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UNIVERSITATEA TEHNICA "GHEORGHE ASACHI" DIN IASI

“BABEŞ-BOLYAI” UNIVERSITY
CLUJ-NAPOCA
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INFLUENCE OF NATURAL HAZARDS ON CRITICAL INFRASTRUCTURE

- PhD Thesis summary -

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The **"DOCTORAL STUDIES FOR EUROPEAN PERFORMANCES IN RESEARCH INOVATION (CUANTUMDOC)"** project POSDRU/107/1.5/S/79407, is a strategic project which has as general objective „*The implementation of the managerial, research and educational strategies for the improvement of the initial training of the future researchers through doctoral studies program, according to the Bologna process, by the development of the research specific proficiency, but also of some other common outcomes: research management, linguistic and communication skills, scientific documentation, elaboration, publication and scientific communication, modern ITC equipment utilisation, entrepreneurship transfer of the research results. The human capital development for research and innovation will contribute to long-term doctoral training at European Union level with interdisciplinary concern. The PhD students' financial support will provide their participation to national doctoral programs, as well as the research internship in European Union universities and research institutes. The project main objective is the training of a young researcher adapted to the new economic and technological environment having theoretical, practical, economic and managerial knowledge, which will be able to promote the sustainable development and the environmental protection principles.* "

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Key words: NaTech accidents, risk assessment methodology, individual and societal risk, seismic hazard, critical infrastructure.

The summary contains a part of the thesis' results, general conclusions, and selective bibliography. The summary has the same notations for the table of contents, chapters, sub-chapters, figures, tables and equations as the thesis.

INTRODUCTION

In the world we live in risk cannot be eliminated, but it can be managed and reduced to acceptable levels. In order to manage and reduce risks, one has to know the risk and what it is influenced by, to be able to take the necessary preventive and protective measures. The protection of critical infrastructures is a subject of great interest for international and national officials alike. The concern of decision factors concentrates on developing procedures and methodologies for the identification and protection of critical infrastructures as the adverse impacts generated by malicious human actions as well as natural disasters and technological accidents are affecting communities worldwide. The European Environmental Agency acknowledges the fact that the implementation of an Integrated Risk Management policy is necessary, a policy that includes prevention, preparedness, intervention and recovery aspects for all hazards in Europe (EEA, 2011). For this policy to be elaborated, the identification and analysis of hazards is necessary.

The European Commission has taken steps towards establishing risk assessment methodologies for disaster management, issuing the “Risk Assessment and Mapping Guidelines for Disaster Management, which gives examples of methodologies for the risk assessment of natural and man-made hazards (EC, 2011). The challenges reside in performing multi-risk analyses, which consider immediate effects of single hazards, as well as cascading, escalation and domino effects that may occur, with the analysis including possible amplification due to interaction with other hazards. Having in view that natural disasters have been more frequent in the last decades, the protection of critical infrastructures against this type of events is a priority (EM-DAT, 2013a). The thesis focuses on sites pertaining to the energy sector of critical infrastructure and more precisely the oil and gas subsectors.

Performing risk analysis for critical infrastructures consisting of industrial sites is often a difficult and resource consuming process, due to the large number of installations and complex processes that take place in these facilities. When the industrial site is located in a densely inhabited area, the risk assessment process is of particular interest, and appropriate methods for risk assessment should be used in order to assess the actual impact the installation could have on the community, not just the environment.

The main objectives of the thesis are the elaboration of a systematic risk assessment methodology for the oil and gas subsectors of critical infrastructure and its application on the case study selected for the analysis, taking into consideration technological causes as well as natural hazards as possible causes for industrial accidents in the field. The case study consists of a petroleum products storage tank farm that is located in a seismic area in the south-central part of Romania. The risk analysis focuses on the emphasis of the difference between the individual and societal risk in case of a technological accident (intrinsic causes) and then adding a NaTech scenario (triggered by earthquake) for the same tank farm.

In order to achieve these main objectives, a series of specific tasks were completed, to give a better understanding of the context and the analyzed subject:

- Synthesis of the legislation available in the field of critical infrastructure protection at European and national level;
- Summary of natural and technological disaster trends at a global level;
- Identification of natural hazards susceptible to occur in the area of the case study;
- Characterization of the case study site, installations and hazardous substances present on site;
- Synthesis of examples of technological and NaTech accidents that occurred on similar sites and elaboration of accident scenarios for the case study site;
- Simulations using acknowledged software tools for the estimation of physical effects and individual and societal risk for the selected site.
- Analysis of results and elaboration of conclusions.

The thesis is structured in two parts, completed by an introduction section and references.

Part I: Theoretical research includes Chapter 1: Theoretical considerations regarding Critical Infrastructure and NaTech research. This chapter includes six subchapters, presenting a literature review of the concept and definitions of critical infrastructure, the legal framework regarding critical infrastructure protection in Europe and in Romania and the vulnerabilities, hazards and threats towards critical infrastructure in Romania. The sectors and subsectors of critical infrastructure in Romania are presented according national legislation. Global trends regarding natural and technological disasters are presented in the theoretical research part as well. The concept of NaTech events is presented and the challenges in the risk assessment process of the NaTech accidents are stated. Conclusions of this chapter summarize the need to perform NaTech risk assessments in addition to technological risk assessments for industrial facilities.

Part II: Applied research, includes Chapter 2. Systematic risk assessment and Chapter 4. Case study: NaTech risk assessment for a petroleum products storage tank farm located in a seismic area in Romania, applying the systematic risk assessment methodology for critical infrastructure – Oil and Gas subsectors.

Chapter 2 describes the concept and general diagram of the systematic risk assessment methodology for the oil and gas subsectors of critical infrastructure. The methodology is an adaptation of the systematic risk assessment methodology developed for the extractive mining industry (Ozunu et al, 2011b; Gheorghiu et al. 2013c; Crişan (Gheorghiu), 2013). The methodology follows a three step approach, comprising the preliminary analysis, criterial analysis and detailed analysis steps, followed by conclusions. Each of these steps and their mode of application are described in this chapter. The criterial analysis step is of particular importance, as it allows the evaluator to assess which scenarios require an in-depth analysis in the detailed assessment stage and which are sufficiently analyzed in the preliminary assessment of the site. Through eliminating from the detailed assessment stage those installations which are pertinently considered not to contribute significantly to the overall risk of the site, time and expenditures can be saved, without compromising the relevancy and adequateness of the conclusions of the risk assessment. As such, the three-step approach enables the evaluators to come to pertinent conclusions regarding the overall risk of a site, through selecting and analyzing the installations and sections that contribute most to this overall risk.

Chapter 3 is the most extensive one and it consists of the application of the risk assessment methodology to the selected case study. The preliminary analysis is comprised of the presentation of the environment in which the site is located (including population data, site history, geology, seismic activity and climate), description of the tanks and hazardous substances stored in the tank farm, identification of natural hazards susceptible to occur in the area of the case study. A description of typical accident scenarios for tank farms and a review of several accidents that occurred on similar sites is also part of the preliminary analysis. Attention was given to selecting accidents that occurred from both technological and NaTech causes. Possible accidents scenarios for the selected site are described and analyzed using risk matrices. After the application of criteria to the scenarios in the criterial analysis stage, some scenarios are selected for the detailed assessment as it was considered that they have the potential to generate significant impact on the site and neighboring residential area. The detailed analysis of the selected scenarios includes the use of EFFECTS and ARIPAR 4.0 advanced modeling tools for the simulation of accident scenarios. A risk assessment for technological and NaTech accidents is performed using consequence based and risk based methods, assuming an earthquake reference scenario which scientific literature in the field states as possible to occur in the area (Ardeleanu et al, 2005, Sokolov et al., 2007, Leydecker et al. 2008). A comparison of the total individual and societal risk for the site is for intrinsic causes versus individual and societal risk including NaTech causes is described in the conclusions of Chapter 3, as well as the determination of the contribution of each top event to the overall societal risk. This ranking of top events according to their contribution emphasizes the areas where risk reduction is most needed and is a useful tool in the decision making process. An important step in the NaTech risk analysis for the selected site is the calculation of frequencies of sets of combinations of tanks that could be damaged simultaneously in case of earthquake, as this determines the relevant number of tanks that could be damaged simultaneously. The overall risk assessment procedure includes both the qualitative identification and analysis of hazards and the quantitative estimation of risk. The combined use of these methods is considered to be the most appropriate for the estimation of risk, taking into account the high level of experience and knowledge in this field and the state of the art in the computer based modeling and simulation.

Chapter 4 presents the final conclusions of the present thesis, personal contributions and future developments.

PART I: THEORETICAL RESEARCH

Chapter 1. Theoretical considerations regarding Critical infrastructure and NaTech research

1.1. Critical Infrastructure – concept, definitions and remarks

CI is determined by the ensemble of vital elements for the proper functioning of a society. The International Journal of Critical Infrastructures defines CIs on its website (IJCIS, 2012) as ‘‘networks for the provision of telecommunication and information services, energy services (electrical power, natural gas, oil and heat), water supply, transportation of people and goods, banking and financial services, government services and emergency services”.

Cohen (2010) considers CI as being something that people depend on, either directly or indirectly, in terms of life and wellbeing, in any timeframe. As such, their proper identification and protection becomes of great importance to Governments, actions in this case being taken by the European Union and countries worldwide (Gheorghiu et. al, 2013a).

1.4. Vulnerabilities, hazards and threats towards Critical Infrastructure in Romania

The assessment of vulnerabilities in correlation with critical infrastructures becomes more and more important, because of the stringent need to protect these against natural disasters, faulty technological exploitation, as well as disasters caused by the human factor, willingly or unwillingly, and other types of disruptions which can affect these elements. In our opinion, vulnerability can be broadly defined as the result of the combination of existing risks for an entity with its capacity to survive and overcome internal and external emergency situations (Gheorghiu et. al, 2013a).

In Romania, the threats towards the physical infrastructure are as much notable, as the vulnerability of this type of infrastructures has increased over the years due to inefficient or inconsistent upgrade measures regarding the physical integrity of the systems which constitute NCI (transport infrastructure, many industrial facilities and generally the built environment).

1.5. Natural disasters, technological disasters, NaTech

Industrial sites have been a common reality in modern ages in urban areas, contributing to the technological progress of society, offering jobs and in general raising life standards for society through high yields in production and efficient production methods. Besides the obvious advantages, hazardous industrial sites have also always represented a threat for communities.

Major accidents within industrial sites can be caused by intrinsic factors, such as equipment malfunction, human error, failure of safety measures etc., as well as external factors, such as natural events. In the case of technological accidents triggered by natural events, such accidents are commonly called NaTech. The general experience is that NaTech accidents cause much higher economic losses and affect much more extended areas as compared to technological accidents triggered by intrinsic causes (Gheorghiu et al., 2013b).

PART II: APPLIED RESEARCH

Chapter 2. Systematic risk assessment

Through a systematic approach we have in view the identification and evaluation of hazards and risks for all installations (sub-systems), sections and equipment on a certain site, as well as operations performed in each installation and section, main equipment involved in operations and the existing substances. Following the identification of hazards for each installation/section, a criterial evaluation is applied, in order to establish the priorities for the detailed risk assessment. This criterial analysis stage is necessary because the total number of installations and sections on a site can be quite large. As not all installations and sections contribute significantly to the risk of a major accident occurring, it is not efficient to include all installations and sections in the detailed risk assessment. As such, the use of a selection method to indicate the installations that contribute most to the risk caused by the site is mandatory. The selected installations are then taken into consideration in the detailed risk assessment.

2.1. Description of the methodology

The systematic risk assessment methodology is based on the definitions in Council Directive 96/82/EC on the control of major-accident hazards involving dangerous substances, amended by Directive 2003/105/EC of the European Parliament and of the Council of 16 December 2003, and the definitions in the "Purple Book" guide (Purple Book, 2005), elaborated by the Dutch company TNO.

The general diagram of the proposed systematic risk assessment methodology is presented in Figure 4.

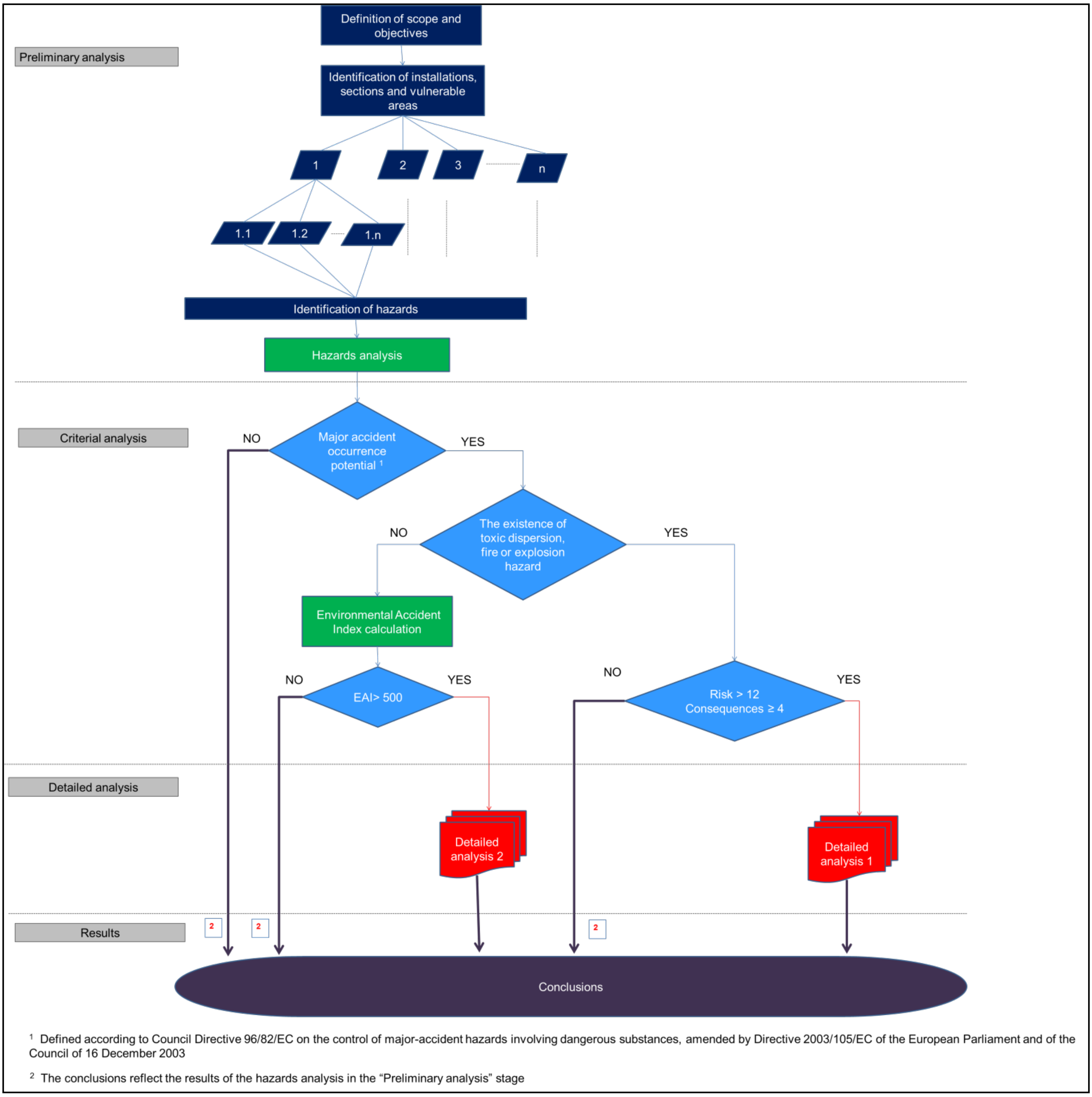


Figure 4. The general diagram of the systematic risk assessment methodology for critical infrastructure – oil and gas subsectors

The general stages of the systematic risk assessment are the following:

- Preliminary analysis
- Criterial analysis
- Detailed analysis
- Results and conclusions

The Systematic Risk Assessment methodology for critical infrastructure – oil and gas subsectors – presented in this thesis is an adaptation of the Systematic Risk Assessment methodology developed for the extractive mining industry (Ozunu et al., 2011b; Gheorghiu et al., 2013c; Crişan (Gheorghiu), 2013).

2.3. Preliminary analysis

The preliminary analysis stage of the Systematic Risk Assessment Methodology includes the following steps:

- Definition of scope and objectives of the preliminary analysis
- Identification of installations and sections undergoing the assessment
- Description of each section
- Identification of hazards for each section (man-made or natural)
- Hazard analysis

2.3.5. Hazards analysis

For each of the hazards identified, it is mentioned if it presents the possibility of a major accident occurring.

The analysis is performed considering the *causes that lead to the occurrence of the accident*, the *immediate and final consequences which are expected in case the hazard becomes an accident*, the *level of severity and likelihood* (estimated through the assignment of grades, defined according to the criteria presented below) and the *existing prevention measures*.

The risk is calculated according to the equation R=LxC, where L is likelihood of the event and C is the severity of the consequences (Lees, 1996; Ozunu, 2000, 2007).

The measure of the likelihood of occurrence is established through a range of five levels, from "Unlikely" to "Frequent". *The qualitative measure of consequences* is established also through five levels of severity, from "Insignificant" to "Catastrophic", resulting in a risk matrix.

The risk assessment matrices have been used for many years in risk ranking (Lees, 1996, Ozunu, 2000, 2007). According to the assessment methodology, the risk is situated on a matrix (Figure 5). The risk levels corresponding to the values in the matrix are presented in Table 3.

			Consequences				
			Insignificant	Minor	Moderate	Major	Catastrophic
			1	**2**	**3**	**4**	**5**
Likelihood	Unlikely	**1**	*1*	*2*	*3*	*4*	*5*
	Isolated	**2**	*2*	*4*	*6*	*8*	*10*
	Occasional	**3**	*3*	*6*	*9*	*12*	*15*
	Likely	**4**	*4*	*8*	*12*	*16*	*20*
	Frequent	**5**	*5*	*10*	*15*	*20*	*25*

Figure 5. Risk matrix

Table 3. Risk levels

Risk levels	Definition
1 – 3	*Very low risk*
4 – 6	*Low risk*
7 – 12	*Moderate risk*
13 – 19	*High risk*
20 – 25	*Extreme risk*

2.4. Criterial analysis

According to the general scheme of the systematic risk assessment methodology (Figure 4) for the selection of hazards corresponding to different installations and sections which may contribute significantly to the overall risk of a site and therefore would require a detailed analysis, a series of criteria for differentiation are applied.

These criteria and their mode of application in the sense of the present methodology are presented as follows.

2.4.1. Major accident occurrence potential

For each section are identified the hazards which have the potential to generate a *major accident* according to Council Directive 96/82/EC on the control of major-accident hazards involving dangerous substances, amended by Directive 2003/105/EC of the European Parliament. As such, the hazards involving hazardous substances classified according to Directive 96/82/EC have been identified as having the potential to generate a major accident.

The hazards identified as having the potential to generate a major accident pass on to the next criterial analysis stage. For the hazards that have not been identified as having the potential to generate major accidents, conclusions will be drawn based on the preliminary analysis.

2.4.2. The existence of toxic dispersion, fire or explosion hazard

The sections in which hazardous substances are present, or can be generated in an industrial chemical process which can lead to toxic dispersions into the atmosphere, fires or explosions (substances which are toxic, flammable or explosive according to Council Directive 67/548/EEC of June 27th 1967 on the approximation of laws, regulations and administrative provisions relating to the classification, packaging and labeling of dangerous substances) are selected for detailed risk assessments.

2.4.3. Risk and consequence criterion

Of the sections selected through the TNO methodology, those hazards which present a risk level, estimated in the preliminary assessment stage, higher than 12 (high or extreme risk) or a consequence level of 4 (major) or 5 (catastrophic) are selected for the detailed risk assessment.

2.4.4. Calculation of the Environmental Accident Index

The Swedish "Environment - Accident Index (EAI)" is an assessment instrument which combines properties of chemical substances with site specific properties.

EAI is based on a series of chemical variables and a few site specific variables, such as soil and groundwater conditions (ec. 1). It is comprised of 3 components: acute toxicity for aquatic organisms (**Tox**); the amount of substance stored or transported (**Am**); three factors which affect the dispersing of chemical substances (**Con, Sol** and **Sur**). Con is the consistency or viscosity/physical state of the chemical substance, Sol is the solubility of the chemical substance in water, while Sur describes the potential of the substance to penetrate the soil, depending on the depth and mobility of groundwater.

$$EAI = Tox * Am * (Con + Sol + Sur) \quad \text{(Ec. 1)}$$

After the calculation of EAI, this can be used for the identification of the level of risk assessment required in a certain scenario, in accordance with a given classification scale (Fischer, 1995).

The classification scale with three levels to determine the necessity of an additional risk assessment is presented in Table 4 below.

Table 4. Classification scale for the Environmental Accident Index

EAI score	**Type of analysis necessary**
EAI: 0 – 100	A hazard analysis (HA) is necessary for the intrinsic properties of the chemical substance;
EAI: 100 – 500	HA + introductive Environmental Risk Assessment (ERA)
EAI: > 500	HA + introductive ERA + advanced ERA

The introductive and advanced environmental risk assessment for soil and groundwater pollution can be performed through various established methods and using modeling and decision support systems and software, described elsewhere (**Stezar et al., 2011, 2013**).

2.5. Detailed analysis

The extent of the risk analysis and the intensity of the prevention and mitigation measures should be proportional to the risk involved. The simple hazard identification and risk analysis methods are not always efficient, therefore the use of detailed assessments is necessary sometimes. There are various methods for quantitative risk assessments. Choosing one particular technique is specific to the accident scenario which is analyzed. The assessment methods proposed in this paper comprise a few popular and extensively used detailed assessment methods (Christou et al, 2006):

2.5.1. Detailed analysis 1

<u>2.5.1.1."Consequence based" methods</u>

The approach "based on consequence" starts from the evaluation of consequences of possible accidents without quantifying explicitly the occurrence probability of these accidents. In this way the quantification of occurrence frequencies of potential accidents and associated uncertainties are avoided.

The consequences of accidents are considered through calculating the distances to which the effects on the population (for example the toxic concentration), on a certain period of time, reach a certain threshold, which corresponds to the beginning of the unwanted effect (for example the irreversible effect on human health or casualties) (Christou et. al, 2006).

2.5.1.2."Risk based" methods

The second main category of approaches is the "risk based" one (also known as the probabilistic approach). Generally, the risk based approach defines risk as a combination of consequences produced by more possible accidents and their probability of occurrence.

Two types of risk can be calculated: *individual risk* and *societal risk*. The individual risk is usually presented as risk curves, while FN curves ensure the visualization of social risk.

2.5.2. Detailed analysis 2: Hazardous substances spills in the environment

Within this module of detailed analysis, is included the modeling and simulations of pollutants dispersion in the underground environment and surface waters. The recommended modeling systems for the simulation of water flow and transport pollutants in the underground environment include: GMS (Groundwater Modeling System, the MODFLOW model, MT3D (Modular Three-Dimensional Multispecies Transport Model for Simulation of Advection, Dispersion and Chemical Reactions of Contaminants in Groundwater Systems).

The mathematic modeling and simulation of pollutant transport in surface waters can be performed with the following modeling systems: SMS (Surface Water Modeling System), Modeling of the impact of pollution in hydrographic systems: the model developed by Chapra and Whitehead (2009).

2.7. Conclusions

The systematic risk assessment methodology for the oil and gas subsectors of critical infrastructure described in this chapter proposes a three-step approach with the use of established methodologies for risk assessment, in order to follow a thorough hazard analysis and risk assessment process.

The three-step approach enables the evaluators to come to pertinent conclusions regarding the overall risk of a site, through selecting and analyzing the installations and sections that contribute most to this overall risk. Through eliminating from the detailed assessment stage those installations which are pertinently considered not to contribute significantly to the overall risk of the site, time and expenditures can be saved, without compromising the relevancy and adequateness of the conclusions of the risk assessment.

Chapter 3. Case study: NaTech risk assessment for a petroleum products storage tank farm located in a seismic area in Romania, applying the systematic risk assessment methodology for critical infrastructure – Oil and Gas subsectors

The case study takes into account an atmospheric storage tank farm for petroleum products, which is located close to a residential area, in an earthquake prone region of Romania. The aim of the analysis is to emphasize the difference between the individual and societal risk in case of the intrinsic (not triggered by earthquake) technological accident and in case of adding a NaTech event triggered by a high magnitude earthquake in the area, for the same tank farm. Of the 46 tanks present in the tank farm, 15 were selected, for ease of calculation and because the selected tanks are closest to the inhabited area.

The case study follows the systematic risk assessment methodology, through the preliminary, criterial and detailed assessment stages.

3.1. Preliminary analysis

3.1.1. Presentation of the environment in which the site is located

3.1.1.1. General information

The tank farm selected for the case study is located in the North-East of Ploieşti and is part of a refinery.

Of particular interest to the area taken in consideration for the case study are the administrative building of the refinery and the residential area located in the immediate vicinity of the tank farm, on the south side. Figure 6 presents the tanks taken in consideration for the case study and the residential areas located in the vicinity of the tanks.

Figure 6. Map representing the study area highlighted in yellow and populated area highlighted in red.

The residential area in the vicinity of the tank farm is comprised of single story houses. As no reliable data was available regarding the exact number of inhabitants for this area, an arbitrary value of 3 inhabitants per house was used, thus resulting a population density of 39,13 inhabitants/ha for the studied area, constituted mostly of refinery workers and their families. The population presence was averaged from standard values for day and night given in Purple Book (Purple Book, 2005), to 96% indoors and 4% outdoors, 100% presence probability.

3.1.1.4. Tectonic structure, seismic activity

Building design for seismic conditions in Romania is based on special maps, such as the one presented din Code P.100-1/2006 (P100, 2006), shown in Figure 7b, which displays the zoning of Romanian territory based on PGA (Peak ground acceleration) values. The map displays PGA values for earthquakes with a recurrence period of 100 years.

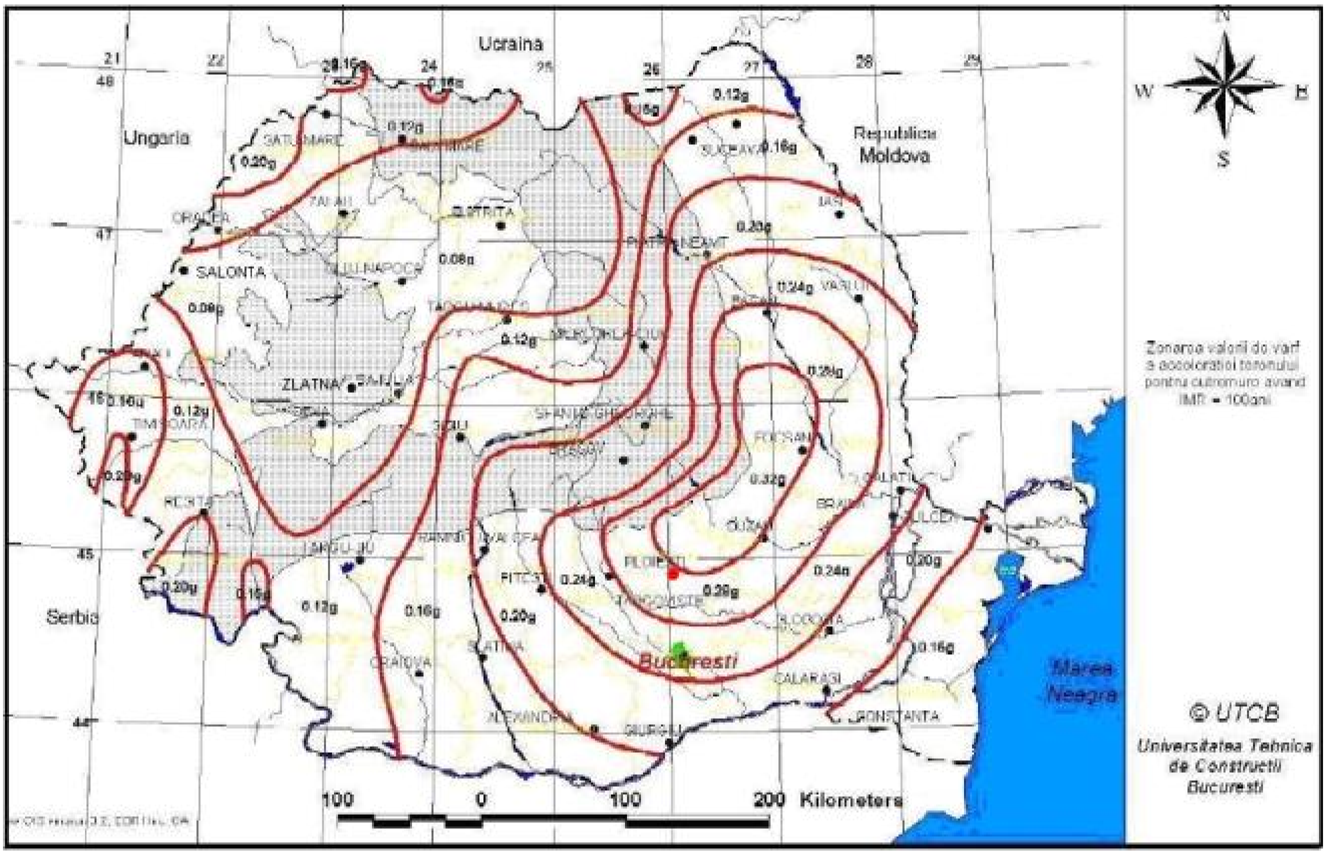


Figure 7b. Zoning of Romanian territory based on PGA values for earthquakes with a recurrence period of 100 years (P100, 2006).

The site is located on the border of the area with PGA value of 0.28g and 0.32g. The second value corresponds to Vrancea area, the highest PGA value for the territory of Romania, for earthquakes with a recurrence period of 100 years.

More recent research has been carried out by the Romanian National Institute for Earth Physics personnel and collaborators, resulting in seismic intensity and PGA maps for earthquakes with various recurrence (return) periods. For NaTech risk assessment, recurrence periods of 475 years are typically used for “important” sites, while for “very important” and “of special importance” sites, recurrence period of 1000 and 5000 years are used, respectively (Cruz et al., 2004). For the studied site a recurrence period of 475 years can be taken into consideration, as this value, along with 100 years recurrence period is recommended by EUROCODE 8 (see reference) for drafting seismic hazard maps for the design of structures for earthquake resistance.

Considering a 475 years return period, the PGA in the area of the studied site can reach up to 3.5 m/s^2 with an intensity of approx. 8.5 MSK (Ardeleanu et al., 2005; Leydecker et al., 2008; Sokolov et al., 2007) (Figure 8.).

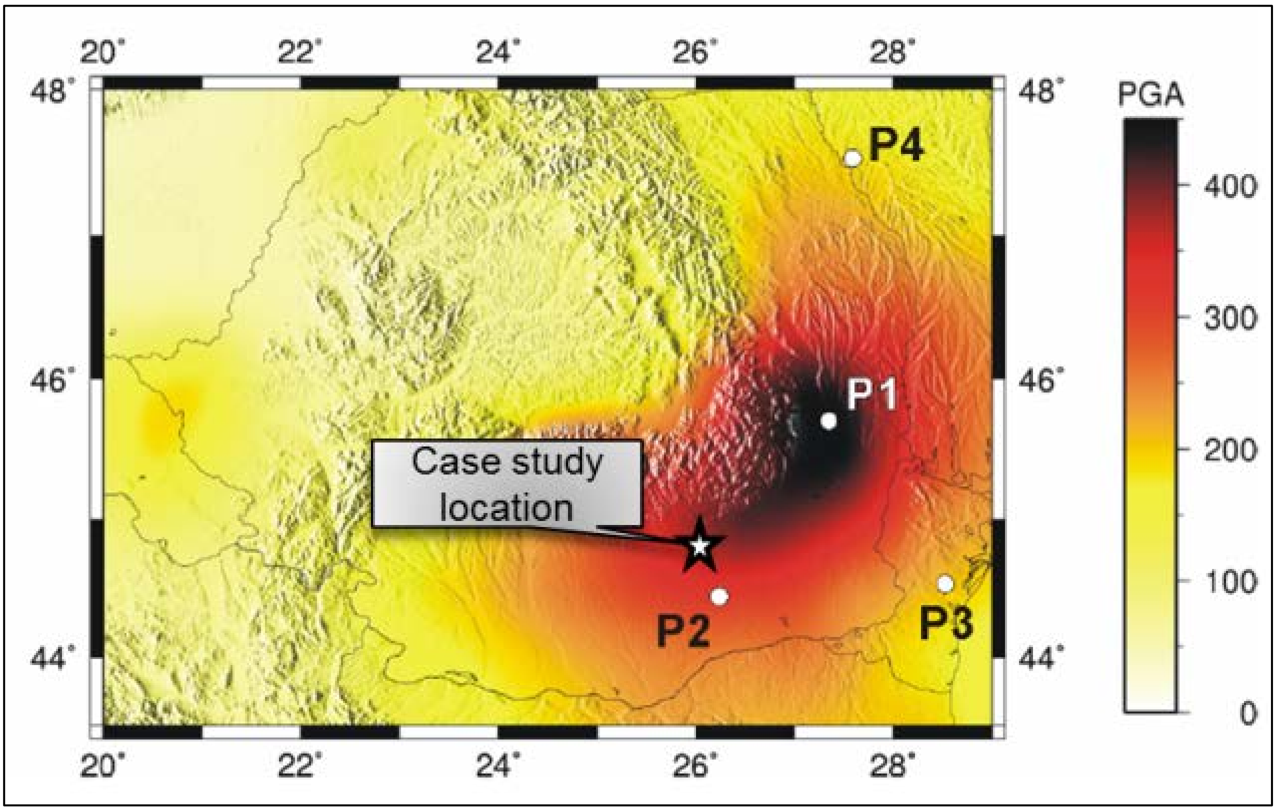


Figure 8. Probabilistic seismic hazard map of Romania for earthquakes with a recurrence period of 475 years. Colors represent PGA in cm/s^2 (source Sokolov et al., 2007).

As per the information presented above, and the provisions of GD 642/2005 (GD 642, 2005) on the approval of Classification criteria for the administrative-territory units, public institutions and economical operators regarding civil protection, depending on specific risks, the site is located in a seismic risk area.

3.1.2. Description of the installation

The installation taken into consideration for the case study includes the 15 tanks A1 to A15, connected piping and pumping facilities. The tanks selected for the risk analysis are vertical cylindrical stainless steel single wall tanks. The tanks are anchored and the bund of the tanks is made of earth berms (dikes). The tanks are grouped in 5 bunds as presented in Figure 9.

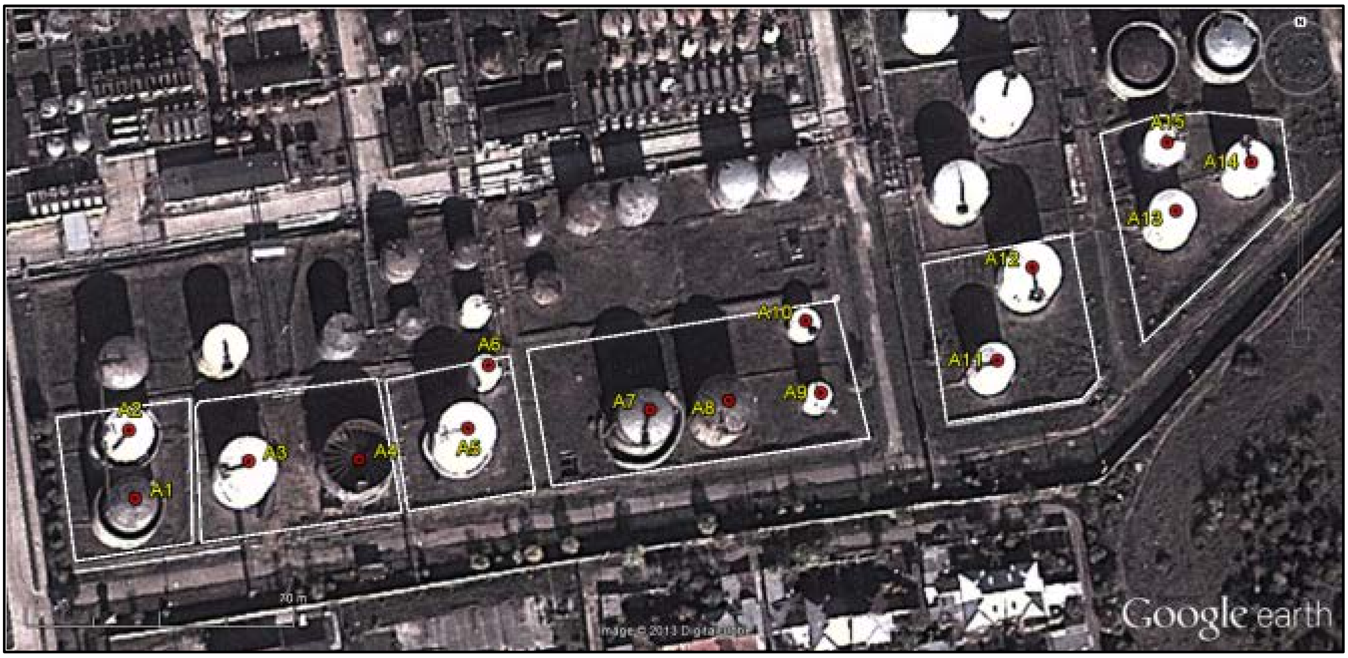


Figure 9. Tanks selected for the case study and the respective bund contours.

3.1.4. Identification of natural hazards in the area

From the presentation of the site in chapter 3.1.1., one can conclude the most significant natural hazard in the area of the site which has the potential to cause major accidents is the seismic potential of the area. The site is not located in a flood or landslide prone area.

As such, for the quantitative risk assessment, a reference seismic event with a recurrence value of 475 years was considered. The value considered for PGA was 300 cm/s^2, corresponding to a value of 0.306g (see chapter 3.1.1.4.).

3.1.5. Description of typical accident scenarios

In the area of the tanks selected for analysis, releases of hazardous substances stored in the tanks can occur, either in liquid or gaseous form, with various possible outcomes, presented in Table 11 (Kirchsteiger et al., 1998).

Table 11.Description of possible major accident scenarios on selected site

	Scenario	**Possible effects**
a.	Petroleum products releases/leaks from pipelines/pumps	- fire/explosion - air, soil and groundwater pollution - harm to personnel
b.	Petroleum products releases/leaks from tanks	- fire/explosion - air, soil and possibly groundwater pollution if released amount of substance exceeds bund capacity - harm to personnel
c.	Fire from leak outside bund	- harm to personnel - damage to installation - explosion - toxic dispersion of smoke and combustion gases - soil pollution with combustion debris

d.	Fire inside tank	- harm to personnel - damage to installation - explosion - toxic dispersion of smoke and combustion gases - soil pollution with combustion debris
e.	Fire – leaked substances in bund	- harm to personnel - damage to installation - explosion - toxic dispersion of smoke and combustion gases - soil pollution with combustion debris
f.	Explosion or flash fire (outside tank)	- harm to personnel - damage to installation - fire - pollution with explosion debris
g.	Tank explosion	- harm to personnel - damage to tank and adjacent installation - pool fire - pollution with fire /explosion debris - toxic dispersion of smoke and combustion gases.

3.1.8. Hazard analysis

The scenarios presented in table 11 are analyzed using risk matrices. All scenarios of accidents developed for the selected site have the potential to generate major accidents, as defined in the Seveso Directives (Seveso II, IIa, III). The hazard analysis table for the accident scenarios developed for the case study site is presented in Table 12.

Table 12. Hazard analysis for accident scenarios on site.

Scenario	Scenario	Likelihood level	Consequence level	Risk level
a	Petroleum products releases/leaks from pipelines/pumps	4	2	8
b	Petroleum products releases/leaks from tanks	3	3	9
c	Fire from leak outside bund	3	3	9
d	Fire inside tank	3	3	9
e	Fire – leaked substances in bund	3	5	15
f	Explosion or flash fire (outside tank)	2	5	10
g	Tank explosion	2	5	10

The risk levels resulted from the hazard analysis range from Moderate risk to High risk, most scenarios having Moderate risk, according to the risk level definition in Table 3, presented in chapter 2.3.5. of the present thesis. There is one scenario that resulted in having high risk: “Fire-leaked substances in bund”. This scenario consists of a fire after the tank rupturing and the contents of the tank spilling in the bund. The likelihood for this scenario was considered 3 (occasional), due to the fact the tanks in the tank farm are old and corrosion is visible on the shell of most of the tanks. Also, tank ruptures are very likely to occur in case of strong earthquakes in the area. The site being in a highly seismic area, this is considered a likely event. In case of ignition of the contents in the bund after spilling, consequences can be catastrophic, due to the fact that there are more tanks stored in common bunds. In case of a fire in the bund, it is very likely that the tanks located in the same bund suffer damage from the fire, thus escalating the effects of the accident. Also, the fact that the residential area is located in the immediate vicinity of the tank farm can aggravate the accident. The risk matrix resulted from the hazard analysis is presented in Figure 10.

			Consequences				
			Insignificant	Minor	Moderate	Major	Catastrophic
			1	**2**	**3**	**4**	**5**
Likelihood	Unlikely	**1**					
	Isolated	**2**					f, g
	Occasional	**3**			b, c, d		e
	Likely	**4**		a			
	Frequent	**5**					

Figure 10. Risk matrix resulted from hazard analysis.

3.2. Criterial analysis

The first criterion in this step of the Analysis is the *Major Accident potential*, defined according to Seveso directive. *All seven scenarios elaborated for the analyzed tank farm have the potential to generate major accidents*, due to the nature of the substances stored in the tank farm. The site is classified as Upper-tier according to Annex I, part II, p.34 (Seveso III).

The second criterion is the *Existence of toxic dispersion, fire or explosion hazard*. As all scenarios include releases of hydrocarbon with the possibility of ignition and/or explosion, *all seven scenarios have a fire or explosion hazard*.

Three of the seven scenarios elaborated for the tank farm *qualify for the detailed assessment based on the risk and consequence criterion: scenarios e, f, and g* (Table 13).

Table 13. Scenarios that qualify for detailed assessment based on the “Risk and consequence” criterion

Scenario	Scenario	Likelihood level	Consequence level	Risk level
e	Fire – leaked substances in bund	3	5	15
f	Explosion or flash fire (outside tank)	2	5	10
g	Tank explosion	2	5	10

None of the elaborated scenarios for the tank farm needed to be analyzed based on the Environmental Accident Index criterion, and as such the EAI was not calculated for these scenarios.

3.3. Detailed analysis

Note. For brevity, in the present summary selective results are displayed only for pool fire in bund of tanks A7-A10, the results for other scenarios and each of the bunds or individual tanks are presented in the thesis.

The scenarios that resulted from the criterial analysis as requiring a more detailed assessment are analyzed using advanced modeling software. The modeling tools (software programs) used for the assessment of scenarios due to technological causes is EFFECTS, elaborated by the Dutch TNO Company. For the most serious scenario type, the fire in the bund of tanks scenario, ARIPAR 4.0 software is used for the assessment of individual and societal risk.

The location-based individual risk assumes the risk of death, as a result of an accident within an establishment, for an unprotected person who is permanently present at a given location.

The social risk is graphically represented through the F-N curve, showing the annual frequency of having N or more fatalities. On the same graph two lines can be represented for dividing the regions Unacceptable-ALARA and ALARA-acceptable risk. ALARA (As Low As Reasonably Achievable) is the region where effort should be exercised to reduce the risk.

Due to the fact that the site is located in a seismic area, the influence of the seismic hazard on the individual and societal risk level of the site is analyzed for the fire in the tank bund scenario, using ARIPAR 4.0 software as well.

3.3.1. Risk assessment for technological accidents

3.3.1.1. Fire – leaked substances in bund – consequence analysis

Pool fires in the bund of tanks were modeled using EFFECTS Software elaborated by TNO. The fires were modeled for two wind speeds: 1m/s and 4 m/s, and results of heat radiation versus distance, and heat radiation versus crosswind distance are presented in the thesis, for each bund.

The results were displayed as values for radius of the heat radiation contours at three different values: 12.5, 5 and 2.5 kW/m^2. These values are recommended as threshold values for the calculation of physical effects by the General Inspectorate for Emergency Situation in Romania (IGSU, 2013, 2009).

3.3.1.1.4. A7 – A10 bund

A. Substance: n-hexadecane (Tanks A7, A9 and A10);

Pool surface (m^2): 3055

Table 21. Results for pool fire in bund of tanks A7 – A10 (n-hexadecane)

Parameter and measuring unit	Value for 1m/s wind speed	Value for 4m/s wind speed
Heat radiation first contour at (m)	**78,042**	**82,772**
Heat radiation second contour at (m)	**56,62**	**65,081**
Heat radiation third contour at (m)	**32,837**	**36,406**

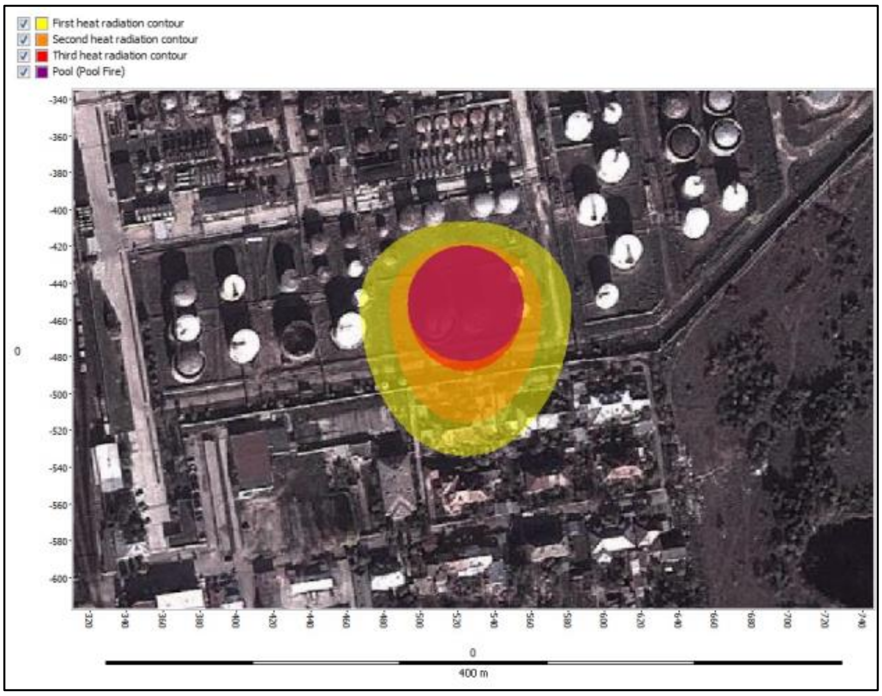


Figure 15f. Risk map for tanks A7 – A10 bund fire, 4m/s wind speed (n-hexadecane).

B. Substance: xylene (Tank A8);

Pool surface (m^2): 3055

Table 22. Results for pool fire in bund of tanks A7 – A10 (xylene)

Parameter and measuring unit	Value for 1m/s wind speed	Value for 4m/s wind speed
Heat radiation first contour at (m)	**67,208**	**75,057**
Heat radiation second contour at (m)	**45,799**	**56,812**
Heat radiation third contour at (m)	**23,236**	**29,284**

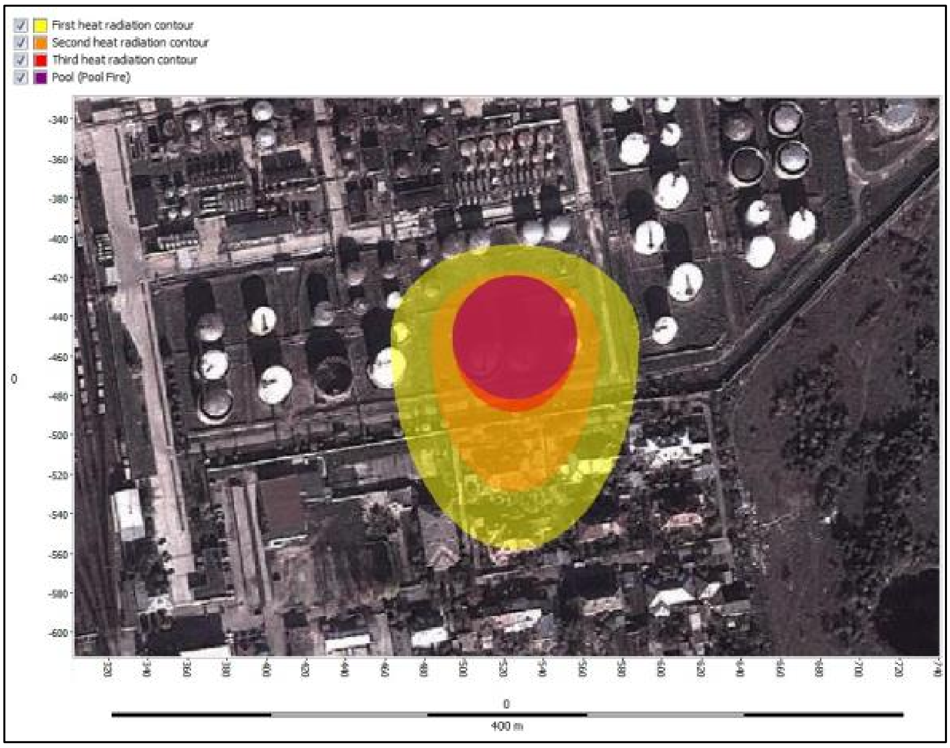


Figure 16f. Risk map for tanks A7 – A10 bund fire, 4m/s wind speed (xylene).

3.3.1.2. Fire – leaked substances in bund – individual and societal risk

3.3.1.2.4. A7 – A10 bund

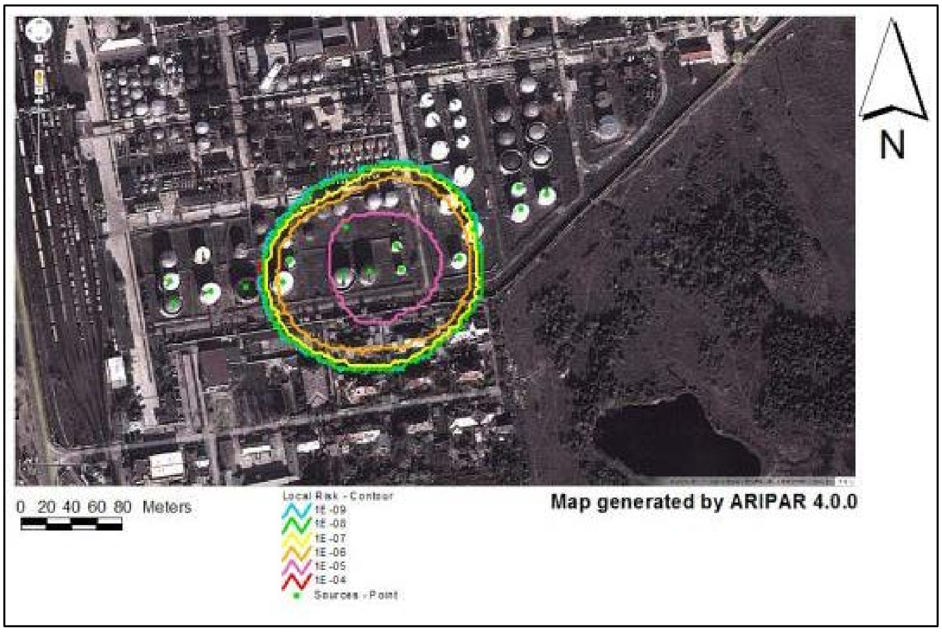


Figure 24a. Individual Risk map for tanks A7-A10 bund fire, intrinsic causes.

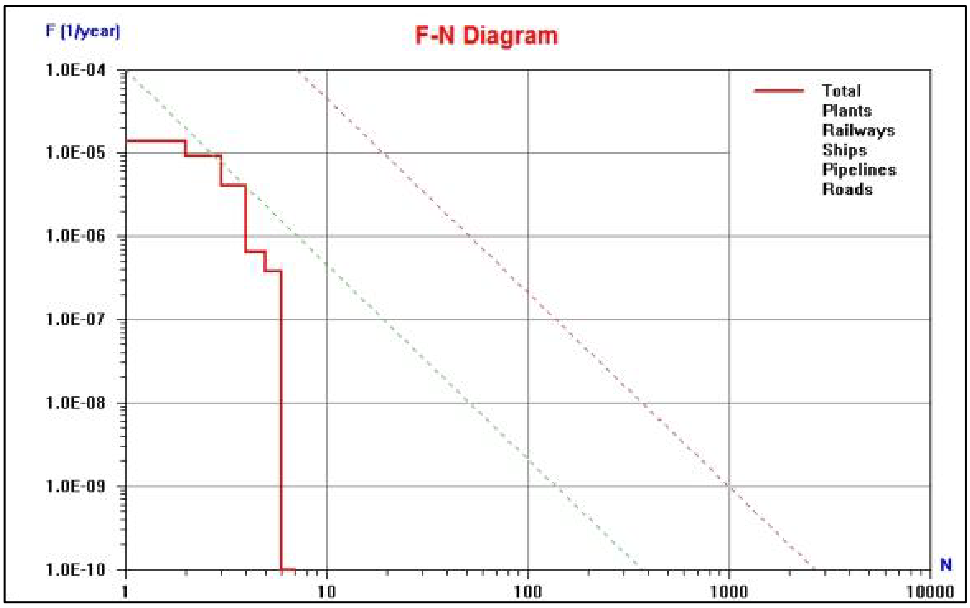


Figure 24b. F-N diagram for tanks A7-A10 bund fire, intrinsic causes.

3.3.1.5. Conclusions of the technological risk assessment

The technological risk assessment for the selected site consisted of fire in bund scenarios for which the risk was assessed using "consequence based" methods as well as risk based methods. For the explosion or flash fire outside tank and tank explosion scenarios only consequence based methods were used, as results from this analysis revealed that the effort of performing individual and societal risk calculations for these scenarios would not be justified in the spirit of the Systematic Risk Assessment methodology described in Chapter 2 of the thesis.

The results of the consequence analysis for the pool fire in bund scenarios revealed that the reversible (Threshold III) and irreversible effects (Threshold II) for thermal radiation contours reaches the residential area in the case of most scenarios, except for scenarios involving tanks A13, A14 and A15. Therefore, the individual risk and societal risk for these scenarios was considered necessary. The calculations were made using ARIPAR 4.0. modeling tool, and results were displayed.

The acceptable individual risk limit values used for LUP (Land Use Planning) purposes, accepted in several EU member states, are 10^{-5} y^{-1} upper and 10^{-6} y^{-1} lower limits (Duijm, 2009; Trbojevic, 2005). The lower limit for individual risk has reached the limit of the residential area in all scenarios, except for the scenario involving the fire in the bund of tanks A13-A15 (these tanks are located further away from the residential area). In the case of the fire in bund of tanks A7-A10, also the upper limit (10^{-5} y^{-1}) contour of the individual risk has reached the residential area limit.

The combined results of the individual risk due to intrinsic technological causes for all tanks selected in the case study is presented in Figure 43.

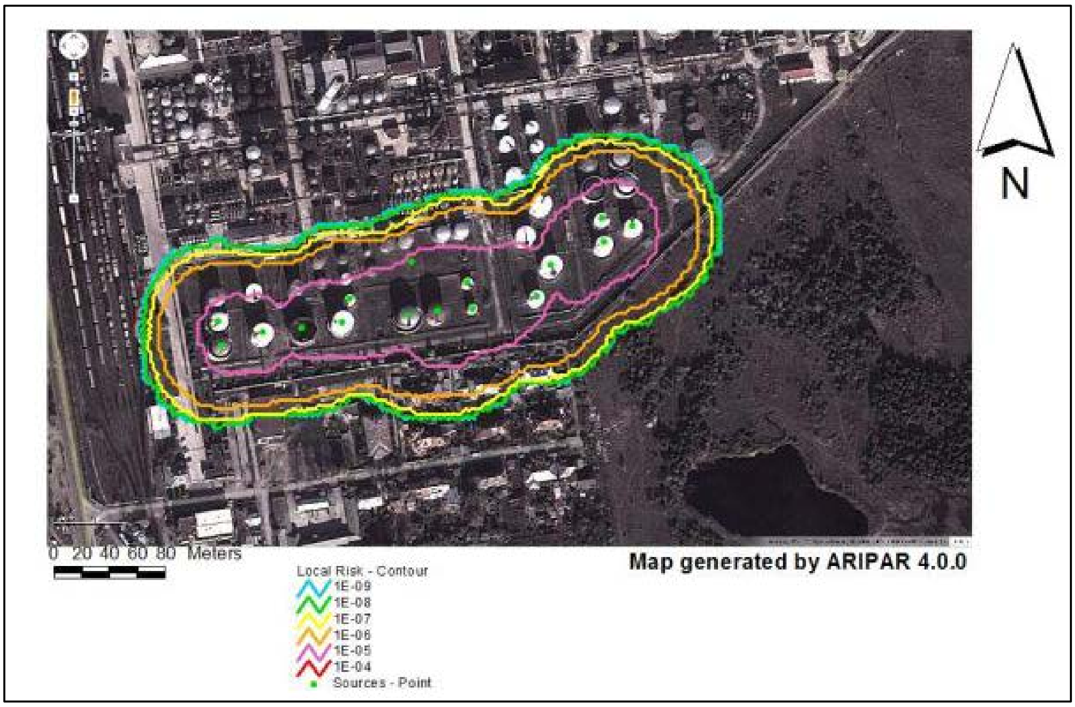


Figure 43. Individual risk due to intrinsic technological causes for the tanks A1 to A15.

Societal risk calculations were also performed for each of the fire in bund scenarios for the selected tanks. None of the separate (for each bund) F-N curves reached the ALARA interval; they were all situated in the acceptable risk limit. When taken together, all fire in bund scenarios due to intrinsic causes, the F-N curve reaches the ALARA limit slightly, as shown in Figure 44.

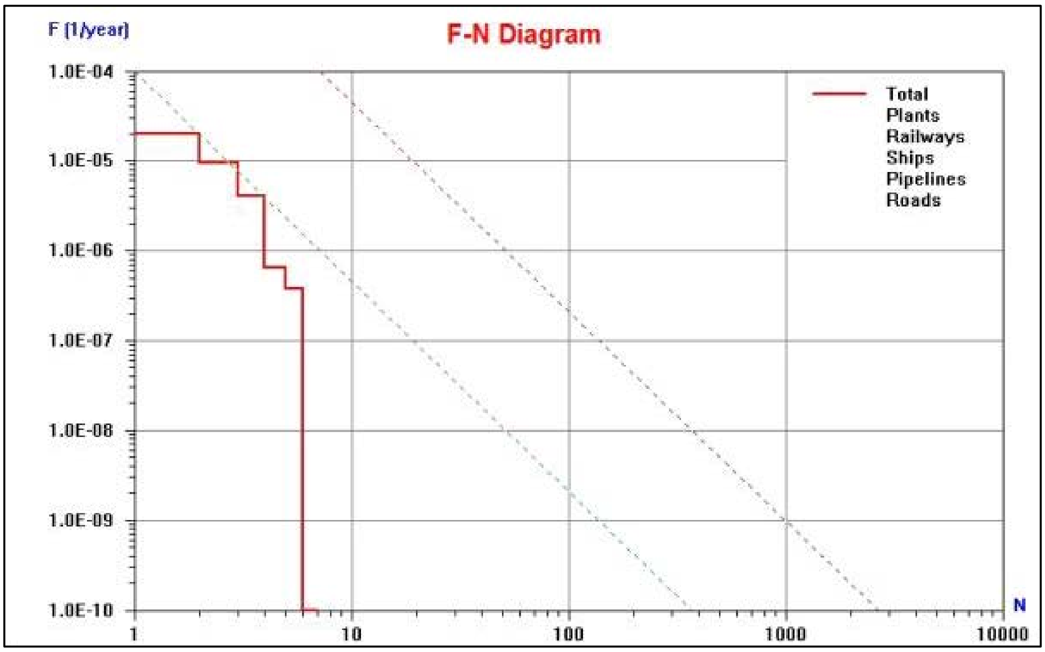


Figure 44. F-N diagram for all scenarios of fire in bund due to intrinsic causes

For some of the scenarios the results were below cut-off values for the societal risk computation which reveals that not all scenarios contribute in the same amount to the F-N diagram for all fire in bund scenarios due to intrinsic causes displayed in Figure 44 above. As such, an F-N diagram with separate curves for each top event was generated. The results are presented in Figure 45 and an explanation of the legend and the percentage of the contribution to the total societal risk for each top event are given in Table 40. There were 8 top events (only six displayed in diagram) that were situated above the cut-off value for calculations of societal risk in ARIPAR, corresponding to 8 tanks and their subsequent fire in bund due to intrinsic cause scenarios. Scenarios that were situated below this value and as such did not contribute significantly to the overall societal risk of the site (due to intrinsic causes) are corresponding to tanks A2, A5, A6, A12,A13, A14 and A15.

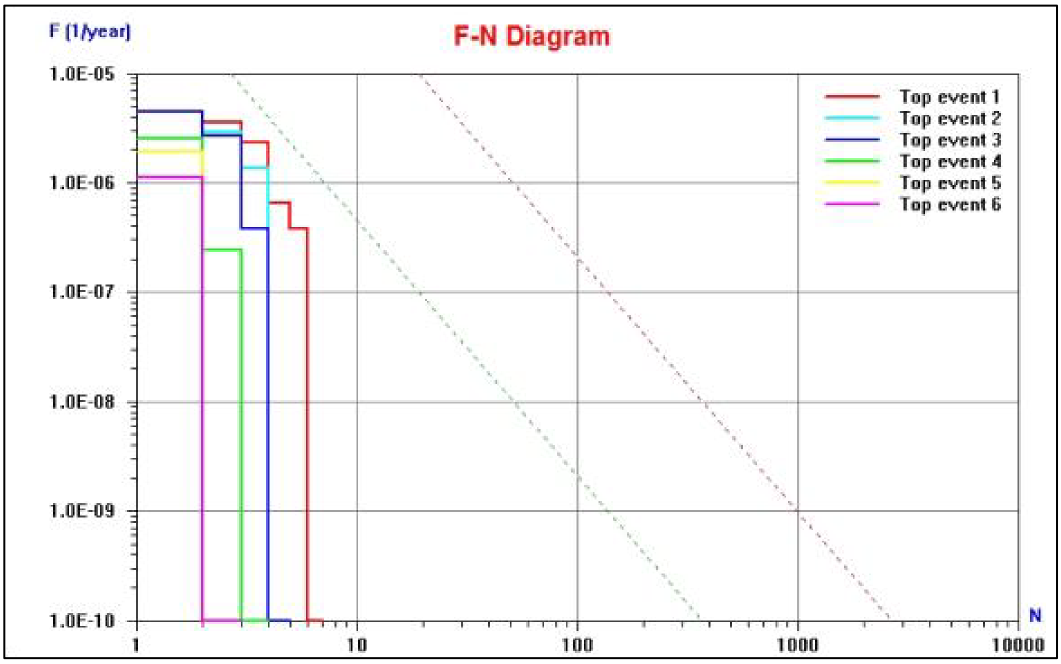


Figure 45. F-N diagram for fire in bund scenarios due to intrinsic causes, separated by top events

Table 40. Top events and their contribution to the overall societal risk level due to intrinsic causes.

Item	Description	Contribution to total societal risk (%)
Top event 1	A8 – Tank catastrophic rupture, intrinsic cause	35.3178
Top event 2	A9 – Tank catastrophic rupture, intrinsic cause	25.4435
Top event 3	A7 – Tank catastrophic rupture, intrinsic cause	21.0440
Top event 4	A11 – Tank catastrophic rupture, intrinsic cause	7.5879
Top event 5	A4 – Tank catastrophic rupture, intrinsic cause	5.1987
Top event 6	A3 – Tank catastrophic rupture, intrinsic cause	3.0859
Top event 7	A1 – Tank catastrophic rupture, intrinsic cause	1.2784
Top event 8	A10 – Tank catastrophic rupture, intrinsic cause	1.0438

The simulation of VCE (outside tank) resulting from the evaporating pool in the bund of tanks (after tank rupture) for the selected case study showed no results.

The simulation of flash fires was performed for two scenarios, for buns of tanks A1 and A3, with xylene, and for the bund of tanks A3 and A4, with n-hexane, both in average meteorological conditions (Pasquill class D-neutral) and in unfavorable meteorological conditions (Pasquill class F-very stable). The LEL threshold concentration was not reached in any of the cases, but for n-hexane; the 0.5 LEL concentration threshold was reached in the case of unfavorable meteorological conditions and has reached a maximum distance of 120.42m. As lethality is considered only inside the flame envelope, individual and societal risk calculations were considered not to be necessary.

Simulation of tank explosion (VCE) has also been performed for each of the selected tanks, for five overpressure threshold values. The 300mbar overpressure threshold level corresponding to the high mortality area has not been reached in any of the cases. As such, the individual and societal risk calculations were not necessary to be performed. The contours that reached the residential area are the 30mbar (reversible health effects) for most tanks (except A13-A15) and the 70mbar contour (irreversible health effects) in case of tanks A1, A2, A3, A4, A5, A7 and A8. Also, in case of tanks A1, A4, A7 and A8, also the 100mbar contour corresponding to the land-use planning area reach the residential area in a small part on the north border. For most tanks the 140mbar domino effect contours reach nearby tanks. This fact shows that safety distances were not taken into consideration when the design of the site was elaborated.

3.3.2. NaTech risk analysis

The calculations for individual and societal risk were performed for scenarios involving intrinsic (technological) accident causes, as well as for scenarios involving seismic causes. Afterwards, the overall NaTech risk was calculated using the same software. A reference seismic event was chosen for the calculation of seismic and NaTech risk, having a PGA of 300cm/s^2 (~ 0.306g) and a return period of 475 years (resulting in a frequency of $2.11 \bullet 10^{-3}$/year) (Ardeleanu et al., 2005; Sokolov et al., 2007) (see chapter 3.1.1.4.). The software allows the analysis of scenarios for more than one reference earthquakes and their subsequent parameters.

The calculation for the damage probability of the tanks in case of earthquake was performed using Probit analysis (Finney, 1971). Vulnerability models based on probit analysis are widely used in QRA (Antonioni et al., 2007, Salzano et al., 2003; Fabbrocino et al., 2005).

3.3.2.1.Results for NaTech risk analysis

3.3.2.1.4. A7 – A10

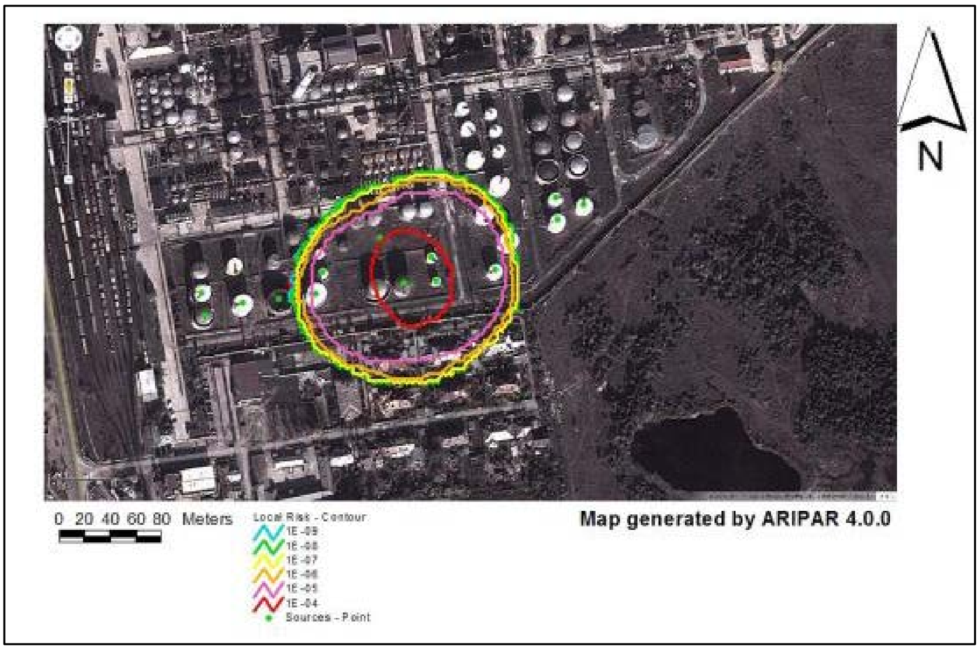


Figure 50a. Individual Risk map for tanks A7-A10 bund fire, intrinsic and seismic causes.

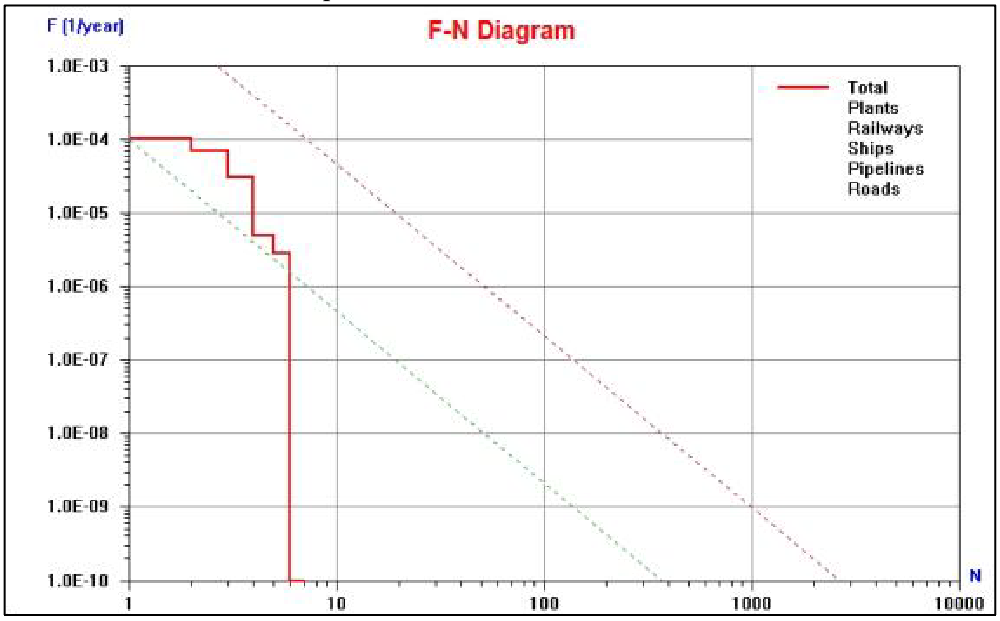


Figure 50b. F-N diagram for tanks A7-A10 bund fire, intrinsic and seismic causes.

3.3.2.2. Conclusions of NaTech risk analysis

The individual risk and societal risk for total risk (including fire in bund scenarios due to NaTech and intrinsic causes) calculations were made using ARIPAR 4.0. modeling tool, and results were displayed for each bund.

The 10^{-6} y^{-1} lower acceptability limit for individual risk for LUP purposes (Duijm, 2009; Trbojevic, 2005), as well as the 10^{-5} y^{-1} upper limit have reached the residential area in all cases, except for the tanks A13 –A15. This means that the individual risk due to both intrinsic and NaTech causes, has reached the unacceptable threshold in these cases. When individual risk is calculated for all intrinsic and NaTech scenarios altogether, the northern part of the residential area is situated within the unacceptable area for LUP purposes, as it can be observed in Figure 53.

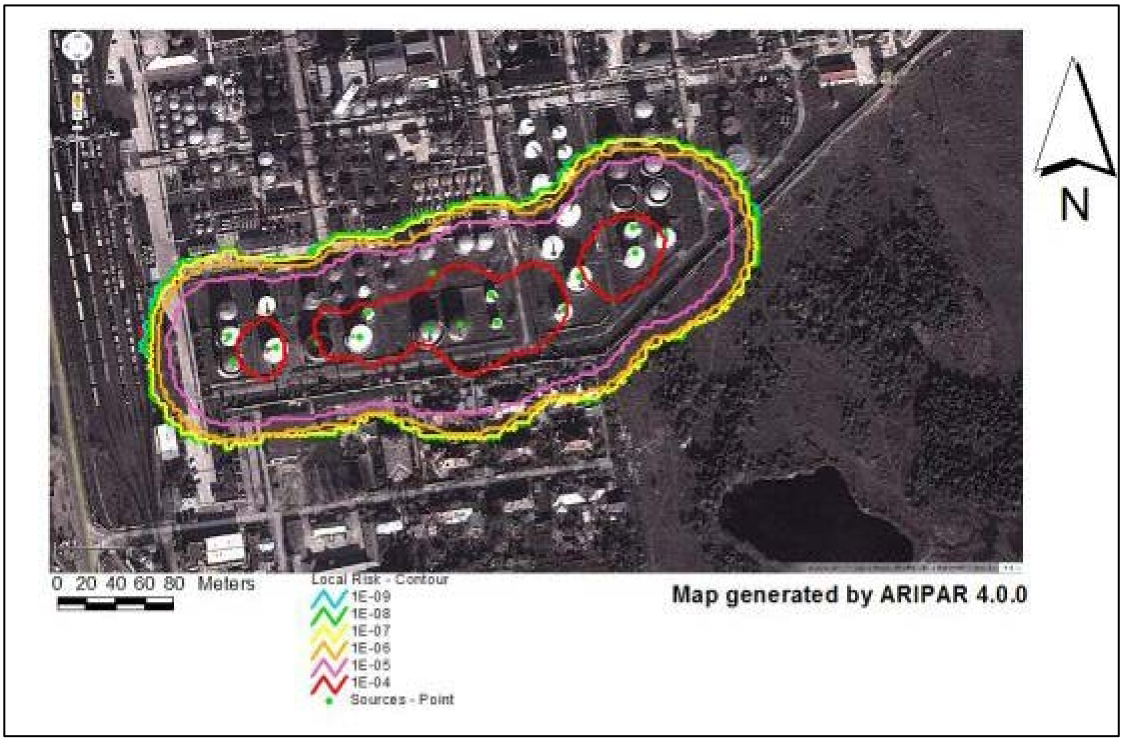


Figure 53. Individual risk – fire in bund scenario due to intrinsic and NaTech causes, tanks A1-A15.

Societal risk calculations were also performed using ARIPAR software. The F-N diagrams for each bund taken separately revealed that the societal risk level for both intrinsic and NaTech causes has reached the ALARA interval for the fire in bund scenario for tanks A7 to A10. The results for societal risk calculations for bunds of tanks A5-A6 and A13-A15 were situated below cut-off values used for computational purposes by the software. A societal risk calculation was performed for all scenarios including intrinsic and NaTech causes, and the results are displayed in Figure 54. As it can be observed in Figure 54, the F-N curve for all scenarios is situated within the ALARA interval. The ALARA principle states that for risk that is situated within this interval, risk reduction measures are desirable, in order to reduce the risk in order to reach the acceptable limit.

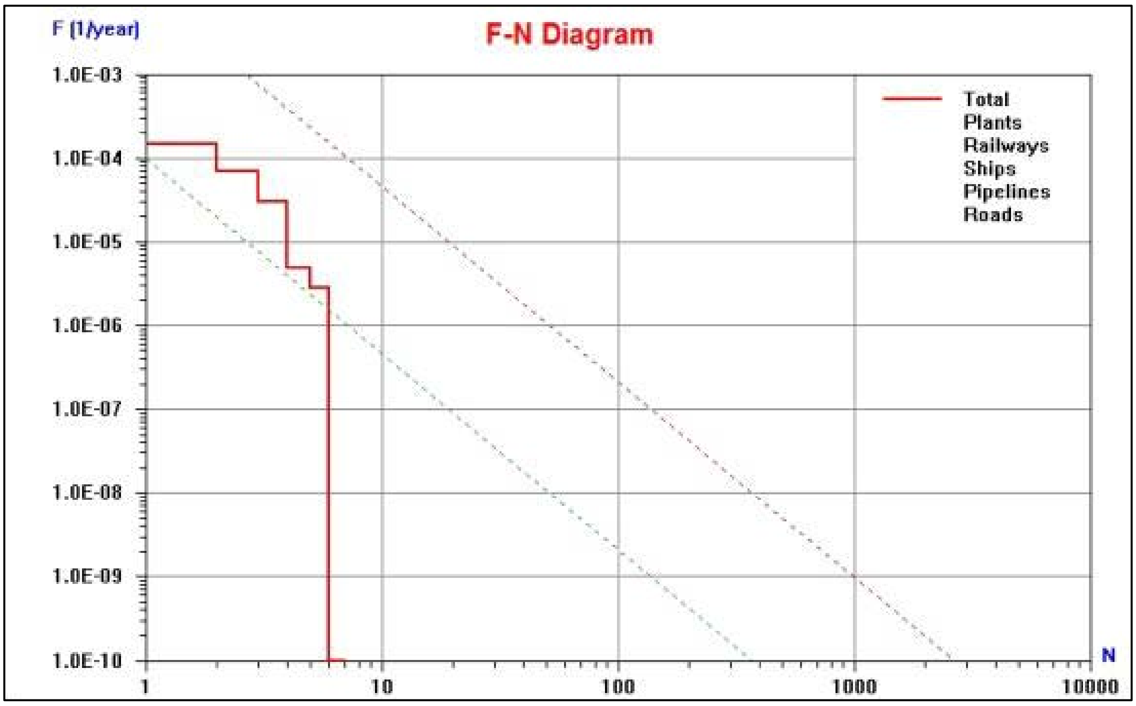
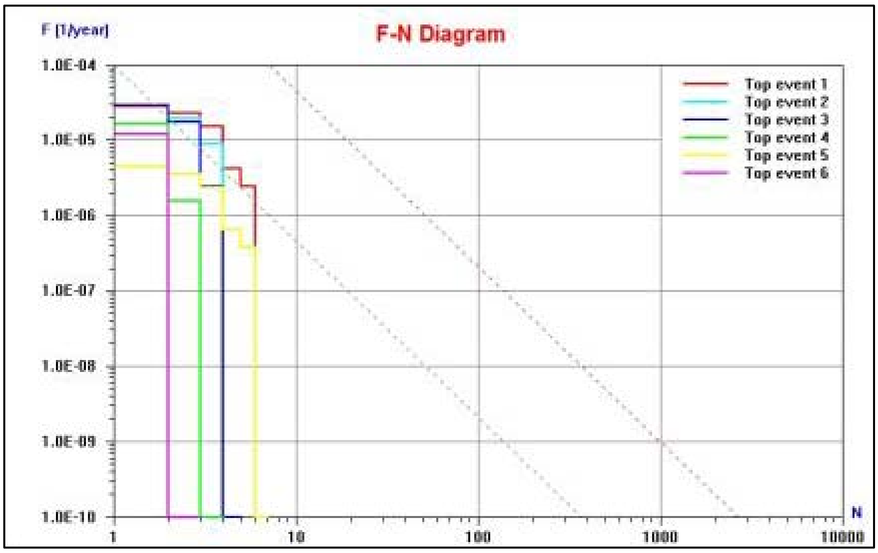
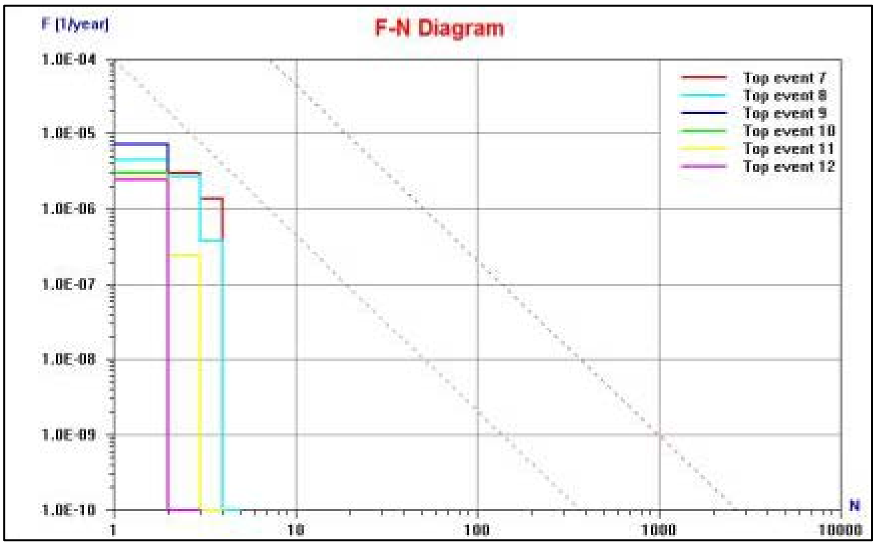


Figure 54. F-N diagram for all scenarios of fie in bund due to intrinsic and NaTech causes.

An F-N diagram with separate curves for each top event was generated, including all possible causes, intrinsic or seismic (NaTech events) for the LOC. As such it is possible to see which of the scenarios contribute mostly to the overall societal risk level of the site, and the societal risk level generated by each top event separately. The results are presented in figure 55, and Table 41 presents an explanation of the legend and percentage of contribution of each scenario to the total societal risk level of the tank farm.

a)



b)


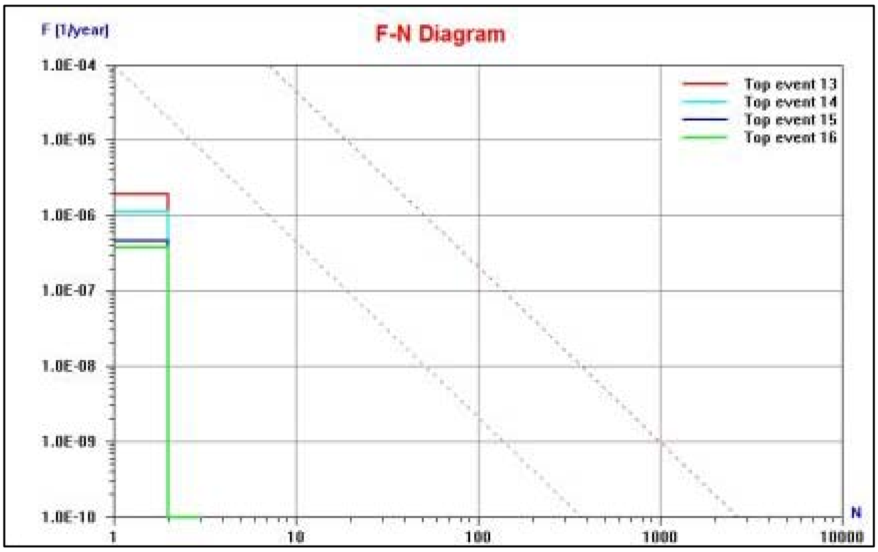
c)


Figure 55 a)-c). F-N diagram for fire in bund scenarios due to intrinsic and seismic causes, by top event

Table 41. Top events and their contribution to the overall societal risk level due to intrinsic and seismic causes

Item	**Description**	**Contribution to total societal risk (%)**
Top event 1	A8 – Tank catastrophic rupture, seismic cause	30.5580
Top event 2	A9 – Tank catastrophic rupture, seismic cause	22.0145
Top event 3	A7 – Tank catastrophic rupture, seismic cause	18.2079
Top event 4	A11 – Tank catastrophic rupture, seismic cause	6.5652
Top event 5	A8 – Tank catastrophic rupture, intrinsic cause	4.7598
Top event 6	A4 – Tank catastrophic rupture, seismic cause	4.4981
Top event 7	A9 – Tank catastrophic rupture, intrinsic cause	3.4290
Top event 8	A7 – Tank catastrophic rupture, intrinsic cause	2.8361
Top event 9	A3 – Tank catastrophic rupture, seismic cause	2.6700
Top event 10	A1 – Tank catastrophic rupture, seismic cause	1.1061

Top event 11	A11 – Tank catastrophic rupture, intrinsic cause	1.0226
Top event 12	A10 – Tank catastrophic rupture, seismic cause	0.9031
Top event 13	A4 – Tank catastrophic rupture, intrinsic cause	0.7006
Top event 14	A3 – Tank catastrophic rupture, intrinsic cause	0.4159
Top event 15	A1 – Tank catastrophic rupture, intrinsic cause	0.1723
Top event 16	A10 – Tank catastrophic rupture, intrinsic cause	0.1407

The ranking of societal risk contribution by top event presents an important advantage: it shows where risk reduction measures would yield the highest benefit (Botezan et al., 2010). From the ranking it can be observed that the first three top events in the list account for over 70% of the risk level; tank A8 is classified highest, with a contribution of approximately 30% to the overall societal risk level of the site. Also all of these top events are due to seismic causes. As such, implementing targeted risk reduction measures for earthquake resistance in these three tanks (A8, A9 and A7) should result in the highest benefits for reducing the overall societal risk level of the site.

3.4. Conclusions and discussion

The Seveso Directive (Seveso II, III) is addressing NaTech risks indirectly requiring the analysis of the external events in the identification and accident risk analysis and prevention methods. The analysis of external events which can lead to chemical accidents implies the consideration of the potential threat of natural hazards in the hazard analysis, and carrying out mitigation measures in case an accident occurs. The methodologies and the actions that can be taken to achieve these requirements are not specified and limited work has been devoted to the development of quantitative assessment procedures for NaTech risk (Cruz et al., 2004).

Taking these aspects into consideration, we consider that assessing the difference between the level of individual and societal risk due to intrinsic causes and due to NaTech causes can emphasize the importance of taking natural hazards into consideration as causes for accidents when performing risk assessments for industrial sites. Figure 55 presents a side-by-side comparison of the individual risk for all tanks due only to intrinsic causes and due to both intrinsic and NaTech causes, for all tanks.

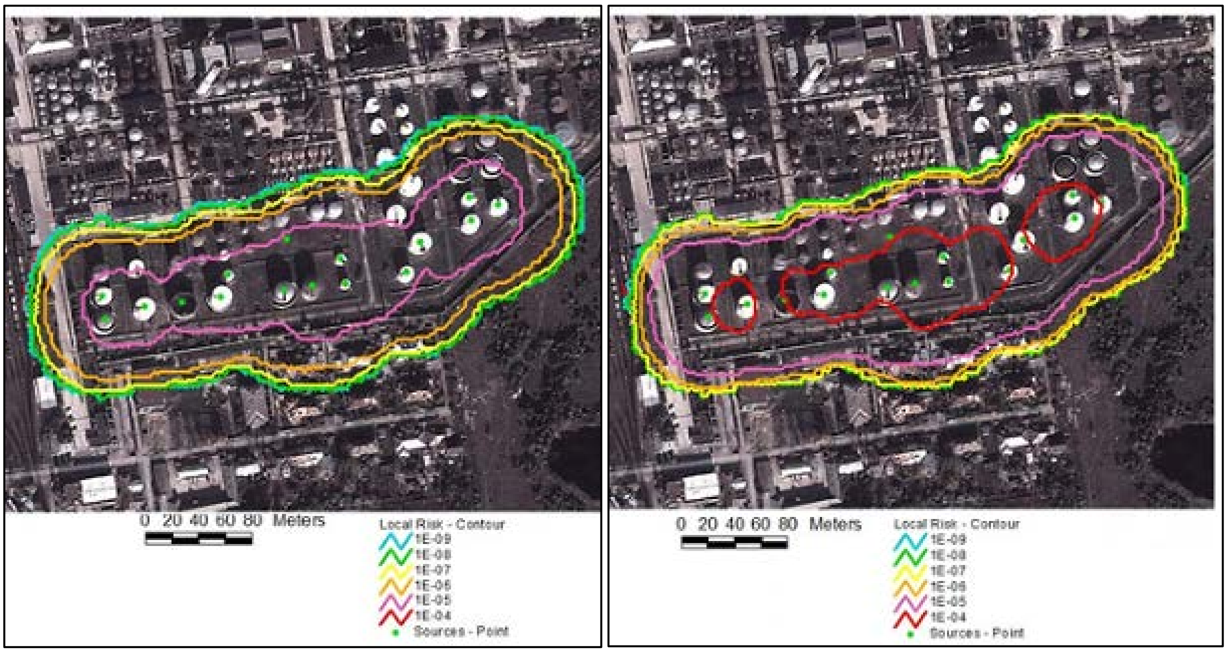


Figure 56. Side-by-side comparison of individual risk for fire in bund scenario for tanks A1-A15. Left-intrinsic causes, Right-total (intrinsic and NaTech)

From Figure 56 it can be observed that when adding NaTech scenarios to the risk analysis, the Individual Risk level for the selected tank farm has increased with one order of magnitude, and the residential area is situated within the unacceptable threshold contour ($10^{-5}y^{-1}$) for individual risk for LUP purposes.

There is a significant increase also in the societal risk when taking into consideration both intrinsic and NaTech causes. A side by side comparison for societal risk with intrinsic causes versus intrinsic and NaTech causes for the site is presented in Figure 57.

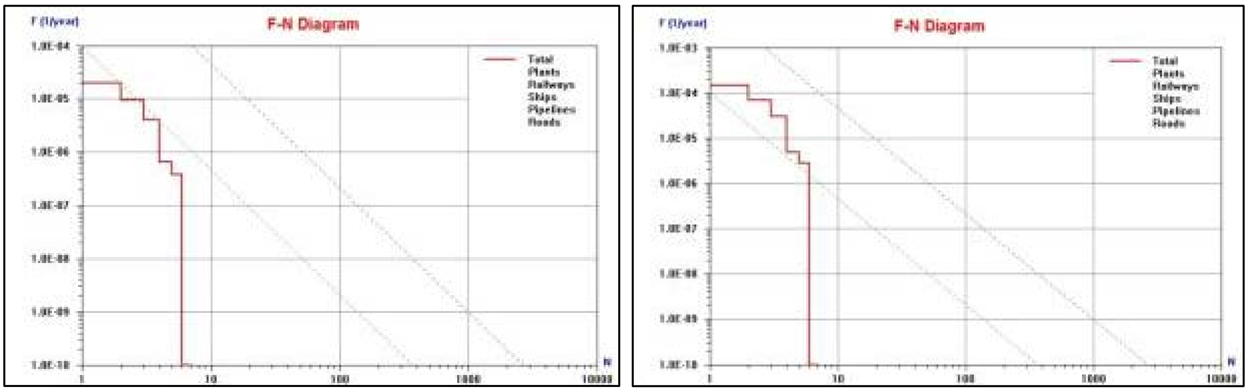


Figure 57. . Side-by-side comparison of societal risk for fire in bund scenario for tanks A1-A15. Left-intrinsic causes, Right-total (intrinsic and NaTech)

As in the case of individual risk, societal risk increases by one order of magnitude when the NaTech causes are added to the risk calculations, and the risk is situated in the ALARA interval, indicating that risk reduction measures should be implemented in order to reduce the risk level to an acceptable one.

Figure 57 displays the total societal risk for the site. The probability however differs for one or more tanks to be damaged simultaneously in case of an earthquake. As such, the calculation of the frequency for each possible combination of simultaneous damage to the tanks is needed. A cut-off value for this frequency is applied, as such the relevant combinations of 1 to x tanks which could be damaged at the same time by the earthquake of the overall 15 tanks taken into consideration is deemed credible because their probability of occurrence is equal or higher to the cut-off value (1e-10/year), while combinations of more tanks that could be damaged at the same time but have a lower frequency are deemed not credible (Antonioni et al., 2009b). The calculation procedure has been used for the calculation of frequencies of domino events in literature (Antonioni et al., 2009b; Cozzani et al. 2005). In this case, the triggering effect has been considered the reference earthquake, generating a damage probability for one tank of 1.53e-02 and having a frequency of 2.11e-03/year. The results of the calculation of frequencies of each combination for the selected case study are presented in Table 42.

Table 42. Calculation of frequency of each set of combinations of tanks damaged simultaneously in case of the reference earthquake event.

Number of tanks	**Number of combinations**	**Probability of damage combination**	**Frequency of each combination (events/year)**
0	1	0.793522177	0.001674332
1	15	0.012329531	2.60153E-05
2	105	0.000191573	4.04219E-07
3	455	2.97661E-06	6.28064E-09
4	1365	4.62497E-08	9.75869E-11
5	3003	7.18615E-10	1.51628E-12
6	5005	1.11657E-11	2.35595E-14
7	6435	1.73489E-13	3.66061E-16
8	6435	2.69562E-15	5.68776E-18
9	5005	4.18838E-17	8.83749E-20
10	3003	6.5078E-19	1.37315E-21
11	1365	1.01116E-20	2.13356E-23
12	455	1.57112E-22	3.31506E-25
13	105	2.44116E-24	5.15085E-27
14	15	3.79301E-26	8.00325E-29
15	1	5.89348E-28	1.24352E-30

A cut-off value for the frequency of each combination was set to 1e-10/year in order to determine the relevant (credible) number of tanks to be damaged at the same time during the reference earthquake. As such, from Table 42 one can note that the highest value for the frequency of each combination that is below the cut-off value was 6.28e-09, corresponding to 3 tanks being damaged simultaneously. Therefore, combinations of 0, 1, 2 or 3 tanks to be damaged simultaneously are credible and are reasonable to assume possible in case of the reference earthquake occurring. This translates to a number of up to 455 combinations for 3 tanks damaged simultaneously, 105 for 2 tanks damaged simultaneously, 15 results for 1 of each of the 15 tanks selected and of course 1 result in which none of the tanks are damaged by the reference earthquake.

From the technological and NaTech risk analysis performed for the selected tanks, one can conclude that pool fire in bund scenarios contribute mostly to the overall risk level of the site. While considering pool fires in bund due to technological accidents alone one can conclude that the individual and societal risk level are considered somewhat acceptable, when adding the NaTech scenarios to the risk analysis, for the selected tank farm, this situation can change significantly, increasing the individual and societal risk level by one order of magnitude.

The calculation of the frequency of each number of combinations of tanks susceptible to be damaged simultaneously in a reference earthquake revealed that a number of up to three tanks damaged simultaneously has a relevant frequency. The societal risk calculation with the F-N curve generated separately for each top event revealed the contribution of each scenario to the overall societal risk, thus making it possible to conclude that the fire in bund due to the catastrophic rupture due to the earthquake for tanks and A8, A9, A7 account for more than 70% of the overall societal risk.

Conclusively, instead of issuing a general recommendation for the reduction of the effects or likelihood of pool fires in the bund for the site owner, conclusion which could have been based on the preliminary analysis, specific suggestions of especially targeting risk reduction measure to tanks A8, A9 and A7 and improving their seismic performance could yield the highest benefits in terms of reducing the overall risk level of the site. Such conclusions could only be drawn on an informed basis after the detailed assessment has been carried on. On the other hand, performing risk-based detailed assessments for all accident scenarios that were elaborated for the site would have implied the use of unjustified time and resources for information that would have not contributed significantly to the end result.

Chapter 4. Final conclusions, personal contribution and future development

4.1. Final conclusions

The main objective of the thesis was to develop and implement a systematic risk assessment methodology for industrial sites that takes into consideration technological causes as well as natural hazards as possible causes for industrial accidents affecting the oil and gas sector of critical infrastructure. NaTech events are generating a growing interest in the scientific community and among stakeholders, as these accidents have significant negative consequences on human health, the environment and the economy. The increase in the number of such events is closely linked with the exponential technological development of the past decades, the increase in the scale of these sites and the number of substances used in technological processes.

The concept of Critical Infrastructure has also gained widespread attention in recent years, emphasizing the need to properly identify the elements and systems that are considered critical infrastructure, in order to take significant actions for their protection. Protection measures should be targeted where they are most needed and where they yield the greatest benefits for the resources deployed, making it necessary to have an analysis of the hazards and threats towards the critical infrastructure elements.

Global trends have proven that the number of natural disasters have registered a significant increase worldwide in the last decades. Even though communities have developed a certain degree of resilience in some parts of the world to natural disasters in terms of number of deaths decreasing, the number of people affected in various ways by natural disasters has increased.

An increase has been registered also in the case of technological disasters, as well as their negative consequences. Given the increasing tendency in the number of natural hazards and the population growth in urban areas where the majority of technological installations are located, there is an increasing awareness for the need of disaster risk reduction and prevention actions for NaTech events. NaTech risk assessments for technological installations and implementation of adequate measures for disaster risk reduction are important aspects of NaTech risk management.

The risk assessment process however can imply various extents in terms of time and resources needed, depending on the complexity of the industrial site, regulatory requirements, methods and techniques used and other factors. The systematic risk assessment methodology for the oil and gas subsectors of critical infrastructure elaborated and described in Chapter 2 of this thesis proposes a three-step approach, from preliminary assessment, through a criterial analysis step, onto the detailed assessment. This ensures a thorough hazard analysis and risk assessment process for industrial sites pertaining to this sector, channeling the efforts of the detailed assessments to the scenarios that contribute significantly to the overall risk level of the site, without compromising the relevancy of conclusions of the risk assessment.

The systematic risk assessment methodology for the oil and gas subsector has been applied on a case study pertaining to this section of critical infrastructure. The aim was to emphasize the importance of taking into consideration natural hazards as well as technological causes in the risk assessment process for these kinds of facilities. The site consists of a tank farm located in the most active seismic region of Romania, the Vrancea area. The methodology was followed step by step for the selected case study.

The preliminary assessment for the selected case study included the general information regarding the site and residential area location, site history, estimated population data, geology, its tectonic structure and seismic activity in the area. The site is located in a region known for its seismic activity. Scientific literature that was analyzed revealed that the PGA for the site can reach values up to $3.5 m/s^2$ for earthquakes with an intensity of approximately 8.5 MSK. National legislation and classification criteria regarding civil protection also classify the site as being located in a seismic risk area. It was considered that a value of $3 m/s^2$ (corresponding to 0.306g) for the PGA is reasonable to consider for a reference seismic event with a recurrence period of 475 years for the location of the site.

The characterization of the site from a climatic point of view was also completed, as this information is also a necessary input data for the software tools used in the detailed assessment. Two time periods ("seasons") were considered: spring-summer and autumn-winter, and two Pasquil stability classes for each season: very stable (F+G) and neutral (D), with reference wind speeds of 1m/s and 4m/s. Extensive processing of hourly weather data for one year for Ploiesti city has been performed in order to compile the reference meteorological data used in simulations. The results are consistent with multiannual average wind speeds and directions for the area of the site.

The preliminary analysis also included the description of the installation, the layout of tanks in their respective bunds and the main characteristics of the tanks and bunds. Of the entire tank farm of the refinery, 15 tanks were selected due to the fact that they are located closer to the residential area at the southern border of the tank farm. A description of general bund regulations and requirements regarding characteristics, building material, capacity and other parameters was performed. The description of the hazardous substances stored in the selected tanks was completed in the preliminary analysis stage. Substances stored in the selected tanks are xylene, n-hexane, n-hexadecane and liquid fuel oil. As liquid fuel oil is a general name for a series of hydrocarbons, the substance used in the modeling tools for liquid fuel oil is n-undecane. For each of the substances the main physical, chemical and toxicological characteristics and behavior were described.

NaTech accidents can be triggered by earthquakes, floods, landslides, extreme weather conditions, etc. and it is thus important to take notice of the natural hazards that are susceptible to occur in the area of the site. The natural hazards are most of the time strongly dependent on local conditions. For the site taken into consideration in the case study, earthquakes cause the most concern in terms of natural hazards with a potential to cause major accidents.

The description of typical accident scenarios for the tank farm and a summary of several typical accidents that occurred on similar sites, based on scientific literature and accident databases research was also completed in the preliminary assessment stage. The typical accidents scenarios for hydrocarbon storage tank farms include releases of hazardous substances, fires and explosions. Fire, explosions and fragment projections from explosions can trigger domino effects, creating "chain" major accidents with extended consequences. There are no neighboring industrial facilities to the selected sites and so domino effects as defined by the Seveso directives are of no concern, but internal domino effects (or accident escalations) are possible. This is confirmed in the detailed analysis of the site.

The description of possible major accident scenarios on the selected site consisted of seven scenarios:

a. petroleum products releases/leaks from pipelines/pumps;

b. petroleum products releases from tanks;

c. fire from leak outside tank bund;

d. fire inside tank;

e. fire-leaked substances in bund;

f. explosion or flash fire (outside tank);

g. tank explosion.

For each of the seven scenarios, the causes, possible effects and potential to generate major accidents were described. The scenarios were then analyzed in the hazard analysis using a 5x5 risk matrix, with grades assigned for the estimate of likelihood and magnitude of consequences. This is a qualitative analysis meant to give a first glance at the risk of the site. The risk levels resulted from the hazard analysis range from moderate to high risk.

After the preliminary analysis of the accident scenarios for the site, they were subjected to the criterial analysis. All scenarios have the potential to generate major accidents due to the nature of the substances stored in the tanks. Also, they all have the potential to generate fires or explosions. As such, none of the scenarios were analyzed using the Environmental Accident Index methodology. The risk and consequence criterion made the separation between scenarios requiring further (detailed) analysis and the ones that did not. Three scenarios resulted as needing a detailed assessment: explosion or flash fire outside tank and tank explosion (based on their possible consequences) and fire-leaked substances in bund (based on catastrophic consequence and high risk level).

The scenarios that resulted from the criterial analysis as requiring detailed assessment were analyzed using advanced modeling software: EFFECTS for the determination of consequences and ARIPAR for the calculation of individual and societal risk. The risk assessment for technological accidents used reference threshold for thermal radiation and overpressure selected from Romanian regulations and guidelines. The consequence analysis was completed for the fire in bund scenarios, for two wind speeds: 1m/s and 4m/s and for each substance present in the bund, taking into consideration the quantity in the largest tank in the bund. The results of heat radiation versus distance and heat radiation versus crosswind distance were displayed for each bund and the contours for three thermal radiation thresholds (2.5 kW/m^2, 5 kW/m^2 and 12.5kW/m^2) were plotted on geo-referenced maps for each bund.

Results from the consequence based analysis for fire in bund scenarios revealed that the contour corresponding 5Kw/m^2 heat radiation level (the area with health effects) reaches the inhabited area in most analyzed scenarios and as such the individual and societal risk was calculated using ARIPAR software. The lower limit for LUP purposes for individual risk (10^{-6} y^{-1}) has reached the limit of the residential area in all scenarios, except for the scenario involving the fire in the bund of tanks A13-A15 (these tanks are located further away from the residential area). In the case of the fire in bund of tanks A7-A10, also the upper limit (10^{-5} y^{-1}) contour of the individual risk has reached the residential area limit. Societal risk calculation showed that when all fire in bund scenarios due to intrinsic causes are taken together the F-N curve reaches the ALARA limit slightly. The F-N diagram with separate curves for each top event revealed that only 8 top events generate societal risk curves above the cut-off value and that the contribution of fire in bund scenarios for tanks A8, A7 and A9 account for more than 80% of the total societal risk level of the site.

Explosion or flash fire outside tank scenarios were also analyzed in detailed using EFFECTS software. The simulation of VCE for the selected tanks showed no results, for any of the substances stored in tanks. For flash fires simulation, the bunds of tanks A1 – A2 and A3 – A4 were selected. In case of tanks A1 and A2 (xylene) the threshold concentration (LEL) was not reached and neither was 0.5LEL, in any of the meteorological conditions. For tanks A3 and A4 (n-hexane), the only 0.5 LEL was reached (corresponding to irreversible effects on health), for unfavorable meteorological conditions, reaching a maximum distance of 120.42m. Given that the LEL concentration threshold was not reached in any of the cases, it is considered that there is no death probability from flash fire in any of the cases, and as such the calculation of individual and societal risk was not considered necessary in this case.

The simulation of tank explosion (VCE) has also been performed for each of the selected tanks, for five overpressure threshold values. The 300mbar overpressure threshold level corresponding to the high mortality area has not been reached in any of the cases. As such, the individual and societal risk calculations were not necessary to be performed. For most tanks the 140mbar domino effect contours reach nearby tanks, revealing the fact that safety distances are not respected in the layout of the tanks farm.

For the NaTech risk analysis of the fire in bund scenarios, the damage probability for one tank in case of the reference seismic event occurring was calculated using probit functions, with the values for the probit constants selected from scientific literature in the field for the types of tanks and filling levels specific to the site selected for the case study. Results for total risk (including technological and NaTech causes for accident scenarios) were displayed for each bund. The individual risk and societal risk for total risk calculations were made using ARIPAR 4.0. The 10^{-6} y^{-1} lower acceptability limit for individual risk for LUP purposes, as well as the 10^{-5} y^{-1} upper limit have reached the residential area in all cases, except for the tanks A13 –A15. This means that the individual risk due to both intrinsic and NaTech causes, has reached the unacceptable threshold in these cases. Societal risk calculation for total risk (including NaTech) revealed that the F-N curve for all tanks is situated in the ALARA interval, while the F-N curves calculated separately for each top event revealed that pool fire in bund due to seismic causes in tanks A8, A9 and A7 account for more than 70% of the overall risk level due to intrinsic and NaTech causes. The ranking of societal risk contribution by top event presents an important advantage: it shows where risk reduction measures would yield the highest benefits in terms of reducing the overall societal risk level of the site.

Assessing the difference between the level of individual and societal risk due to intrinsic causes and due to NaTech causes can emphasize the importance of taking natural hazards into consideration as causes for accidents when performing risk assessments for industrial sites. Side by side comparisons of individual and societal risk for the site considering only intrinsic causes and then including NaTech scenarios in the risk analysis showed an increase in one order of magnitude when the NaTech scenario was included, and the threshold limits for unacceptable risk were exceeded for LUP purposes in the residential area, while the societal risk level has reached the ALARA interval, suggesting that risk reduction measures should be implemented.

The side-by-side comparison between individual and societal risk with intrinsic and intrinsic +NaTech causes has been made for the total risk for the selected site. As the probability for one tank to be damaged in case of the reference earthquake differs from the probability of more tanks to be damaged in the same earthquake, a calculation of the frequency of each possible combination of tanks to be damaged simultaneously was performed, adapting a methodology used in literature for the assessment of domino events. A cut-off value of 1e-10/year for the frequency of the combinations was set in order to select the relevant number of tanks that could be damaged simultaneously in case of the reference earthquake occurring. Results showed a number of up to 3 tanks being damaged simultaneously is relevant.

The result of the calculation of the frequencies for each combination of tanks susceptible to simultaneous damage combined with the results of the consequence based risk analysis as well as the individual and societal risk calculations for the site can lead to pertinent conclusions regarding the risk reduction opportunities. As such, instead of issuing a general recommendation for the reduction of the effects or likelihood of pool fires in the bund for the site owner (based on the preliminary analysis) specific suggestions of especially targeting risk reduction measures to tanks A8, A9 and A7 and improving their seismic performance could yield the highest benefits in terms of reducing the overall risk level of the site. Such conclusions could only be drawn on an informed basis after the detailed assessment has been carried on.

4.2. Personal contribution and future development

This thesis proposes an original approach to assessing hazards and risk for industrial sites, following a systematic risk assessment methodology. Personal contributions to the present thesis are summarized below:

- Literature review of the critical infrastructure concept and definitions and synthesis of the legal framework regarding critical infrastructure in Europe and in Romania.
- Review of vulnerabilities, hazards and threats towards critical infrastructure in Romania.
- Literature and database review of natural and technological global disaster trends, NaTech accidents and challenges in NaTech risk assessment.
- Development of the Systematic Risk Assessment methodology for the oil and gas subsectors of critical infrastructure, based on the Systematic Risk Assessment Methodology elaborated for the extractive mining industry. The Systematic Risk Assessment methodology for critical infrastructure – oil and gas subsectors consists of three steps, followed by conclusions: preliminary analysis, criterial analysis and detailed analysis. The criterial analysis step consists in the application of a series of criteria that allows the selection of hazards (scenarios) that contribute significantly to the overall risk of the site and as such concentrating the efforts of the detailed analysis on these scenarios.
- Taking into consideration and assessing the potential of some scenarios to generate long term pollution of soil and groundwater when performing risk analysis, for scenarios that do not generate fires, explosions or toxic dispersion. The introduction of the Environmental Accident Index calculation in the criterial analysis step of the methodology allows the selection for detailed assessment of the scenarios that have the potential to affect the environment, while not causing immediate effects upon population.
- Application of the systematic risk assessment for critical infrastructure – oil and gas subsectors to a case study - tank farm storing hydrocarbons, located in a seismic area of Romania.
- Preliminary analysis of the case study:
    - Presentation of the environment in which the site is located: estimated population data, site history, geology, tectonic structure, seismic activity, and climate. Characterization of the site regarding the seismic potential and literature review for the establishment of PGA for a reference earthquake in the area.
    - Description of the installation and substances stored in the tank farm.
    - Identification of natural hazards in the area of the case study.
    - Description of typical accident scenarios for this type of installation and review of several accidents that occurred in similar sites, due to intrinsic (technological) causes and NaTech events.
    - Description of possible accident scenarios on the selected site.
    - Hazard analysis for the accident scenarios on the selected site using risk matrices.
- Criterial analysis of the accident scenarios elaborated for the case study and selection of scenarios that will undergo detailed analysis
- Detailed analysis of the selected scenarios, using advanced modeling software: EFFECTS and ARIPAR 4.0.

- Risk assessment for technological accidents using consequence based methods and risk based methods (individual and societal risk) for pool fire scenarios.
- Risk assessment for technological accidents using consequence based methods for flash fire and vapor cloud explosions
- NaTech risk analysis for pool fire in bund scenarios: estimation of damage probability in case of the reference earthquake occurring for one tank and individual and societal risk calculations using ARIPAR 4.0 software.
- Comparison of individual and societal risk for the site for intrinsic causes versus total individual and societal risk including intrinsic and NaTech causes.
- Determination of the contribution of each top event to the overall societal risk level of the site for intrinsic causes and adding the natural hazards (in this case earthquake) as causes for the LOC events. This allows for the decision makers to have pertinent conclusions as where the risk reduction measures are most necessary and where they would be most effective in reducing the societal risk level of the site.
- Description of protection measures in installation
- Calculation of frequencies of sets of combinations of tanks damaged simultaneously in case of the reference earthquake occurrence and determination of relevant number of tanks that could be damaged simultaneously in case of the reference earthquake.

➢ Interpretation of results of technological and NaTech risk assessment for the selected case studies and discussion

To our knowledge individual and societal risk studies have never been developed for the selected case study and NaTech events have not been considered in the previously elaborated risk analyses for the site from a quantitative point of view. Including the NaTech events in the risk assessment proved to increase the overall individual and societal risk of the site by approximately one order of magnitude. This is especially important for the selected site, since a residential area is located in the immediate vicinity of the tank farm. The risk analysis revealed that unacceptable contours for land use planning purposes for the individual risk overlap on the residential area when Natech risk is of concern.

Future developments concern the systematic risk assessment methodology on one side and the case study on another.

The systematic risk assessment methodology elaborated in the present thesis for the oil and gas subsectors of critical infrastructure can be modified and future developed to fit other sectors and subsectors of critical infrastructure. The methodology has been initially elaborated for the extractive mining industry. While the principles of the methodology can stay the same, criteria and detailed analysis methodologies can be modified according to needs, depending on the field it is applied to. Also, an application of the methodology developed in the thesis to other case studies in this field could yield to an improvement of the criteria and terminology, making it easier to apply and clarifying any uncertainties that users may have.

The systematic risk assessment methodology developed in the present thesis for the oil and gas subsectors of critical infrastructure could be a useful tool for environmental authorities, consultants and owners/administrators of facilities in the oil and gas industries in developing risk assessment studies and reports, as it allows for a thorough analysis of an industrial site while directing resources on the scenarios which contribute most to the overall risk level of the site.

Regarding the case study, future developments should seek an accurate and up to date collection of data regarding the site, in terms of actual population data and specifics of the installations, and working the updated information into the input data for the risk analysis. As a formal agreement with site owner was not possible to establish in due time for the completion of this thesis, the data used in the present paper is either public data or estimated based on satellite images.

The consequence based risk assessment for the tank explosion scenario revealed that for most tanks the 140mbar domino effect contours reach nearby tanks. As such, an in-depth analysis of the domino effect is recommended and the subsequent implementation of mitigation measures.

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1. **Crişan (Gheorghiu), A.-D.**, 2013, Metodologie de utilizare într-o manieră sistematică a metodelor şi tehnicilor de analiză a riscului pentru amplasamentele industriale, Volum lucrări Workshop „Tendinţe şi cerinţe de interdisciplinaritate în cercetare. Prezentarea rezultatelor obţinute de doctoranzi" – in Romanian, Universitatea Tehnică "Gheorghe Asachi" din Iaşi, Editura POLITEHNIUM IAŞI, ISBN 978-973-621-408-0.

2. **Gheorghiu A.-D.**, Ozunu Al., 2013, Natech accidents and ethical decision making (Accidentele natech si etica luarii deciziilor) – in English and Romanian, Environmental Engineering and Sustainable Development Entrepreneurship (Ingineria Mediului şi Antreprenoriatul Dezvoltării Durabile), Vol. 2, No. 2-2013, 57-64.

3. Ozunu Al., Török Z., Vana Al. D., Coşara Gh. V., **Crişan A. D.**, Roman E. G., Kocsis V., Muntean L., 2011, Analiza sistematică de risc în industria minieră extractivă (Systematic risk analysis in the mining industry) – in Romanian, Revista Protecţia Civilă, nr. 1/2011, ISSN 1223-575X

4. Botezan C., **Crişan D.**, Ozunu Al., 2010, Cursul de pregătire „Reducerea Riscului de Dezastre" (Risk Reduction Training Course) – in Romanian, Revista Protecţia Civilă, nr. 4 -5/2010, ISSN 1223-575X

Participation to national and international scientific events:

1. Participation to 1 training, 4 scientific communication sessions and 2 doctoral seminaries for the dissemination of results, project „STUDII DOCTORALE PENTRU PERFORMANŢE EUROPENE ÎN CERCETARE ŞI INOVARE (CUANTUMDOC)" ID 79407, organized throughout three years of Ph.D. studies, (October 2010 – September 2013) in the Faculty of Environmental Science and Engineering, Romania, Cluj-Napoca.
2. Participation and presentation at international conference U.A.B. – B.EN.A., „Environmental Engineering and Sustainable Development", 23 – 25 May, 2013, Alba Iulia, Romania.
3. Participation at Workshop Quantitative Risk Assessment (QRA) in the process industries, organized by CK Trikolor Kft., 6-10 May 2013, Budapest, Hungary.
4. Participation at workshop within the framework of the Integrated Nutrient Pollution Control project, „Suntem ceea ce consumăm. Apa infestată ne poate îmbolnăvi. Putem opri poluarea cu nitraţi.", organized by the Ministry of the Environment and Forest, 23-24 August 2012, Cluj-Napoca, Romania.
5. Participation at workshop „Valorificarea resurselor de energie regenerabilă şi crearea unui mediu de viaţă ecologic, în conformitate cu tendinţele actuale din ţările UE", European Commission, Enterprise Europe Network, Research Institute for Analytical Instrumentation – ICIA, Technological Transfer Center – CENTI, 11 Mai 2012, Babes-

Bolyai University, Faculty of Environmental Science and Engineering, Cluj-Napoca, Romania

6. Participation and poster presentation „Systematic risk assessment methodology for critical infrastructure elements - Oil and Gas subsectors”, authors: Augusta-Diana Gheorghiu, Alexandru Ozunu, European Geoscience Union General Assembly 2012, Copernicus Meetings, 22-27 April 2012, Vienna, Austria.
7. Participation at Environment & Progress 2011 Environment – Research, Protection and Management conference , Babes-Bolyai University, Faculty of Environmental Science and Engineering, 11 - 12 November 2011, Cluj-Napoca, Romania.
8. Participation at training course „Community Mechanism Induction Course”, organized by the Civil Protection Mechanism of the European Committee, The Firefighting Academy of Hamburg, Germany, and the Danish Emergency Management Agency (DEMA), 27 August – 2 September 2011, Hamburg, Germania.
9. Participation with poster and oral presentation „Vulnerability of critical infrastructure to natural hazards. Case study: Fire at hexane tank park damaged by earthquake”, authors: Augusta-Diana Crisan, Alexandru Ozunu, Zoltan Torok, Alexandru Vana, European Geoscience Union General Assembly 2011, organized by the European Geoscience Union, 03-08 April 2011, Vienna, Austria.
10. Participation at seminar „Analiza sistematică de risc în industria minieră extractivă” and presentation „Analiza criterială”, Organized by the Faculty of Environmental Science and Engineering, General Inspectorate for Emergency Situations, APELL National Center Foundation, 31 March 2011, Babes-Bolyai University, Cluj-Napoca, Romania
11. Participation at the 4th international workshop „Optoelectronic Techniques for Environmental Monitoring”, National Institute of R&D for Optoelectronics, 19-21 October 2010, Romania, Cluj-Napoca.
12. Participation at the international conference „Environmental Legislation, Safety Engineering and Disaster Management” (ELSEDIMA), Organized by the Faculty of Environmental Science and Engineering, Babes-Bolyai University, 21-23 October 2010, Cluj-Napoca, Romania.