptability aim at being tested during validation exercises involving end-users such as emergency responders, critical infrastructure operators, researchers and members of the civil society.

An Incident Evolution Tool based upon the methodology is also being developed. Its aim is, as for the methodology, to help decision makers to objectify the impacts of their decisions through webGIS and visualization application. The development and use of the tool is described elsewhere.

In the future, one way to exploit the methodology would be to create a central hub able to communicate to all stakeholders involved in emergency response and preparedness information on potential impacts and vulnerabilities of the environment system (in open data) and to the Public and private systems (with data available only when required). In that case, for private systems, Step 1 should be under the responsibility of the private system operators, the remaining steps being under the responsibility of the central hub coordinator.

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Annex 1 – Dependence probability of the originating system category on impacted system

To ease the use of probability, the dependence probability between different categories of systems are listed below as a decreasing priority order ranking. For each line, for a certain originating system category, the dependence probability decreases.

Originating Category of system	Dependence probability (ranking in decreasing order)
Power Supply	"Power supply" **>** "Business and industry" – "The public" **>** "Telecommunication" – "Water supply" – "Health care" **>** "Emergency response" **>** "Sewage" – "Oil and Gas" – "Road transportation" – "Rail transportation" – "Financial" **>** "Government" **>** "Education" – "Agriculture" – "Media" **>** "Air transportation" – "Sea transportation" – "Environment" **None for the other categories of system**
Telecommunication	"Telecommunication" **>** "Health care" – "Emergency response" – "The public" **>** "Financial" **>** "Education" – "Business and industry" – "Government" **>** "Political" **None for the other categories of system**
Water supply	"Water supply" **>** "Business and industry" – "The public" **>** "Health care" **>** "Power supply" – "Education" – "Food supply" **>** "Road transportation" – "Rail transportation" – "Government" **None for the other categories of system**
Sewage	"Sewage" **>** "Road transportation" – "The public" – "Environment" **>** "Health care" **>** "Power supply" – "Water supply" – "Oil and Gas" – "District heating" – "Education" – "Rail transportation" – "Financial" – "Emergency response" **None for the other categories of system**
Oil and Gas	"Oil and Gas" **>** "The public" **>** "Power supply" **>** "Business and industry" – "Environment" **>** "Agriculture" – "Emergency response" **>** "Telecommunication" – "Health care" – "Road transportation" – "Rail transportation" **None for the other categories of system**
District heating	**None for all the categories of system**
Health care	"Health care" **>** "The public" **>** "Government"

Originating Category of system	Dependence probability (ranking in decreasing order)
	None for the other categories of system
Education	“Education” – “The public” **None for the other categories of system**
Road transportation	“Road transportation” **>** “Business and industry” – “The public” **>** “Health care” – “Emergency response” **>** “Rail transportation” **>** “Sewage” – “Education” – “Government” – “Food supply” **None for the other categories of system**
Rail transportation	“Rail transportation” **>** “The public” **>** “Oil and Gas” **>** “Environment” **None for the other categories of system**
Air transportation	“Air transportation” **>** “Business and industry” **>** “The public” **None for the other categories of system**
Marine transportation	“Sea transportation” **>** “Agriculture” – “The public” – “Environment” **None for the other categories of system**
Agriculture	“Agriculture” **>** “The public” **>** “Food supply” **>** “Business and industry” – “Environment” **None for the other categories of system**
Business and Industry	“Business and industry” **>** “The public” **>** “Agriculture” **>** “Telecommunication” – “Water supply” – “Health care” – “Road transportation” – “Rail transportation” – “Government” – “Emergency response” **None for the other categories of system**
Media	**None for all the categories of system**
Financial	“Financial” **>** “The public” **>** “Business and industry” **None for the other categories of system**
Government	“Government” – “Sewage” **None for the other categories of system**
Emergency response	“Emergency response” – “The public” **None for the other categories of system**
The public	“The public” **>** “Telecommunication” – “Emergency response” **>** “Business and industry” **>** “Government” **>** “Road transportation” – “Financial” **>** “Health care” – “Education” – “Rail transportation” – “Political”

Originating Category of system	Dependence probability (ranking in decreasing order)
	None for the other categories of system
Environment	“Environment” **>** “Agriculture” **>** “Power supply” – “Sea transportation” – “Emergency response” **None for the other categories of system**”
Political	“Political” **None for the other categories of system**
Food supply	“Food supply” – “The public” **None for the other categories of system**

The calculations have been done for initiating effects in one or more categories. The dependence probability of a given system category impacted by more than one originating categories effects is the result of a cumulative combination of individual probabilities. For example, as shown Figure 3-10 Dependence probability of system categories “Power supply” (a), “Oil and Gas” (b) and “Power supply” + “Oil and Gas” (c) as the originating categories (c), when originating effects occur simultaneously on “Power supply” (n° 1) and “Oil and Gas” (n° 5), the dependence probability of “Water supply” (n° 3) - amongst the lowest for effects coming from “Oil and Gas”- increases due the dependence probability to “Power supply”. Furthermore, “District heating”, “Political” and “Food supply” categories have null dependence probability since in this case, “Power supply” and “Oil and Gas” are solely the originating category.

Annex 2 - Initiating events and systems vulnerability in the framework of an industrial site

The following Annex describes available tools do build a cascading effect sequence within an industrial site context. This includes:

- Characterising the initiating event
- Evaluating the vulnerability system

A2.1 Initiating events: accidental loadings

A2.1.1 Introduction

Industrial equipment failure can cause dangerous phenomena, whose effects can be categorized into four types:

- Thermal effects
- Blast effects
- Toxic effects
- Natech Effect (Natural Hazard Triggering Technological Disasters)

Thermal effects are linked to a self-sustaining exothermic chemical reaction involving a combustible and an oxidizer (very often the oxygen in the air). This can only occur if a minimal starting energy, the source of the fire, is provided. The fire then sustains itself (more or less) by the heat effect produced by the combustion. These thermal effects instigate radiative and convective effects on industrial structures situated in its near surroundings. Multiple events leading to human and material losses are documented in the accident records. On July 30, 2004, a defective pipeline for transporting natural gas started a flame with an estimated height of 100 m. As a result of this accident, 24 people were killed and 132 injured[6]. Extensive material damages were reported, particularly on surrounding buildings, as shown in Figure A2-1.

Figure A2-1 Damages to buildings caused by jet fire (http://www.aria.developpement-durable.gouv.fr/accident/27681/).

[6] http://www.aria.developpement-durable.gouv.fr/accident/27681

Thermal effects are characterized as a signal of heat flux density defined as a function of time. Figure A2.2 shows the progression of the heat flux caused at a certain distance for a BLEVE type phenomenon.

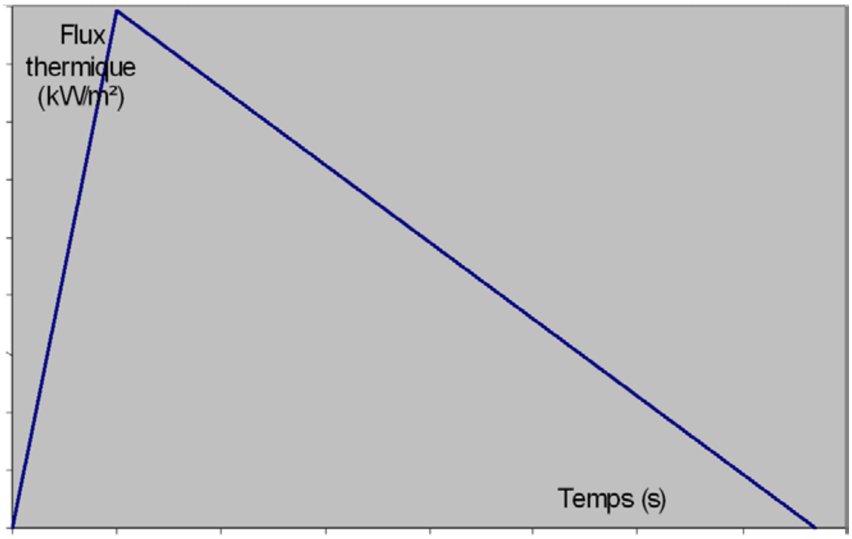

Figure A2-2 Theoretical heat flux density for a BLEVE type phenomenon.

Blast effects correspond to the dynamic transformation of one or more materials defined in a given state into another material, or the same material into another state. The volume of the new material or new state is greater and generally in the form of a gas. Thus, there are considered to be two principal types of explosion:

- Explosion following the high-speed combustion of an explosive substance, most often associated with thermal effects,
- Explosions related to a sudden pressure reduction of a material following the rupture of a containment vessel under pressure. This is known as a pneumatic explosion.

The most devastating industrial accident in France took place in the AZF factory in Toulouse on September 21, 2001[7]. This event caused the death of 21 people, as well as major material damage to all surrounding structures.

[7] http://www.aria.developpement-durable.gouv.fr/accident/21329/

Figure A2-3 Illustration of damages on the AZF site in Toulouse. (http://www.aria.developpement-durable.gouv.fr/accident/21329/).

A blast wave is characterized by a value of pressure progressing as a function of time, as shown in the Figure A2-4.

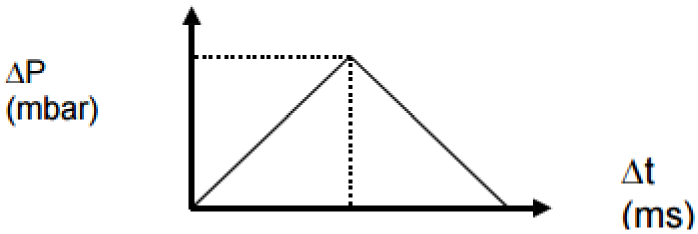

Figure A2-4 Pressure wave as a function of time.

Toxic effects are related to the exposure of targets to danger, which here entails a cloud generated after an accidental release of a chemical substance into the atmosphere (leak, deteriorated tank, etc.).
Toxic gas emission can be continuous (in a jet) or brief (in a blast). It disperses into the atmosphere under the effects of its initial speed, the effect of gravity due to density of the gas, wind, atmospheric conditions (atmospheric stability, or the vertical profile of temperatures), hygrometry and landscape.

A natural hazard (flood, earthquake, forest fire, storm, ground movement, avalanche, cyclone, extreme cold, heat wave, etc.) can have an impact on an industrial installation and thus can be the source of an accident or series of accidents with major effects on the exterior of the site to people, goods or the environment. This is known as a "**NaTech**" accident, a combination of the words "natural" and "technological." These consequences can be direct (material damages: buildings, equipment, installations, etc.) or indirect (social, operating losses, market losses,

etc.). In the framework of CascEff INERIS has developed tools dedicated to seismic and flooding vulnerability.
Earthquakes and their often dramatic consequences represent a significant portion of NaTech accidents accounted for abroad (15%)[8]. These earth tremors cause fragility or collapse of structures, or trigger tsunamis, causing widespread submersions. A practical way to describe an earthquake is with a seismic spectrum that associates a maximum acceleration value as a function of the excitation period, considering a simple oscillator with the same period of vibration.
Floods are often instigated by periods of severe and prolonged rainfall, which can lead to rises in water level higher than the levels of protection of industrial sites, or even by significant rises in water level in storm water systems.
The ARIA Database has been developed by French authorities to analyse every technological accident that occurred over the last years[9]. The survey of NaTech accidents in the ARIA database is consistent with the preponderance of natural disasters related to water levels and their consequences, since heavy rains and flooding represent half of all phenomena that have triggered one or more industrial accidents in French territory.
The two characteristic dimensions commonly used to describe flood-related stress are water level and flow speed.

The aim of this chapter is to present the calculation tools that may be employed by a user of the IET in order to estimate the distances of effects associated with each of these effects. Specifically, it deals with how best to identify accidental sequences in an industrial site where a major natural or technological event has occurred.

A2.1.2 Thermal effects

A2.1.2.1 Pool fire

A pool fire is a fire resulting from the combustion of a pool of flammable liquid. This combustion phenomenon takes place at the interface between the pool surface and the air.

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[8] http://www.limousin.developpement-durable.gouv.fr/IMG/pdf/Presentation_BARPI_Accidentologie_Risque_NaTech.pdf
[9] http://www.aria.developpement-durable.gouv.fr

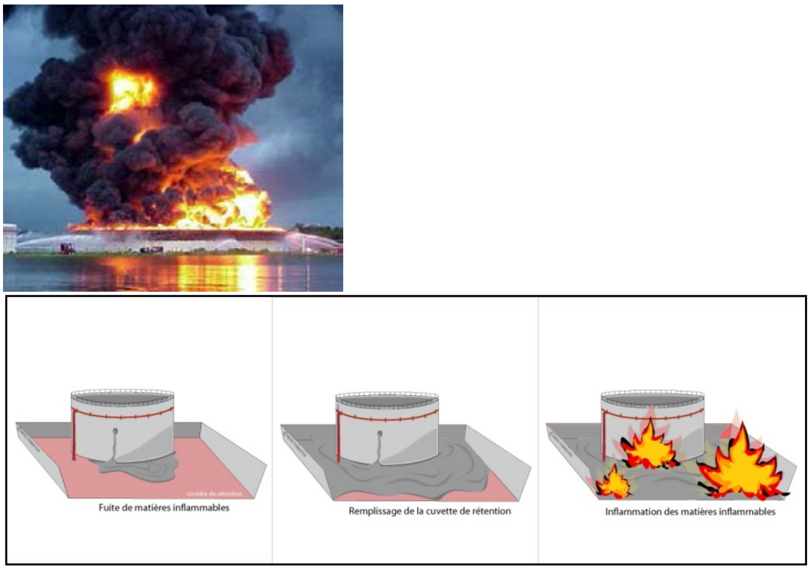


Figure A2-5 Illustration of a pool fire.

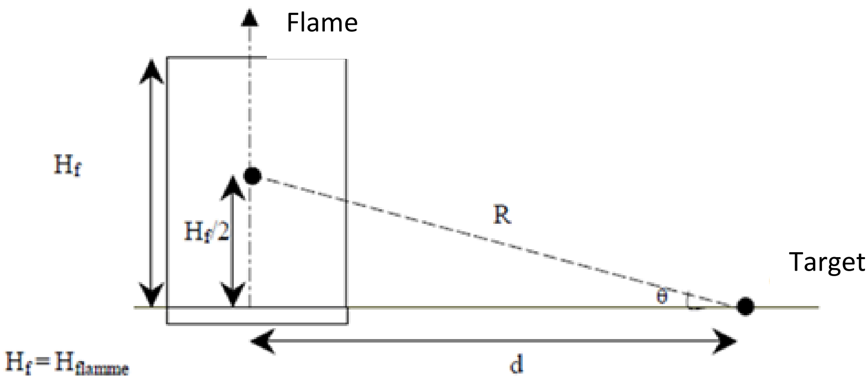
Various tools available on the internet such as ALOHA (areal locations of hazardous atmosphere[10]) provide distances of effects associated with pool fires. The input data are the type of material and the surface area of the pool. Another tool developed by INERIS can be used to assess distance effects induced by a pool fire (http://www.ineris.fr/aida/consultation_document/files/aida/file/text4554_v4.xls).

Below is a summary of the theoretical considerations of the model.

The thermal load density received by a target located at R meters from the fire is provided by the following formulation:

$$q_a = Q_r \cos\theta / 4 \pi R^2 \qquad [W / m^2]$$

Qr: radiated power [kW]
R: distance between the fire (origin) and the target [m]
q_a: Thermal load density transferred to the target [kW/m²]



This formulation needs to evaluate the power emitted by the fire Q_r:

[10] http://response.restoration.noaa.gov/aloha

$$Q_r = \eta_r\, Q = \eta_r\, m''\, \Delta H_c\, A$$

Qr : radiated power [kW]
Hf : Flame height (m)
nr : fire radiative fraction [-]
Q : Total power of the fire [kW/m²]
m'' : mass rate of combustion [kg/m²s]
ΔHc : heat of combustion [kJ/Kg]
A : pool Area (ground)

A2.1.2.2 Jetfire

In an industrial environment, jet fires, also called torch fires, can occur following an accidental leak of flammable fluids or intentional dumpling of industrial by-products using flares.

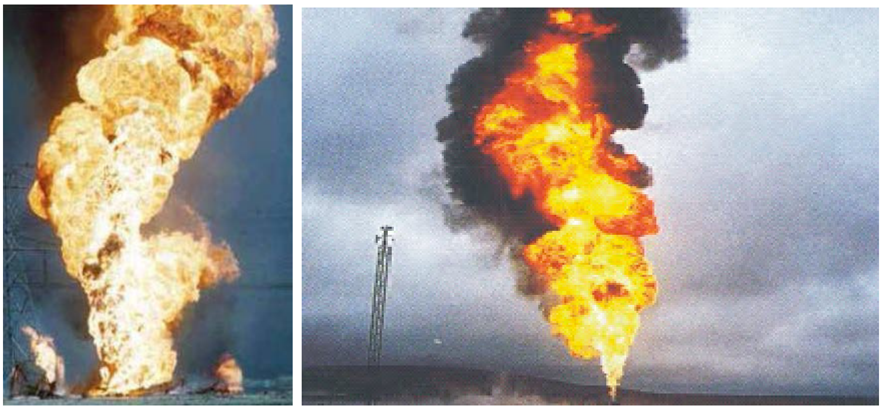


Figure A2-6 Photographs of jet fires.

As with pool fires, several modelling tools, such as ALOHA or Pool fire on the web portal Primarisk[11], can be used to calculate the distances of effects associated with a jet fire. The input data are the size of the breach, the pressure of the piping and the diameter of the piping.

A2.1.2.3 BLEVE

A BLEVE (boiling liquid expanding vapour explosion) can be defined as a violent, explosive vaporization following the rupture of a tank containing a liquid at a temperature significantly higher than its boiling point at atmospheric pressure. A BLEVE can occur with any liquid, flammable or not, when it is heated in an enclosed vessel.

The Figure A2-7 shows the accidental sequence leading to a BLEVE.

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[11] http://primarisk.ineris.fr/

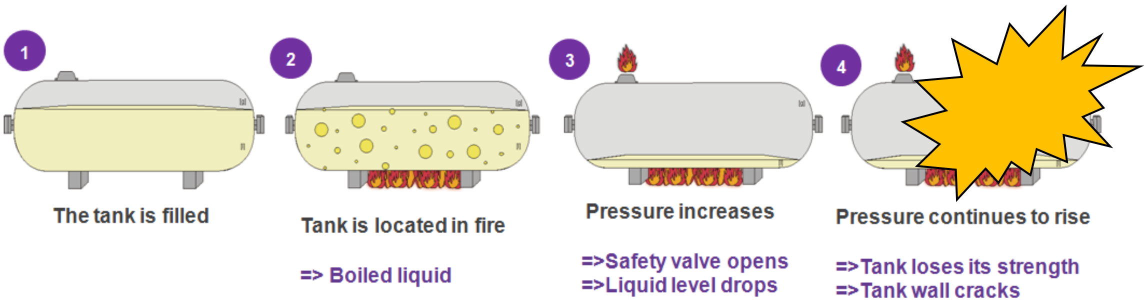

Figure A2-7 BLEVE accidental sequence.

Cracking, and the BLEVE associated with it, occurs when the tank's resistance pressure is reduced to the same value as the rising pressure from the liquid being heated.

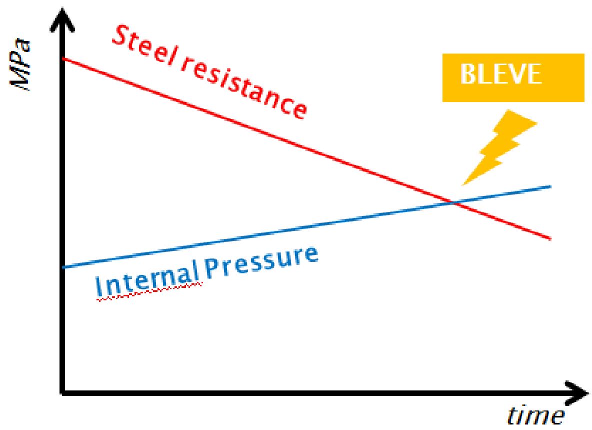

Figure A2-8 Progression of tank's resistance pressure and pressure induced by the vessel's contents.

Simple formulas have been developed to calculate thermal effects related to BLEVEs in a vessel under pressure.

Whenever health consequences are to form the basis of a decision concerning the effects of an accident involving a BLEVE, knowledge of the intensity of thermal radiation is not sufficient. The effect on human health of the exposure to thermal radiation depends not only on the intensity of the radiation but also on the duration of the exposure. A quantitative measure of the severity of the effect of a particular exposure is given by the so called dose function for thermal radiation given by the relationship

$$d(r) = [Q(r)]^{4/3} t$$

d(r) is the thermal dose at point r
Q(r) is the thermal flux at a distance r (kW/m^2)
T is the duration of the exposure (s)

The formulas for distance of effects related to 3 thresholds are included in the Table A2-1. Input data to be plugged in are the type and mass m (kg) of the material (LPG only).

Table A2-1 Formulas for calculating effect distances (meters).

	Butane, butanes, butadienes, chlorure de methyl, chlorure d'éthyle et CVM	Propane, propylene
Distance effects: 1800 $(kW/m^2)^{4/3}.s$ (Serious lethal effects threshold) 5% lethality	$0.81\ m^{0.471}$	$1.28\ m^{0.448}$
Distance effects: 1000 $(kW/m^2)^{4/3}.s$ (First lethal effects) 1% lethality	$1.72\ m^{0.437}$	$1.92\ m^{0.442}$
Distance effects: 600 $(kW/m^2)^{4/3}.s$ (Irreversible effects threshold)	$2.44\ m^{0.427}$	$2.97\ m^{0.425}$

A2.1.3 Blast effect

The most commonly used method for evaluating the distances of effects caused by an explosion is known as the TNT equivalent (Multi-Energy method to evaluate blast effects - TNO Book)
This methodology can be used to determine the blast levels produced at a distance "d" from a source term. The source term is defined in equivalent TNT mass. Required input data are the type, mass and enthalpy of the product's combustion.

Software that can apply this method has been developed and available on internet, such as ALOHA and the tools available on the web portal Primarisk.

A2.1.4 Toxic effects

Among models used in a first approach, the Gaussian model is widely used to evaluate the cloud propagation. The Gaussian model is only valid for products whose volumic density is close to that of the air.
The formula for this model is presented below.

Data for the model:

leakage parameters:

- Filling mass M [Kg]
- Flowrate Q(t) [Kg/s]
- Leakage duration (t_{stream})
- Leakage height h_o [m]
- Wind velocity u [m/s]

Instantaneous leakage

$$C(x,y,z,t)=\frac{M}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z}\exp\left(-\frac{(x-x_0-ut)^2}{2\sigma_x^2}-\frac{(y-y_0)^2}{2\sigma_y^2}\right)\left[\exp\left(-\frac{(z-h_0)^2}{2\sigma_z^2}\right)+\alpha\exp\left(-\frac{(z+h_0)^2}{2\sigma_z^2}\right)\right]$$

With:

- *M [Kg] : leakage mass*
- *σx, σy, σz [m] : standard deviation gas distribution*
- *x0, y0, z0 [m] : breach position*
- *α : ground reflexion coefficient*

The Figure A2-9 presents an example of toxic cloud propagation calculated with the Gaussian formulation.

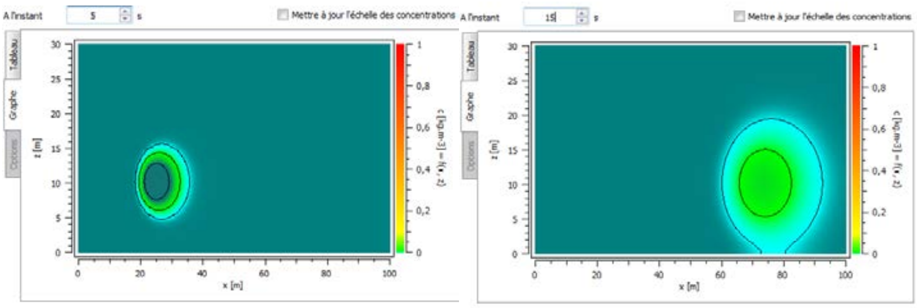

Figure A2-9 Toxic cloud evolution over the time.

Results on Figure A2-9 indicate the location of the cloud at two points in time (1 and 15 seconds).
It is then possible to identify the distances of associated effects when the thresholds of toxic effects are known.

The Table A2-2 shows concentration (in mg/m3 and in ppm) corresponding to various lethal thresholds and various elapsed time for hydrochloric acid.

Table A2-2 Thresholds of toxic effects (January 2003/April 2005).

Concentration (mg/m3 – ppm) (http://response.restoration.noaa.gov/toxiclocs)	**Time (min)**				
	1 min	**10 min**	**20 min**	**30 min**	**60 min**
SELS (serious lethal effects threshold) 5% lethality	29 763 mg/m3 19 975 ppm	3 202 2 149	1 638 1 099	1 106 742	565 379
SPEL (first lethal effects threshold) 1% lethality	16 390 11 000	1 937 1 300	1 013 680	700 470	358 240
SEI (irreversible effects threshold)	3 590 2 410	358 240	179 120	119 80	60 40

To evaluate the propagation of others products (which volume density is not close to that of the air) or to obtain results with more precision, more complex models can be used such as PHAST (Integrated Consequence and Risk modelling aimed at the onshore petrochemical and chemical process industry).[12]

A2.1.5 Natech effects: seismic loading

Damages inflicted on an industrial site impacted by an earthquake are generated by dynamic oscillating movements induced at the bases of equipment. Earthquakes are caused by waves of movement that reach to and propagate on the earth surface, and are thus characterized by temporal variations of ground movement, which are then transferred to structures at their foundations. These waves of movement are dependent both on the starting impulse at the earthquake epicentre, the media passed through on the way to the surface and the local geographic configuration. Thus, characterizing seismic loading on structures is generally an essential prerequisite to mechanical diagnostics and structure reinforcement.

In practice, the physical parameter to be determined is the acceleration induced by the earthquake in the structures. For a given earthquake, the temporal variations in acceleration recorded at one point on the earth's surface form an accelerogram, like the one illustrated in Figure A2-10. The recorded accelerograms can be used directly as input data for calculating a structure's behaviour in an earthquake.

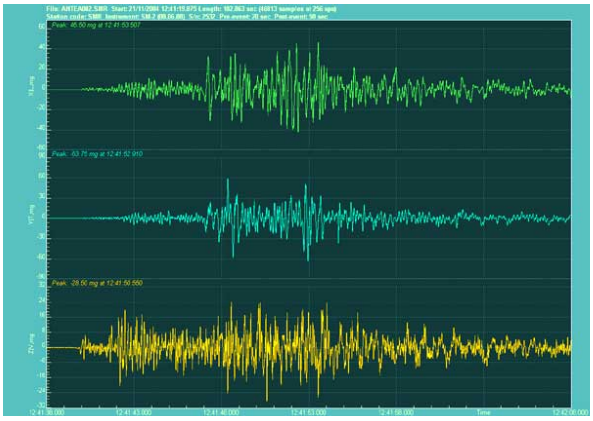

Figure A2-10 Example of an accelerogram measured at the base of structures [Source: BRGM http://www2.brgm.fr/sismicit%E9_guad_accelero.htm].

The specific characteristic of dynamic loading on a mechanical system with a certain amount of inertia consists of an associated dynamic amplification, which means that the acceleration induced in the system is potentially greater than the acceleration of its stressor. For a simple oscillator as shown in Figure A2-11, consisting of a mass "M" connected to its mount by a spring "k" and a shock absorber "c," the maximum acceleration induced by an earthquake is obtained when the period of seismic loading corresponds to the oscillator's period of vibration.

[12] https://www.dnvgl.com/services/process-hazard-analysis-phast-1675

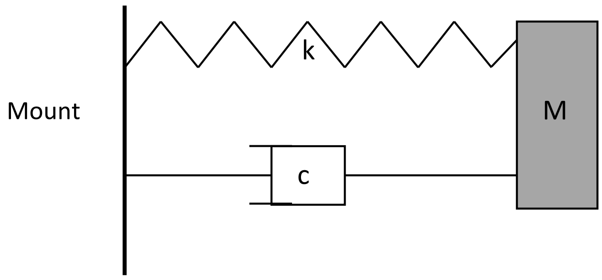

Figure A2-11 Simple oscillator with a degree of flexibility.

Consequently, a practical way to describe an earthquake is as a seismic spectrum that associates a value of maximum acceleration as a function of the period of excitation, by considering a simple oscillator with the same period of vibration.

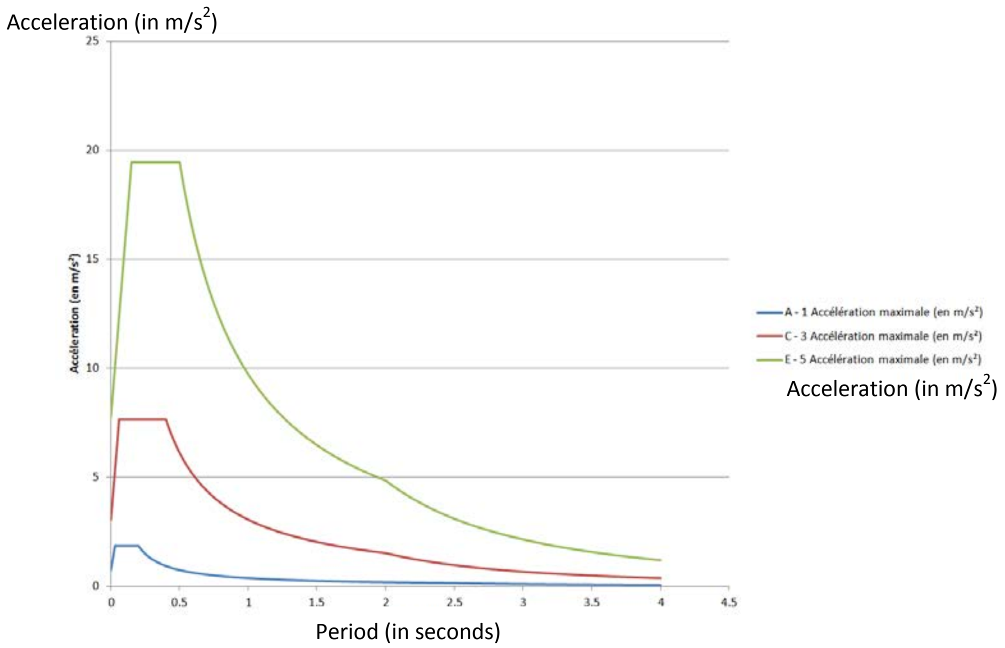

Figure A2-12 Shape of elastic response spectrum (Seismic zone 1, Ground class A; Seismic zone 3, Ground class C; Seismic zone 5, Ground class E; Existing installation, Shock absorption of 5%) (according to special risk regulations from the French Ministry and standard NF EN 1998-1).

A2.1.6 Natech effects: flood loading

To properly identify the systems impacted by flooding, a map of the extent of the flooding and a ground plan showing the location of the installations using several topographical reference points are necessary. These maps are created by special organizations (IRSTEA in France), and associate precise flow calculations with a historical survey of the most significant past flooding events. In certain configurations, a more detailed characterization of the flood at the industrial site may be necessary in order to clarify the accidental sequences and to optimize risk control solutions. The principal parameters useful in characterizing floods are listed with comments in Table A2-3.

Table A2-3 Characteristic parameters used for in-depth analysis of NaTech flood risk.

Parameters	Comments
Water level on site	The water level parameter is needed to determine mechanical loading on structures. A conservative diagnosis can be made with an accuracy of within 50 cm. However, in terms of optimization, the reinforcements are generally measured using more precise input data.
Flow speed on site	The flow speed parameter is important for calculating mechanical loading on industrial structures, at times when it is relatively high. Configurations where the influence of speed is most important include those related to ruptures in hydraulic works or tsunamis. For lower speeds, a diagnosis based on impact from floating objects can prove useful for fine structures.
Water elevation speed	The water elevation speed parameter is important for designing a safety strategy. Water elevation speed can, for example, be deduced by analysing a hydrogram in case of floods. A conservative estimate is sufficient to develop a strategy that can be adapted to real-life water elevation conditions when managing a crisis.
Submersion duration	An approximate idea of submersion duration is important when specific equipment must be kept in operation for security purposes or when planned technical solutions make use of stock/inventory.

A2.2 System vulnerability

A2.2.1 Introduction

As part of the CascEff project, INERIS developed a set of tools that can assess an industrial installation capacity to resist a given load. Specifically, it improves on tools for predicting the vulnerability of industrial equipment subjected to technological or natural stresses and develops models of domino effects.

Within the CascEff project, these tools are not designed to be integrated in the IET. Certain models make use of complex numeric tools, which require a calculation time that is incompatible with the reaction time needed in a crisis situation. Instead, the chosen approach consists of developing fragility curves or graphs of results that can be integrated in the IET. Fragility curves is a statistical tool representing the probability of exceeding a given damage state (or performance) as a function of an engineering demand parameter that represents the ground motion (preferably spectral displacement at a given frequency).

A certain number of tools were thus developed for this purpose. These are briefly described below.

A2.2.2 Thermal effects endurance: The behaviour of LPG tanks under thermal loading

Introduction

Over a period of 10 years, 3 explosions of pressurized tanks of liquefied gas occurred in France (Dagneux 2007, Port La nouvelle 2010, Bassens 2016).
The feedback from these experiences report a certain number of events during which a fire that started at the base of the tank incited an increase in pressure followed by a BLEVE (Boiling Liquid Expanding Vapour Explosion).

Figure A2-13 LPG tank

Moreover, dominos effects within an industrial site are currently considered regarding an empirical threshold defined by the French Ministry of the Environment (8 kW/m²)[13]. This heat flux corresponds to a conservative approach to identify dominos effects within an industrial site.

A tool was developed with the purpose of predicting the kinetics of a rise in temperature in a piece of equipment under pressure when subjected to a thermal flux, in order to:

- Assess the duration between the start of the fire and the tank explosion, so as to allow intervening services to put in place the appropriate countermeasures.
- Design systems for protecting the tanks in order to slow or even stop the explosion.

Specifically, the purpose of the tool is to calculate the period of time separating the start of the fire from the loss of the vessel associated with the explosion. In a crisis situation, this information could, for example, improve emergency service management.

Graphs of results for a sampling of sufficiently significant tanks were then developed.

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[13] http://www.ineris.fr/aida/consultation_document/5123

Graphs for calculating BLEVE kinetics

Calculations have been led using the following parameters:

- Total tank volume
- Filling rate
- Nominal Diameter of the PRV (Pressure Relief Valve)

Using the tool, heat calculations were taken on LPG tanks for small and large carriers in Europe. The type of tanks studied, as well as their calculated endurance duration, are presented in the Table A2-4.
The thermal load applied is a full fire engulfment.

Table A2-4 Elapsed time before BLEVE occurs for 3 tanks (15m^3, 30m^3, 60m^3).

Volume (m3)	Lenght (m)	Radius (m)	Filling rate	Nominal Diameter of Pressure Relieve Valve (mm)	elapsed time before BLEVE (seconds)
15	4.6	1	20 %	NO	357
30	6	1.20		NO	389
60	12	1.22		NO	406
15	4.6	1		DN45	820
30	6	1.20		DN45	830
60	12	1.22		DN45	835
15	4.6	1		DN90	845
30	6	1.20		DN90	1230
60	12	1.22		DN90	1380
15	4.6	1	50 %	NO	371
30	6	1.20		NO	405
60	12	1.22		NO	427
15	4.6	1		DN45	No collapse
30	6	1.20		DN45	No collapse
60	12	1.22		DN45	470
15	4.6	1		DN90	No collapse
30	6	1.20		DN90	No collapse
60	12	1.22		DN90	No collapse
15	4.6	1	80 %	NO	362
30	6	1.20		NO	389
60	12	1.22		NO	417
15	4.6	1		DN45	No collapse
30	6	1.20		DN45	391
60	12	1.22		DN45	417
15	4.6	1		DN90	No collapse
30	6	1.20		DN90	395
60	12	1.22		DN90	424

The following figures (Figure A2-14, Figure A2-15, Figure A2-16) present the behaviour curves for 3 tanks. These tanks have no Pressure Relief Valve, a volume of 30 m^3 and various filling rate (20%/50%/80%):

The mechanical behaviour of LPG tanks subjected to thermal loads is characterized by the simulation of two physicals parameters:

- The pressure applied on the internal shell tank (red curve)
- The steel resistance (blue curve)

The intersection between the two curves corresponds to the tank collapse.

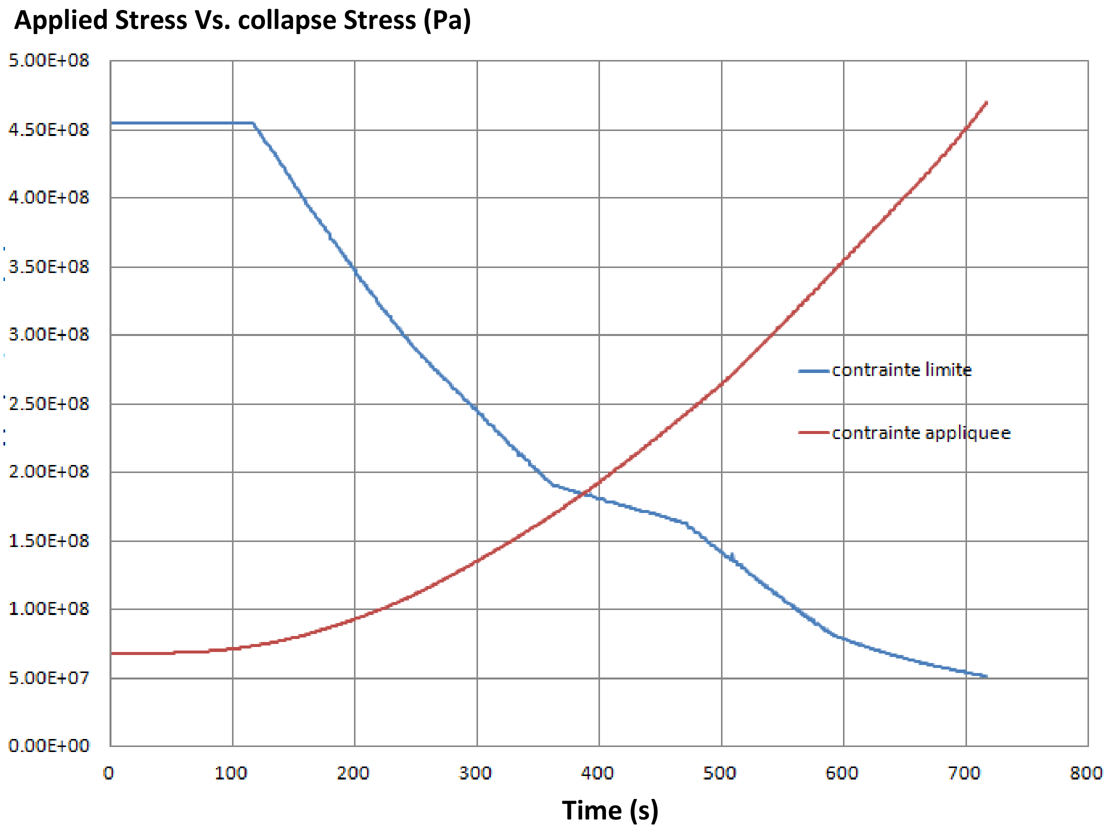

Figure A2-14 Tank Behaviour Curve (filling rate: 20 %).

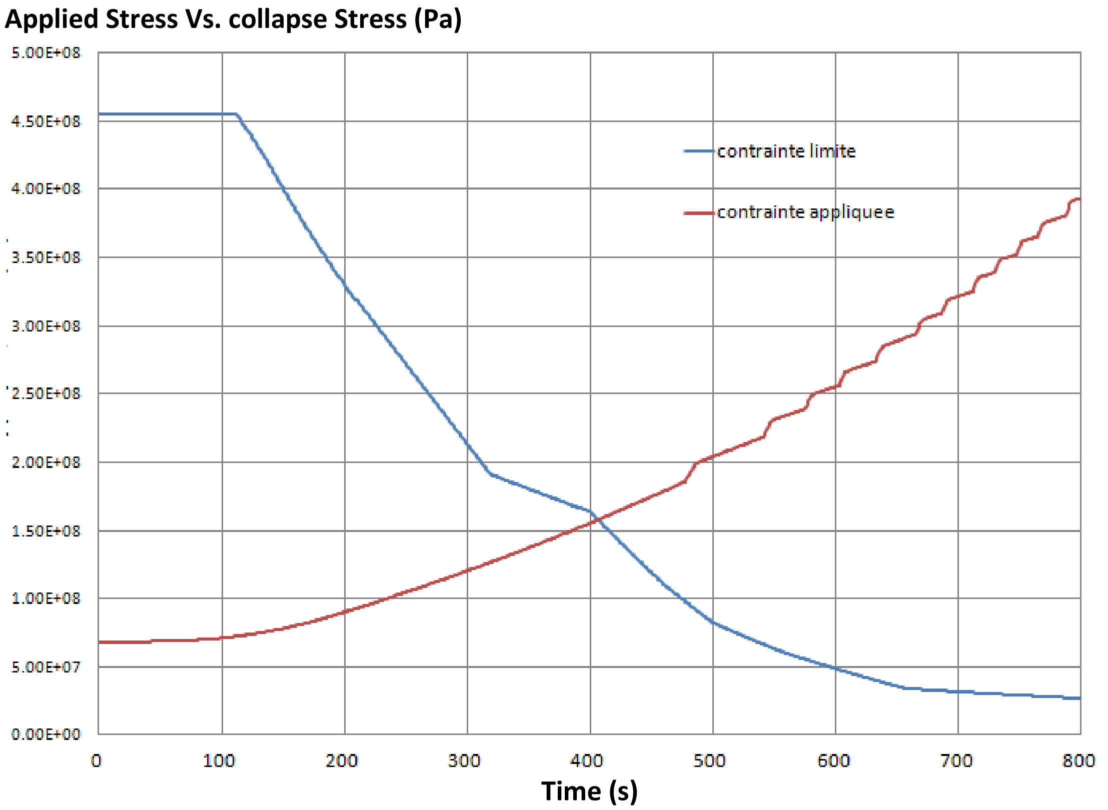

Figure A2-15 Tank Behaviour curve (filling rate: 50 %).

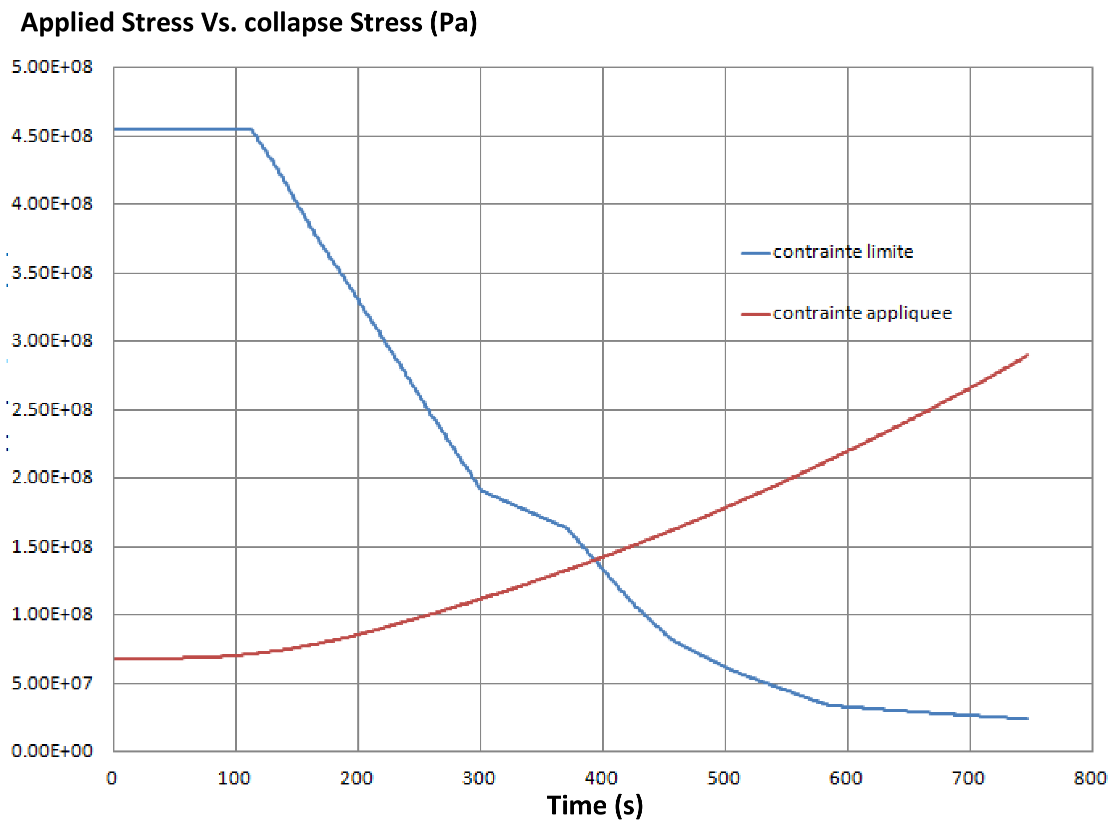

Figure A2-16 Tank Behaviour (filling rate: 80 %).

Validating the tool for predicting temperature rise in a tank subjected to fire

This tool underwent a validation process that compared the results obtained from it to those in the literature.
Over the past 30 years, analytical and numeric models have been developed to analyze the behaviour of tanks subjected to fire. Nevertheless, INERIS was more interested in the work done in the last 10 years, especially the analytical models developed by Xing, Jiang and Zhao[14].
The model developed for the CascEff project can analyze the endurance of a pressurized tank shell containing liquefied gas when subjected to an engulfing fire.

The model developed by INERIS is a finite element model that combines a thermodynamic model, which can take into account temperature changes between the gaseous and liquid phases; and a thermomechanical model, which can predict temperature diffusion in the tank shell. Figure A2-17 shows the thermal transfers in an LPG tank subjected to external thermal stress, which are also used in the model developed by INERIS.

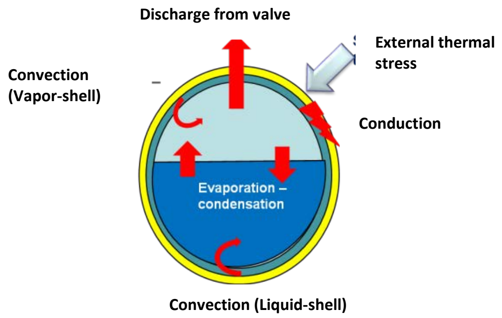

Figure A2-17 Thermal transfers – LPG tank subjected to thermal stress.

The heat conducted by the tank's steel shell is transferred to the liquid and gas inside, leading to evaporation and condensation.

The model consists of the following 5 equations:

- Conservation of mass – Gaseous phase

$$\frac{\partial}{\partial t} n_g = q_e - q_p$$

- Conservation of mass – Liquid phase

$$\frac{\partial}{\partial t} n_l = -q_e$$

- Conservation of volume

$$\frac{n_l}{\rho_l} + \frac{n_g}{\rho_g} = V_0$$

- Energy equation – Gaseous phase

[14] The Model of Thermal Response of Liquefied Petroleum Gas Tanks Partially Exposed to Jet Fire. Xing Zhixiang, Jiang Juncheng, Zhao Xiafang, Chinese J. Chem. Eng., 12 (5) 639-646 (2004)

$$\underbrace{n_g C_{pg}\frac{\partial T_g}{\partial t}}_{\text{Internal energy variation}} = Q_g - q_e \underbrace{\left(h_g(T_g) - h_g(T_l)\right)}_{\text{Exchange due to evaporation}} - \underbrace{q_p h_g(T_g)}_{\text{Loss due to escape through valve}}$$

- Energy equation – Liquid phase

$$\underbrace{n_l C_{pl}\frac{\partial T_l}{\partial t}}_{\text{Enthalpy variation}} = Q_l - q_e \underbrace{\left(h_g(T_l) - h_l(T_l)\right)}_{\text{Exchange due to evaporation}}$$

With:
n_g, n_l, quantity of molar mass of gas and liquid
ρ_l, ρ_g, density of liquid portion (l) and gas portion (g)
Q_l, Q_g, thermal flux received in the liquid portion (l) and gas portion (g)
h_l, h_g, enthalpy of the liquid portion (l) and gas portion (g)
T_l, T_g, temperature in the liquid phase (l) and the gaseous phase (g)
q_e, evaporation rate
q_p, rate of release through valve
C_{pl}, C_{pg}, heat capacities

In order to determine the 8 unknowns of this system (T_g, T_l, n_g, n_l, q_e, q_p, ρ_l, ρ_g), three additional equations are added:

- The Yen-Woods correlation, which will determine the density of the liquid portion based on the temperature of the liquid phase.
- The Van der Waals equation of state, assuming that the pressure P is equal to the saturation pressure at the temperature of the liquid:

$$\left(P + \frac{a'}{\left(1/\rho_g\right)^2}\right)\left(1/\rho_g - b'\right) = RT_g$$

- The equation for the rate of escape through the valve q_p is calculated as follows.

If the pressure is greater than the saturation pressure and the shock pressure is greater than the atmospheric pressure, the rate of release through the valve is calculated as follows:

$$q_p = C_d \frac{\pi d^2}{4}\sqrt{\rho P \gamma \left(\frac{2}{\gamma+1}\right)^{\left(\frac{\gamma+1}{\gamma-1}\right)}}$$

On the other hand, if the pressure is greater than the saturation pressure but the shock pressure is lower than the atmospheric pressure, the rate of release through the valve is calculated as follows:

$$q_p = C_d \frac{\pi d^2}{4}\sqrt{2\rho P \frac{\gamma}{\gamma-1}\left(\frac{P_{atm}}{P}\right)^{\frac{2}{\gamma}}\left(1 - \left(\frac{P_{atm}}{P}\right)^{\frac{\gamma-1}{\gamma}}\right)}$$

With shock pressure being calculated using the following equation:

$$P_{choc} = \max\left(\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \times P \ , \ P_{atm}\right)$$

In order to evaluate the quality of results provided by the INERIS model, a comparison have been realised with experimental tests lead by Petrell[15] As to develop VessFire Software.

The test characteristics are summarized in Table A2-5.

Table A2-5 Characteristics of Vessfire test.

	Partially filled tank
Tank volume	10.25 m^3
Fill level	22% (commercial propane)
Material	Steel
Dimensions	Length: 4.88 m External diameter: 1.7 m Thickness: 11.85 mm
Initial conditions	Initial pressure: 5.5 bars Initial temperature: 5.7°C
Valve	Opening pressure: 14.3 bars Effective area of opening: 8.87 * 10^{-4} m^2

Sensors were put in place to measure the gas temperature, liquid temperature, steel temperature and the internal pressure of the tank. These data were compared to the results given by the model developed by INERIS.

Figure A2-18 shows the temperature progression in both the gas and the liquid. Figure A2-illustrates the progression of the internal pressure.
On each figure, results obtained by the INERIS model are compared with results from the Vessfire experimental test.

[15] Vessfire Software validation - http://petrell.no/wp-content/uploads/2014/07/VessFire_Technical_Reference.pdf

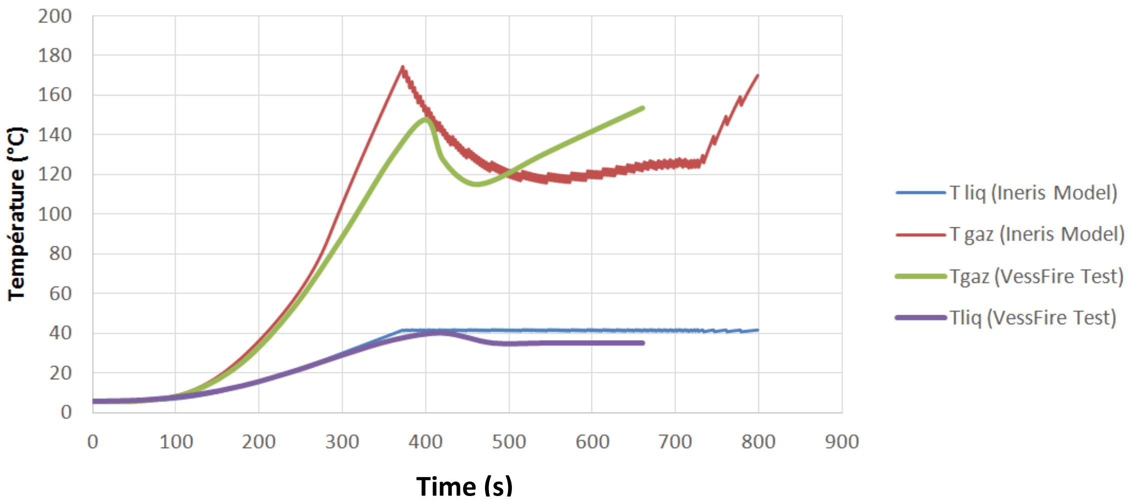

Figure A2-18 Temperatures of the gaseous phase and liquid phase (INERIS model: red curve & blue curve / Vessfire Model: green curve & purple curve).

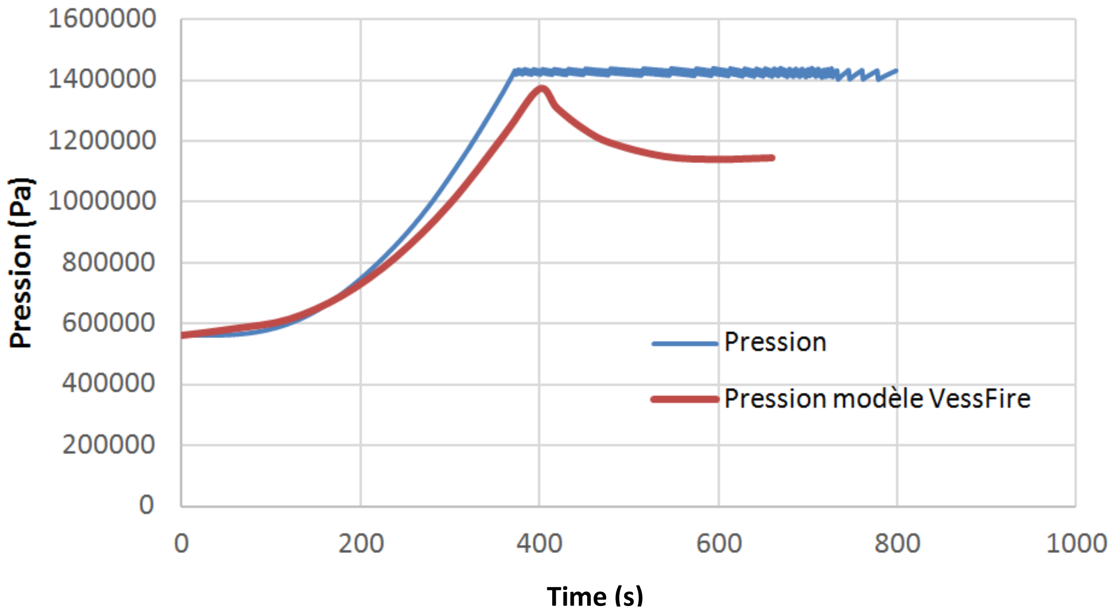

Figure A2-19 Internal pressure (INERIS model: blue curve / Vessfire Model: red curve).

Results obtained with the INERIS model are in accordance with results from the Vessfire Test.

A2.2.3 Blast effects endurance

The blast effect tools designed in the CascEff project are still in the development stage. However, this chapter lists a set of standard results used to obtain an initial trend of equipment vulnerability to blast effects.

A2.2.3.1 Standard thresholds for buildings

Table A2-
Table A2-6 shows the standard minimum blast levels[16] to which structural elements of a building are estimated to be vulnerable.

Table A2-6 Standard minimum blast levels for structural elements of building.

Structure	Supporting structure			Roofing			Windows	
Type of element	Wood	Brick	Cinder block	Light elements	Small covering elements	Large covering elements	Single pane glass	Double pane glass
Threshold (in mbars)	100	140	300	100	100	300	20	50

A2.2.3.2 Standard thresholds for equipment

The French Ministry of Environment has defined empirical thresholds for considering cascading effects between industrial facilities within an industrial site[17] :

- For blast effects: 200 mbar
- For thermal effects: 8 kW/m²

Table A2-7 specifies the types of equipment for which various empirical thresholds are defined based on experience feedback[18]:

Table A2-7 Standard allowable blast levels for industrial equipment.

Collapse Blast Loading	Equipment			
	atmospheric	horizontal	Small (a few m3)	Pressurized equipment
Small leakage	70 mbar Small pool fire	140 mbar Small pool fire Small flash fire	70 mbar Small pool fire Small flash fire	70 mbar Small jetfire
Medium leakage	160 mbar Pool fire Flash fire UVCE	370 mbar Pool fire Flash fire UVCE	370 mbar Small Pool fire Small Flash fire	380 mbar Jetfire Flash fire UVCE
Global collapse	200 mbar Pool fire Flash fire UVCE	450 mbar Pool fire Flash fire UVCE	590 mbar Small Pool fire Small Flash fire	610 mbar BLEVE Flash fire UVCE

[16] http://primarisk.ineris.fr/node/960
[17] http://www.ineris.fr/aida/consultation_document/5123
[18] http://primarisk.ineris.fr/node/960

This vulnerability table for equipment is provided for information purposes only. More complex calculations (e.g. Finite Elements Model Simulation) would provide more precise results.

A2.2.3.3 Atmospheric tanks response under blast loading

Introduction

In the framework of CascEff, INERIS has developed a model to predict the mechanical behaviour of atmospheric tanks under blast loading. The model presented above focus on shell buckling. The feedback shows the main failure mode implied on a tank subjected to blast loading is shell buckling.

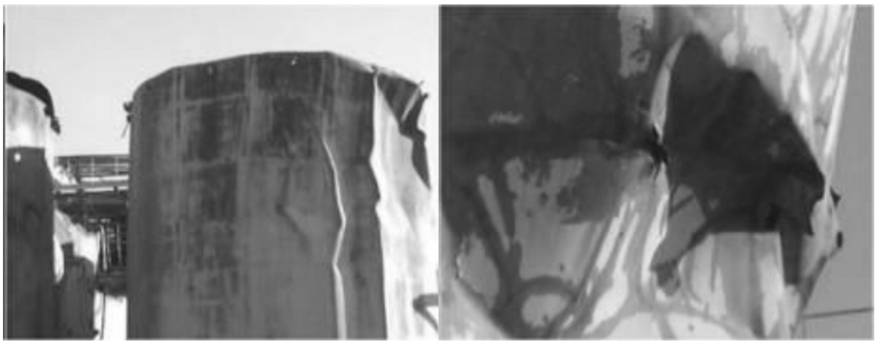

Figure A2-20 Global and local buckling on tanks under blast loading [19]

Buckling is a phenomenon of instability of a structure occurring when a light increase of a load implies large strain. It can lead to the ruin of the structure.

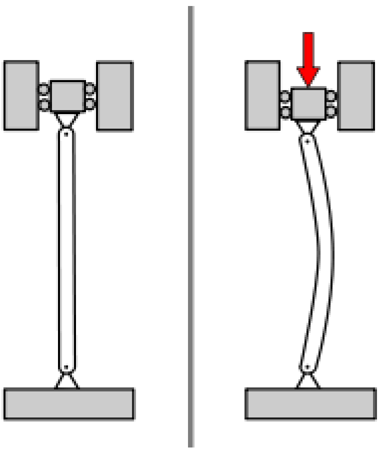

Figure A2-21 A column under a concentric axial load exhibiting the characteristic deformation of buckling[20].

[19] Mouilleau Y., Dechy N., Première analyse des dommages observés à Toulouse après le sinistre du 21 septembre 2001 survenu sur le site AZF de la société Grande Paroisse. Accident investigation report, 2001, INERIS.

The load corresponding to buckling is called **critical buckling load.** The buckling phenomenon is due to the growth of an initial geometrical defect until a critical size associated to plasticity. In the framework of CascEff, INERIS has developed a prediction model of buckling for metallic tanks.

Lindberg[21] built a simplified model allowing to define critical curves of buckling in a pressure-impulse diagram. To develop this model and provide relevant results on a few tanks, buckling have been studied considering an initial defect. This initial defect has been identified considering empirical defects provided by tanks manufacturers. The Lindberg theory suppose that elastic dynamic buckling is based on the equilibrium static equations of Donnel[22], by adding the dynamic terms and the initial defect.
Tests[23] shows that dynamic plastic buckling implies that the cylinder is first uniformly plastically deformed, with a decrease of its radius. The retained material behaviour is plastic with a linear strain hardening. So every type of dynamic buckling is approached by a hyperbolic branch, as shown on Figure A2-22. The simplified model for elastic and plastic buckling is proposed including two hyperboles considering a critical amplification of buckling equal to 20. The critical load associated with elastic buckling corresponds to the lower horizontal asymptote of the model of Lindberg.

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20 https://en.wikipedia.org/wiki/Buckling

21 Lindberg H. E., Florence A. L., Dynamic pulse buckling: theory and experiment, M. Nijhoff, Dordrecht; Boston: 1987.

22 Donnell L., “A new theory for the buckling of thin cylinders under axial compression and bending”, *Transactions of the ASME*, vol. 56, p. 795-806, 1934.

23 THESIS : Etude de la vulnérabilité de structures cylindriques soumises à une forte explosion externe, Duy-Hung DUONG, Université d'Orléans.

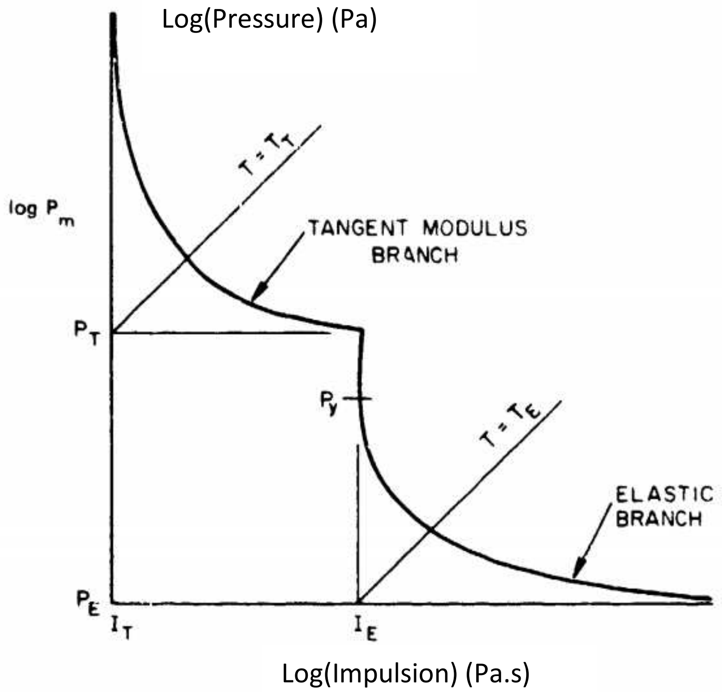

Figure A2-22 Schematic representation of the critical buckling curves (Lindberg approach).

Simplified formulas characterizing horizontal and vertical asymptotes of hyperboles are established taking into account a maximal amplification of 20. Buckling occurs when the point determined by pressure and impulse values is situated over the critical curve of buckling. Simplified formulas, characterizing the asymptotes of two hyperboles (plastic and elastic) are presented below:

$$P_T = 0{,}75\sigma_y \frac{e}{r}$$

$$\mathrm{I_T} = 1{,}807\rho\,\mathrm{c\,r}\,\widehat{\mathrm{D}}\left(\frac{\mathrm{e}}{\mathrm{r}}\right)^{3/2} \text{ si } \frac{\mathrm{r}}{\mathrm{e}} \leq \frac{0{,}405}{\widehat{\mathrm{D}}^{\mathrm{Z}}}$$

$$\mathrm{I_T} = 1{,}15\rho\,\mathrm{c\,r}\left(\frac{\mathrm{e}}{\mathrm{r}}\right)^{2} \text{ si } \frac{\mathrm{r}}{\mathrm{e}} \geq \frac{0{,}405}{\widehat{\mathrm{D}}^{\mathrm{Z}}}$$

$$P_E = 0{,}92\, E_O \frac{r}{h}\left(\frac{e}{r}\right)^{5/2}$$

$$I_E = 3\,\rho\,\mathrm{c\,r}\frac{r}{h}\left(\frac{e}{r}\right)^{2}$$

With:

σ_y, material yield strength
e, thickness of the tank
r, radius of the tank
h, height of the tank
ρ , material density
E_O, Young's modulus of elasticity
c , velocity of mechanical waves
$\widehat{\mathrm{D}}$, material parameter considering elastic-plastic behaviour

Both elastic and plastic branches of the critical buckling curve are presented with two hyperboles with their asymptotes defined by the formulae above. Equations of hyperboles with the consideration of asymptotes are described as follows:

$$\left(\frac{P}{P_x} - 1\right)\left(\frac{I}{I_x} - 1\right) = 1$$

The P_E pressure of the model of Lindberg corresponds to the critical pressure associated with elastic static buckling of shell.

Results presentation

Damage diagrams are constructed and a reliability analysis is performed on specific examples to estimate the sensibility to overpressure and durations and to compare the critical buckling pressure-impulse curves for several tanks. Tanks geometries are presented Table A2-8.

Table A2-8 Tanks geometries

Tank number	Tank radius (m)	Tank Height (m)	Minimal wall thickness of the shell (m)
1	5.75	8	0.005
2	7	10	0.005
3	10	19	0.007
4	20	30	0.01
5	40	30	0.015
6	6.5	10	0.004
7	8	15	0.006
8	11.5	17	0.007

Damage Diagrams are presented on the following figures (Figure A2-23, Figure A2-24, Figure A2-25, Figure A2-26, Figure A2-27, Figure A2-28, Figure A2-29, Figure A2-30). One curve has been edited for each tank geometry presented in the Table A2-17.

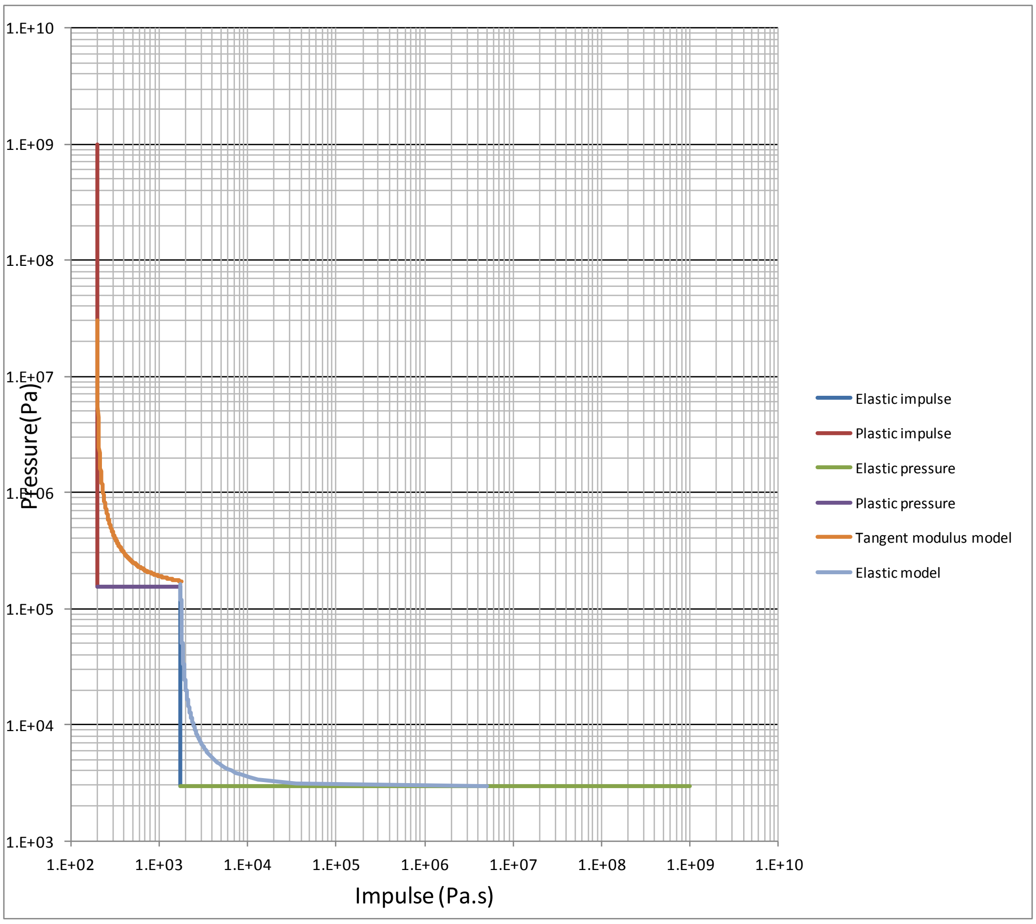

Figure A2-23 Impulse-pressure diagram for tank n°1.

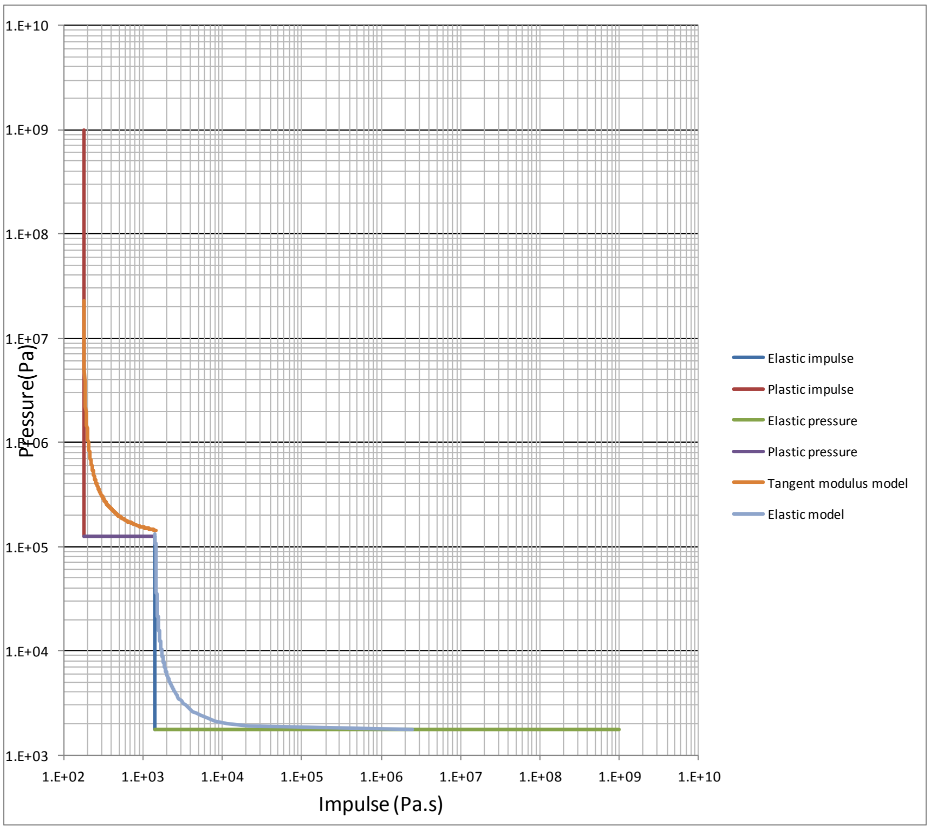

Figure A2-24 Impulse-pressure diagram for tank n°2.

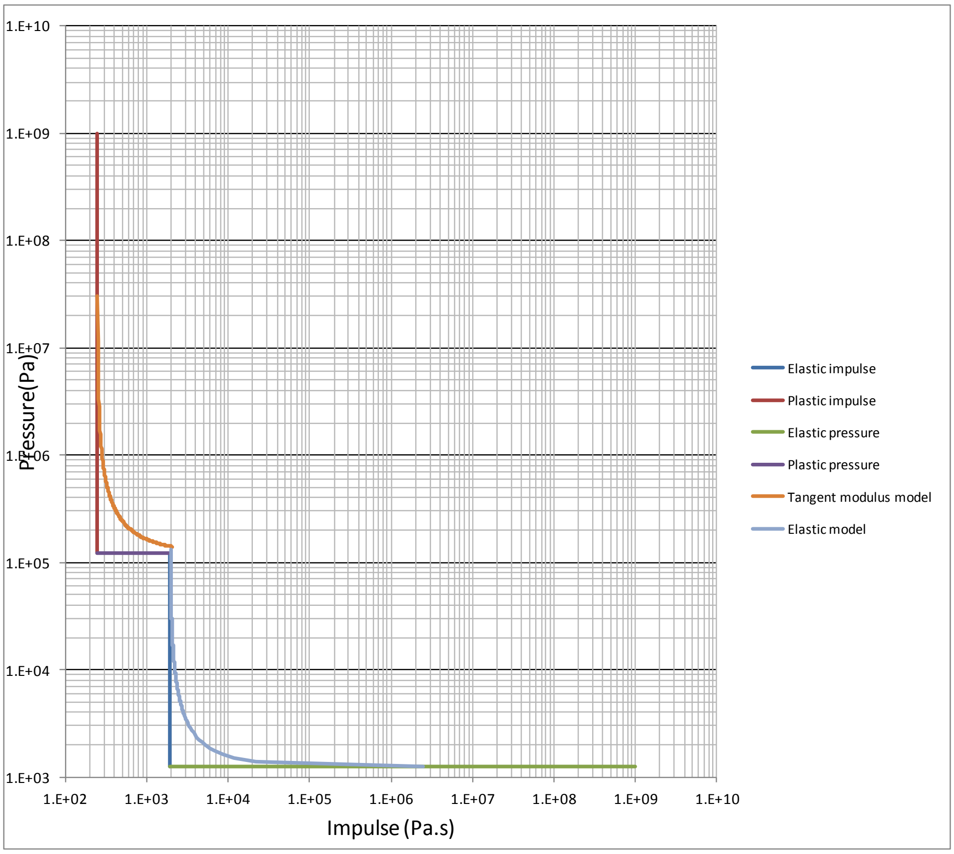

Figure A2-25 Impulse-pressure diagram for tank n°3.

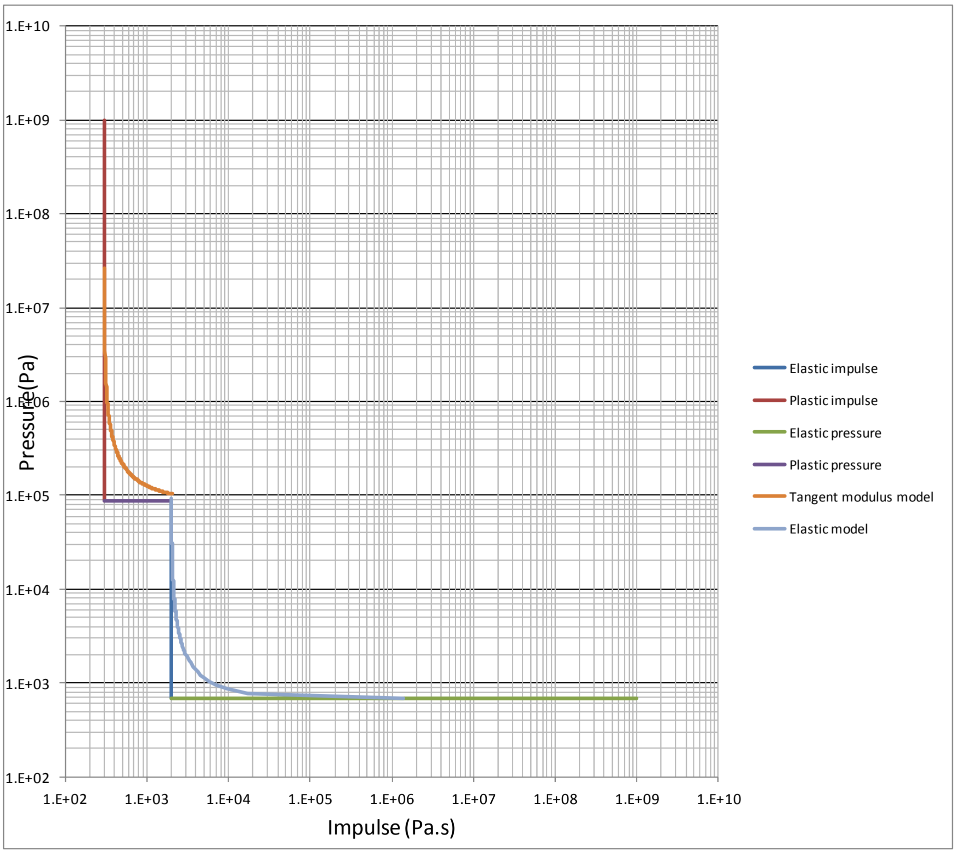

Figure A2-26 Impulse-pressure diagram for tank n°4.

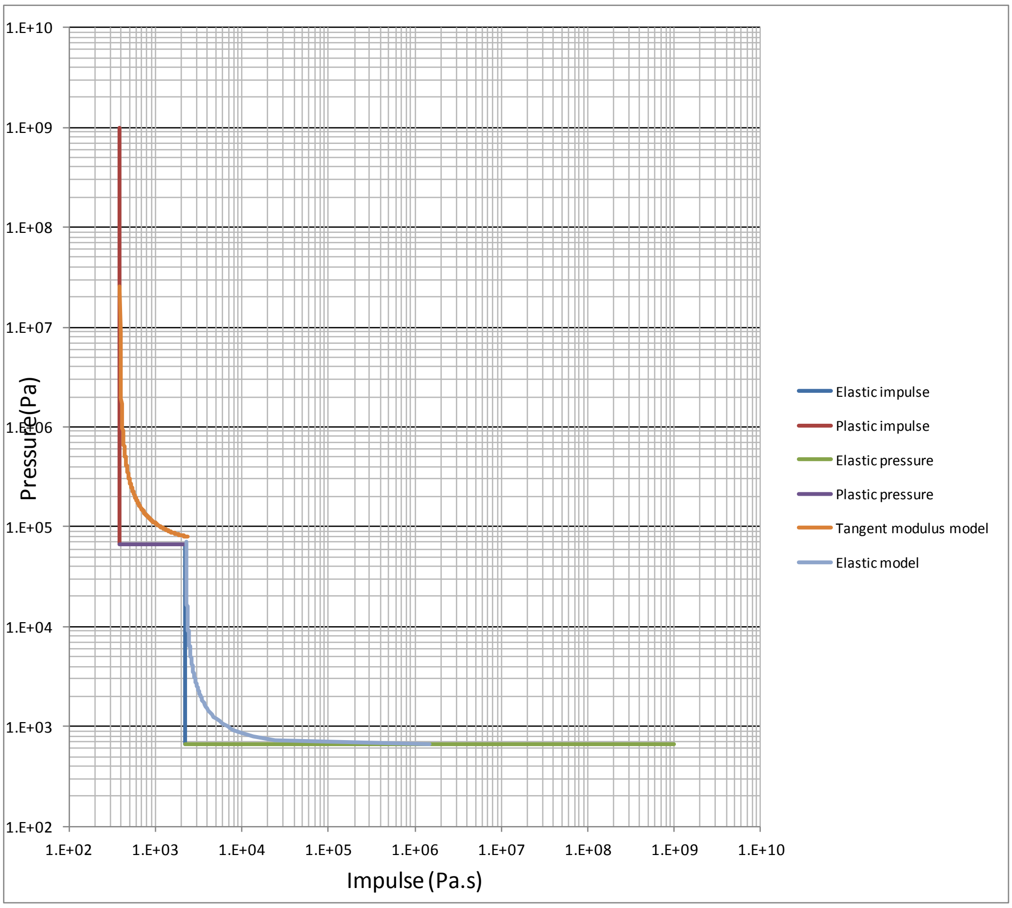

Figure A2-27 Impulse-pressure diagram for tank n°5.

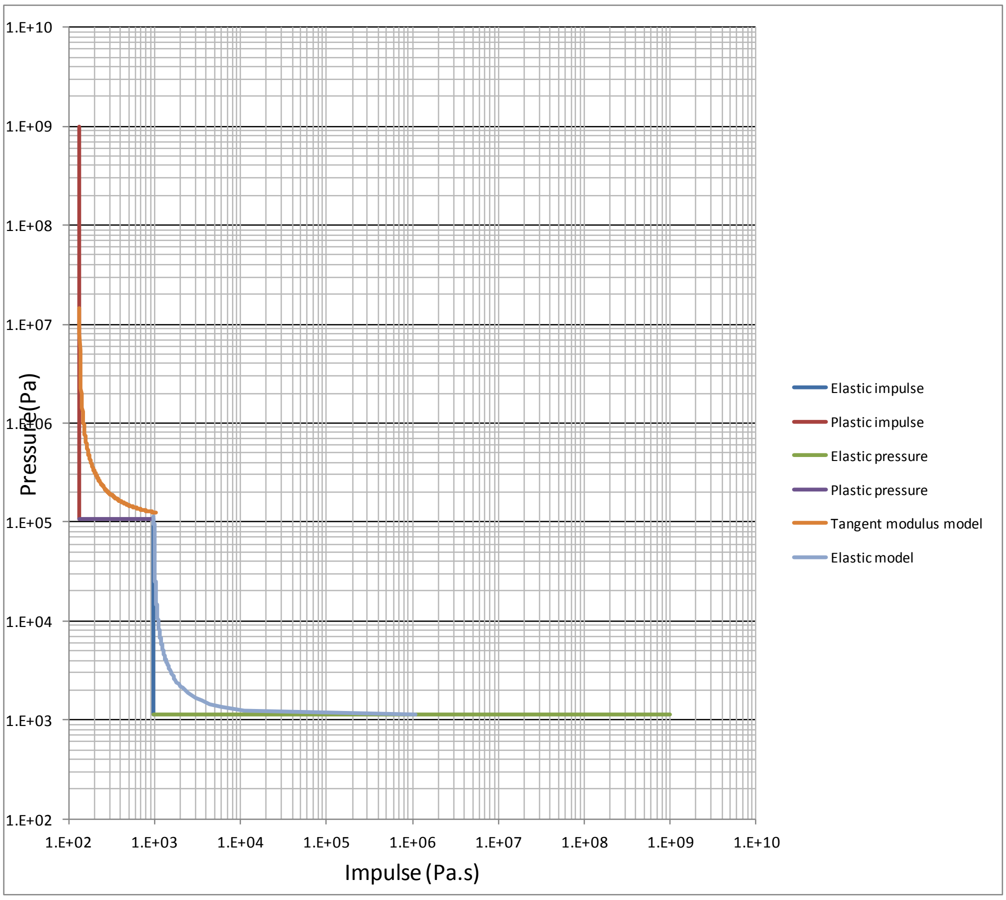

Figure A2-28 Impulse-pressure diagram for tank n°6.

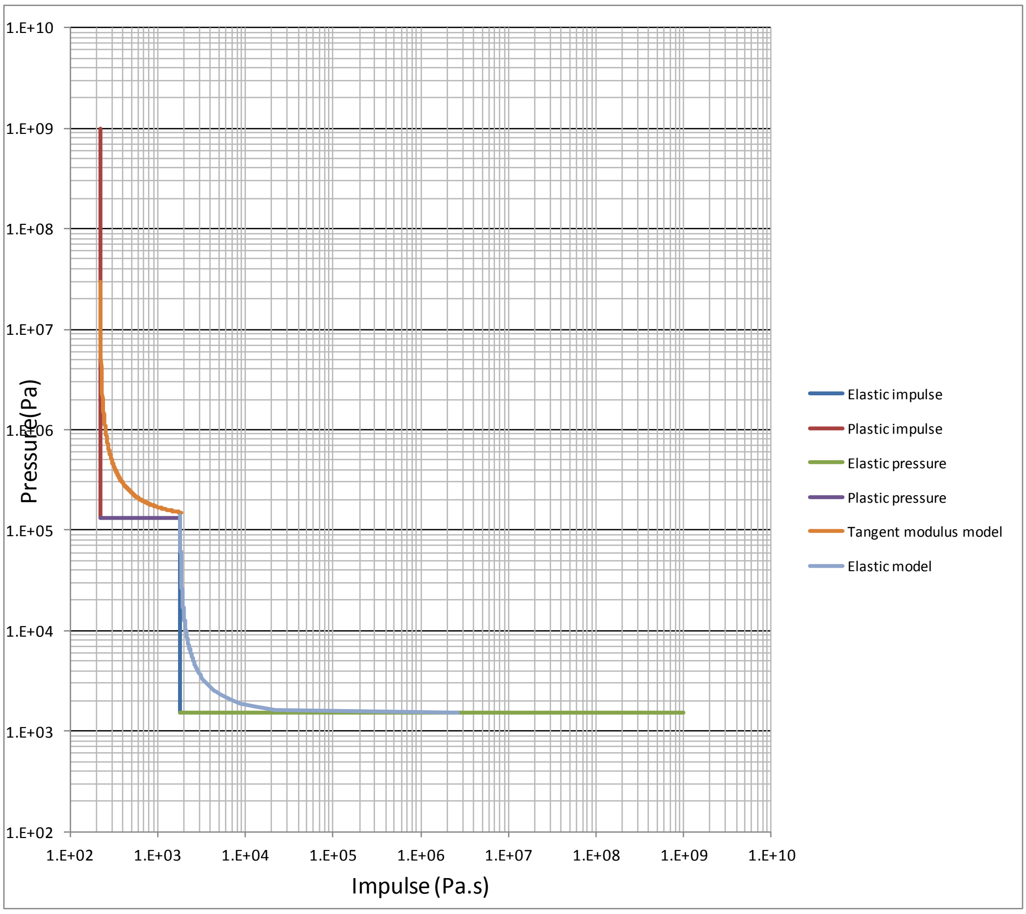

Figure A2-29 Impulse-pressure diagram for tank n°7.

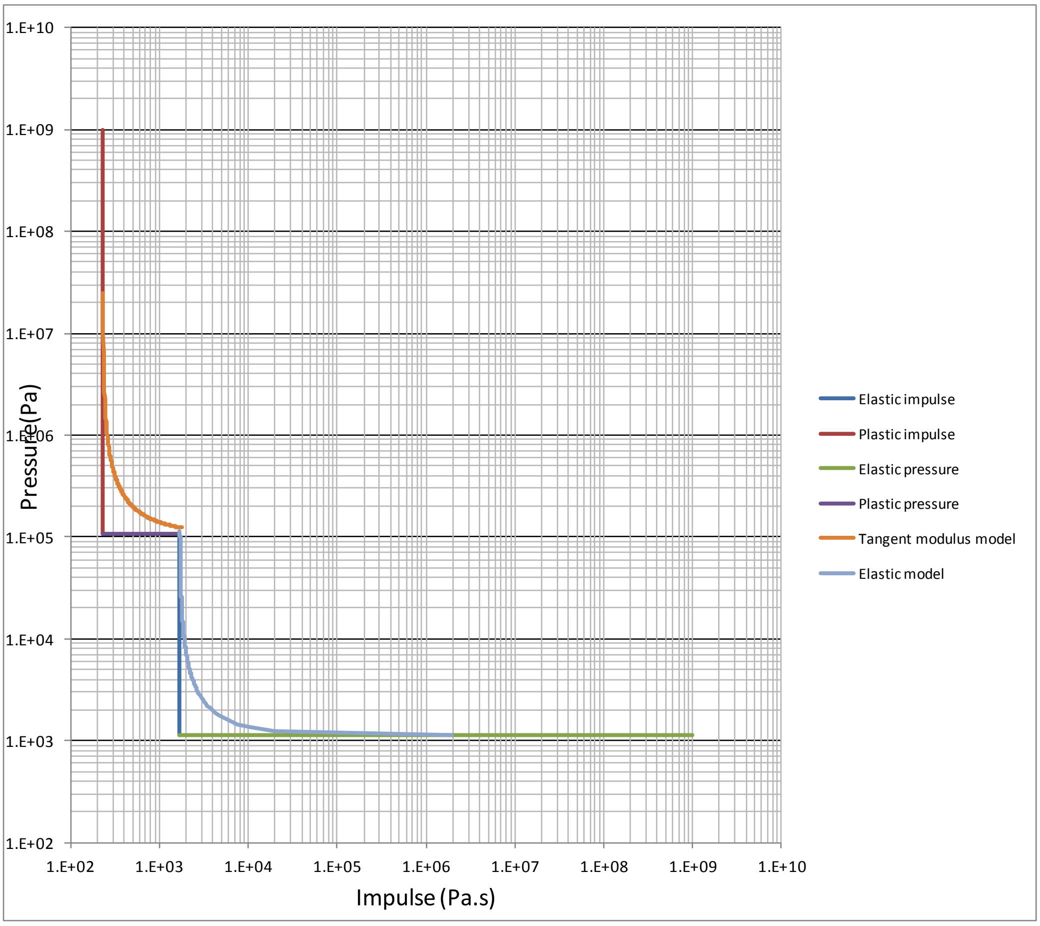

Figure A2-30 Impulse-pressure diagram for tank n°8.

A2.2.4 NaTech effects endurance

A2.2.4.1 Endurance of hydrocarbon tanks to flooding

The idea here is to characterize the mechanical endurance of the walls and anchoring of an atmospheric tank to flooding effects. Failure is characterized by loss of containment, which can lead to the release of a large quantity of hydrocarbons.
The loss of integrity of a tank can potentially be the source of:

- Spilling of polluting substances into the environment
- An initiation of a domino effect (fire, explosion) on other industrial structures due to spilling of flammable and/or explosive liquids

Prior experience shows that this type of equipment may prove vulnerable to flooding due to the thinness of the walls that form the ferrules of the shells.

Figure A2-31 Atmospheric tanks

Types of rupture and areas of fragility

The action of water on an atmospheric tank depends on several parameters. Naturally, the characteristics of the flooding event will play a fundamental role in determining how the tank will rupture. Mechanical forces produced by a flood are dependent on two variables:

- Level of flow
- Speed of flow

The principal types of rupture identified for an atmospheric tank in the event of flooding are as follows:

- Circumferential warping of the tank shell due to lateral hydraulic pressure
- Overturning of the tank due to a combination of buoyant force (Archimedes' principle) and lateral hydraulic pressure
- Sliding of the tank
- Rupture of the tank shell due to impact from floating objects

All these types of rupture can be the cause of a loss of containment due to mechanical failure of:

- The tank shell
- The base of the tank
- The shell-base connection
- The shell-pipe connections (taps)

Given the variety of foreseeable ruptures to tanks, it was decided to conduct a simplified study of each action on tanks typically found in Europe, with the following characteristics:

Table A2-9 Characteristics of tanks studied.

Tank data	TANK 1	TANK 2	TANK 3	TANK 4	TANK 5
Height of tank (m)	8	10	19	30	30
Internal radius (m)	5.75	7	10	20	40
Volume (m^3)	830	1540	5970	37700	150800
Maximum shell thickness (m)	0.008	0.01	0.015	0.020	0.030
Minimum shell thickness (m)	0.005	0.005	0.007	0.010	0.015
Base thickness (mm)	5	5	10	12	12
Young's Modulus (MPa)	210 000	210 000	210 000	210 000	210 000
Number of ferrules	10	10	10	10	10
Liquid density (Kg/m^3)	800	800	800	800	800

<u>**1st type of rupture: Circumferential buckling of the tank shell**</u>

The model for critical buckling pressure used to generate the graphs is supported by laws on calculations used to estimate the vulnerability of tanks to the actions of wind as defined in the Eurocodes (ENV 1993-4-1). This law is derived from principles for characterizing the strength of shell structures (ENV 1993-1-6 [8]).

Table A2-10 Formula for calculating shell buckling.

Formula	Characteristics
$P_{nRcu} = 0{,}92 C_b C_p E \left(\frac{r}{l}\right)\left(\frac{t}{r}\right)^{2{,}5}$ Avec C_b=0,6 et $C_p = \frac{2{,}2}{1+0{,}1\sqrt{C_b \frac{r}{l}\sqrt{\frac{r}{t}}}}$	With C_b: buckling parameter C_p: dimensional factor E: Young's Modulus of steel (Pa) r: tank radius (m) t: thickness (m) l: length of ferrule (m)

A critical pressure value is calculated for each ferrule of the tank before being compared to the level of pressure induced by hydraulic forces.

<u>**2nd type of rupture: Overturning or sliding of tank**</u>

When water flow speeds reach considerable levels, tanks with narrow profiles are susceptible to overturning or sliding. These two phenomena can be observed when water levels are lower than those needed to uplift the tanks.
A tank is a structure with thin walls that are meant to be subject to circumferential stresses only. The smallest imbalance of pressure following the initial uplifting or sliding causes meridional stress and can lead to damaging levels of stress in the areas of fragility identified above.

Consequently, INERIS studied the water speeds and levels necessary to cause overturning or sliding in the 5 tanks identified.

A tank is considered a rigid system. It is a question of studying the risk of overturning of a tank subjected to a steady flow defined by the pair flow speed/water level.
The calculations performed by INERIS are based on a statistic model, to which the following were applied:

- Force balance equation, to estimate the flow speeds required to cause sliding
- Moment balance equation to determine the flow speeds and water levels required to cause overturning

In order to characterize overturning and sliding of a tank, the following forces were taken into account:

- Hydrodynamic force
- Buoyant force (Archimedes' principle)
- Weight of tank and its contents
- Reaction force (tangential component and normal component)

Figure A2-32 represents the distribution of forces taken into account for the tank.

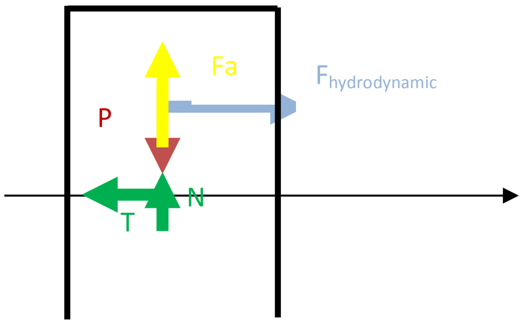

Figure A2-32 Diagram of forces applied to tank.

The vulnerability criterion used for this mechanical analysis is the initiation of overturning and/or sliding.

3rd type of rupture: impact from floating objects

The aim here is to characterize the behaviour of each atmospheric tank following impact from 3 different floating objects:

- Barrel, 100 L
- Vehicle, 1500 kg
- Tank-container, 3000 kg

The first step of the study is to determine the permissible energy level of a tank. Taking into consideration the complex shape of a tank (shape of shell and ferrules of varying thickness) and the form of loading (pressure applied to a limited surface area), INERIS chose to model each tank using the finite element method. The software programs CODE ASTER[24] and ANSYS WORKBENCH[25] (Finite Elements Codes) were used for the modelling.

The second step is to compare this internal energy level to the kinetic energy of the floating object to calculate permissible impact speed.

In the case of tank no. 1, the models showed that the plastic strain limit was reached for a deflection of 35 cm and an applied pressure of 6.1 bars. The Figure A2-33 shows the strain on the tank for this value of applied force:

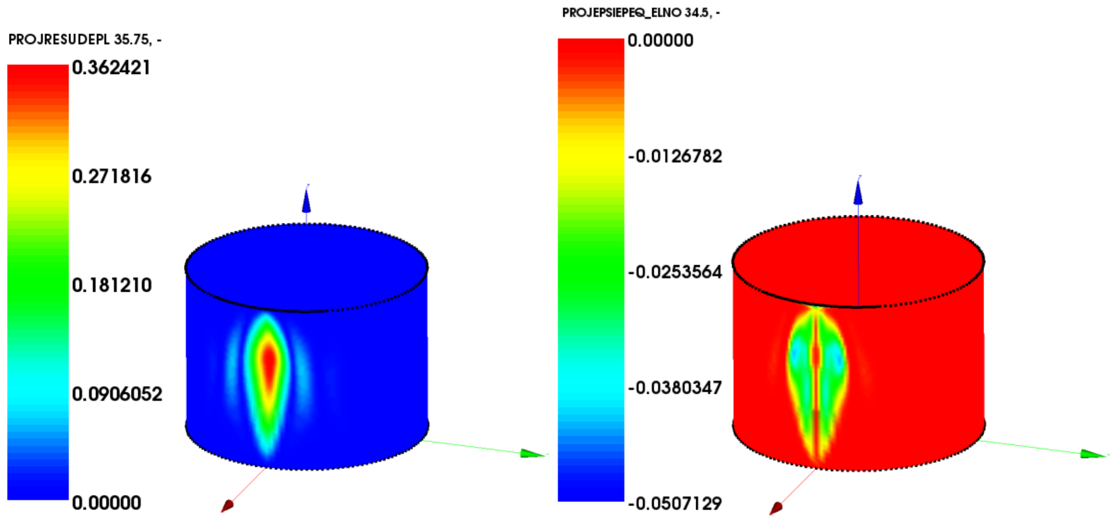

Figure A2-33 Representation of strain on tank following impact (left) and principal plastic strain along axis 1 (right).

But the only result post-processed to assess the tank resistance under impact, was the energy capacity corresponding to the admissible strain. These energy values have then been converted to flooding velocity associated with floating objects, as shown on Table A2-.

Result graphs

The result graphs (Figure A2-34, Figure A2-35, Figure A2-36) were generated by taking into account the two modes of failure described above. Based on these graphs, permissible water levels according to flow speed can be determined.

[24] http://www.code-aster.org/

[25] http://www.ansys.com/

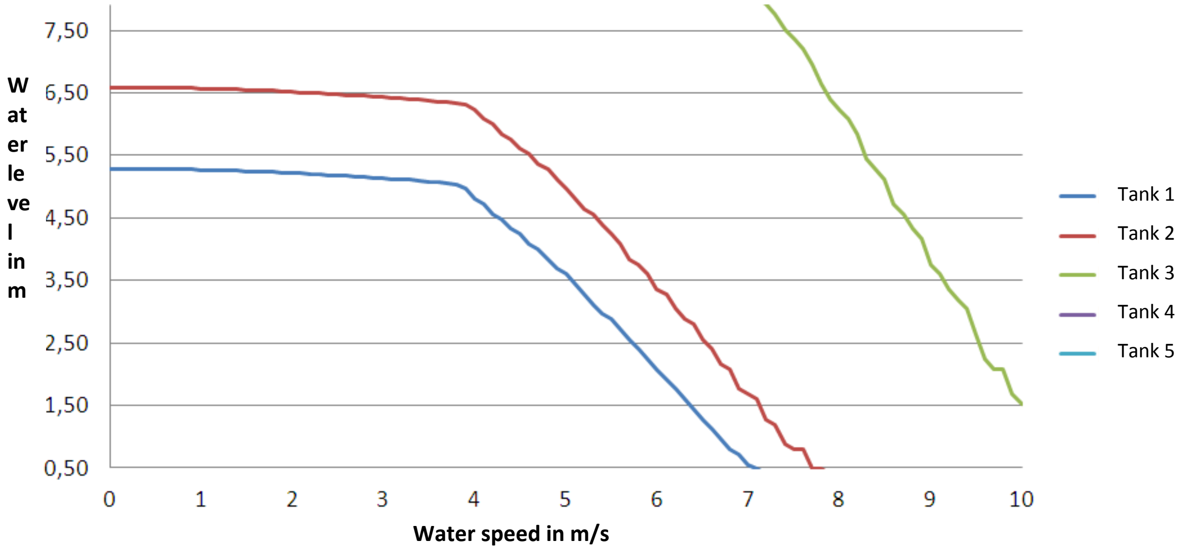

Figure A2-34 Permissible water level for anchored tanks with fill rate of 80%.

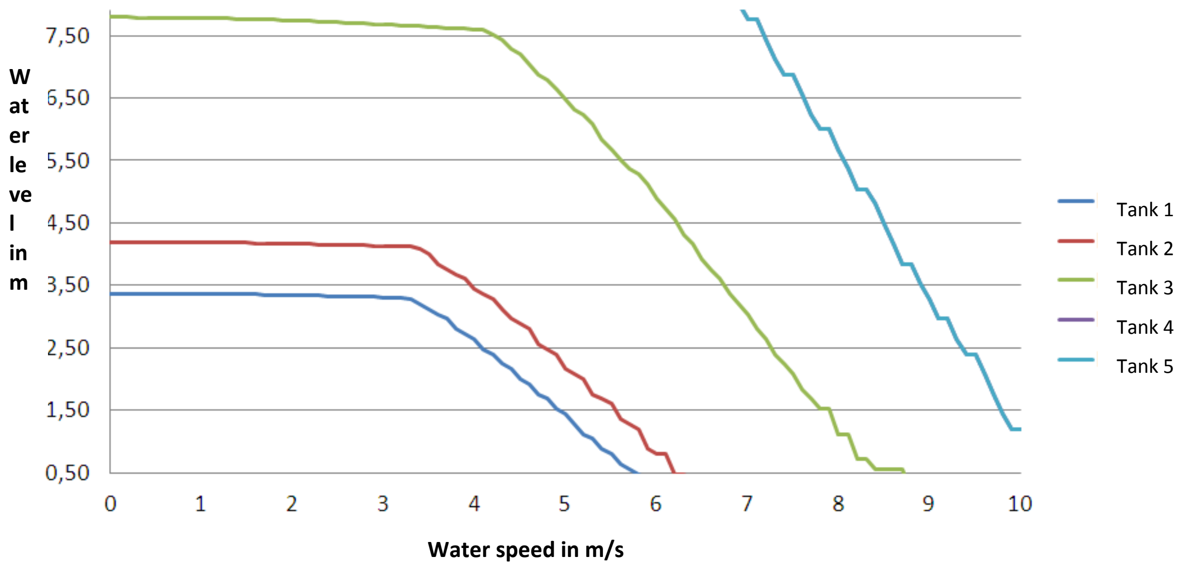

Figure A2-35 Permissible water level for anchored tanks with fill rate of 50%.

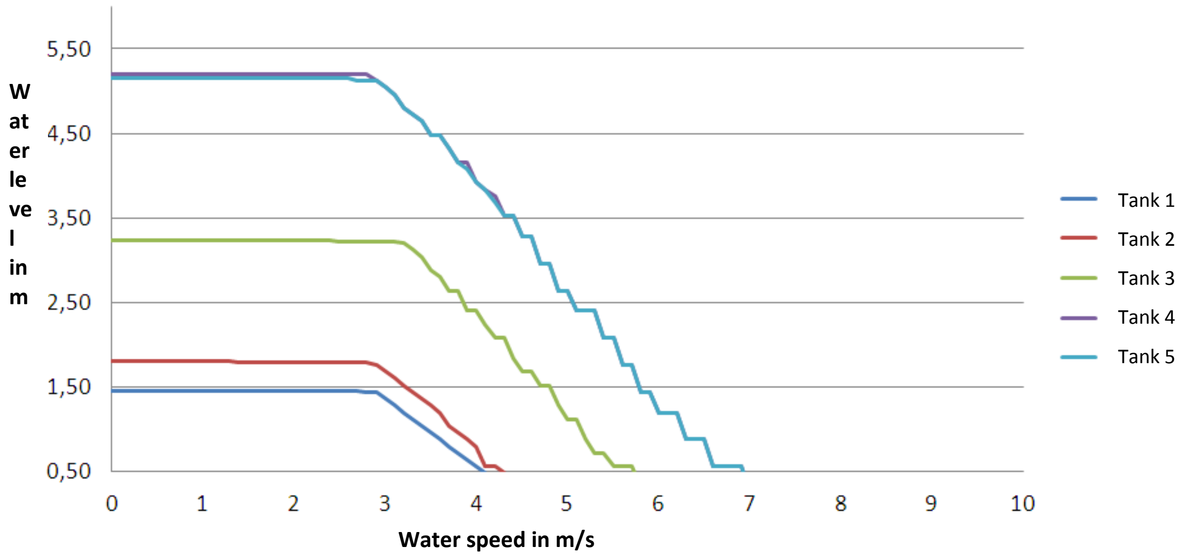

Figure A2-36 Permissible water level for anchored tanks with fill rate of 20%.

These graphs can be used by non-specialists in structural resistance, and can be used to determine the vulnerability of a specific piece of equipment based on the characteristics of the flood.

In cases of impact from floating objects, permissible energy levels and associated admissible speed values were calculated for each type of floating object and for each tank. The results are shown in the table A2-11.

Table A2-11 Permissible impact speeds (in m/s) for 3 types of floating objects.

Tank type	Tank 1	Tank 2	Tank 3	Tank 4	Tank 5
Permissible energy level (J)	72000	71 000	165 000	215 000	220 000
Full barrel, 200 litters	21	21	33	37	38
Automobile vehicle	9	9	14	17	17
Shipping container	6	6	9	11	11

A2.2.4.2 Endurance of industrial pipelines to flooding

As with the atmospheric tanks, the goal here is to characterize the stresses that lead to loss of containment in an industrial pipeline when subjected to flooding.
Pipelines situated on industrial sites are particularly vulnerable to flooding. They can contain polluting and especially flammable substances.

Figure A2-37 Industrial pipes

Types of rupture

The study was conducted on a range of generic pipelines with nominal diameters ranging from ND 25 to ND 700. Pressure levels ranging from 1 bar to 40 bars were considered.

These characteristics were chosen by researching the different types of pipelines currently used in the majority of industrial sites. Note that the calculations were made under the assumption that these pipes adhere to design regulations defined in CODETI for pipes subjected to interior pressure.

The types of rupture of most concern in the event of flooding on an industrial site are as follows:

- Lifting of the pipe due to buoyant force (Archimedes' principle)
- Rupture of the pipe due to impact from a floating object

For each mode of failure identified, a model was developed with the purpose of determining the behaviour of several pipes as reference. The criterion for failure is the plastification of the pipe in its solid part: the defined vulnerability criterion is the appearance of irreversible deformations in the section of pipe. The pipe was studied by using a doubly-clamped beam model. The approach for formulating the corresponding static beam model is presented Table A4.12. The vulnerability criterion is attained for M_{max}>M_{adm}.

Table A4.12 Calculation methodology used to determine the plastification of a pipe's shell.

Variable	Value
Moment applied	$Mx = \frac{qL^2}{12}(6xL - 6x^2 - L^2)$ With q load uniformly distributed (N/m) L: Length of pipe (m) x: Position on the beam (m)
Maximum moment applied	$Mmax = \frac{qL^2}{12}$
Moment permissible (Madm)	$Madm = \frac{\sigma_{lim} * I}{\frac{h}{2}}$ σ_{lim} : elastic limit of steel I: moment of inertia of section H: diameter of pipe

<u>1st type of rupture: Lifting of the pipe</u>

Full or partial immersion of a pipe can cause it to lift. As part of a worst-case approach, INERIS considered lifting of the pipe to be a failure, though it is not necessarily synonymous with damage.

This simple lifting study was conducted by comparing the weight of the pipe and its contents to the value of buoyant force. The pipe's density and design pressure have a significant influence on its weight. The higher the pipe's design pressure and the greater its thickness, the greater its weight will be. Note also that the greater the nominal diameter, the greater the risk of lifting, because when the nominal diameter increases, the ratio of steel thickness to pipe diameter decreases.

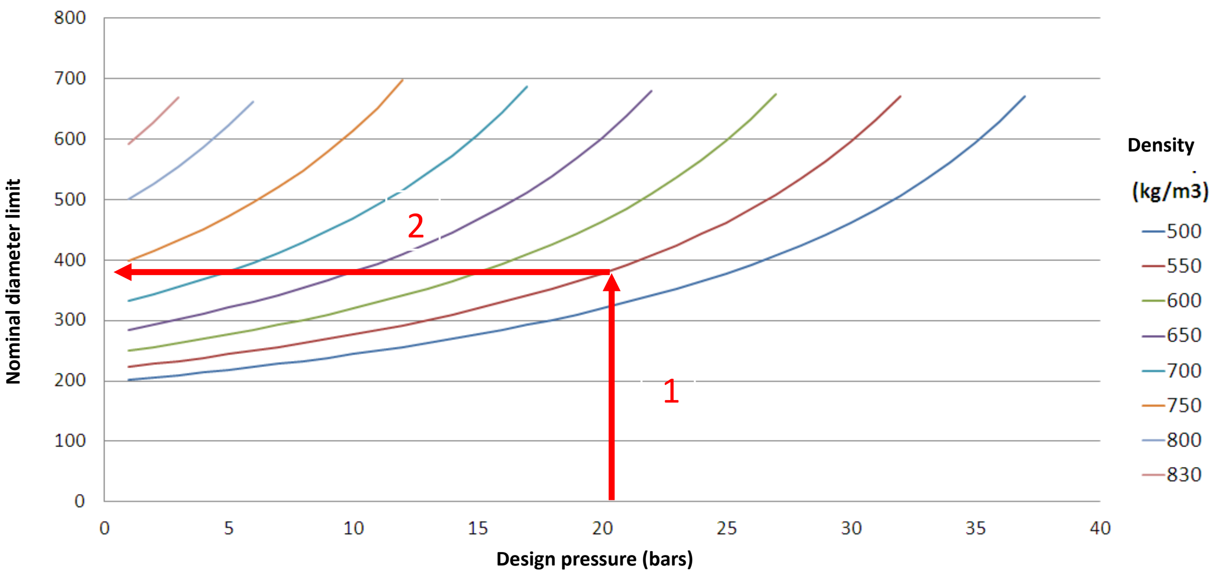

Figure A2-38 Graph of permissible diameters for pipes filled with liquids.

The results show that a risk of lifting is present for nominal diameters greater than 200. But for Pipes which the nominal diameter is inferior to DN200, lifting can be excluded.
Also note that pipes transporting products whose density is greater than 830 kg/m^3 do not pose a risk of lifting.

<u>Example of an application for characterizing lifting:</u>
A pipe with a design pressure of 20 bars is filled with propane with a density of 550 Kg/m^3 (Step 1 in the diagram above). The above graph shows that lifting does not occur for nominal diameters less than ND 375 (step 2).

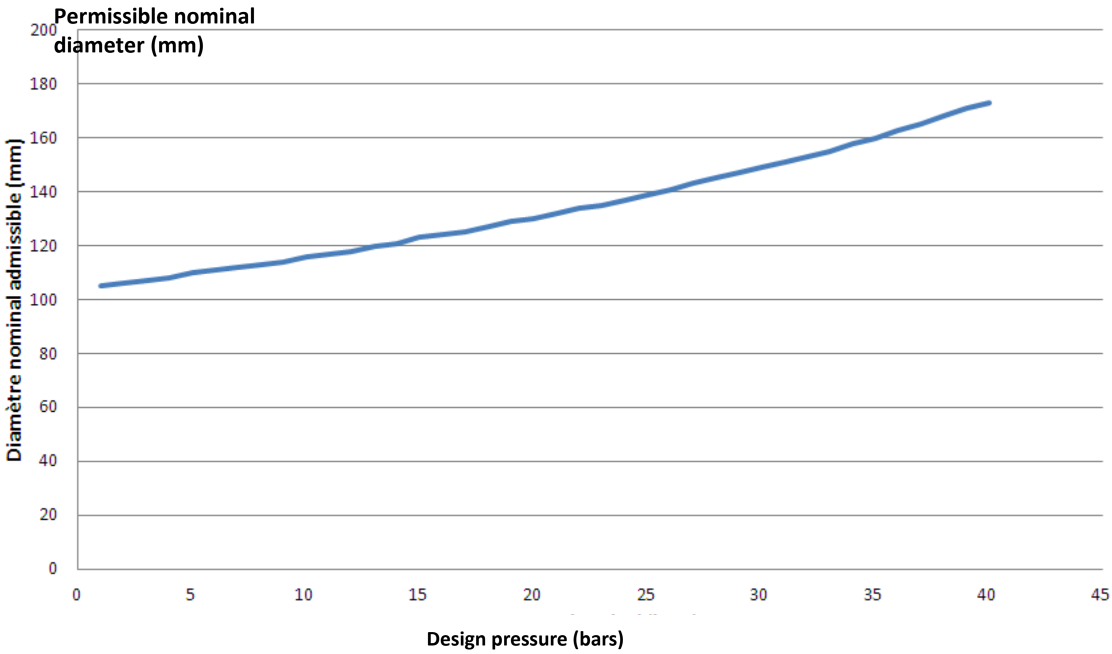

Figure A2-39 Graph indicating permissible nominal diameter for pipes filled with gas.

2nd type of rupture: Impact from objects carried by water flow

The aim here is to characterize the behaviour of sections of pipe when subjected to impact from floating objects. This is done by calculating the pipe's permissible internal energy level and determining the permissible speed for each floating object.

Figure A2-40 Deformation of a pipe impacted by the walls of a retention pond after they were torn out of the ground.

Permissible energy levels and their relative permissible speeds were thus calculated for each type of floating object and for each pipe. This energy calculation was performed numerically on a Finite Element model where the elements were pipe shells. The failure criterion used is a level of equivalent plastic deformation greater than 5 %. The calculation assumed that the impacting object would maintain its full rigidity when it came in contact with the post.

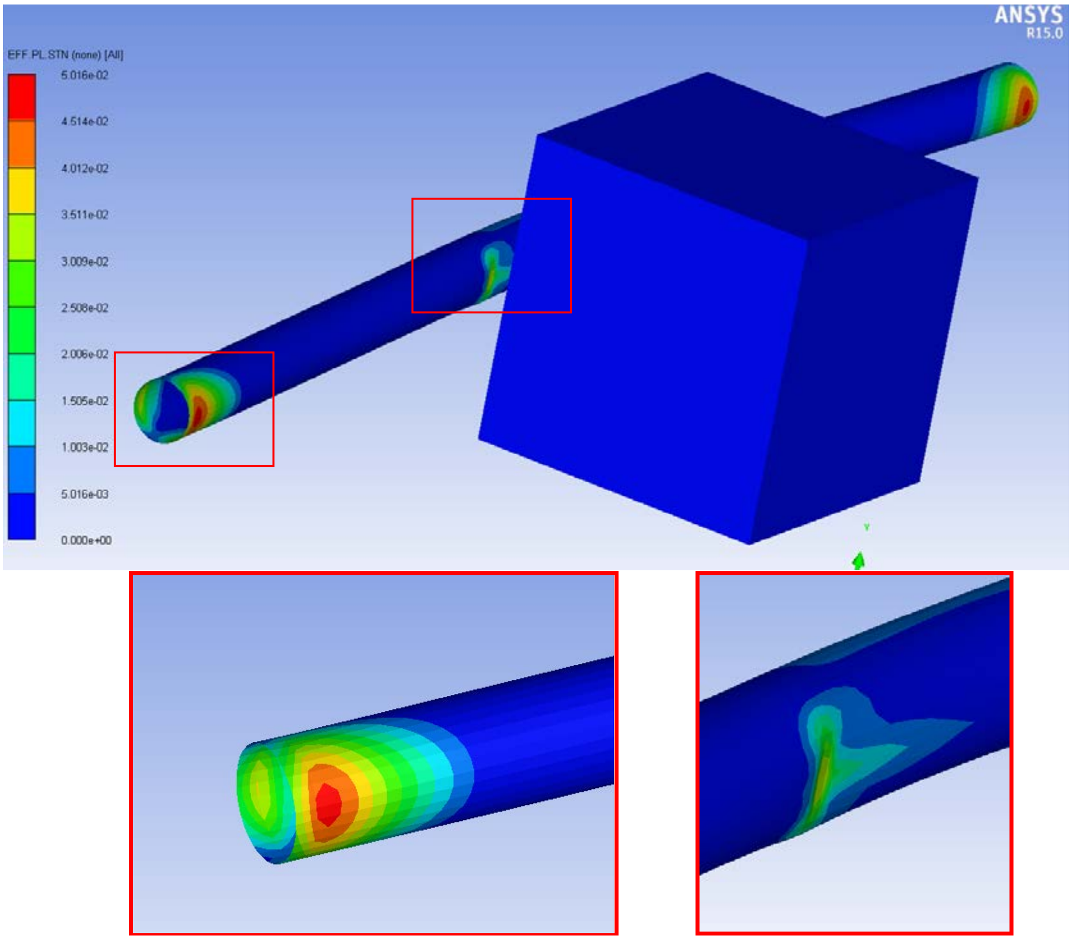

Figure A2-41 Plastification of the ends of the pipe (left) and the area of impact (right).

Table A2-13 and Table A2-14 present the values of permissible speed for these 3 floating objects:

- Barrel, 100L
- Vehicle, 1500 Kg
- Tank-container, 3000 Kg

Table A2-13 Permissible impact speeds and equivalent deformation energy for a pipe with span of 5m.

Pressure (bars)	ND	Energy (J)	S1 (m/s)	S2 (m/s)	S3 (m/s)	Reaction (N)
0	40	1470	3.8	1.4	0.9	678
0	100	5070	7.1	2.6	1.7	4954
0	150	9188	9.6	3.5	2.3	11538
0	200	17280	13.1	4.8	3.1	20869
0	300	27908	16.7	6.1	4.0	47770
0	400	39968	20.0	7.3	4.8	85658
20	40	1688	4.1	1.5	1.0	716
20	100	5880	7.7	2.8	1.8	5801
20	150	10830	10.4	3.8	2.5	14613
20	200	18750	13.7	5.0	3.3	28425
20	300	31688	17.8	6.5	4.3	74196
20	400	42188	20.5	7.5	4.9	149411
40	40	1688	4.1	1.5	1.0	752
40	100	6308	7.9	2.9	1.9	6602
40	150	13230	11.5	4.2	2.7	17527
40	200	19508	14.0	5.1	3.3	35588
40	300	35708	18.9	6.9	4.5	99257
40	400	54188	23.3	8.5	5.6	209884

Table A2-14 Permissible impact speeds and equivalent deformation energy for a pipe with span of 10 m.

Pressure (bars)	ND	Energy (J)	S1 (m/s)	S2 (m/s)	S3 (m/s)	Reaction (N)
0	40	2430	4.9	1.8	1.2	814
0	100	6750	8.2	3.0	2.0	102790
0	150	17280	13.1	4.8	3.1	29638
0	200	19508	14.0	5.1	3.3	6961
0	300	35708	18.9	6.9	4.5	312439
0	400	50430	22.5	8.2	5.4	104272
20	40	3000	5.5	2.0	1.3	13846
20	100	7208	8.5	3.1	2.0	836
20	150	18750	13.7	5.0	3.3	141547
20	200	26108	16.2	5.9	3.9	34110
20	300	45630	21.4	7.8	5.1	7448
20	400	75000	27.4	10.0	6.5	385009
40	40	3308	5.8	2.1	1.4	57324
40	100	7680	8.8	3.2	2.1	15715
40	150	21068	14.5	5.3	3.5	859
40	200	36750	19.2	7.0	4.6	179293
40	300	75000	27.4	10.0	6.5	38466
40	400	126750	35.6	13.0	8.5	7922

A2.2.4.3 Endurance of atmospheric tanks to earthquakes

Introduction

The industrial structures most commonly damaged by seismic stress are atmospheric tanks. Atmospheric tanks have thin walls that can undergo significant stress when their liquid contents are tossed around by seismic waves.

Figure A2-42 Buckling of the shell at the base of a tank after an earthquake.

Consequently, a set of design standards was developed (NF EN 1998-4 March 2007 Eurocode 8 Design of structures for earthquake resistance - Part 4: Silos, tanks and pipelines). These standards are also used to determine the earthquake endurance of existing tanks. Thus, INERIS created a tool based on this standard to determine a tank's vulnerability to rock acceleration. Note that the spectrum of seismic stress used in the tool adheres to the European standard "NF EN 1998-1 (May 2013) – Design of structures for earthquake resistance - Part 1 – General rules, seismic actions and rules for buildings." The tool developed by INERIS only focus on unanchored tanks.

The vulnerability criteria used by this model are listed below:

- Tank shell's endurance to circumferential stress
- Tank shell's endurance to buckling effect stress
- Anchoring resistance
- Damage to plate at bottom of tank due to uplifting
- Damage to top or overflowing of tank due to convective wave
- Sliding of the tank

Presentation of result graphs

For each of the criteria above results are derived for three sample tanks. Tanks have been studied with 2 hypotheses:

- Tank characteristics are very low
- Tank characteristics are very high

Tanks characteristics are summarized in the Table A2-15.

Table A2-15 Tanks characteristics studied in this example.

Tank number	Tank radius (m)	Tank Height (m)	Maximal wall thickness of the shell (m)	Minimal wall thickness of the shell (m)	Bottom shell thickness (m)
1	6	8	0.005	0.004	0.0055
2	7	10	0.006	0.004	0.0055
3	8	14	0.0065	0.006	0.0055
1’	6	8	0.007	0.006	0.0075
2’	7	10	0.0078	0.006	0.0075
3’	8	14	0.0087	0.008	0.0075

Table A2-16 describes the allowable peak ground acceleration (m/s²) for each failure mode involved by the earthquake.

Table A2-16 Allowable peak ground Acceleration (PGA) for each failure mode involved by seismic motions

Tank	Circumferential stress	Shell Buckling	Collapse of the bottom shell	Sliding
1	>8 m/s²	4.14 m/s²	**2.04 m/s²**	>8 m/s²
2	7.54 m/s²	2.04 m/s²	**1.95 m/s²**	>8 m/s²
3	4.03 m/s²	1.18 m/s²	**1.00 m/s²**	>8 m/s²
1	>8 m/s²	>8 m/s²	**3.67 m/s²**	>8 m/s²
2	>8 m/s²	4.14 m/s²	**2.34 m/s²**	>8 m/s²
3	5.55 m/s²	2.04 m/s²	**1.45 m/s²**	>8 m/s²

In certain configurations, a more detailed characterization of the flood at the industrial site may be necessary in order to clarify the accidental sequences and to optimize risk control solutions. The principal parameters useful in characterizing floods are listed with comments in Table A2-17.

Table A2-17 Characteristic parameters used for in-depth analysis of NaTech flood risk.

Parameters	Comments
Water level on site	The water level parameter is needed to determine mechanical loading on structures. A conservative diagnosis can be made with an accuracy of within 50 cm. However, in terms of optimization, the reinforcements are generally measured using more precise input data.
Flow speed on site	The flow speed parameter is important for calculating mechanical loading on industrial structures, at times when it is relatively high. Configurations where the influence of speed is most important include those related to ruptures in hydraulic works or tsunamis. For lower speeds, a diagnosis based on impact from floating objects can prove useful for fine structures.
Water elevation speed	The water elevation speed parameter is important for designing a safety strategy. Water elevation speed can, for example, be deduced by analysing a hydrogram in case of floods. A conservative estimate is sufficient to develop a strategy that can be adapted to real-life water elevation conditions when managing a crisis.
Submersion duration	An approximate idea of submersion duration is important when specific equipment must be kept in operation for security purposes or when planned technical solutions make use of stock/inventory.