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FINAL MASTER THESIS

Master in Chemical Engineering

MODELIZATION AND QUANTITATIVE RISK ANALYSIS OF NATECH ACCIDENTS INITIATED BY WILDFIRES

Report and Annexes

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Abstract

Technological accidents triggered by natural events or NaTech events are a rising threat to industrial facilities since their consequences have been typically overlooked in conventional quantitative risk analysis (QRA). Earthquakes, floods, storms, volcanic activity, etc. suppose a risk with severe consequences to chemical and industrial installations and, therefore, their effects must be addressed. In this thesis, a survey of NaTech accidents and incidents triggered by wildfires is performed in order to reflect the frequency of this type of events along with their consequences and the locations and types of installations more commonly affected. A more detailed analysis of specific accidents is carried out making use of the Bow-Tie and MTO (Humans, Technology and Organization) analysis. Besides, a model for QRA of accidents caused by wildfires is developed and applied in a case study where a comparison between the results of the recently developed model and the ones obtained through a conventional approach is performed.

Resum

Els accidents tecnològics causats per esdeveniments naturals o *NaTech events* són una amenaça creixent per a les instal·lacions industrials perquè les seves conseqüències són habitualment ignorats en les anàlisis quantitatives de riscs (ACR) convencionals. Terratrèmols, inundacions, tempestes, activitat volcànica, etc. suposen un risc amb conseqüències severes per a les plantes químiques i industrials i, per tant, els seus impactes han d'ésser estudiats.

En aquesta tesi, una recopilació d'esdeveniments NaTech provocats per incendis forestals és portada a terme per reflectir la freqüència d'aquesta mena d'esdeveniments junt amb les seves conseqüències, localitzacions i tipus d'instal·lacions més comunament afectades.

Es porta a terme una anàlisi més detallada de dos accidents concrets fent servir els mètodes Bow-Tie i MTO (Man, Technology and Organization). A més a més, es desenvolupa i aplica un model per realitzar ACRs d'accidents causats per incendis forestals, els resultats dels quals són comparats amb els obtinguts mitjançant un ACR convencional.

Resumen

Los accidentes tecnológicos causados por eventos naturales o *NaTech events* son una amenaza creciente para las instalaciones industriales debido a que sus consecuencias son comúnmente ignorados en los análisis cuantitativos de riesgos (ACR) convencionales. Terremotos, inundaciones, tormentas, actividad volcánica, etc suponen un riesgo con consecuencias severas para las plantas químicas e industriales y, por lo tanto, sus impactos han de ser estudiados.

En esta tesis, una recopilación de eventos NaTech provocados por incendios forestales es llevada a cabo para reflejar la frecuencia de este tipo de eventos junto con sus consecuencias, localizaciones y tipo de instalaciones más comúnmente afectadas.

Se lleva a cabo un análisis más detallado de dos accidentes concretos usando los métodos Bow-Tie y MTO (Man, Technology and Organization). Además, se desarrolla y aplica un modelo para realizar ACRs de accidentes causados por incendios forestales, cuyos resultados son comparados con los obtenidos mediante un ACR convencional.

Contents

Preface

Thesis origin and motivation

An increase in the number of wildfires in Europe and the rest of the world has been noticed in the last decades mainly enhanced by climate change. Wildfires, as any other natural disaster, can trigger a technological event in the industry whose consequences may be catastrophic. For this reason, different stakeholders alert of the need of developing integrated risk management approach to deal with this kind of accidents.

The European Commission Joint Research Centre (JRC) established in their 2020 report (Kern and Krausmann 2020) that researchers and scientist should work on behaviour modelling skills to offer local fire spread projections to help operators respond appropriately. Besides, academics must work on better comprehension of the interaction of industrial facilities with wildfire scenarios and also develop wildfire impact models on industry in order to ease risk assessment.

From these recommendations, projects like this one arise in order to attempt to fill the knowledge gap regarding the topic and diminish the consequences in case of a hypothetical event triggered by wildfires.

1. Introduction

In this section, an explanation of what NaTech events are is elaborated along with a classification of them based on the natural catastrophe that serves as main root cause. Besides, the importance of studying the topic of NaTech events triggered by wildfires is also mentioned below, linking it to current climate evolution and to the increase in the frequency of such phenomenon.

1.1. NaTech events

NaTech events or NaTech accidents (Technological accidents triggered by Natural events) are the secondary effects suffered by industrial facilities due to natural disasters like floods, earthquakes or wildfires (Krausmann et al, 2016) (Khakzad and Cozzani 2020).
These accidents have been forgotten or underestimated in current quantitative risks analysis, more focused on losses of containment and accidents due to initiating events occurring within the plant limits and during process operations rather than external causes like a natural event. NaTech accidents can be classified according to different criterion. Even though the industrial sector affected or the type of consequence event may be used to sort them, a more appropriate way to categorize NaTech is to group them according to the natural event category. The Centre for Research on the Epidemiology of Disasters (CRED) fixed four main natural event categories that can provoke a NaTech scenario (CRED, 2020):

- Geophysical: A hazard originating from solid earth. This term is used interchangeably with the term geological hazard.
- Meteorological: A hazard caused by short-lived, micro- to meso-scale extreme weather and atmospheric conditions that last from minutes to days.
- Hydrological: A hazard caused by the occurrence, movement, and distribution of surface and subsurface freshwater and saltwater.
- Climatological: A hazard caused by long-lived, meso-to-macro-scale atmospheric processes ranging from intra-seasonal to multi-decadal climate variability.

Making use of these categories Ricci et al. (2021) elaborated a description of the taxonomy of natural events. They examined the characteristics of each category and ended up assigning natural events to them. Thus, Table 1 shows the final aspect of the taxonomy.

Table 1 Taxonomy of the Natural Events.

Natural Event Category	Natural Event Example
Geophysical	Earthquakes, Landslides, Tsunamis, Volcanic activity
Meteorological	Storms, Extreme temperatures, Lightnings, Fogs
Hydrological	Floodings, Wave action
Climatological	Wildfires

Even though natural events are less considered than typical in-site technological events, the NaTech that they trigger may be more frequent than a standard basic event (tank loss of containment, pipe leak or full-bore rupture, etc.) as long as the plant is based in a region prone to a given natural disaster. Table 2 compares the frequencies of the standard initiating events (Guidelines for quantitative risk assessment, 2005) in industry with the frequency of earthquakes and major hurricanes in different areas of the US.

Table 2. Frequencies of natural and technological events.

Technological / NaTech accident	Frequency (year^{-1})
Instantaneous Release of an Atmospheric Tank	$5{\cdot}10^{-6} – 1{\cdot}10^{-8}$
Instantaneous Release of a Pressure Vessel	$5{\cdot}10^{-7}$
Pipe Full-Bore Rupture	$1{\cdot}10^{-6} – 1{\cdot}10^{-7}$
Pipe Leak through a hole	$5{\cdot}10^{-6} – 5{\cdot}10^{-7}$
Pump Catastrophic Failure	$1{\cdot}10^{-5} – 1{\cdot}10^{-4}$
Major Hurricane in the South Cost of the US	$2{\cdot}10^{-2}$
Earthquake over 5.5 magnitude in California (CA gov, 2019)	2 - 3

Thus, accidents caused by the effects of a natural event must be accounted in QRAs when aiming to carry out a comprehensive analysis of the risks present in industrial installations. High periodicity of these kind of natural disasters are already taken into account when designing and building installations sited in areas affected by them, so the high probability of natural event is mitigated with proper design and planning. However, wildfires are actually not really considered in early stages of industrial projects when evaluating possible hazards in QRAs yet.

1.2. Future perspectives

More frequent and more severe Natech events are projected as the frequency of some extreme natural phenomena increases, owing mostly to climate change. Moreover, the susceptibility of their impact increases, responding primarily to population development and the expansion of industrial facilities. When the implications of such incidents are an issue, the susceptibility and interdependence

of Industrial – Urban interfaces can lead to catastrophic cascading disasters, intensifying both the early and long impacts on human health and safety, business, the economy, and the ecosystem and environment (Khakzad, Cozzani 2020).

Regarding the issue of this project, wildfires are one of the natural phenomena that may create accidents with serious consequences. Fire seasons are beginning to start earlier and ending later as a result of climate change, with an accompanying trend towards more intense wildfire occurrences in terms of geographic range and length, intensity, severity, suppression costs, and loss of life and property (Bowman et al. 2017).

The frequency of wildfires has grown, not only as a consequence of climate change, as forests and wild area are being more exploited nowadays Figure 1 shows the increase of the yearly burned area[1] in the US**.** Human activities are responsible for more than 90% of wildfires in Mediterranean nations (Khakzad 2019). Aside from the involvement of humans in triggering wildfires, rising development in urban and industrial regions has expanded the wildland-human interface, exposing assets to a higher risk of harm in the case of a wildfire.

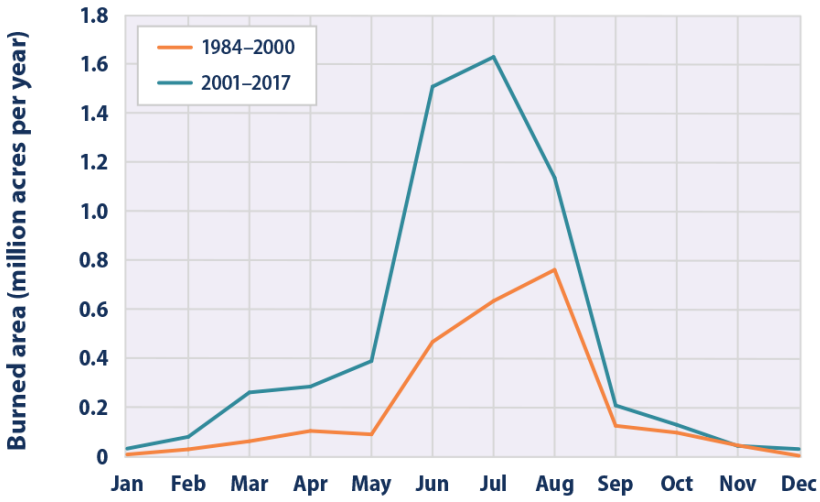

Figure 1. Monthly burned area due to wildfires in the us between 1984–2000 and 2001–2017 (US EPA, 2019).

[1] 1 acre = 0,405 Ha

Similarly, the evolution of the burnt area in the Mediterranean Europe is represented in Figure 2.

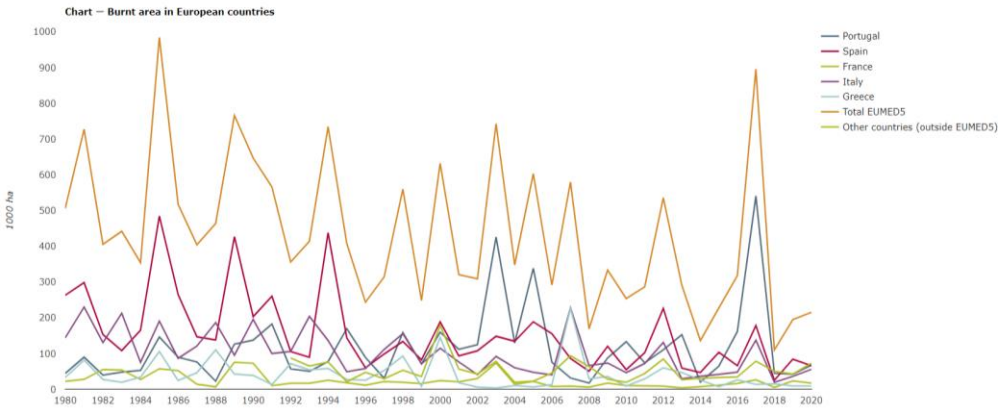

Figure 2. Yearly burnt area in Mediterranean EU countries (EFFIS, JRC, 2020)

2. Analysis of risk notions

This section provides an insight on how wildfires can affect industrial installations. A theoretical basis of how wildfires evolve and how their heat and smoke reach the facilities is exposed followed by a summary of a recent case study of wildfire impact on industrial facilities (Almeida, 2019). Next, a series of different events around the world is collected in order to extract possible tendencies regarding involved installations.

2.1 Wildfire impact on industry

Forest fires, whether caused by natural or human sources, have detrimental and catastrophic effects on people, environment and assets either directly or indirectly. Because of the ever-increasing concentration of people and industrial regions in wildlands, they have a major impact on the environment and the people who live there. Despite the fact that forest fires are an inextricable feature of these ecosystems, their disregard can result in considerable economic and environmental harm. Forest fires now affect a huge portion of the world's forests, putting unique species in jeopardy and burning thousands of hectares of vegetation and human installations such as housing, warehouses, etc (Naderpour et al. 2019).

It is remarkable that wildfires have unique characteristics when compared to normal accidental fires that occur in industrial settings. Barrows (1951) developed a report on fire behaviour in forests in which he presented the fire triangle shown in Figure 3.

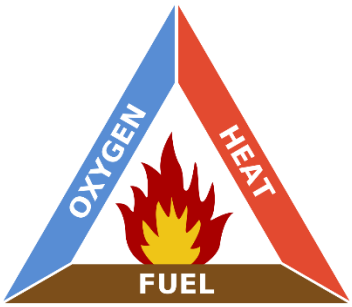

Figure 3. Fire Triangle.

Barrows (1951) stated that heat, oxygen, and fuel must all be present in the appropriate proportions for ignition and combustion to occur. In order for ignition to take place, a source of heat is required so the temperature is increased over the flash point of the substance. Moreover, if there is no fuel to burn, a fire cannot start. Lastly, an oxidizing agent is required in order to react with the combustible material that serves as fuel (Fire Action, 2017). A fourth element is typically added creating the fire tetrahedron. Chemical chain reaction is added to the previous three-element explanation.

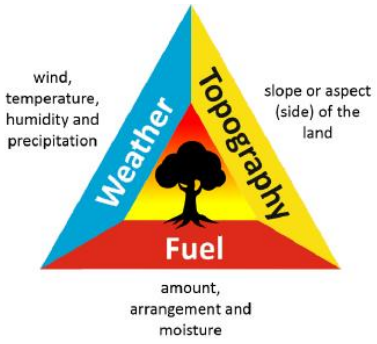

Figure 4. Wildfire triangle (Kern and Krausmann 2020).

The same concept is applied with the aim of building an analogue triangle which describes the conditions of wildfires (Figure 4). Fuel remains common for both while the weather and the topography are introduced now. Wildfire propagation is exacerbated by increasing wind speeds and uphill slopes. Regional factors, such as small canyons or valleys, may contribute to more intense fires or extreme fire behaviour. On the other hand, different kinds of vegetation acting as fuel lead to different fires in terms of flame intensity, combustion, etc. (Kern and Krausmann 2020). Thus, fire regime can also be changed if the fuel or vegetation situation changes, so proper forest management is especially important for wildfire safety in locations where forests are used commercially. Wildfire evolution is characterized by two feedback loops between fire and control parameters (Moritz et al. 2005). Figure 5 shows how wildfire evolves from immediate effects to long term changes: fire regime of a given location can be changed after decades due to action of wildfires in the area, which in its turn affects the probability of ignition and intensity of future wildfires. Consequently, proper land management policies which maintain good vegetation conditions are key in order to avoid hypothetical future fires.

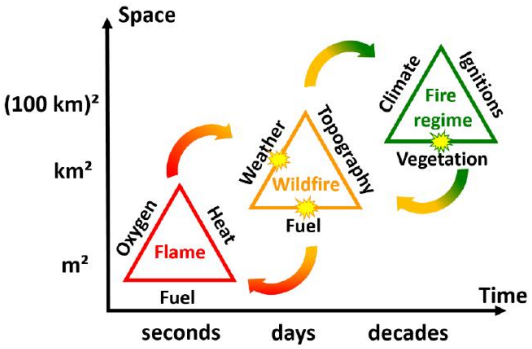

Figure 5. Controls on fire at different scales (Moritz et al. 2005).

In order to analyse the consequences of wildfires in industrial facilities, the different interface concepts must be introduced. Even though there is no total consensus on the definition, Wildland-Urban Interface (WUI) is defined as the area where homes or other structures are in or near wildland vegetation and therefore wildfires entail the higher risks regarding high probability of people affected and difficulty to fight against fire (Radeloff et al. 2018). Besides that, areas where industrial values meet

with or are dispersed within wildland vegetation will be referred to as Wildland-Industrial Interface (WII) (Johnston and Flannigan 2018).

Those interfaces are areas in which wildfire risks are remarkable, especially in chemical facilities that have a large inventory of toxic or flammable substances. Wildfires may cause direct and indirect effects on industrial sites. Smoke, flames, heat radiation, and spot fire ignition by firebrands are all direct impacts of wildfires. Instead, indirect consequences are linked to the fire's direct effects, however they do not directly affect plant infrastructure. Such occurrences could be linked to corporate operations, supply chains, disaster preparedness, or other plant-related activities. Examples include power outages, product supply disruptions, and a crew that is unavailable due to an emergency evacuation.

Regarding direct effects, there are three main ignition routes (Figure 6): direct flame contact, firebrands and radiant heat (Pastor 2020). Most installations were designed taking into account possible fires taking place in it and resultant safety measures were applied. However, heat released by wildfires comes from kilometre-wide fire fronts which may lead to completely surrounded equipment, causing a possible non-considered threat. Ignition provoked by heat radiation can take place even at 30 m distance between the object and the flame (FEMA, 2020), enabling the fire to jump between wide, empty spaces with the risk that this entails. Heat is emitted as an electromagnetic radiation of the infrared spectrum, which makes it able to being absorbed by flammable objectives (Mitchell, 2018). It is governed by the following expression:

$$\frac{d\dot{q}}{dA_1A_2} = \in \sigma T^4 \frac{cos\theta_1 cos\theta_2}{\pi r^2} \quad (1)$$

Where $\frac{d\dot{q}}{dA_1A_2}$ is the heat flux from an infinitesimal radiator (1) incident on an infinitesimal absorber (2), $\in$ is the emissivity, σ is the Stefan-Boltzman constant, T is the temperature of the radiator and r is the distance. Besides, θ_1 and θ_2 are the angles between the absorber and the normal angle of the radiating surface (θ_1) and the angle of the absorber with the incoming radiation (θ_2). For wildfires, the radiator is represented as a vertical flame front while the absorber is represented as a vertical target.

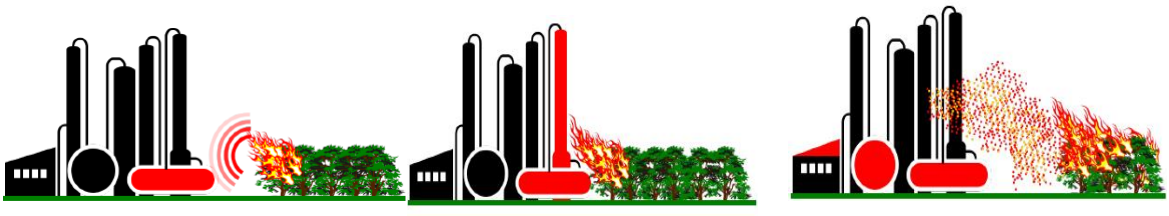

Figure 6. Different ignition routes: radiation, direct contact and firebrands (Kern and Krausmann 2020).

Direct flame contact or flame impingement occurs when the fire is close enough to directly touch the affected material or structure. This ignition pathway is the most dangerous since it presents turbulent flames with variations in the geometry and temperature. Also, due to the proximity

between the flame and the affected surface, heat is transferred to the surface in a highly efficient way by convection (flame and hot gases) and radiation. While radiation is governed by flame composition, flame thickness and temperature, convection depends on temperature difference between flame and the object, flow configuration and the shape of the exposed surface.

Even though flame engulfment and heat radiation are the most obvious dangers related to fires, firebrands must be also taken into account. Firebrands are burning particles generated in fires that are able to start new fires in a phenomenon called spotting (Babrauskas, 2018). In order to being able to generate new fires, particles must be ignited and must not be completely burnt before landing into the fuel so it has heat of combustion. Among all the possible firebrands' sources, it is remarkable that particles coming out of vegetation from the family of eucalyptus are the ones that are able to fly largest distances. Spotting distances near 10 km are common and even 30 km have been recorded.

Not only flames and firebrands can cause effects. Smoke and high temperatures can also be a factor that causes danger during wildfires. Smoke is a complex mixture of gases and particles emitted by the combustion of natural or man-made substances that may cause acute or chronic health effects (Reisen, 2019). Smoke from a nearby fire can be transported locally, resulting in poor air quality near the ground. Due to inversions, smoke can become trapped near the ground and stay there for a long time (Shotorban, 2018). This phenomenon is represented in Figure 7. Atmospheric stability is the tendency of the atmosphere to enable (instability) or to prevent (stability) the vertical displacement of air originated by mechanical causes (such as the wind). It is a function of the temperature profile and when sufficiently stable conditions are achieved; inversions can take place.

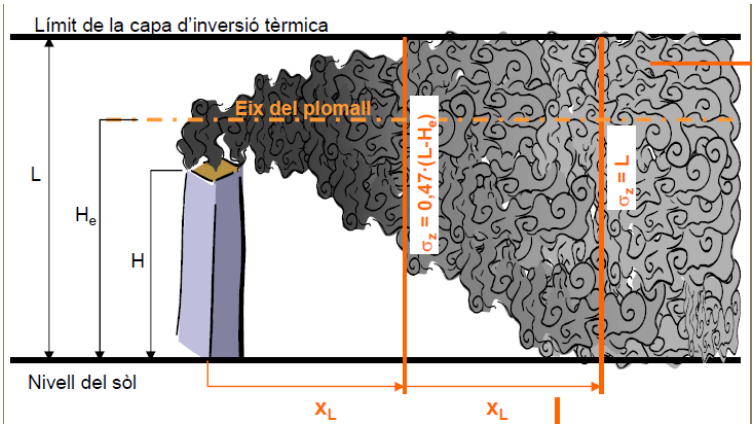

Figure 7. Inversion layer that maintains the smoke near the ground.

2.1.1 Critical equipment

There are certain units which are especially susceptible to be exposed to wildfires. Equipment or structures may be highly affected by wildfires if they present a certain design, construction material, etc which makes them either more prone to be ignited or to suffer more severe consequences once

ignited**.** Wildfires effects on structures with openings or made of easily ignited construction materials, equipment under explosive atmospheres and tanks with openings or with venting systems are studied in this section.

Vulnerable to firebrands

As it was stated in previous paragraphs, firebrands are small burning particles capable of flying distances over 10 km and therefore ignite structures far from the fire. The clearest example of a unit vulnerable to firebrands is the open floating roof tank.

Floating roof tanks are containers whose roof is made of a metallic layer that lays directly on the liquid (Figure 8). Contrary to the fixed roof tanks, floating roof tanks are suitable to store flammable liquids with low boiling points since the roof is floating over the liquid stored, avoiding the vapour formation.

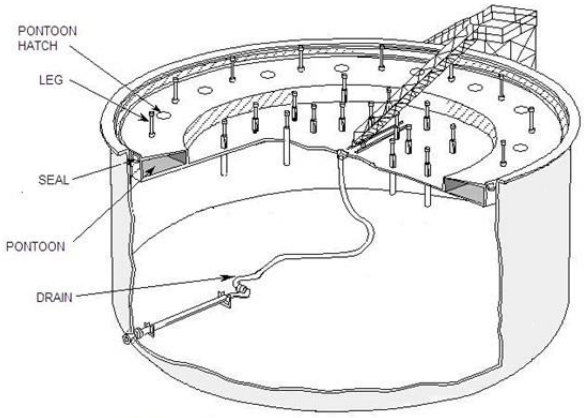

Figure 8. Open floating roof tank (HSE, 2014).

Despite being recommended to store oil, gasoline etc, open floating roof tanks lack of robustness against climatological effects because of being uncovered against rain, snow, and of course wildfire effects, either nearby heat radiation or direct contact or firebrands. Apart from obvious causes of accidents related to functioning and operation (sparks from welding, overfilling, leaking etc), ignition due to the effects of a natural disaster like earthquakes or wildfires or climatological phenomenon such lightings are responsible for more than 95% of the events recorded (Lastfire, 2012). Lightning affects not only directly causing a fire in the rim of the tank but also acting as ignition source to the flammable vapours emitted by the venting of fixed roof tanks (Sharma et al., 2018). Regarding earthquakes, a fixed

roof tank got on fire in 1964 in Japan[1] due to an earthquake which caused the collision of the tank roof with the side wall and, consequently, sparks that acted as ignition source. Figure 9 shows different types of fires that can take place in this type of unit.

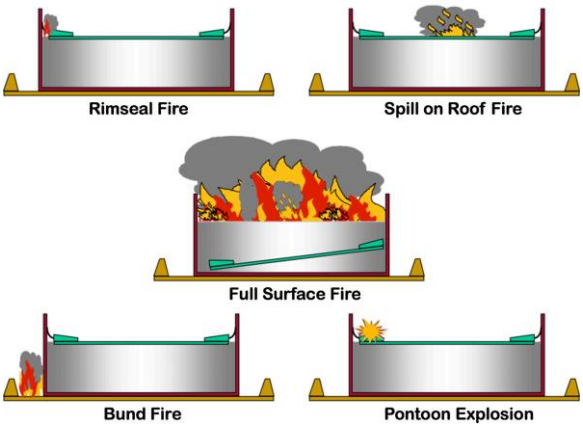

Figure 9. Types of fire in open roof tanks (Moshashaei et al., 2017).

Vulnerable due to construction material

Most of the equipment, conductions, instrumentation, etc are made of different varieties of steel and other metals, and therefore made of non-combustible materials. However, polymers are also a relevant construction material acting as coat and steel substitute in pipelines in sensitive to corrosion applications. Plastic materials are preferred in economic terms since they are lighter and easier to produce than conventional construction materials and they do not need secondary treatments to resist the actions of chemicals like the ones carried out in metals (AIP Precision, 2019). In the same vein, as it was mentioned above, plastics are inherently resistant to corrosion and they are thermal and electrical insulators, while metals do not present these properties. Thus, pipelines and other equipment may be substituted and made of polymers instead of metals (Figure 10) despite they might cause a threat related to fire security due to being flammable materials, in opposition to metals.

[1] Case Details: Fire of Petroleum Tank, etc. by Niigata Earthquake. (n.d.). Retrieved May 19, 2022, from http://www.shippai.org/fkd/en/cfen/CB1012035.html

Figure 10. PVC flexible pipe[1].

Storage of heat sensitive substances

Heat sensitive substances can be defined as substances which may lead to hazardous scenarios when temperature conditions cannot be guaranteed (Misuri and Cozzani, 2021). Wildfires may origin environments with elevated temperatures that, even though there is no flame or ignition source, an accident could take place if there is any leak or spill happen. The maximum storage temperature is a concept introduced to describe the temperature at which above it, a product is decomposed and product loss arises. Besides, the Self-Accelerating Decomposition Temperature (SADT) is the temperature above which the decomposition rate increases rapidly, producing heat and making temperature rising further (Figure 11).

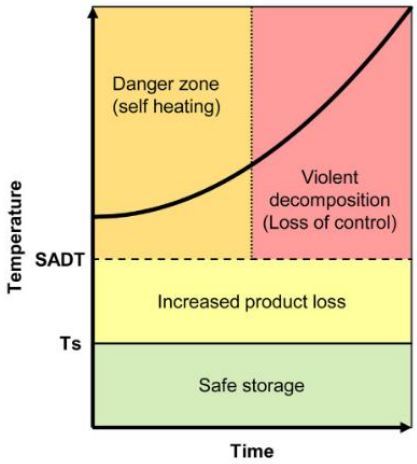

Figure 11. Thermal sensitivity diagram (Misuri and Cozzani, 2021).

Heat sensitive substances are classified using the H phrases of the GHS, giving Table 3.

[1] Flexible PVC pipe: https://races-shop.com/heat-shields/59567-flexible-pipe-pvc-60mm.html

Table 3. Heat sensitive substances classification.

Hazard statement	Hazard code (GHS)
Self-heating; may catch fire	H251
Self-heating in large quantities; may catch fire	H252
Heating may cause an explosion	H240
Heating may cause a fire or explosion	H241
Heating may cause a fire	H242
Risk of explosion if heated under confinement	EUH044
May react explosively even in the absence of air	H230
May react explosively even in absence of air at elevated temperature and/or pressure	H231

Moreover, it is typical that this kind of substances is stored connected to a refrigeration system and therefore heat sensitive substances are doubly vulnerable: vulnerable to direct effects, i.e the fire affects it through one of the routes mentioned in previous section, and vulnerable to the indirect effects of a wildfire like a hypothetical power shutdown provoked by the fire that disables the refrigeration system and accelerates the decomposition of the substance.

Explosive atmospheres

An explosive atmosphere is defined as a mixture of air and hazardous substances in form of vapour, gas, dust, etc in which combustion is spread easily to the entire mixture if an ignition takes place (INSST, 2021). Certain industrials sectors in which fine organic dust is generated during normal activities are especially vulnerable to present explosive atmospheres. Vehicle factories in which the vehicles are painted with sprays, industries working with wood and above all food industry working with flour or sugar must be very careful regarding the existence of an explosive atmosphere and how to prevent it.

Typical ignition sources are sparks mechanically generated by friction between two materials, surfaces that become hot enough to act as ignitors and flames and hot gases (European Standards, 2011). The last ones are consequences of fires and therefore must be included in QRAs regarding fire safety. Not only fires generated within the plant can cause explosions under explosive atmospheric conditions, since NaTech events such as lightning or wildfires are also relevant initiators and must be considered. So, installation under this issue must count on firefighting systems that are designed so the explosion is prevented or, if avoiding the blast was not possible, to keep working after the explosion took place.

Venting equipment

Floating roof tanks were described earlier in this section. On the other hand, fixed roof tanks (Figure 12) are also common in industrial facilities due to being less expensive and simpler and present certain features due to the way they work. While floating roof tanks avoid or reduce vaporization of the liquid they store, in fixed roof tanks vapor generation in the space between the liquid level and the roof is more likely. In order to control the level of the tank and the vapor, venting systems must be installed in these tanks, leading to a potential hazard if an ignition source is present.

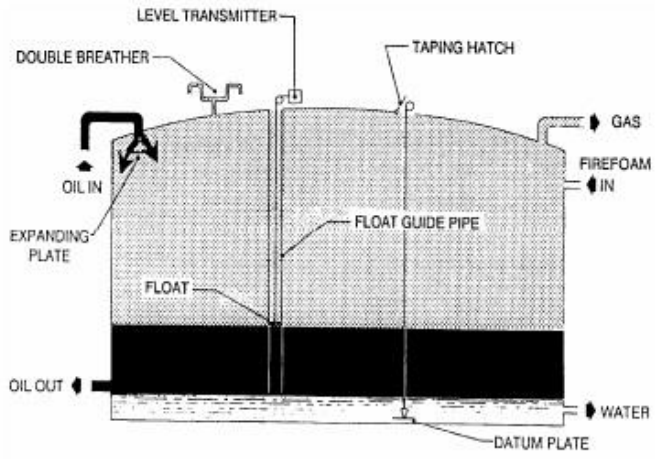

Figure 12 . Fixed roof tank (AONG, 2022)

Accidents like the one that took place in Rouseville, USA in 1995 manifest the dangers of this kind of units entail. Sparks generated during welding operation ignited the vapours at the opening of the tank, killing five workers and igniting nearby tanks (Taveau, 2011).

2.1.2 Portugal 2017 fires analysis (Almeida 2019)

Industrial installations can be affected in many different ways. Plants, buildings and equipment suffer the consequences of uncontrolled wildfires when an ignition source reaches their boundaries. The Coimbra University has conducted a report on the impacts suffered by industrial facilities during the wave of wildfires that took place in Portugal in 2017. Despite that, Ribeiro et al. 2020 concluded that just 1.4% of the total damaged structures were industrial facilities.

Tens of visits to affected industrial locations were carried out during the months following the fires. Due to the huge number of damaged sites, a selection criterion must be applied in that time. Thus, a representative set of accidents to visit was chosen attending to consequences of each fire, both human and economic. Companies interested submitted applications to the research centre stating that wanted to be part of the programme, resulting in over 150 companies interested from which would

result the final 140 visits performed, even though some visits were carried out to companies that did not apply by themselves.

A review of the events was developed after carrying out all the visits programmed. In the mentioned review, factors like company sector, type of building affected, vegetation present in the surroundings were recorded in order to look for some type of tendency. Several ideas were inferred from the study in terms of likelihood of severe damage in different types of installations.

The first finding was regarding the affected companies as a function of their size. From 140 visits, 64% were 'micro companies' (less than 10 workers), 28% were small companies (between 10 and 50 workers) and 7% were medium companies (between 50 and 250 workers). However, data from the National Statistics Institute of Portugal showed that there were only 49 medium companies in the studied regions, corresponding to less than 0.5% of the total existing companies. From that, it may be inferred that medium size and big companies are more exposed and more prone to suffer consequences when NaTech events triggered by wildfires happen. Facilities with larger extension, larger inventories of flammable chemicals and equipment susceptible of being damaged can cause this phenomenon.

On the other hand, ignition source and type of contact on each specific event was also studied and one of the main conclusions extracted from the report was related to this topic. After analysing the situation in each infrastructure, firebrands were found to be the most frequent ignition source (53%) followed by direct contact with fire coming from forest fire (27%) and from nearby structures (12%). Figure 13 shows the distribution of primary ignition sources. In relation to this, the proximity of the company's facilities to vegetation was also investigated with the aim of searching for a correlation between distance to vegetable fuel and the facility and probability of ignition. Table 4 relates the distance of installations to forest fuel and the ignition source responsible for each accident, showing that for fires caused by direct contact, 50% of them took place in structures in which forest fuel was separated less than 2 m. On the other hand, for fires caused by firebrands and the rest of sources there is no patron or tendency that can correlate distance and frequency. It is remarkable that Portuguese legislation states that industrial parks and logistic infrastructures are forced to manage and maintain their vegetation surrounding the installations in a 100 m radius. In the light of the developments, the importance of proper land management and vegetation maintenance has been confirmed according to the number of accidents caused by direct contact at different distances.

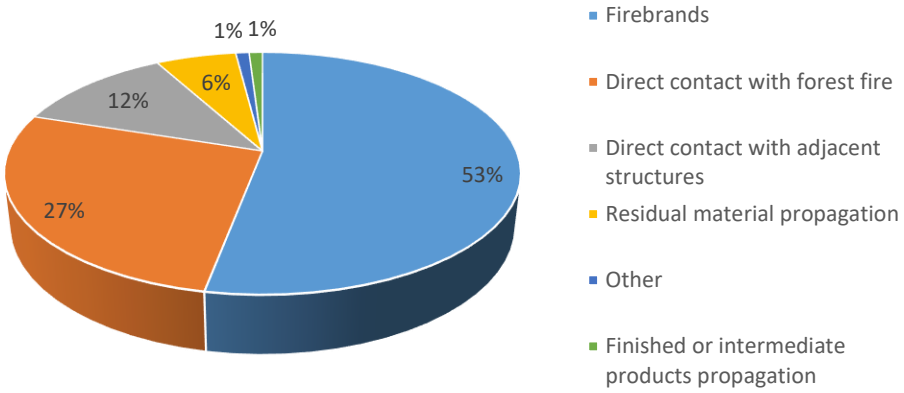

Figure 13. Primary ignition sources.

Table 4. Proximity between forest fuel and structure and which is the primary ignition source.

Primary ignition source	**Proximity of the installations to forest fuel (m)**				**Total**
	0-2	2-10	10-50	>50	
Direct contact with adjacent structure	4	2	6	4	16
Direct contact with forest fire	19	11	7	1	38
Firebrands	10	19	26	19	74
Residual material propagation	3	2	3	1	9
Finished products propagation	-	-	1	-	1
Other	1	-	1	-	2
Total	37	34	44	25	140

Besides, the architecture of the installations and the possible openings from which the fire could have got through were also studied. Those openings, even though they make sense in terms of architecture, heat management of the industrial site and so on, they must be avoided when designing and building

plants in areas surrounded by forests or prone to wildfires. Table 5 includes a report for the different locations from which ignition started.

Table 5. Ignition location for each type of mechanism.

Ignition mechanism	**Possible first ignition location**							**Total**
	Open structure	Windows	Walls	Door	Breathers	Roof	Other	
Direct contact with adjacent structure	1	3	5	2	2	3		16
Direct contact with forest fire	**14**	2	**9**	2	3	4	4	38
Firebrands	**24**	5	**7**	5	5	**15**	13	74
Residual material propagation	1	2	5			1		9
Finished products propagation	-		1					1
Other	-			1			1	2
Total	**40**	12	27	10	10	23	18	140

Even though there are several ignition locations, it is clear that plants that are opened to the exterior are the most vulnerable group of installation, being by far the type of structure most affected by direct contact and firebrands. Moreover, firebrands also tend to affect the structures through the roof mainly due to possible accumulation of fuel like leaves or branches. These residues are prone to ignite when contacted by firebrands and are sited in a location in which it is easy to propagate the fire to the interior of the building. Regarding the study of walls as ignition location, it has been concluded that the great number of walls made totally or partially of metallic elements imply a possible threat to installations when facing a wildfire, since their thermal properties can cause an expansion of the wall and therefore create openings for the fire.

2.2 Survey of accidents

A survey of accidents in which different industrial, municipal, domestic installations were affected or threatened directly or indirectly by wildfires will be presented. In that survey, the events are described in terms of date, location, type of wildfire, infrastructure threatened, type of impact, indirect effects, corrective measures and consequences.

2.2.1 Screening methodology

With the aim of collecting the set of accidents, National Response Centre (NRC) and Analysis, Research, Information on Accidents (ARIA) databases were checked looking for events caused by wildfires.

The National Response Centre (NRC) is the "designated federal point of contact for reporting all oil, chemical, radiological, biological and etiological discharges into the environment, anywhere in the United States and its territories" (National Response Center, US EPA, 2021). NRC elaborates a yearly database which contains all the reported accidents, incidents and any type of episode related to atypical functioning of industrial facilities, equipment, domestic services, work environment and so on. Not only the location and time of the accidents are recorded in it, but also the gathered information about a given event: remedial measures that were taken, whether any evacuation was needed, description of the release if any along with an identification of the material leaking, consequences affecting the surrounding areas and so on are present in the database.

ARIA (Analysis, Research and Information on Accidents) database was also checked. It is a database developed by the Bureau for Analysis of Industrial Risks and Pollutions (BARPI) which gathers incidents and accidents that have harmed or may have harmed health, public safety, or the environment (Aria Database, BARPI, 2019). Despite the fact that the database contains occurrences from all over the world, it mainly consists of French events.

The work done by Ricci et al 2021 was continued in this thesis, now focusing on wildfires. Keywords such as wildfire, forest fire, woods, etc. were used to filter through the database and find events related to the topic in the time span following the 2021 publication, from 2019 to 2021. However, the criterion used by Ricci et al to include an event in their register was stricter than the one applied on this study. While Ricci et al required the event to fit under the accident, incident or loss of containment definition, in this thesis events without consequences and near misses were also included**.** Type of contact, corrective measures and direct and indirect effects were inferred from the database and used in order to evaluate the consequences of each event as it will be explained in the next section.

2.2.2 Evaluation of consequences

The consequences were evaluated following the criteria established in the European Scale of Industrial Accidents (Committee of Competent Authorities, European Union, 1994). It is based on a set of 18 technical characteristics established to characterize the effects or repercussions of accidents in an objective way. There are six levels to each of these characteristics, with the highest level setting the accident's index grade (Committee of Competent Authorities, European Union, 1994). Among the technical characteristics, 2 indicators measure the effects caused by a release of dangerous material in the accident (Table 6), 7 indicators are related to the effects on people and society (Table 7), 5 deal with environmental consequences (Table 8) and 4 with economical ones (Table 9).

Table 6. Indicators related to dangerous material released.

Dangerous material released	**1**	**2**	**3**	**4**	**5**	**6**
Substance effectively lost or released in relation to the 'Seveso' threshold (% of Seveso threshold)	Q<0,1%	0,1%<Q<1%	1%<Q<10%	10%<Q<100%	1-10 times	More than 10 times
Explosive substance having actually participated in the explosion (eq. in TNT[1])	Q<0,1 t	0,1t<Q<1t	1t<Q<5 t	5t<Q<50t	50t<Q<500t	Q > 500t

[1] Expressed in kg of TNT equivalent

Table 7. Indicators related to human and social consequences.

Human/social consequences	**1**	**2**	**3**	**4**	**5**	**6**
Total Number of deaths	-	1	2-5	6-19	20-49	>50
Employees	-	1	2-5	6-19	20-49	>50
Rescue personnel	-	-	1	6-19	6-19	>50
Public	-	-	-	2-5	2-5	>6
Total Number of hospitalisations >24h	1	2-5	6-19	20-49	50-199	>200
Employees	1	2-5	6-19	20-49	50-199	>200
Rescue personnel	1	2-5	6-19	20-49	50-199	>200
Public	-	-	2-5	6-19	20-49	>50
Total Number of hospitalisations <24h	1-5	6-19	20-49	50-199	200-999	>1000
Employees	1-5	6-19	20-49	50-100	200-999	>1000
Rescue personnel	1-5	6-19	20-49	50-199	200-999	>1000
Public	-	1-5	6-19	20-49	50-199	>200
Total number of homeless or unable to work	-	1-5	6-19	20-99	100-499	>500
Number of residents evacuated or confined in their home > 2 h x number of hours	-	<500	500<N<5k	5k<N<50k	50k<N<500k	N>500k
Number of persons without supplies (water, electricity…) > 2h x number of hours	-	N<1000	1000<N<10k	10l<N<100k	100k<N<1 million	N>1 million

Human/social consequences	1	2	3	4	5	6
Number of persons under extended medical supervision (>3 months)	-	N<10	10<N<50	50<N<200	200<N<1000	N>1000

Table 8. Indicators related to environmental consequences.

Environmental consequences	1	2	3	4	5	6
Quantity of wild animals killed, injured or rendered unfit for human consumption (tons)	Q<0,1	0,1<Q<1	1<Q<10	10<Q<50	50<Q<200	Q>200
Rare or protected animal or vegetal species destroyed in the zone of the accident (%[1])	P<0,1	0,1<P<0,5	0,5<P<2	2<P<10	10<P<50	P>50
Volume of water polluted (V, m^3)	V<1000	1000 < V < 10k	10k < V < 100k	100k < V < 1M	1M<V<10M	V>10M
Surface of soil or underground water requiring cleaning or specific decontamination (S, ha)	0,1<S<0,5	0,5<S<2	2<S<10	10<S<50	50<S<200	S>200
Water channel requiring cleaning or specific decontamination (L, km)	0,1<L<0,5	0,5<L<2	2<L<10	10<L<50	50<L<200	L>200

[1] Percentage of damaged species in relation to the total available in the area

Table 9. Indicators related to economic consequences.

Economic consequences	1	2	3	4	5	6
Property damage in the establishment (C, M€)	0,1<C<0,5	0,5<C<2	2<C<10	10<C<50	50<C<200	C>200
Establishment's production losses (C, M€)	0,1<C<0,5	0,5<C<2	2<C<10	10<C<50	50<C<200	C>200
Property damage or production loss outside the establishment (C, M€)	-	0,05<C<0,1	0,1<C<0,5	0,5<C<2	2<C<10	C>10
Cost of cleaning, decontamination, rehabilitation of the environment (C, M€)	0,01<C<0,05	0,05<C<0,2	0,2<C<1	1<C<5	5<C<20	C>20

2.2.3 Accidents

The survey of accidents performed following indications stated in sections 2.2.1 and 2.2.2 is shown in Annex 1. Remarkable information could be extracted after elaborating the table shown in Annex I: Survey of Accidents.

- 42% of the accidents listed in the survey are related to pipelines. These structures move liquids and gases between locations and facilities making them prone to suffer from wildfires effects since they usually cross wide extensions of forests and vegetation.
- 24% of the accidents presented indirect effects aside from the direct flame contact and the heat transmitted. Power shut downs are the most frequent indirect effect caused by wildfires.
- Despite wildfires are more frequent in hot seasons, Annex I: Survey of Accidents lists events that took place all over the year in spring and fall, not only summer.

Even though the number of accidents with severe consequences in terms of casualties are limited, it was easy to find tens of events that altered the normal functioning of industrial and public installations. The latter, along with the warnings of future increase in the frequency of wildfires, must raise awareness of the need of a holistic approach in quantitative risk analysis which take into account the possible effects of wildfires near facilities and not only the fires created within the boundaries of the building.

2.3 Detailed analysis

To perform a more in-depth analysis of specific accidents is the objective of this section. By means of these analysis', the events that initiated the accidents are identified along with the chain of happenings and the final scenario of the studied case. The two analysed accidents (Hazelwood mine and DOPCO tank fire) were selected based on the available information and the representability of the studied topic. DyPasi and MTO methods are applied in order to describe the events and asses the safety barriers performance.

2.3.1 Methods of accident investigation

Different investigation methods are assessed in this section. Qualitative methods like the bow-tie analysis, MTO analysis and so on, study accidents evaluating the performance of successive barriers called layers of protection. Layers of protection are those safety barriers that come in between the hazards of a process and the people, property and environment that could be affected. There are prevention layers and mitigation barriers, being the former ones based on avoiding a hypothetical accident by implementing an inherently safe design and an effective control and alarms system. On the other hand, mitigation layers take action once the accident has started. Among the types of layers of protection, they can be physical (walls for containing), functional and symbolic and immaterial (safety planning).

DyPASI Approach

The first step when studying risks through a Quantitative Risk Analysis (QRA) is to define the context and the system to which the study will be applied and to identify hazards that could be present in a given scenario. Focusing on this topic, Paltrinieri et. al. (2013) developed a new hazard identification (HAZID) approach called Dynamic Procedure for Atypical Scenarios Identification (DyPASI) with the aim of recognize atypical events that were being disregarded or not included in conventional HAZID techniques (Paltrinieri et. al., 2013). According to the authors, "DyPASI is an HAZID method aiming at the systematization of information from early signals of risk related to past accident events, near-misses and risk studies" and consists of the Figure 14.

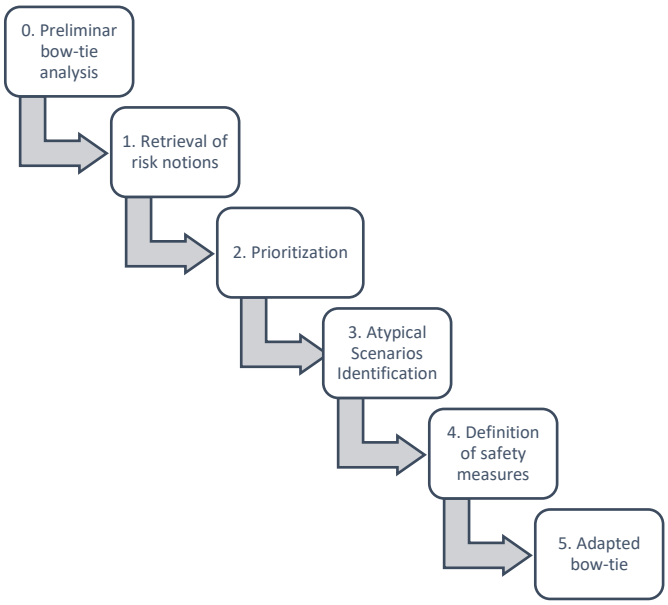

Figure 14. DyPASI steps.

DyPASI methodology starts taking the conventional bow-tie analysis as basis. Bow-tie is a combination of a fault tree and its basic events and an event tree and its outcome events or consequences. Both trees converge on a critical event that can be a loss of containment or any alteration that may cause a major accident. It is graphically represented in Figure 15.

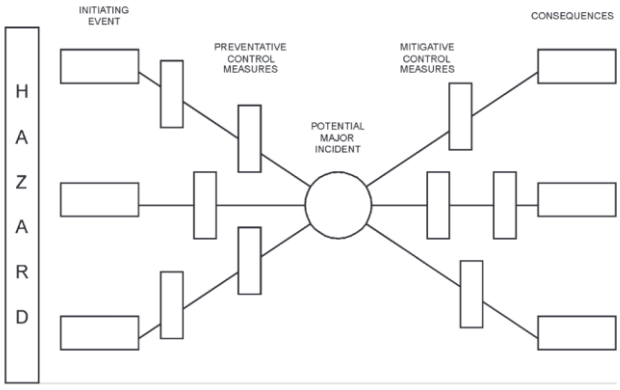

Figure 15. Bow-tie template (Cockshott, 2005).

Once the conventional bow-tie is performed, relevant information about possible undetected hazards of the studied case is gathered (Step 1: Retrieval of risk notions) and classified according relevance and impact (Step 2: Prioritization). Atypical scenarios are extracted from the previous two steps and, using the new collected info and past experience, the safety measures that are needed are identified. With all of that, a new, integrated bow-tie can be developed.

MTO Analysis

MTO (Man, Technology and Organization) analysis is a method to study accidents based on analysing three different factors that describe an accident: structured analysis, change analysis and barrier analysis (Han and Gao 2011). A template of this method is represented in Figure 16. First, the structured analysis which considers the events and casual factors is performed. Following, the change analysis explains how the events occurred, looking for their root cause and how events have deviated from normal functioning. Lastly, the barrier analysis indicates which safety barriers failed and how they did it and also if there is any barrier missing that could have helped preventing or mitigating the accident.

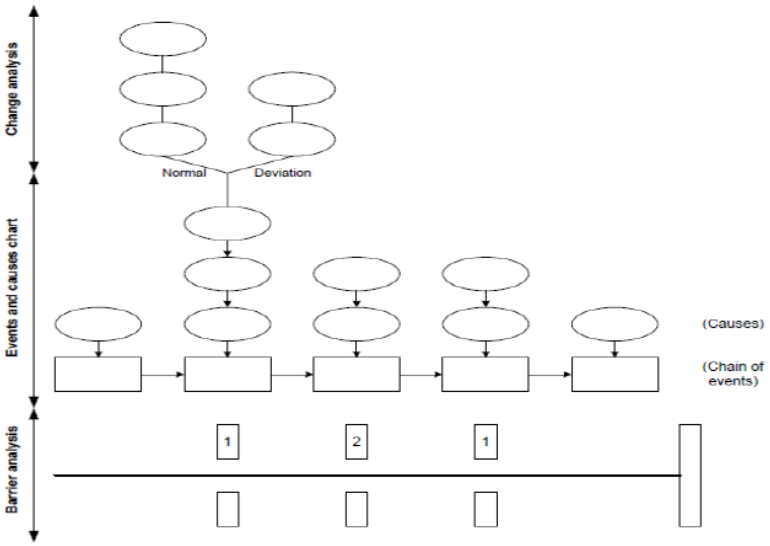

Figure 16. MTO flowsheet diagram (Han and Gao, 2011).

2.3.2 Accident 1: Hazelwood coal mine

On 9 February of 2014, Hazelwood coal mine got on fire as a consequence of embers spotting into the mine from bushfires that took place nearby the mine, that was located in the region of Victoria, Australia. It lasted 45 days and it supposed a complex, hard to extinguished fire and a public health issue for the Victoria population. For this reason, the government of the region of Victoria requested an independent inquiry about such fire, report which was compiled by B. Teague (Teague et. al, 2014).

Chronology

On February 7, the Hernes Oak-McDonald's fire started. Parting from eyewitness testimonies, it was concluded that the fire propagated until close to the mine leading to the fire within the mine being caused by embers spotting in multiple locations of the facility on February 9. From then, the Hazelwood

coal mine fire can be split in three stages: the first phase corresponds to the first day of the fire, while the second one includes from 10 to 18 and the last one until march 25.

The fire was noticed at 2 pm on 9 February and started in the eastern part of the mine. Rapidly, the staff acted an initiated the protocols: opening gates to facilitate vehicles circulation, turning on sprinklers and other extinction equipment, etc. Due to the complexity of the fire and how quickly it was expanding, one hour after noticing the full-blown, emergency state was declared and thus the consequent protocol was implemented. Fighting against fire took place during the rest of the day, even though it was not possible to avoid damage to power supplies systems, which complicated the labour of the firefighting staff. The lack of power led to having to relocate the command centre, along with causing water shortage. An incident response plan was elaborated by the Australian agency responsible for fire issues (CFA) in order to restore the power lines and protect key infrastructure in the mine, and was carried out during the early morning of Feb 9 – Feb 10.

Second phase of the fire lasted for a week. Once the fire became more stable, a command structure was designed along with a plan for the suppression based on "containing and securing perimeter lines of the various fires in the Latrobe Valley region", protecting key infrastructure and facilitate the restoring of normal business and economic activity in the region. The priority was to divide the fire in regions and extinguish them as well as trying to reduce the smoke release in order to avoid or minimize health effects in the community. Related to this, the fire was eventually declared a *Hazmat incident* due to the health implications of the smoke that was being released as a cause of the fire.

Finally, the third and last phase of the fight against the fire lasted for a month, until 25th march when the fire was declared safe. This step of the fire was characterized by the particularities which coal fires have. Coal is a highly combustible material that is stored in layers from which it is mined. The combustion can take place naturally or ignited by other reasons, but when a coal seam catches fire and nothing is done to put it out quickly enough, it can burn for tens to hundreds of years, depending on the supply of coal and oxygen[1].

In order to extinguish a coal fire, fuel and heat must be removed, air must be also eliminated to stop combustion and prevent chemical oxidation reactions from happening. Unfortunately, the fire services

[1] Anupma Prakash, 2007. https://anupma-prakash.github.io/coalfires/faq_general.html

and the staff of the company did not have the desired equipment to deal with this type of fire like water, foam, helicopter water bombing and removing the coal on fire.

MTO Analysis

The methodology explained in Section 2.3.1 was followed to carry out the MTO Analysis. First, the chain of events was established, considering that all started with the three wildfires surrounding the mine. Those wildfires spotted into the mine starting the mine fire, which was aggravated by bad initial communication both onsite and offsite.

Once the events were set, the technical analysis of what changes had happened in the mine that explain the events was performed. According to the information given by witnesses and gathered by Teague et al. (2014), mine fire started due to the embers coming into the mine acting as ignition source. On the other hand, there were complaints about the communications between agents at early stages of the fire. There were some flaws in the strategy regarding preparation since the prediction models that warned about possible danger in the mine at those days were ignored leading to a too optimistic emergency approach. Besides, not only preparation was improvable but also the communication once the fire started. The people in charge did not declare full emergency and the CFA was not notified soon enough. The third deficiency in this stage of the strategy was the lack of human and material resources available at that time due to the existence of a large number of fires taking place in the region simultaneously.

More related to the extinguish of fire itself, the fight against the fire was difficult due to different reasons even though they all come from a common cause, which was the power shutdown that took place in the mine as a result of the fire that caused damage in power lines. During the time that the power shutdown took place, pumps were not working so water service was severely reduced, acting as an obstacle in the fire extinguishing. Moreover, the study demonstrated that the water service network design was not optimal since there were batters (vertical faces in which the coal is deposited) without proper sprays, sprinklers and different extinguishing tools and since that, it was evidenced that all the sprays could not be turned on at the same time. The last factor affecting the lack of equipment designed specifically to extinguish coal fires, as it was mentioned in the previous section.

The MTO analysis finishes with a survey of possible safety barriers or remedial measures that could have avoided or limited the effects of the events that took place in the mine. First and foremost, the most obvious option is to avoid optimistic preparation for emergencies and to have an approach that takes into account the warnings that may be given. One of the most important areas in which the performance against fires can be improved is the communication as it was stated by the report of the accident. The development of a new, effective and autonomous communication system should be considered in order to optimize the response to emergencies, ask for support soon enough and

collaborate in a more efficient way with the agencies and local governments. The shortage of resources, both material and human, is also something to correct. Invest more in hiring more employees dedicated to prevent and act against fires could be something to evaluate.

Regarding the extinction procedure, the most significant factor that affected the performance of fire services was the power shutdown described in the change analysis. The company should have designed an electrical system in which power came through power lines distanced from each other, not like the current one in which the same fire burnt both high tension power lines. A backup generator would be another interesting option, as well as the addition of a connection with an alternative power substation located apart from the main one. Related to this, water system design should also be reconsidered in order to depend on more than one power supply and encompass the entire extension of the installation. Lastly, both fire services and employees of the company agreed on the fact that having the best available technology for fighting coal fires would have made way easier the battle against the fire.

This analysis is represented using the typical MTO diagram structure as shown in Figure 17.

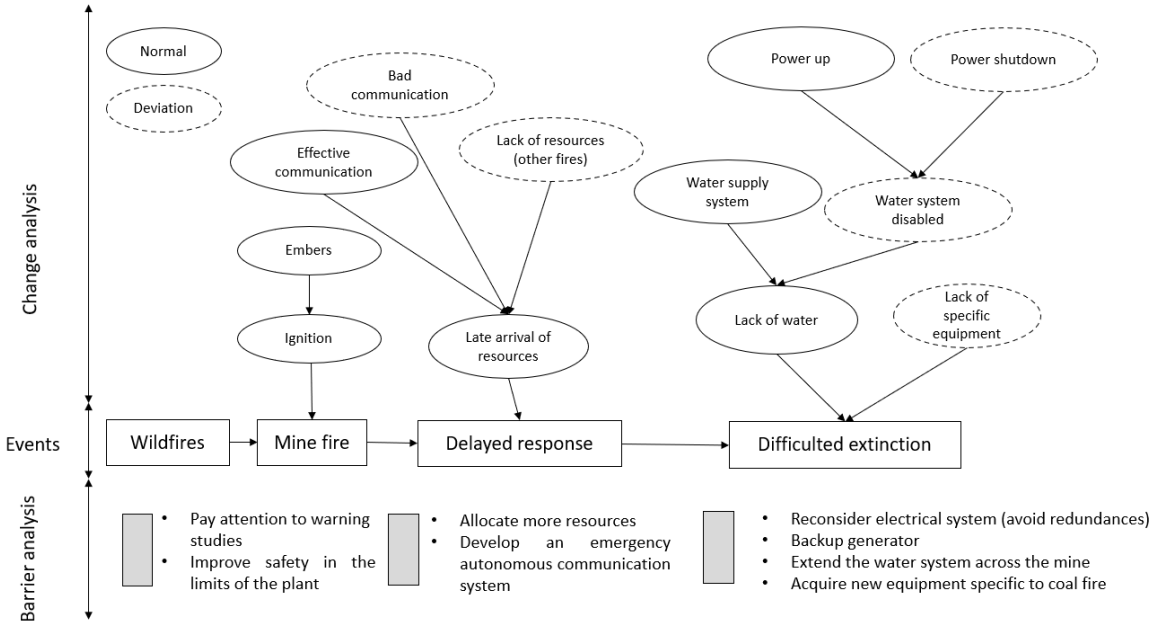

Figure 17. Hazelwood mine MTO analysis.

2.3.3 Accident 2: Goyang DOPCO plant accident

Chronology

The Goyang DOPCO (Daehan Oil Pipeline Corp) plant suffered an explosion in one of their gasoline tanks in 7th October of 2018. 2.6 million litres of gasoline were burned during more than 15 hours due to a lost sky lantern falling within the site. A man working in adjacent construction threw the lantern

that he had found into the sky and it unfortunately ended up falling into the installation, serving as ignition source to the grass and vegetation that was present in the facility.

The explosion happened due to initially unknown reasons, and after that the tank got on fire. Toxic fumes were released as a consequence of the fire caused by the explosion, so the community must be warned to stay at home with the windows closed until the fire was extinguished.

Extinguishing tasks were being carried out when a second explosion occurred, enhancing the fire again. Firefighters were forced to be distanced more than 100 m due to the large amount of heat that was being released from the tank. The oil that was still in the tank had to be extracted through a water recovery system in order to maintain control of the fire. Preventing the fire from spreading to adjacent tanks was the priority for a while, and the 60 cm wall that was surrounding the tank was key to achieve it.

Finally, the fire was suffocated successfully and propagation to nearby equipment was avoided without any human casualty. More than 10 M$ were lost as a result of this event and also legal consequences were suffered by three officials from the company and even a former member of the government who fraudulently stated that flame prevention system had been correctly installed in 2014[1]

MTO Analysis

Based on the chronology of the accident, the chain of events could have been established. A grass fire took place within the limits of the DOPCO plant after the ignition caused by the sky lantern. After that, an explosion followed by a fire in the tank which released toxic fumes happened until it was suffocated by the firefighters.

Regarding the technical analysis of which are the causes that lead to the events, closed-circuit television was used to determine the reason of the fire. As it was said, the sky lantern shown in Figure 18 unintentionally fell into the plant and provoked the fire using the grass present in the facilities as fuel.

[1] The Investor, 2018 http://m.theinvestor.co.kr/view.php?ud=20181106000714

Figure 18. Korean police holding the sky lantern[1]

As it was explained before, the grass fire ended up causing the explosion of the internal, floating roof tank shown in Figure 20. Internal, floating roof tanks are containers like the ones explained in 2.1.1 but with a fixed roof protecting the floating one from climatological effect. Despite being safer tanks than the open floating roof tanks, they are more prone to explosions since an explosive mixture could be formed between roofs. Figure 19 exhibits the venting vulnerability of these tanks that explained the Korean accident.

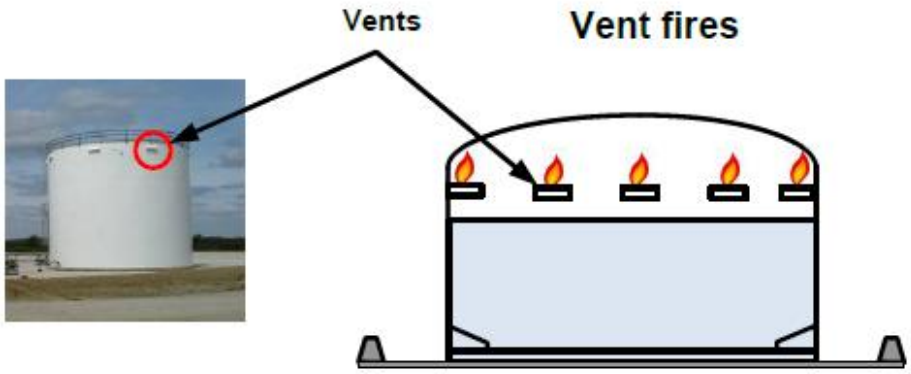

Figure 19. Internal, floating roof tank vulnerabilities.

It was determined that embers from the grass fire entered in touch with vapours coming out of the venting system of the oil tank, causing a flash fire and subsequently an explosion and a toxic smoke release. Then, firefighting efforts started and lasted for hours until it was fully controlled. Actions like

[1] Korean Herald, 2018 http://www.koreaherald.com/view.php?ud=20181009000228)

extracting the gasoline that had not started to burn prevented the fire to extend to other tanks and causing more damage.

Figure 20. Gasoline tank after the fire.

This accident is a very simple one in terms of what happened and why did it happen. However, such simplicity is what makes it interesting since it can be used as an example of how often deficient safety measures are present everywhere even in industrial installations belonging to important or even public companies -DOPCO is a private, ex-governmental company-. Companies like this one would be affected by SEVESO Directive in case of being sited in Europe and they should carry out comprehensive safety studies and risk analysis that would end up in safety barriers improvement against technological or natural events. Oil and gas sector is extremely sensitive to these events and should therefore be especially careful regarding safety barrier implementation and maintenance, even though the opposite was observed after studying this accident.

The most evident safety barrier failure was the lack of maintenance of the fire prevention system. The explosion would not have taken place if the fire was avoided in first place. It was observed that, even though the facility counted with a net to prevent combustible hazards to get into it, such net was damaged and not repaired allowing the infiltration of the sky lantern. Besides, lack of attention along the years led to the raise of dry, easily ignitable grass around the plant. These two factors together represent a vulnerability in the fire prevention system of the plant. On the other hand, 18 minutes went by between the start of the fire and the explosion with nobody noticing among the workers. Explosion may have been prevented if fire detection would have been faster, so something as basic as installing fire detectors in the area could be remarkably helpful in order to avoid future events.

Safety measures to minimize the impact of previous fires are also a relevant issue. For instance, the explosion and fire in the tank could have been prevented if a vapour collection system had been installed. Even though current legislation affecting the installation at that time did not force to have them, a good system which would have collected the vapour emissions that may take place in storage tanks would have reduced the explosion risk when an ignition source is present nearby. Another critical point of the accident was the continuous risk of the fire being trespassed to nearby deposits, being avoiding this issue a priority for the firefighting agents. Despite counting with a 60 cm wall which helped

to contain the flames, working on improving the storage tanks' insulation may be an interesting option for the safety managers of the plant. The sequence of events in the accident was recorded by CCTV cameras (Figure 21).

Figure 21. CCTV footage of the accident.

In general, most of the safety flaws mentioned in this section could have been identified and then corrected if more attention and resources had been allocated to safety revisions. Since the installation was not classified as critical by Korean legislation, external safety auditory was required every eleven years. This time lapse seems to be too large, especially taking into account the hazardous products the plant worked with, and therefore, more frequent safety barriers revision would definitely help avoiding future accidents. Figure 22 graphically summarizes the MTO analysis.

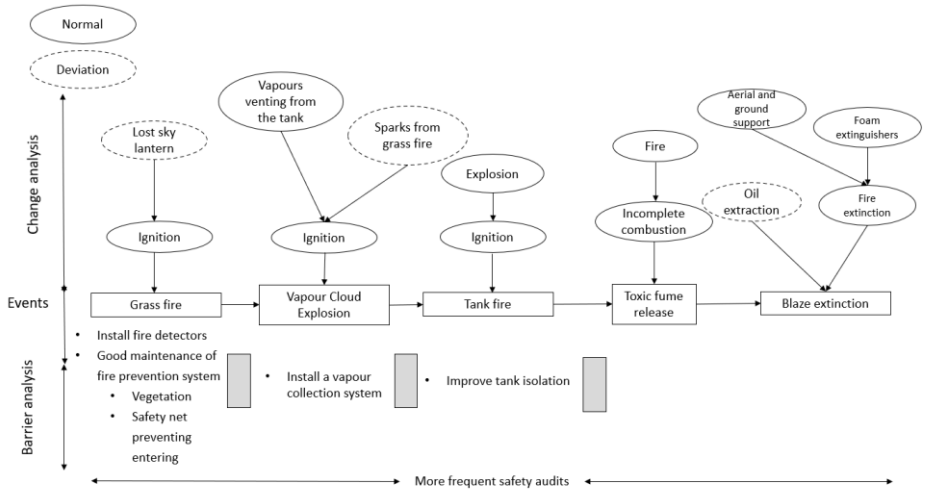

Figure 22. Oil tank fire MTO analysis.

2.3.3.1 DyPASI analysis

Tank fires are analysed here by means of the DyPasi approach explained in section 2.3.1. A conventional bow-tie diagram built on *BowTieXP* software[1] is shown in Figure 23 and it is used as basis for the DyPasi study. The intermediate steps of the method can be skipped for the purpose of this specific analysis since wildfire impacts are the focus of the study. Storage tanks use to be located at the boundaries of the plant and, therefore, they are the most exposed equipment in case of wildfire threatening the installation (Ricci et.al., 2021).

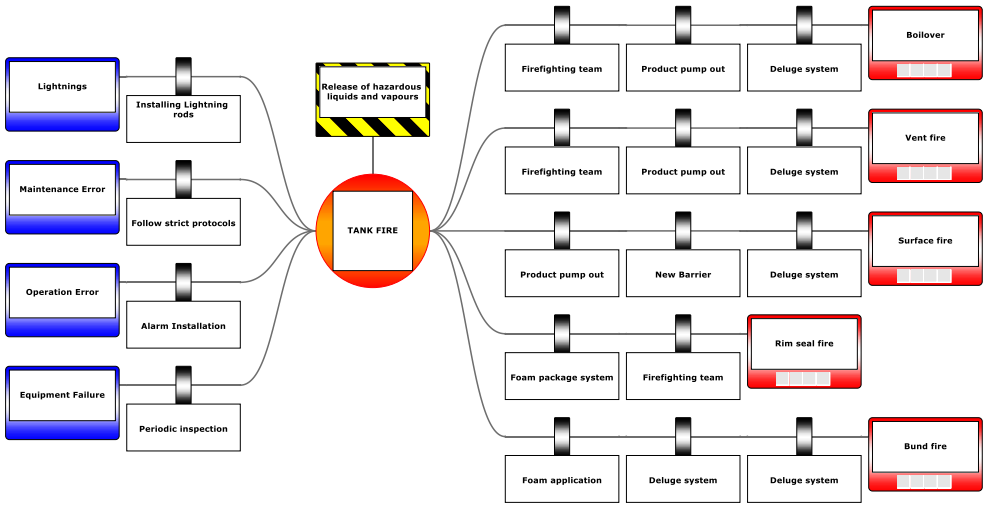

Figure 23. Tank fire preliminary bow-tie (BowTieXP)

Early warnings mentioned in previous section along with accidents like the one that took place in the Korean plant make a statement about the need of including wildfires as initiating events when performing the HAZID step of a QRA. According to the info extracted, proper vegetation management is one key, basic safety measure that may prevent the propagation of a wildfire into the proximities of the plant and consequently the fire contact of any kind (direct, radiation or embers). Fireproofing the tanks would also be a recommendable measure in order to avoid ignition in the tank if the previous safety barrier have failed.

[1] BowTie Suite | Wolters Kluwer: https://www.wolterskluwer.com/en/solutions/enablon/bowtie

With that, a new branch that describes the atypical scenario of wildfires as initiating event and the corresponding safety measures can be added to the preliminary bow-tie. This new diagram is shown in Figure 24.

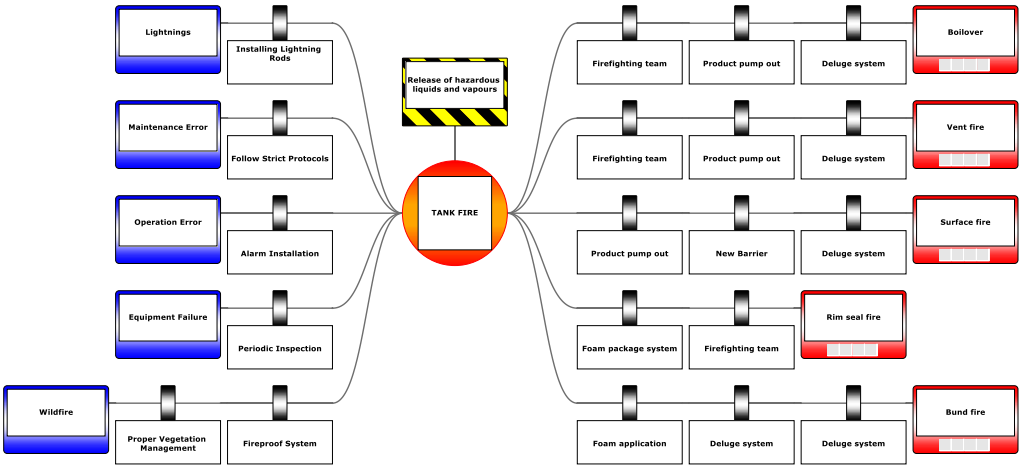

Figure 24. Final bow-tie (BowTieXP)

2.4 Conclusions

Different equipment that may be present in industrial plants was analysed in this section with the aim of finding out which is the most vulnerable to wildfires. Tanks whether open roof or closed ones, and equipment storing heat sensitive substances or under explosive atmospheres or made by plastic construction materials end up being the most susceptible to fire effect.

A comprehensive analysis of two industrial events triggered by wildfires has also been made. In the first one, embers from an important forest fire got into the facilities provoking a spot fire within the mine. Embers were also responsible for the fire in the Korean tank, even though they did not come from a forest fire but from a small grass fire. The first accident gives an example of how a fire can also cause indirect effects like power lost and therefore difficult communication and lack of utilities, i.e., water supply. Regarding the units affected, the Korean accident impacted an internal floating roof tank sited on an oil and gas facility. Such installation should have presented much more effective safety measure taking into account the type and quantity of hazardous materials that are stored in it. This accident manifest how vulnerable certain equipment is and how easily severe consequences could take place, even though in this case the fire was prevented to propagate and to cause more damage. On the other hand, the mine accident was characterized by the difficulted extinction provoked by the water system failure due to the power shutdown caused by the fire, highlighting one of the main indirect impacts that fire may have.

3 Quantitative Risk Analysis of an event triggered by wildfires

The concept of Quantitative Risk Analysis (QRA) is explained in this chapter. The main steps that conform the QRA are enumerated and the particularities of this methodology when dealing with Natech scenarios are remarked and compared with conventional QRAs. Besides, an example of a QRA of an LPG tank affected by the conventional initiating events is developed but taking into account the possible impact of wildfires.

3.1 Quantitative Risk Analysis Steps

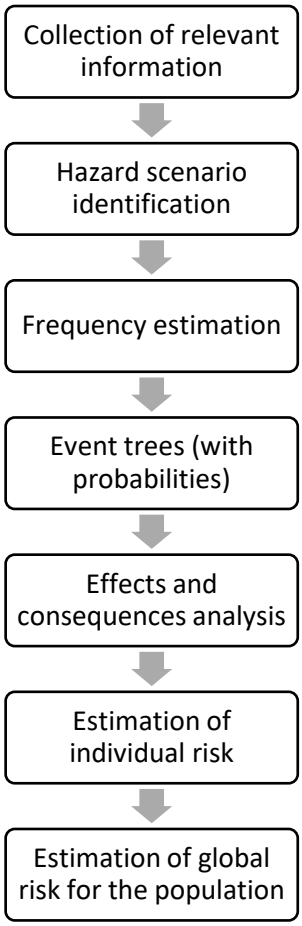

Figure 25. QRA steps (Casal, 2007).

Typical QRA consist of seven steps (Casal, 2007) (Figure 25). QRAs start by gathering all of the relevant information regarding geographical location: topography, coordinates, etc.; climate conditions: relative humidity, solar radiation and temperature, wind rose, stability of the atmosphere, etc.; substance characterization: physical and chemical properties, intrinsic hazards, etc.; and about the process itself.

This information is put together and analysed in order to carry out a hazard identification step. Guidelines set a series of loss of containment scenarios to be considered and their principal causes from which a more in-depth study can be carried out in order to perform some of the HAZID methodologies mentioned in Section 2.3.1, i.e., bow-tie or DyPASI.

Once all the possible hazards are identified, the frequencies of each scenario must be determined. Fault trees were built in the previous step and, parting from them, the frequency of a given critical event is determined multiplying the individual frequencies of each previous event that lead to such critical event.

While, in previous steps, the causes for a given loss of containment scenario were considered, QRA continues studying the consequences of such scenario. In an analogue way as in the fault trees, event trees are developed in order to study the effects provoked by a loss of containment. Consequences will depend on the type of release since each one leads to different sequences with different frequencies. Figure 26 shows the event tree for an instantaneous release with the different paths that can take place and their individual frequencies. It starts with the initiating event *Liquid spill/aerosol release* which has a frequency of f year^{-1} that has been determined by means of the fault trees like the one shown in Figure 27. There, the chain of events needed to cause the top event is studied qualitatively with logical gates and quantitatively when adding the frequencies of each basic or intermediate event.

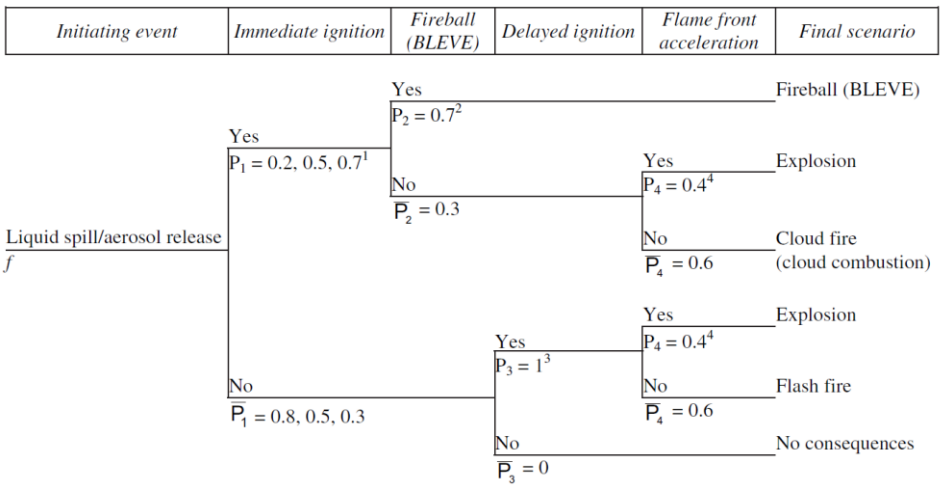

Figure 26. Example of an event tree for instantaneous releases of extremely flammable pressurized liquefied gases (Vílchez et.al., 2011).

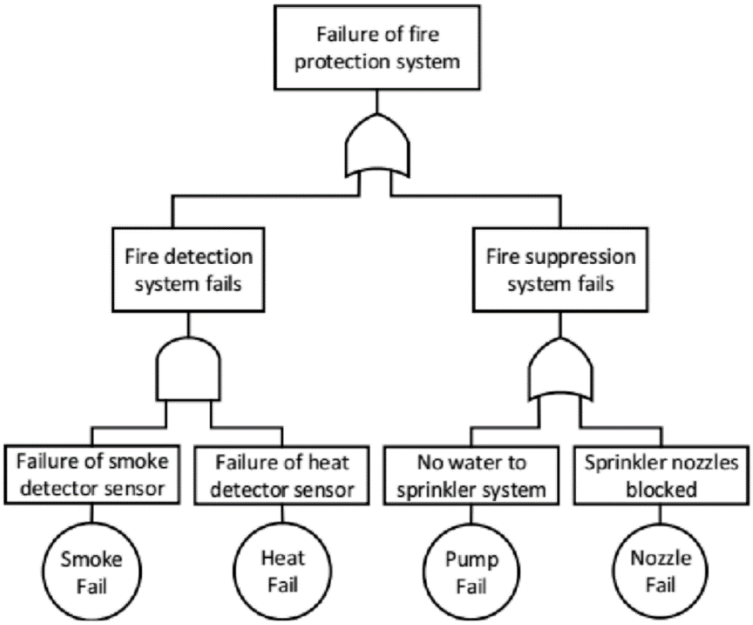

Figure 27. Fault tree analysis of a fire protection system[1]

QRA is ended introducing the concepts of Individual Risk (IR) and Societal Risk. IR is defined as the risk to a person located 24 h/day 365 day/year in a given point nearby a hazard and is expressed in year^{-1}. It is expressed as:

$$IR_{x,y} = \sum_{i=1}^{i=n} IR_{x,y,i} \quad (1)$$

Where $IR_{x,y}$ is the total IR in a x, y location, $IR_{x,y,i}$ is the IR of a *i* accident scenario in the x,y location and *n* is the total number of accidents considered in the x,y location. In turn, $IR_{x,y,i}$ depends on the frequency of the accident *i*, determined using the event tree, and the probability that the accident causes a fatality.

$$IR_{x,y,i} = f_i \cdot P_{Fi} \quad (2)$$

On the other hand, the societal risk uses the IR to determine the expected number of casualties per year taking into account the population sited in a given affected area:

[1]From : https://blog.infraspeak.com/fault-tree-analysis-fta/

$$SR = \int IR \cdot [population\ density(x, y)]dxdy \tag{3}$$

3.2 QRA modification to include wildfire effects

Collection of relevant climatological information was focused on humidity, atmospheric stability and data regarding dispersion behaviour in case of a leak. However, future perspectives that are reflected on studies and literature along with the register of early warnings and accidents performed on this thesis and other texts express the need of including wildfire-related information in order to carry out a comprehensive QRA.

On the other hand, the HAZID step must include now wildfire as a threat that may generate a critical event. Frequency estimation is typically made using the values provided by guidelines. These values explain the frequency at which typical loss of containment events take place. Despite being accurate, checked values, they do not take into account the accident likelihood increase that wildfires may cause in certain areas where such natural phenomenon takes place regularly. Consequently, the outcome of the QRA will show more severe risks in terms of yearly fatalities.

Misuri and Cozzani presented an innovative paradigm for the inclusion of NaTech events in QRAs. This framework's steps are shown in Figure 28.

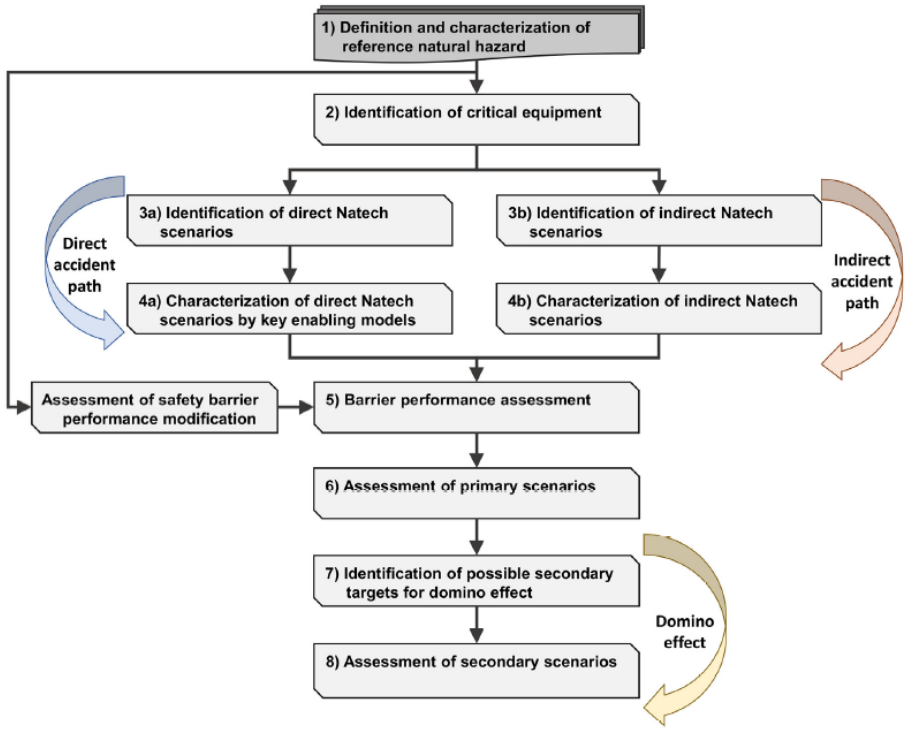

Figure 28. NaTech assessment framework (Misuri and Cozzani, 2021).

Thus, wildfire frequency must be determined. The Fire Weather Index (FWI) is a dimensionless measure of the fire potential of a given region that uses the temperature, humidity, precipitation, fuel and wind conditions to provide a result. It can be used whether as a current situation indicator or as a forecast value. Figure 29 shows the prediction made by Copernicus Climate Change Service, the EU agency that works with the FWI. Copernicus predicts that FWI near to 20 may be reached, supposing a moderate to high risk (EEFIS, 2022) that must be taken into account when carrying out a QRA.

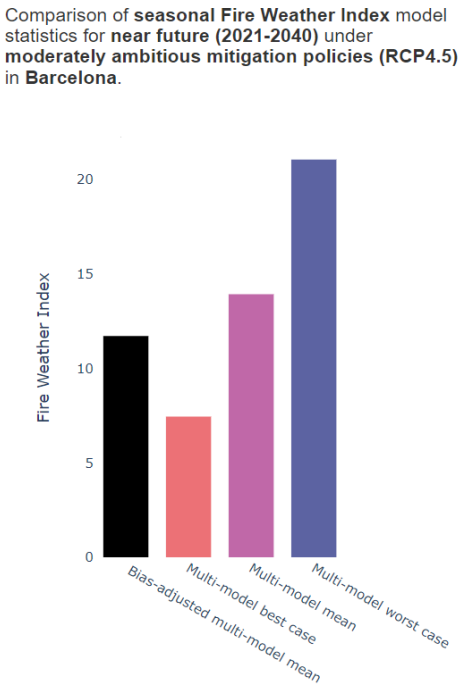

Figure 29. Barcelona FWI for the near future (2021-2040) (Copernicus, 2022).

3.3 Case study

A case study is developed in this section. It consists of the comparison between a conventional QRA and one taking into account the risk increase associated to the presence of a wildfire. Initiating events and their frequencies are identified by a fault tree analysis (FTA), while event trees analysis (ETA) is employed to determine the sequence of consequences and frequencies of each accidental scenario along with the IR on a given location.

3.3.1 Scenario description

The QRA of a liquified propane tank is presented. An 82 m^3 floating roof tank is loaded from a tanker truck (50% filled) using a 40 m, 2 “pipe that has a valve that interrupts the flow if 3.5 kg/s flow rate is reached. Besides, propane gas is taken back to the tanker by a pipe with the same characteristics. The

tanker truck has 20 m^3 volume and is connected to the loading pipe through a 2.5", 1.6 m flexible duct. On the other hand, the tank is also connected to the distribution system by a 2", 40 m pipe.

The installation is located at 100 m east of the woods (tree height 10 m). According to Ricci et al 2021, an atmospheric tank can fail in 7 min if fire residence time is higher and response time is higher. The installation is located in a region in Alt Empordà and Figure 30 gives a schematic representation of the road tanker, the plastic flexible duct, the storage tank and the pipes connecting them. The wildfire must be ignored for the conventional QRA that will be performed in the following sections.

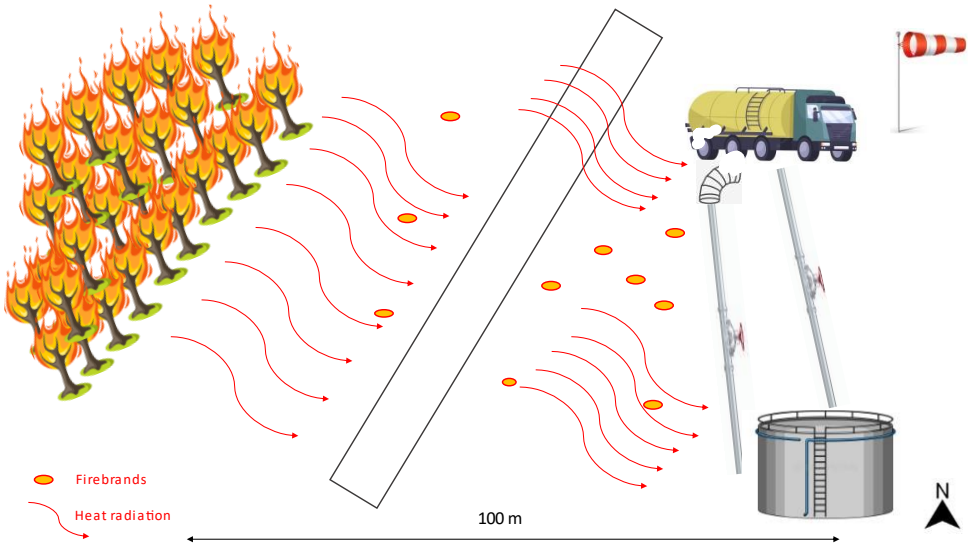

Figure 30. Schematic representation of the scenario when a wildfire takes place.

Operation data:

- Loading takes place 87 h/year and always under supervision of an operator.
- During winter (90 d/year), an evaporator is used to evaporate the liquified propane. Pipe to the evaporator: 40m, 2".

Geographic and climatological data:

- Conditions: 1.103 bar, 25 °C, RH 60%.
- Stability class: F (2 m/s wind velocity).
- Location: Alt Empordà
- Wind rose (Figure 31, Table 10).

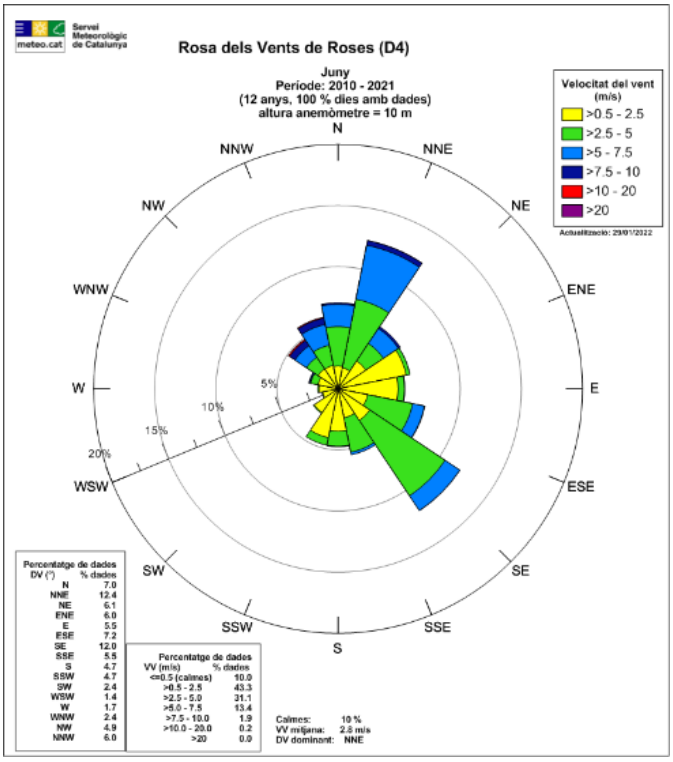

Figure 31. Alt empordà wind rose (Meteocat, 2022).

Table 10. Wind probability.

Wind Origin	Probability
N	0.07
NNE	0.124
NE	0.061
ENE	0.06
E	0.055
ESE	0.072
SE	0.12
SSE	0.055
S	0.047
SSW	0.047
SW	0.024
WSW	0.014
W	0.017
WNW	0.024
NW	0.049
NNW	0.06

3.3.2 Initiating events

A series of initiating events is considered in this QRA. LPG releases may take place as a result of full-bore or partial rupture of the pipe connecting the road tanker and the tank (Events 1 and 2), or as a

result of full-bore or partial rupture of the pipe connecting the tank with the evaporators (Events 3 and 4). On the other hand, a loss of containment of propane gas could take place due to a release through the safety valve (Event 5) or due to the full-bore rupture of the pipe that connects tanker and tank (Event 6) or the one that connects tank and distribution system (Event 7). All of these events have a given frequency marked by literature in function of the length of the pipe and the time that the responsible equipment is acting. Table 11 gives the list of events along with their respective frequencies, that are extracted from the literature (Ministerie van Verker en Watersaat, Purple Book; RIVM, 2009).

Table 11. Initiating events and frequencies.

Event	Description	Frequency
1	LPG release due to full-bore rupture of the flexible pipe	$f = 4 \cdot 10^{-6}\, h^{-1} \cdot \frac{87 \frac{h\ loading}{y}}{8760 \frac{h}{year}} = 3.48 \cdot 10^{-4} y^{-1}$
2	LPG release due to partial rupture of the flexible pipe	$= 4 \cdot 5\, h^{-1} \cdot \frac{87 \frac{h\ loading}{y}}{8760 \frac{h}{year}} = 3.48 \cdot 10^{-3} y^{-1}$
3	LPG release due to Full-bore rupture of the pipe connecting the road tanker and the tank	$f = 10^{-6}\, m^{-1} y^{-1} \cdot \frac{87 \frac{h\ loading}{y}}{8760 \frac{h}{year}} \cdot 40\ m = 3.97 \cdot 10^{-7} y^{-1}$
4	LPG release due to Partial rupture of the pipe connecting the road tanker and the tank	$f = 5 \cdot 10^{-6}\, m^{-1} y^{-1} \cdot \frac{87 \frac{h\ loading}{y}}{8760 \frac{h}{year}} \cdot 40\ m = 1.98 \cdot 10^{-6} y^{-1}$
5	LPG release due to Full-bore rupture of the pipe connecting the tank with the evaporators	$f = 10^{-6}\, m^{-1} y^{-1} \cdot \frac{90 \frac{d}{y}}{365 \frac{d}{y}} \cdot 40\ m = 9.86 \cdot 10^{-6}\, y^{-1}$

Event	Description	Frequency
6	LPG release due to Partial rupture of the pipe connecting the tank with the evaporators	$f = 5 \cdot 10^{-6}\, m^{-1} y^{-1} \cdot \frac{90\frac{d}{y}}{365\frac{d}{y}} \cdot 40\, m = 4.93 \cdot 10^{-5}\, y^{-1}$
7	Propane gas release through safety valve	$f = 2 \cdot 10^{-5}\, y^{-1}$
8	Propane gas release due to full-bore rupture of the pipe that connects tanker and tank	$f = 6 \cdot 10^{-6}\, m^{-1} y^{-1} \cdot \frac{87\frac{h\ loading}{y}}{8760\frac{h}{year}} \cdot 40\, m = 2.38 \cdot 10^{-6}$
9	Propane gas release due to full-bore rupture of the pipe that connects tank and distribution system	$f = 6 \cdot 10^{-6} m^{-1} y^{-1} \cdot 40m = 2.4 \cdot 10^{-4}\, y^{-1}$

3.3.3 Event trees

Each initiating event leads to a given event tree. According to the characteristics of propane, the more likely consequences are a Boiling Liquid Expanding Vapour Explosion (BLEVE) + Fireball in the road tanker, BLEVE + Fireball in the tank, a gas cloud that leads to a flash fire and a jet fire.

In order to build the event trees, the probability of failure of safety measures must also be set. The excess flow valve is expected to work 95% of the time, just like the tank system against flame impingement. On the other hand, the supervising operator is expected to fail 20% of the time. This safety measures mitigate the consequences of some of the events.

Full bore rupture of road tanker – tank pipe

The event tree corresponding to full-bore rupture of the pipe connecting the loading road tanker and the tank is presented here as an example. Besides the estimated probabilities mentioned before, for this event tree a 0.15 flame impingement probability in the tank is assumed while a 0.02 of flame impingement probability in the road tanker is set (Casal, 2007). Figure 32 shows the final event tree for this initiating scenario.

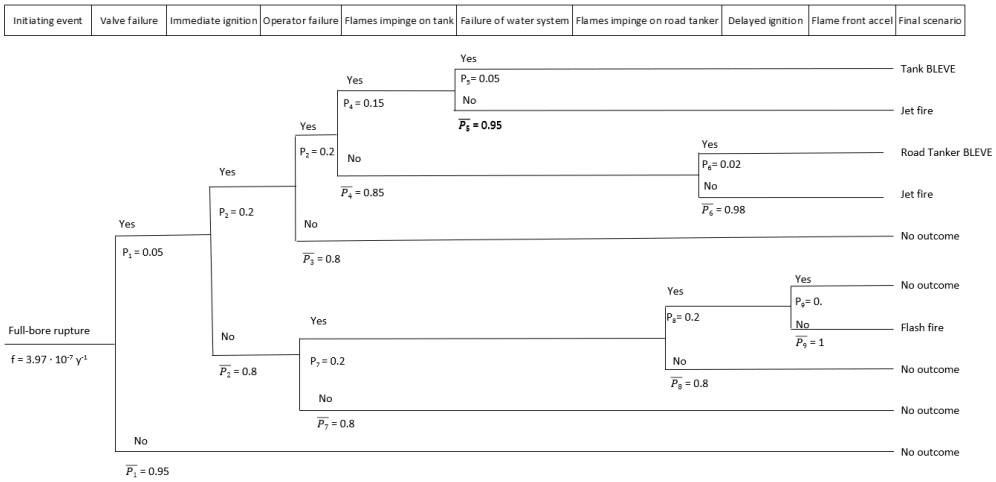

Figure 32. Event tree of the full-bore rupture of the loading tank pipe.

Other event trees

The rest of the event trees are extracted from Casal, 2007. Frequencies of each final scenario can be obtained from the corresponding event tree. Table 12 shows these frequencies.

Table 12. Accidental scenarios frequencies.

Final Scenario	Frequency
Jet fire	$f = (3.97 \cdot 10^{-7} \cdot 0.05 \cdot 0.2 \cdot 0.2 \cdot 0.15 \cdot 0.95) + (3.97 \cdot 10^{-7} \cdot 0.05 \cdot 0.2 \cdot 0.2 \cdot 0.85 \cdot 0.98) = 7.75 \cdot 10^{-10}$ year^{-1}
Flash fire	$f = 3.97 \cdot 10^{-7} \cdot 0.05 \cdot 0.8 \cdot 0.2 \cdot 0.2 \cdot 1 = 6.35 \cdot 10^{-10}$ year^{-1}
Road tanker BLEVE	$f = 3.97 \cdot 10^{-7} \cdot 0.05 \cdot 0.2 \cdot 0.2 \cdot 0.85 \cdot 0.02 = 1.35 \cdot 10^{-11}$ year^{-1}
Tank BLEVE	$f = 3.97 \cdot 10^{-7} \cdot 0.05 \cdot 0.2 \cdot 0.2 \cdot 0.15 \cdot 0.05 = 6 \cdot 10^{-12}$ year^{-1}

This procedure is repeated for each event tree and the frequencies of individual scenarios are put together.

Table 13. Aggregated frequencies of the final scenarios.

Final Scenario	Frequency
Jet fire	$f = 7.75 \cdot 10^{-10} + 7.8 \cdot 10^{-8} + 9.29 \cdot 10^{-8} + 4 \cdot 10^{-6} + 4.9 \cdot 10^{-10} + 4.8 \cdot 10^{-7} + 2.3 \cdot 10^{-6} = 6.95 \cdot 10^{-6}$ year^{-1}
Flash fire	$f = 8.7 \cdot 10^{-7} + 1.11 \cdot 10^{-4} + 6.35 \cdot 10^{-10} + 3.2 \cdot 10^{-8} + 3.9 \cdot 10^{-9} + 3.9 \cdot 10^{-7} = 1.12 \cdot 10^{-4}$ year $^{-1}$
Road tanker BLEVE	$f = 8 \cdot 10^{-7} + 6.96 \cdot 10^{-5} + 1.35 \cdot 10^{-11} + 1.36 \cdot 10^{-9} + 1.62 \cdot 10^{-9} + 8.4 \cdot 10^{-11} + 8.38 \cdot 10^{-9} + 4.08 \cdot 10^{-8} = 7.05 \cdot 10^{-5}$ year^{-1}
Tank BLEVE	$f = 6 \cdot 10^{-9} + 6 \cdot 10^{-12} + 6 \cdot 10^{-10} + 7.14 \cdot 10^{-10} + 3.7 \cdot 10^{-11} + 3.7 \cdot 10^{-9} + 1.8 \cdot 10^{-8} = 2.9 \cdot 10^{-8}$ year^{-1}

3.3.4 Individual Risk

The IR will be calculated in a point 100 m away from the tank in the direction at which the wind is more probable to blow. According to Table 10, South-Western wind is the most likely type, so the studied point will be 100 m away at NE direction (45°). The death probability is needed in order to use equation X to determine the IR. Flash fire caused by ignition of a flammable propane cloud and both possible BLEVES +Fireball situation (road tanker and propane tank) are studied.

3.3.4.1 Flash fire

Flash fires are rapid and non-explosive combustion of a flammable cloud whose size and position must be estimated using atmospheric dispersion models. It is assumed that people sited within the limits of the cloud would die since they would suffer radiation intensities between 160 and 300 kW/m^2 and people outside the cloud will suffer no consequences.

$$P_{Flash\ Fire} = P_{wind} \cdot P_{death} = 0.182 \cdot 1 = 0.182 \quad (4)$$

$$\Delta IR_{Flash\ Fire} = \Delta f_{Flash\ Fire} \cdot P_{Flash\ Fire} = 1.12 \cdot 10^{-4} \cdot 0.182 = 2.04 \cdot 10^{-5}\ fatalities/year \quad (2)$$

3.3.4.2 Road tanker BLEVE/Fireball

Contrary to the flash fire case, in this scenario death probability must be estimated. Boiling Liquid Expanding Vapour Explosion (BLEVE) occurs when a liquid stored in a tank is heated up above its boiling point. If the container is ruptured, the vapour will expand and the liquid will vaporize instantaneously,

causing a volume increase and an overpressure wave. The mechanism is shown in Figure 33. This phenomenon comes along with a fireball as shown in Figure 34, so its thermal effects at a given distance are calculated along with the overpressure caused by the explosion.

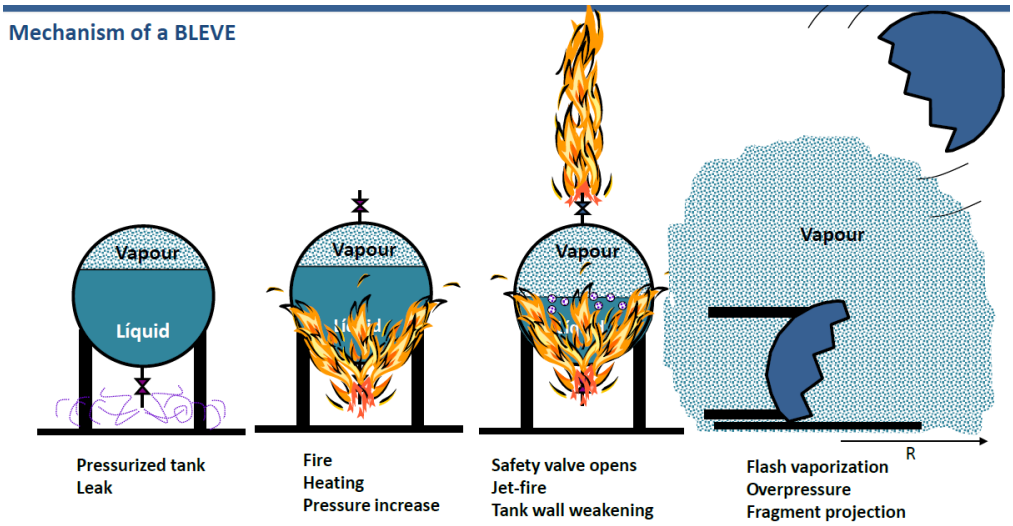

Figure 33. Mechanism of a BLEVE.

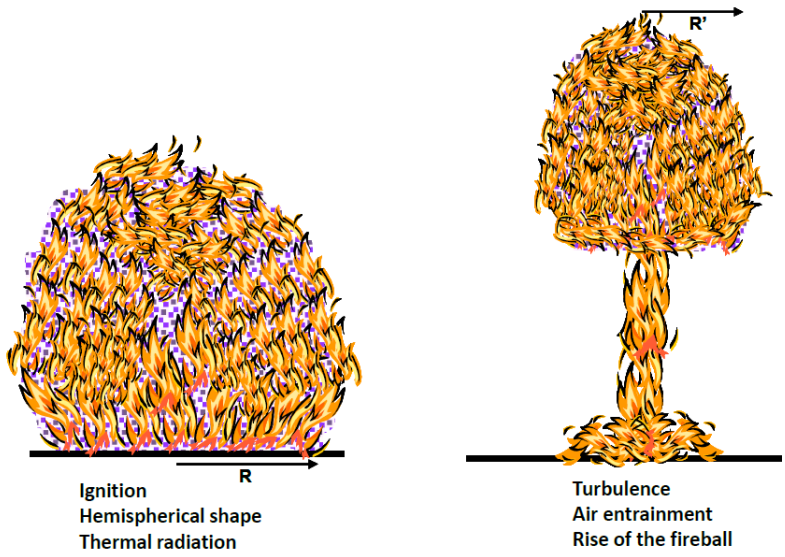

Figure 34. Fireball generation in BLEVEs.

Fireball thermal effect

The solid flame model is applied with the aim of estimating the effects of a fireball. The mass of propane available is:

$$M = 20\,m^3 tank \cdot 0.5 \frac{m^3 propane}{m^3 tank} \cdot 500\,kg \frac{propane}{m^3 propane} = 5000\,kg \quad (5)$$

The fireball diameter, the duration and the height depend on the fuel mass:

$$D = 5.8 \cdot 5000^{\frac{1}{3}} = 99\, m \tag{6}$$

$$t = 0.9 \cdot 5000^{\frac{1}{4}} = 7.5\, s \tag{7}$$

$$H = 0.75 \cdot 99 = 74\, m \tag{8}$$

On the other hand, the radiant heat fraction must be obtained in order to find the emissive power. The tank is assumed to be at 9.5 bar at the moment of the explosion.

$$\eta_{rad} = 0.00325 \cdot (9.5 \cdot 10^5)^{0.32} = 0.266 \tag{9}$$

$$E = \frac{0.266 \cdot 5000\ kg \cdot 46000\ kJ/kg}{\pi \cdot 99^2 m^2 \cdot 7.5\ s} = 260 \frac{kW}{m^2} \tag{10}$$

The distance between the fireball and the studied point is determined (Figure 35).

$$d = \sqrt{100^2 + 74^2} - \frac{99}{2} = 75\, m \tag{11}$$

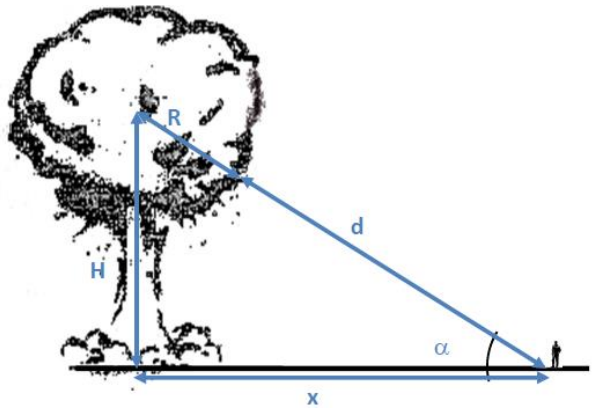

Figure 35. Fireball geometry.

The other two parameters of the solid flame model are the atmospheric transmissivity and the view factor. For obtaining the atmospheric transmissivity (τ), 1857 Pa water partial pressure is defined.

$$\tau = 2.85\ (1857 \cdot\ 75)^{-0.12} = 0.69 \tag{12}$$

The view factor is a geometrical parameter that describes how the flame affects the target at a given distance and angle.

$$F = \frac{99^2}{4\left(75 + \frac{99}{2}\right)^2} = 0.158 \tag{13}$$

$$Fv = F \cdot \cos\alpha = 0.158 \cdot \frac{100}{75 + \frac{99}{2}} = 0.127 \tag{14}$$

With that, the thermal radiation intensity towards a vertical surface is obtained.

$$Iv = 260\frac{kW}{m^2} \cdot 0.127 \cdot 0.69 = 22\ \frac{kW}{m^2} \tag{15}$$

Such thermal intensity is translated to vulnerability using probit functions. The lethality is calculated by means of the dose (intensity during a given time) received by the target.

$$V = I^{\frac{4}{3}} \cdot t = 22000^{\frac{4}{3}} \cdot 7.5 = 4623365\ J/m^2 \tag{16}$$

$$Y = -36.38 + 2.56\ln(4623365) = 2.9 \tag{17}$$

A probit value of 2.9 corresponds to a lethality around 1.8 %. So, P_D = 0.018:

$$IR_{\,RoadTanker\ fireball} = 0.018 \cdot 7.05\ \cdot\ 10^{-5} = 1.27 \cdot 10^{-6}\ fatalities/year \tag{2}$$

Overpressure

First step is to determine the superheating energy (SE), which represents the enthalpy difference between the liquid just before the explosion and at normal boiling temperature. For liquid propane, assuming explosion at 9.5 bar.

$$SE = 265.3 - 100 = 165.3\frac{kJ}{kg} \tag{18}$$

Assuming an irreversible adiabatic process, this SE is transformed in energy as follows.

$$E = 165.3\frac{kJ}{kg} \cdot 5000\ kg \cdot 0.1 = 82650\ kJ \tag{19}$$

This Energy is converted to mass of TNT equivalent. 50% of the energy is dedicated to create overpressure.

$$W\ TNT = \frac{82650 \cdot 0.5\ kJ}{4680 \frac{kJ}{kgTNT}} = 8.8\ kg\ TNT \quad (20)$$

Analysing a point 100 m from the tank, the normalized distance is.

$$d_N = \frac{d}{\sqrt[3]{W\ TNT}} = \frac{100}{\sqrt[3]{8.8}} = 48.4 \frac{m}{kg^3} \quad (21)$$

And finally, the overpressure at that point.

$$\frac{\Delta P}{P_0} = \frac{1}{d_N} + \frac{4}{d_N^2} + \frac{12}{d_N^3} = 0.00014\ bar \quad (22)$$

This overpressure does not cause any threat.

3.3.4.3 Propane tank BLEVE/Fireball

Fireball thermal effects

Same procedure as in section 3.3.4.2, using equations 5-17. The propane tank is filled up to 70% of its capacity and it will be assumed that the BLEVE takes place quickly after flame contact, so all the fuel is still present. Table 14 gives the fireball characteristics for a point 100 m away from the tank.

Table 14. Fireball parameters.

Parameter	Value
Propane mass (kg)	28700
Fireball Diameter (m)	178
Fireball duration (s)	11.7
Fireball Height (m)	133
Radiant fraction	0.266
Emissive power (kW/m^2)	300
Distance from target (x) (m)	100

Parameter	Value
Distance fireball – target (d) (m)	77.5
View factor	0.29
Atmospheric transmissivity (τ)	0.685
Fire intensity (kW/m^2)	35.35
Probit	5.66

The probit value that was obtained leads to a death probability of 75%. So,

$$IR_{Tank\ fireball} = 0.75 \cdot\ 2.9 \cdot 10^{-8} = 2.18 \cdot 10^{-8}\ fatalities/year \quad (2)$$

Overpressure

The results of applying the same procedure (eq 18-22) as in the previous section are shown in Table 15.

Table 15. Overpressure of the tank BLEVE.

Parameter	Value
Superheat Energy (kJ/kg)	165.3
Energy released (kJ)	$4.75 \cdot 10^6$
W TNT (kg TNT)	50.9
d_N (m/kg^3)	27
ΔP (bar)	0.0008

The obtained overpressure does not suppose a threat to a target located at 100 m, even though it is 7 times larger than the caused by the road tanker BLEVE.

3.3.4.4 Total IR

The total IR will correspond to the flash fire caused by a flammable cloud and to the BLEVEs fireball. The total risk is:

$$\Delta IR = 2.04 \cdot 10^{-5} + 1.27 \cdot 10^{-6} + 2.18 \cdot 10^{-8} = 2.17 \cdot 10^{-5}\ fatalities/year \quad (1)$$

3.3.5 Wildfire risk assessment

Section 3.2 gave an insight into the importance of taking into account the possibility of a wildfire taking place. Catalunya, as all the Mediterranean cost and southern Europe, is threatened by wildfires frequently and, according to the tendency and the future perspectives warned by several studies collected for this thesis, it will be more threatened in the future. Catalunya government has been collecting climatological data and using the FWI in order to create a daily wildfire risk map that classifies the risk in 5 categories between low and extreme.

The studied tank would only be affected by a wildfire in case of such wildfire takes place and propagates until the installation (Khakzad et.al., 2018).

$$P(wildfire) = P\ (Small\ fire) \cdot P(Wildfire|Small\ fire) = PI \cdot PB \quad (23)$$

Where PI refers to the probability of ignition and PB the probability of that ignition to burn and propagate across the area. Related to this, Catalan government along with the Forest Sciences Centre of Catalonia developed a map of the fire regime of different regions of Catalunya based on the type of vegetation and meteorological conditions (Previncat, 2020). As it was stated in 3.3.1 (Scenario Description), the tank is in a plant located in Alt Empordà where the wildfire probability is found to be 0.0204 year^{-1} (one wildfire in 49 years). The types of ignitions caused by wildfire were previously stated in Section 2.1, and, taking into account the scenario situation, only radiation and firebrand's threats must be considered. On the other hand, just BLEVE occurrence will be considered since immediate ignition is assumed to be sure and no cloud that may lead to flash fire would be formed in that case.

3.3.5.1 Direct Road Tanker/Storage Tank BLEVE

Frequencies of a BLEVE are found to be $2.9 \cdot 10^{-8}$ and $7.05 \cdot 10^{-5}$ year^{-1} for the storage tank and the truck respectively. However, this frequency does not account for the possible harm that wildfire may cause on the structures. Radiation is considered the only possible path to tank ignition attending to the distance between the vegetation on fire and the installation. Thus, in order to obtain a more accurate frequency that actually entails wildfire impact, wildfire frequency must be obtained. Taking into account the installation location, the wind origin probability and how prone is the area to have vegetation and relative humidity that favours the propagation and enough residence time flame to cause tank failure, an overall frequency is obtained (Table 16).

Table 16. Overall frequency of wildfire able impact the tank.

	Frequency / Probability
Wildfire frequency	0.0204
Wind blowing in tank direction probability	0.017
Dry and favourable conditions to high residence time flame probability	0.2
Overall frequency	**$6.94 \cdot 10^{-5}$**

The event tree that describes this scenario is shown in Figure 36. The wind rose of the area (Figure 31) states that the wind blows from the west to the east 1.7 % of the time and the FWI for the fire season in the Alt Empordà area indicates moderate risk, which is translated to 20% probability of presenting conditions that lead to flames with sufficiently high residence time to cause tank failure (Ricci et.al., 2021).

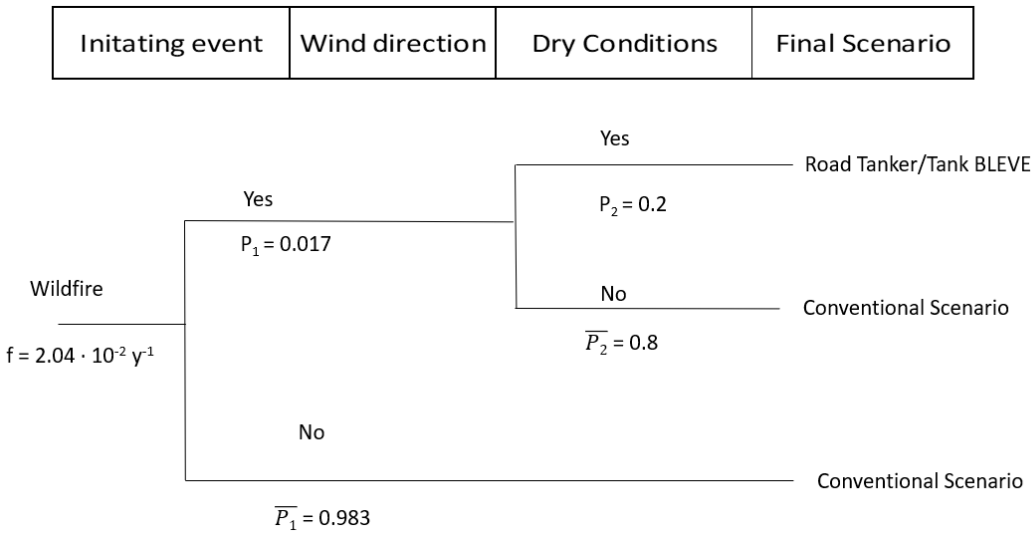

Figure 36. BLEVEs due to wildfire event tree.

Therefore, the BLEVE frequency resulting from this new event tree ($6.94 \cdot 10^{-5}$ y^{-1}) must be added to the one developed in the conventional QRA. This way:

$$f\ (Tank\ BLEVE) = f(Conventional) + f\ (Wildfire) = 6.94 \cdot 10^{-5} + \ 2.9 \cdot 10^{-8} \approx \quad (24)$$

$$\approx 6.94 \cdot 10^{-5}\ year^{-1}$$

$$f\ (Road\ Tanker\ BLEVE) = f(Conventional) + f\ (Wildfire) \quad (24)$$
$$= 6.94 \cdot 10^{-5} + \ 7.05 \cdot 10^{-5} = \ 1.4 \cdot 10^{-4}\ year^{-1}$$

And the corresponding Individual Risk:

$$IR_{\,Tank\ BLEVE} = \ 6.94 \cdot 10^{-5} \cdot 0.75 = 5.2 \cdot 10^{-5}\ fatalities/year \quad (2)$$

$$IR_{\,Road\ Tanker\ BLEVE} = \ 1.4 \cdot 10^{-4} \cdot 0.018 \ = 2.52 \cdot 10^{-6}\ fatalities/year \quad (2)$$

3.3.5.2 Flexible pipe LOC

On the other hand, besides the conventional full-bore rupture of the flexible pipe (Figure 37), loss of containment in this part of the structure can also take place due to firebrands coming from the wildfire and landing on the pipe wall, which is probably made of polymers. The special danger that polymers have was mentioned in Section 2.1.1. Therefore, an estimation of the frequency of this event is made assuming that 5% of the wildfires would release firebrands that reach and ignite the flexible pipe, resulting

$$f\ (Firebrands) = 6.94 \cdot 10^{-5} \cdot 0.05 = 3.47 \cdot 10^{-6}\ y^{-1} \quad (25)$$

Under these conditions, the event tree of this scenario must be adapted since the safety barriers are affected by the unusual situation. The safety barriers are influenced by the Performance Modification Factors introduced on Misuri et.al (Misuri et. al., 2020) and, for this analysis, immediate ignition probability is assumed to be certain (P=1), operator failure probability also increases (P=0.7) since its tasks are difficulted by the fire and, regarding the safety barriers, valve failure increases to 0.4 while fireproofing of the tank failure probability increases to 0.2 and failure of water system will be more probable (P=0.2) due to possible power shut-down caused by the fire. The event tree describing this is shown in Figure 38.

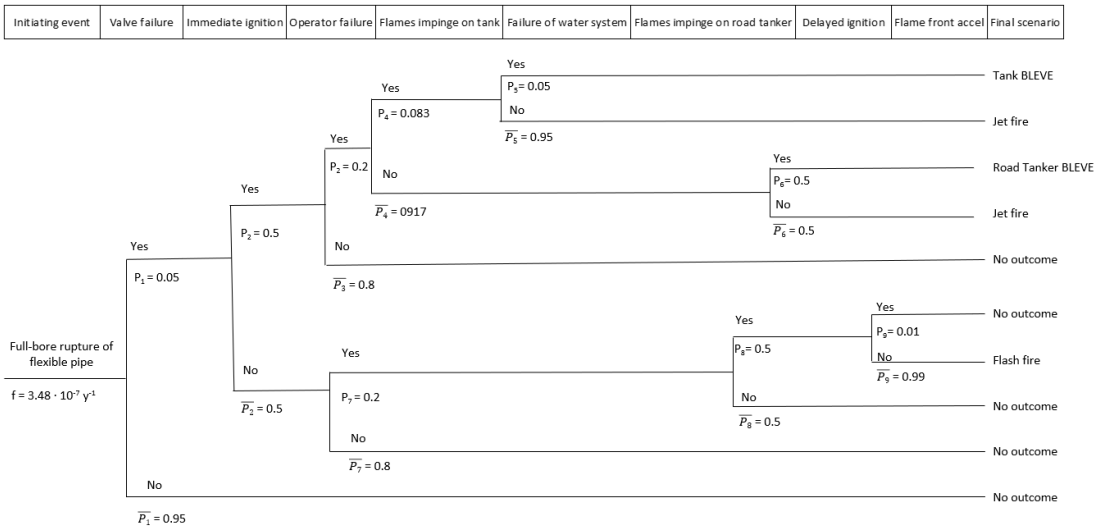

Figure 37. Conventional full-bore rupture of the flexible pipe.

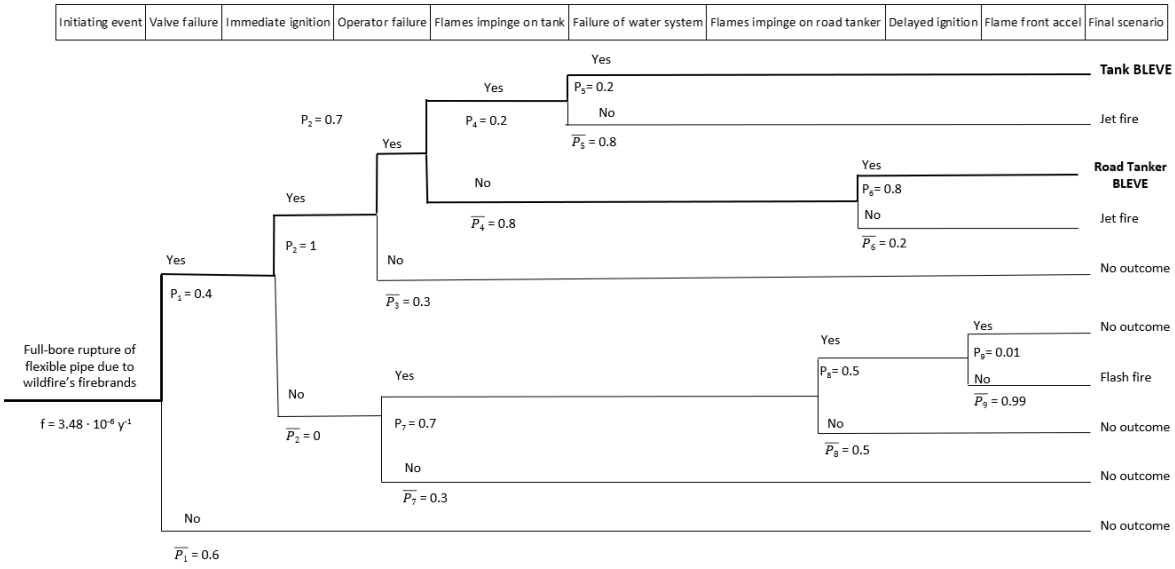

Figure 38. Full-bore rupture due to wildfire's firebrands.

The frequency for both BLEVEs is determined by means of the event tree. Such frequencies must be added to the standard ones of this initiating event since the loss of containment is still possible due to other reasons than the firebrands.

$$f\ (Tank\ BLEVE) = 6 \cdot 10^{-9} + 3{,}47 \cdot 10^{-6} \cdot\ 0.4 \cdot 1 \cdot 0.7 \cdot 0.2 \cdot 0.2 = 4.49 \cdot 10^{-8}\ y^{-1} \qquad (26)$$

$$f\ (Road\ Tanker\ BLEVE) = 8 \cdot 10^{-7} +\ 3{,}47 \cdot 10^{-6} \cdot\ 0.4 \cdot 1 \cdot 0.7 \cdot 0.8 \cdot 0.8 = 1.42 \cdot 10^{-6}\ y^{-1} \qquad (26)$$

Regarding the Individual Risk:

$$IR_{Tank\ BLEVE} = 4.49 \cdot 10^{-8} \cdot 0.75 = 3.36 \cdot 10^{-8}\ fatalities/year \quad (2)$$

$$IR_{Road\ Tanker\ BLEVE} = 1.42 \cdot 10^{-6} \cdot 0.018 = 2.56 \cdot 10^{-8}\ fatalities/year \quad (2)$$

3.3.5.3 Total IR

The IR determined for the wildfire-related scenarios must be added to the conventional ones since normal initiating events and wildfires are not excluding. Consequently, the total Individual Risk:

$$\begin{aligned} Total\ IR &= IR_{conventional} + IR_{Wildfire} = IR_{Conventional} + IR_{BLEVEs} + IR_{Firebreands} \\ &= 2.17 \cdot 10^{-5} + 5.2 \cdot 10^{-5} + 2.52 \cdot 10^{-6} + 3.36 \cdot 10^{-8} + 2.56 \cdot 10^{-8} \\ &= 7.5 \cdot 10^{-5}\ fatalities/year \end{aligned} \quad (1)$$

Which supposes a 246% increase with respect to the conventional scenario.

3.3.6 Conclusions

Two IR results were obtained in previous sections. Nine different initiating events were considered for the conventional scenario, resulting in three final potentially lethal scenarios: origination of a flammable cloud that ends up provoking a flash fire, a BLEVE in the truck that contains the propane and a BLEVE in the storage tank. Nevertheless, when taking into account the wildfire possibility, new event trees and BLEVEs frequencies are determined and added to the conventional one along with the consideration not only of ignition by heat radiation but by firebrands falling over the plastic flexible pipe. Then, with just these modified frequencies, global IR result increased by almost 3.5 times comparing it with the one found in the conventional scenario. This manifests the relevance of assessing wildfire impacts in QRAs of industrial installations since with very little modifications in the studied scenarios a considerable rise in the IR may be found. More initiating events could have been influenced by the action of wildfires, aggravating the gap between conventional and wildfire-influenced QRAs.

Conclusions

The importance and severity of the so-called NaTech events, and more specifically the ones triggered by wildfires has been assessed in this thesis. It has been verified that wildfire frequency is increasing during the last decades and, therefore, the need for deeper research regarding its impact on industrial installation arises. Concerning this issue, several industrial equipment was studied in order to figure out which are the most vulnerable units when a wildfire takes place in the proximities of the plant and in which way can the wildfire disturb the unit. Equipment storing heat sensitive substances and tanks storing flammable substances are found to be the most defenceless equipment against wildfires along with units or pieces made of polymers. Besides, a review of accidents and near misses related to the action of wildfires was carried out allowing to draw certain conclusions about the type of ignition routes and the type of industry affected. Pipelines are predominantly affected since an important number of them cross large extensions of forests and vegetation susceptible of suffer a wildfire.

On the other hand, a comprehensive analysis of two specific accidents was performed. From it, detailed scrutiny of the causes and consequences was obtained, highlighting the possible effects that a wildfire can have on an installation: from direct effects like the embers igniting the venting to the indirect effects like the power supply shutdown of the mine. These analyses were executed by means of qualitative methods of hazard identification and accident description.

Besides, QRA for a pre-set scenario was performed first from a conventional approach and then considering wildfire probability. The IR was obtained for both situations, being the one calculated taking into account wildfire as initiating event more than three times higher than the one for the standard situation. Related to this, more thorough analysis would be pertinent in order to obtain a more accurate estimation of the result gap between conventional QRA and the ones that account for NaTech events. This could be achieved by finding specific factors to describe the safety barriers performance modification under wildfire conditions and by applying more exhaust examination of possible final scenarios caused by wildfires that may have not been taken into account in this case scenario.

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Annex I: Survey of Accidents

Accident number	Location	Date	Main Wildfire triggering event	Type of impacted /threatened infrastructure	Direct Impact type	Indirect Impact type	Remedial measures	Consequences (ARIA model):
1	Osage, Ok, USA	12/04/21	Grass fire	Oil pipeline	Direct flame contact	No indirect impact	The main river was boomed of for containment	Release of crude oil into the river DMR: aprox 1400 kg (3% Seveso threshold) 3/6 Human/social: 0/6 Environmental: +100000 m3 water affected 4/6 Economical: no data. 1/6 (assumed 10-50k€ to clean)
2	Pawhuska, OK, USA	14/4/21	Grass fire	Brine pipeline	Direct flame contact	No indirect impact	Removing all materials with a	Release of brine into the river. DMR: 0/6 (brine) Human/social: 0/6

							vacuum truck	Environmental: 1/6 3Economical: 1/6
3	Rustic, CO	20/7/2021	Forest fire	Pipeline	Flame contact	Burn scars created after wildfires facilitate mud slides.	Remove the debris and clean up the area.	DMR: 1/6 (unknown amount of oil) Human/social: 0/6 Environmental: 1/6 Economical: 1/6
4	Roseburg, OR, USA	13/9/2020	2020 Oregon Wildfires	Supermarket warehouse	No direct impact (smoke)	No indirect impact	No actions	DMR: 0/6 Human/social: 1/6 Environmental: 0/6 Economical: 0/6
5	North Fork,		2020 Creek fire	Turbine from power plant	Flame contact	No indirect impact	San Joaquin River was	DMR: 1/6 (1 gallon) Human: 0/6 Environmental: 1/6

	Madera, CA	17/9/2020		(San Joaquín Valley Energy)			boomed as security system. The facility was unable to clean up the location due to the brush fires in the area.	Economical: 1/6
6	Mill City, OR link	9/9/2020	Beachie creek fire	Big Cliff Dam	Flame contact	Transmission lines were shut down: evacuation and electronical systems not working	Once fire was contained and evacuation order was lifted, USACE returned to facility to perform additional	DMR: 1/6 (10 gallons) Human: 0/6 Environmental: 1/6 Economical: 2/6

							assessment and response. (Same fire also affected Detroit dam)	
7	White River Canyon, OR	24/8/2020	White River Fire	Helicopter	Unknown if any contact with flame	Fuel and oil leak	Recovery of the crashed helicopter and cleaning of the leaked combustible.	DMR: 2/6 (50 gallons of diesel aprox 0,4% of Seveso limit) Human: 3/6 (Pilot killed) Environmental: 1/6 Economical: 1/6
8	Linn, OR	13/9/2020	2020 Oregon Wildfires	Warehouse/ Distribution Center	No direct impact (smoke)	No indirect impact	No actions	DMR: 0/6 Human: 1/6 Environmental: 1/6

								Economical: 0/6
9	Salem, OR	15/9/2020	2020 Oregon Wildfires	Warehouse/Distribution Center	No direct impact (smoke)	No indirect impact	No actions	DMR: 0/6 Human: 2/6 (H6) Environmental: 0/6 Economical: 0/6
10	Santa Rosa, Ca link link	11/2017	Tubbs fire	Benzene pipelines and water supply system	Radiation over benzene pipe	No indirect impact	Some services line must be replaced	DMR: 2/6 Human: 2/6 (H8) Environmental: 2/6 Economical: 3/6 ($3.4m)
11	Hazelwood, Virginia, Australia (Teague, 2014)	9/02/2014	Hernes-Oak fire	Hazelwood coal mine	Embers entering the barriers of the mine	Power lines burnt in the fire.	Prevent the fire from spreading towards the mine	DMR: 2/6 Human: 4-5/6 (341 survey people with symptoms) Environmental: 3/6 (buscar más) Economical: 5/6 (+100mAU$)

12	Fort McMurray, Alberta, Canada link	05/2016	Fort McMurray Fire	Oil sands plants and pipelines	No direct impact	No indirect impact	Preventive shutdowns of pipeline carrying diluents. Reduction of barrels produced per day.	DMR: 0/6 Human: 2-3/6 (tens of installations shut down) Environmental: 0/6 (no consequences due to wildfire contact with pipes) Economical: 6/6 (€15, 3.6BCA$)
13	Esmeraldas, Ecuador link	10/2018	Brush fire	Esmeraldas refinery	No direct impact	No indirect impact	Fire extinguished before it reached the plant.	DMR: 0/6 Human: 0/6 Environmental: 3/6 (9 Ha of brush burnt) Economical: 1/6
14	Fairbanks, AL link	07/2015	Aggie Creek Fire	Alyeska Trans-Alaska Pipeline	Flame contact	No indirect impact	Controlled, preventive burn to clean the pipe from	DMR: 0/6 Human: 0/6 Environmental: 0/6

							combustible material.	Economical: 1/6
15	Bay point, San Francisco, CA link	10/2018	Grass fire caused by a fallen power line	Natural gas pipeline	Direct flame impingement	No indirect impact	Pipeline purged with nitrogen in order to remove natural gas.	DMR: 0/6 Human: 4/6 (H7: 4000 evacuated for a few hours) Environmental: no data Economical: no data
16	Goyang, KR Link	10/2018	Grass fire caused by a lost sky lantern	Oil storage facility. Gasoline tank.	Flame contact	No indirect impact	Firefighters extinguished the fire.	DMR: 3/6 (21000 t of TNT eq 4% of gasoline Seveso threshold) Human: 1/6 Environmental: 0/6 Economical: 3/6 (3.7M$)
17	Agoura, Los	11/2018	Woolsey fire	Landfill. Gas collection system.	Flame contact	GtE power plant shut down	Key equipment moved to	DMR: 0/5

	Angeles, Ca (Pipeline journal Jan 2019						safe areas of the plant. Staff evacuated. An emergency generator was brought to restore the gas collection system	Human: 2/6 (tens of workers unable to work) Environmental: 2/5 Economical: 3/6 (+2M$)
18	Flegentreu, Brandenburg, Germany link	06/2019	Brandenburg fires	Former military training ground and biogas plant.	No contact	No contact	Firefighters and army extinguished the fire. Aerial support. It was intended to adapt the vegetation	DMR: 0/6 Human: 2/6 Environmental: 2/6 Economical: 1/6

							to avoid further fires and reconstruct the area.	
19	San Clemente, CA link	11/2018	Woolsey fire	Decommissioned nuclear generation station	No contact	No contact	Evacuation of non-essential workers. Surrounding vegetation	No consequences DMR: 0/6 Human: 0/6 Environmental: 0/6 Economical: 0 /6
20	Cleveland, OK	07/04/2017	Grass fire	Oil pipeline	Direct contact	No indirect impact	Excavated and removed soil. The soil was replaced and re-seeded	DMR: 0/6 Human: 0/6 Environmental: 1/6 Economical: 0 /6

21	Redding, CA	28/07/2018	Carr fire	Natural gas pipeline	Direct contact	No indirect impact	Shutting in all gas lines that can be accessed.	DMR: 1/6 (unknown amount) Human: 0/6 Environmental: 1/6 Economical: 2/6 ($50k)