University of Ghent

Faculty of Engineering

Department of Flow, Heat and Combustion Mechanics

Academic Year 2016-2017

RISK ASSESSMENT AND COST-BENEFIT ANALYSIS OF PROTECTION MEASURES FOR BUND FIRES IN STORAGE FACILITIES

Andres Camilo Forero Jimenez

Promoter: Bart Merci

Supervisor: Kris De Troch

Master thesis submitted in the Erasmus+ Study Programme

International Master of Science in Fire Safety Engineering

Disclaimer

This thesis is submitted in partial fulfilment of the requirements for the degree of **The International Master of Science in Fire Safety Engineering (IMFSE).** This thesis has never been submitted for any degree or examination to any other University/programme. The author(s) declare(s) that this thesis is original work except where stated. This declaration constitutes an assertion that full and accurate references and citations have been included for all material, directly included and indirectly contributing to the thesis. The author(s) gives (give) permission to make this master thesis available for consultation and to copy parts of this master thesis for personal use. In the case of any other use, the limitations of the copyright have to be respected, in particular with regard to the obligation to state expressly the source when quoting results from this master thesis. The thesis supervisor must be informed when data or results are used.

Read and approved,

Andres Camilo Forero Jimenez

April 30, 2017

Abstract

Bund fires in storage facilities are a big concern due to the risk of fire escalation to multiple tanks. Thus, the fire protection measure requirements have become more stringent.

However, the risk has not been properly assessed to establish fire protection requirements. Therefore, some fire protection strategies may not be economically beneficial due to the high implementation cost.

The aim of this work is to perform a quantitative risk assessment for bund fires and thus, a cost-benefit analysis of the bund fire protection measures.

A methodology is developed to determine whether a fire protection measure(s) is economically beneficial or not, according to the risk level. The most common bund fire protection measures are discussed and evaluated. Then, a case study is presented to exemplify the methodology applicability.

The results show that the some common fire protection measures are not economically beneficial for the actual bund fire risk level. Nevertheless, these protection measures might become a feasible option if other risks were considered in the assessment.

Resumen

Los incendios en los diques de las unidades de almacenamiento son de gran preocupación debido al riesgo de un incendio que envuelva múltiples tanques. Por lo que, los requerimientos en las medidas de protección contra incendios se han vuelto más estrictas.

Sin embargo, el riesgo no ha sido evaluado apropiadamente para establecer los requerimientos en protección contra incendios. Por lo tanto, algunas estrategias de protección contra incendios puede que no sean económicamente favorables debido a su alto costo de implementación.

El objetivo de este trabajo es realizar un análisis cuantitativo de riesgos para incendios en diques y seguidamente, un análisis de costo-beneficio de las medidas de protección contra incendios.

Una metodología es desarrollada para determinar si una medida de protección contra incendio es económicamente favorable o no de acuerdo con el nivel de riesgo. Las medidas contra incendio en diques más comunes son discutidas y evaluadas. Luego, un caso de estudio es presentado para ilustrar la aplicación de la metodología.

Los resultados muestran que algunas de las medidas comunes de protección contra incendios no son económicamente favorables para el nivel real de riesgo de un incendio en un dique. No obstante, estas medidas de protección podrían ser una opción rentable si otros riesgos fueran considerados en el análisis.

Acknowledgments

This thesis project would not be possible without the support of many people, to whom I would like to express my gratitude.

To Kris De Troch and Ralf Bruyninckx, who assisted me with their interminable understanding about industrial fire protection engineering and allowed me to obtain new knowledge and skills.

To my promotor, Bart Merci, who always encouraged us to perform better and who taught us to think beyond what is evident.

To my family. My parents Hector and Mercedes who are my role model and have unconditionally supported me. To Yuliana, who is my mirror and of whom I am very proud. To Marisol, Emmanuel, Iahaira and Cesar, who have made me miss home.

To Isabel, for always being there for me and for making me a better person.

To the all the IMFSE staff, who have made this remarkable life experience possible.

Table of Contents

Abstract III

Resumen III

Acknowledgments IV

Table of Contents V

List of Tables VIII

List of Figures X

1. Introduction 1
   - 1.1. Atmospheric Storage Tanks 2
     - 1.1.1. Fixed Roof Tanks 2
     - 1.1.2. Internal Floating Roof Tank 3
     - 1.1.3. Open Top Floating Roof Tank 3
   - 1.2. Storage Terminal Fires 4
     - 1.2.1. Rim Seal Fires 5
     - 1.2.2. Spill on Roof Fires 5
     - 1.2.3. Full Surface Fire 5
     - 1.2.4. Bund Fire 6
     - 1.2.5. Boilover 6
     - 1.2.6. Multiple Tank Fire 6
   - 1.3. Fire Protection Measures 7
     - 1.3.1. Passive Fire Protection 7
     - 1.3.2. Active Fire Protection 8
     - 1.3.3. Fire Brigade Intervention 9
2. Objectives and Methodology 11
   - 2.1. Objectives and Scope 11
   - 2.2. Methodology 11
3. Bund Fires – Risk Based Analysis 13
   - 3.1. General Framework for Risk Assessment 13
     - 3.1.1. Values and Objectives 13
     - 3.1.2. System Description 13
     - 3.1.3. Risk Evaluation 14
     - 3.1.4. Risk Management 14
   - 3.2. Risk Scenarios 15
     - 3.2.1. Bund Fire Initiating Events 15

3.2.2. Frequency of Initiating Events 18
3.2.3. Risk Scenarios Analysis 20
3.3. Likelihood Estimation 21
3.3.1. Event Tree Analysis 21
3.3.2. Bund Fire Likelihood Analysis 23
3.4. Consequences Estimation 25
3.4.1. Consequences on Values 25
3.4.2. Calculation Method 29
3.4.3. Consequence Estimation Analysis 32
4. Risk Reduction Measures 34
4.1. Passive Fire Protection Measures 34
4.1.1. Separation Distance and Bunds 34
4.1.2. Fireproof Coating – Double Shell Tanks 35
4.2. Active Fire Protection Measures 36
4.2.1. Instrumented Systems 37
4.2.2. Water Cooling Systems 39
4.2.3. Foam Systems for Tanks 40
4.3. Firefighting Intervention 42
4.3.1. Escalation probability 42
4.4. Layers of Protection Scheme – Bow Tie Diagram 43
4.5. Risk Reduction Measures Analysis 44
5. Cost-Benefit Analysis 45
5.1. Risk Annualised Cost 45
5.2. Risk Reduction Measures Cost 45
5.2.1. Bund and Separation Distances 45
5.2.2. Heat Insulation – Fire proofing 46
5.2.3. Instrumented Systems 47
5.2.4. Cooling Water Systems 47
5.2.5. Fixed Foam Systems 49
5.3. Cost-Benefit of Risk Reduction Strategies 50
6. Case Study 52
6.1. Risk Scenarios 53
6.2. Likelihood 53
6.3. Consequences 54

6.3.1. Life Loss 55
6.3.2. Property Loss 55
6.3.3. Business Interruption Loss 56
6.3.4. Environment Loss 56
6.3.5. Reputation Damage 56
6.3.6. Annualised Consequences 56
6.4. Risk Reduction Measures 57
6.4.1. Bund and Separation Distances 57
6.4.2. Heat Insulation – Fireproofing 58
6.4.3. Instrumented System 59
6.4.4. Water Cooling System 59
6.4.5. Fixed Foam Systems 61
6.4.6. Fire Brigade Intervention 62
6.5. Cost-Benefit Analysis 63
6.5.1. Risks not Contemplated 64
6.5.2. Combination of Protection Measures 66
6.5.3. Uncertainty Analysis 67
7. Conclusions 71
7.1. Risk Assessment 71
7.2. Risk Reduction Measures 71
7.3. Cost-Benefit Analysis-Case Study 72
7.4. Uncertainty 72
7.5. Limitations and Future Work 73
8. References 74
Annex A. Heat Radiation Results 78

List of Tables

Table 1. Probabilities for initiating events. 15
Table 2. Frequencies for tank shell failure and leakage according to Belgian authorities. 19
Table 3. Frequencies for tank shell failure and leakage according to Dutch authorities. 19
Table 4. Frequencies for pipeline failure and leakage according to Belgian authorities. 19
Table 5. Frequencies for above ground pipeline failure and leakage according to Dutch authorities. 20
Table 6. Direct ignition probability according to Dutch authorities. 22
Table 7. Direct and delay ignition probability according to Belgian authorities. 22
Table 8. Probability of a person dying due to heat exposure. 25
Table 9. Purchase cost for different atmospheric tanks 26
Table 10. Commonly Stored Product Prices 28
Table 11. Distances Tank-Tank and Bund-Tank according to different legislations 34
Table 12. Frequencies for overfill individual failures 38
Table 13. Cooling water system efficiency according to the flowrate density 40
Table 14. Fixed foam pouring devices according to the bund area. 41
Table 15. Average cost of insulation material 46
Table 16. Average market price of instruments per tank 47
Table 17. Average market price of a water cooling system. 48
Table 18. Average market price of a fixed foam system. 50
Table 19. Storage Facility Tank Description – Case Study 52
Table 20. Storage Facility Bund Description – Case Study 53
Table 21. Frequencies of Bund Fire Scenarios– Case Study 54
Table 22. Heat Flux Values for Bund Fire Scenarios – Case Study 54
Table 23. Time to failure of adjacent tanks – Case Study 55
Table 24. Economic property loss estimation – Case Study 56
Table 25. Economic consequences according to the value affected – Case study 56
Table 26. Impact on economic consequences of independent bunds– Case study 57
Table 27. Cost of implementing independent bunds– Case Study 58
Table 28. Impact on economic consequences of fireproofing - Case study 58
Table 29. Cost of implementing insulation – Case Study 58
Table 30. Impact on economic losses of instrumented systems - Case study 59
Table 31. Cost of implementing automated instrumentation. - Case study 59
Table 32. Impact on the time to failure of the water cooling systems - Case study 59
Table 33. Impact on economic consequences of water cooling system. - Case study 60

Table 34. Average market price of a water cooling system – Case Study 60
Table 35. Cost of implementing fixed cooling systems – Case Study 61
Table 36. Impact on economic consequences of bund fix cooling system - Case study 61
Table 37. Average market price of a bund fixed foam system - Case study 61
Table 38. Cost of implementing bund fixed foam systems - Case study 62
Table 39. Probability of escalation with fire brigade intervention – Case Study 62
Table 40. Impact on economic consequences of fire brigade intervention - Case study 63
Table 41. Average market price of a roof fixed foam system 65
Table 42. Cost of implementing roof fixed foam systems 65

List of Figures

Figure 1. Typical design of a fixed roof tank..2
Figure 2. Typical design of an internal floating roof tank 3
Figure 3. Typical design of a double deck floating roof tank 4
Figure 4.Pantograph seal (left) and rubber seal (right) configurations 4
Figure 5.Potential tank fire scenarios. Used with authorisation..5
Figure 6.Buncefield Aftermath 7
Figure 7. Water Spray System 8
Figure 8. Bund Pouring System..9
Figure 9. General Framework for Risk Assessment 12
Figure 10. Bund spillage event tree 21
Figure 11. Bund fire event tree with frequency values of final events 24
Figure 12. Time to failure of atmospheric tanks according to the intensity of the heat radiation.........32
Figure 13. Instrumented System Scheme as a Protection Barrier for Tank Overfilling 37
Figure 14. Tank overfill fault tree..38
Figure 15. Bow-tie diagram 43
Figure 16. Bow-tie diagram for bund fire events...43
Figure 17. Tank Storage Facility Layout – Case Study 52
Figure 18. Cost benefit analysis chart of risk reduction measures –Case study. 63
Figure 19. Cost benefit analysis chart with active protection systems cost reduction–Case study.......66
Figure 20. Cost benefit analysis chart for combined reduction measures–Case study. 67
Figure 21. Sensitivity Analysis – Effect of assumption change in annualised risk (loss)....................68
Figure 22. Sensitivity Analysis – Effect of assumption uncertainty on a protection measure cost. 69
Figure 23. Sensitivity Analysis – Effect of case study specifications on the annualised risk...............69
Figure 24. Sensitivity Analysis –Effects of case study specifications on a protection measure cost. ..70

1. Introduction

Storage facilities play a very important role in modern industry. Nowadays, the increasing storage demand keeps boosting the construction of new storage facilities. Besides, the rise in both the variety of products and storage capacities make this a very challenging field.

One challenge for this industry is the storage of flammable products. Flammable substances can cause major fire incidents. Furthermore, event like the Buncefield incident (Hertfordshire, UK, 2005) showed the real magnitude of multiple tank fires. The economic losses are likely to reach billions and many stakeholders are not willing to assume the risk. As a result, the concerns have increased and many authorities are demanding for more rigours fire protection strategies to avoid multiple tank fires.

Fire regulation authorities are also urging to bring some attention to bund fires. Large bund fire scenarios are very difficult to control and they are likely to rapidly evolve into a multiple tank fire. Therefore, the risk of a large bund fire needs to be assessed and managed by selecting proper fire protection measures.

Yet, to select the wrong fire protection strategy could result in a detrimental outcome. Some fire protection measures are costly and the risk level might not justify the investment. Consequently, a cost-benefit analysis should be done to select the most beneficial and cost-effective fire protection measure.

This work aims to perform a bund fire risk assessment, to propose and discuss some fire protection measures and to do a cost-benefit analysis of the proposed protection measures and to select the most advantageous risk reduction strategy.

This work is divided in seven chapters. The first chapter presents an introduction to the topic. First, the types of storage tanks are explained. Then, the different tank fire types are described. Later, the most common fire protection strategies are briefly addressed.

The second chapter presents the objectives and methodology of this work.

The third charter shows the risk assessment methodology used to evaluates bund fire risk. The first part is focused on explaining the general framework for risk assessment. The second part defines the bund fire risk scenarios. The third part shows how to estimate the likelihood of these scenarios. And, the fourth and last part explain how to estimate the consequences of every scenario.

The forth chapter is focused on the risk reduction measures. Here, all the most common fire protection measures are discussed. The first section starts the analysis on the passive fire protection measures, such as bunds and fireproofing. The second section focusses on active fire protection measures, like overfill protection systems, water cooling systems and fixed foam systems. Finally, the last section analyses the firefighting intervention as a protection measure.

The fifth chapter presents the methodology to perform a cost-benefit analysis. The first section explains how to calculate the annualised risk loss. The second section shows how to estimate the risk reduction measures cost. This section present the major premises to estimate the cost of every protection measure. Finally, the third section gives details of the cost-benefit calculation method.

The sixth chapter applies the entire methodology to a case study. The results of the assessment are presented and discussed in detail along the chapter.

Finally, the conclusion of this work are presented in the seventh chapter. The conclusion are separated according to the section analysed. Lastly, some limitations are expressed and some future work is recommended.

1.1. Atmospheric Storage Tanks

Atmospheric storage tanks are widely used in industry to store liquids. They operate at atmospheric pressure but can withstand a small internal overpressure (up to 3500 Pa) (Mansour 2012). They can be constructed either above or underground. Above ground tanks are usually made of steel and underground tanks are often made of concrete and fiberglass.

Aboveground tanks are grouped and placed in bunds, which act as a spill collector. Atmospheric tanks are further classified according to their type of roof. They are divided in:

- Fixed roof tanks
- Internal floating roof tanks
- Open top floating roof tanks

Each of these types of tanks are described below.

1.1.1. Fixed Roof Tanks

Tanks with fixed roofs include cone roof tanks, dome roof tanks and column supported tanks. In all cases, the roof is fixed (e.g. welded) to the tank walls. Fixed roof tanks are the cheapest to construct (for small diameters) and can store a wide range of liquids, from crude-oil to petroleum derivate products with high flash points. The liquid level inside the tank varies as loading and unloading processes take place, leaving always an empty space between the roof and the liquid surface. Figure 1 (MC Integ 2017) shows the typical design of a fixed roof tank fire.

As atmospheric tanks are designed for low pressure changes, they are provided with a pressure relief valve design to prevent internal overpressure or excessive vacuum, as the liquid level changes. Nevertheless, the relief valve will not protect the integrity of the tank from an internal explosion. In case of extended fire exposure, the liquid and the vapour inside the tank start to heat up, causing the pressure to rise. If a flammable mixture is formed above the liquid surface, the presence of an ignition source would cause an internal explosion. This internal explosion might lead to a total surface fire and even the total failure of the tank. (Centrum Industriële Veiligheid 2017) (Mansour 2012)

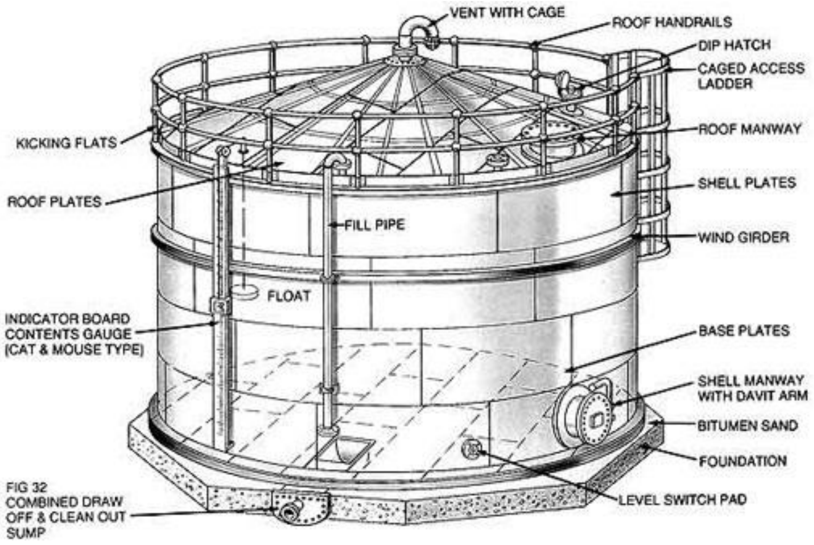


Figure 1. Typical design of a fixed roof tank

1.1.2. Internal Floating Roof Tank

Internal floating roof tanks are similar to fixed roof tanks but with an internal layer floating on the liquid. The internal roof is usually made of a light material like aluminium or some polymers. The most common type of internal floating roof is the aluminium pontoon type. Figure 2 (Tianjin Anson International Co. Ltd. 2017) shows the typical design of an internal floating roof tank.

These tanks commonly used for volatile flammable or toxic products that in a fixed roof tank would escape to the atmosphere thought the venting valve when the pressure rises. The presence of the internal roof reduces considerably the product losses to the atmosphere. However, for this type of tanks, the risk of explosion increases when flammable vapours accumulate between the fixed and the floating roof.

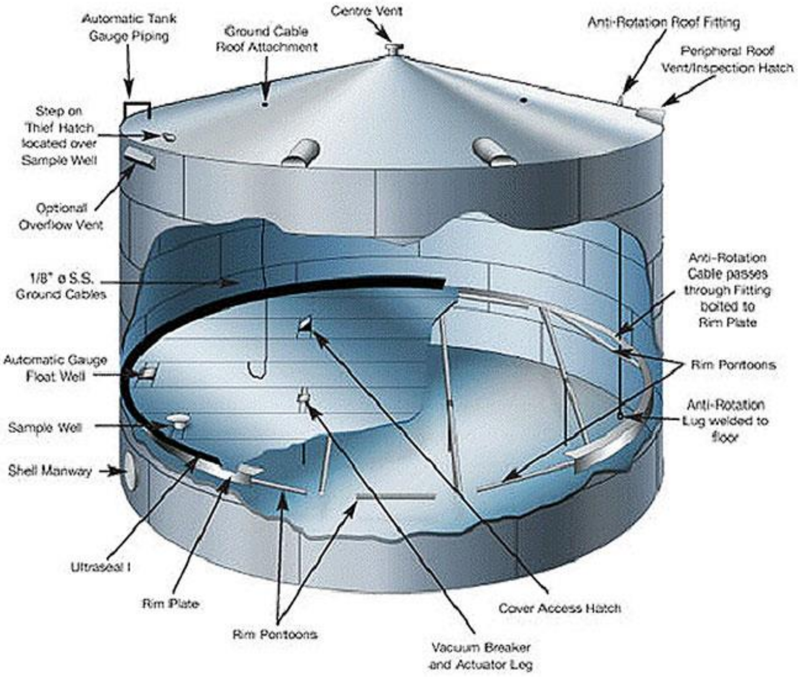


Figure 2. Typical design of an internal floating roof tank

1.1.3. Open Top Floating Roof Tank

For open top floating roof tank, the roof floats on the liquids product surface. It considerably reduces the vaporization and loss of the volatile products. Nonetheless, the floating roof is exposed to overloads like snow, rain and ice, what might cause it to sink.

These tanks are becoming more popular in industry because they tend to be cheaper to construct for large diameter tanks. Floating roof tanks may be used to store several product from crude oil to all volatile liquid products.

The flotation of the roof is achieved by the use of either a pontoon single deck roof or a double deck floating roof. Pontoon roofs have a compartmented annular ring of pontoons and a centre single deck which slightly slopes downwards towards the centre of the tank. Double deck roofs have two decks joined by a set of concentric rims. The air in between the decks acts as an insulation layers from environmental conditions. Figure 3 (EPA 2006) shows the design of an open top floating roof tank. (Centrum Industriële Veiligheid 2017)

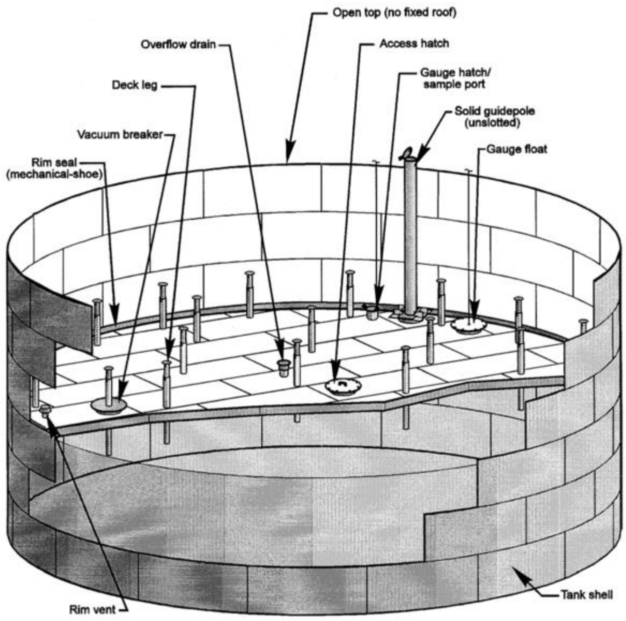


Figure 3. Typical design of a double deck floating roof tank

There is a seal around the rim of the roof that prevent the product from leaking out of the tank. The most used sealing devices range from rubber or foam tubes, to pantograph mechanism (e.g. mechanical seal). Figure 4 (Centrum Industriële Veiligheid 2017) shows both types of rim seals.

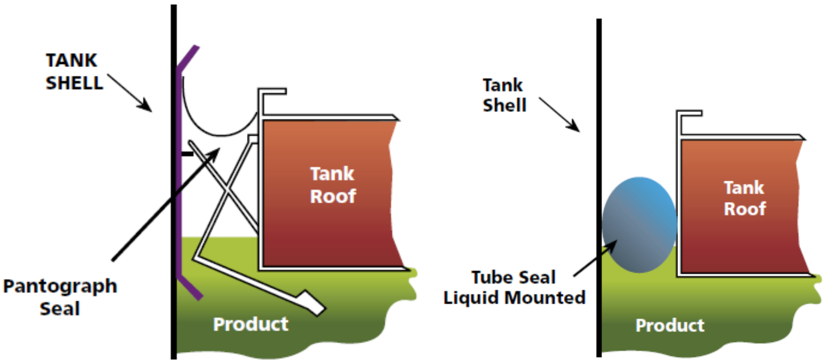


Figure 4.Pantograph seal (left) and rubber seal (right) configurations

Although floating roof are design to prevent vapours escaping the tank, flammable vapours can flow through the rim seal where they can be ignited. According to LASTFIRE project, rim seal fires are the most common fire scenarios in industry, though rim seal fires are unlikely to escalate to bigger fire events (Argyropoulos, et al. 2012).

In case of an external fire exposure for long periods of time, vapours will locally form on the side exposed to the fire. This would cause a local pressure rise under the floating roof, close to the seal area creating an asymmetric tension on the roof. If these vapours locally generated are not release through the pressure relief valve, the force generated might tilt the roof and cause it to sink (Mansour 2012).

1.2.Storage Terminal Fires

Storage tank fires are not uncommon in industry and economic losses of large fire events tend to be considerably high due to the amount of product involved. Besides, companies tend to construct larger and larger atmospheric tanks to store, in most of cases, large amounts of flammable products. Under these circumstances, a single fire event might represent a great risk due to the amount of flammable liquid stored in a single tank.

However, not all fire events carry the same consequences. The main types of fire event in storage facilities are:

- Rim seal fire – Floating roof tanks
- Spill on roof fire
- Full surface fire
- Bund fire
- Boilover
- Multiple tank fire – domino effect

Figure 5 (Argyropoulos, et al. 2012) shows all the main types of fire events that may occur in a storage facility. Each of the fire types mentioned are described below (Crippa, et al. 2009).

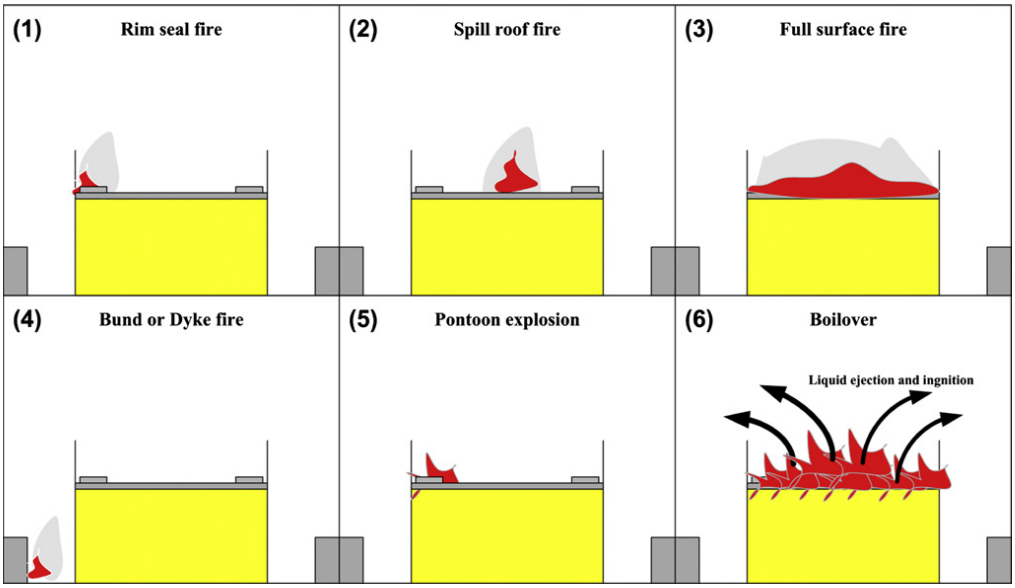


Figure 5.Potential tank fire scenarios. Used with authorisation

1.2.1. Rim Seal Fires

A rim seal fire occurs when the seal material fails at some part of the rim, allowing the flammable vapours to escape the tank and ignite, creating a rim seal fire. Rim seal fires are the most common fires in tanks. The fire extend might vary from a small localised area to the whole circumference of the tank. If the fire is not extinguished, it might spread causing the roof to fail. As a result, the rim seal fire might become a full surface fire.

1.2.2. Spill on Roof Fires

A spill on roof fire occurs when flammable product spilled on the roof ignites, but the roof maintains its integrity. The presence of flammable liquid on the roof may be caused by the rupture of some part of the floating roof, or liquid expelled through the pressure relief valve. Similar to rim seal fires, spill on roof fire might lead to a full surface fire.

1.2.3. Full Surface Fire

A full surface fire occurs when the roof of a floating roof tank loses its integrity and sinks or when an internal explosion occurs inside a fixed roof tank. The flammable product then ignites causing the full surface of the tank to be covered by flames.

Full surface fire might be consequence of smaller fires like rim seal fires of spill on roof fires that were not properly controlled. Full surface fires are a big concern for tank storage facilities because they are hard to extinguish and might escalate to a multiple tank fire.

1.2.4. Bund Fire

A bund fire is a type of fire that occurs within the containment area outside the tank shell. This kind of fires might vary from small spill fires up to a fire covering the entire bund surface. This type of fires may be caused the rupture of pipelines, rupture of the tank shell, tank overfilling, among others. Ignition is usually generated by an external source.

A bund fire is likely to affect other storage tanks located inside the bund. If the fire is not controlled, the single tank fire will grow to involve multiple tanks.

1.2.5. Boilover

Boilover is an extremely hazardous situation. It occurs when a fire starts to heat up the water settled at the bottom of the tank, below the flammable liquid layer. At some point, the water violently vaporises causing a rapid volume expansion. This volume expansion causes the burning hydrocarbon to be expelled out of the tank, travelling several meters away. Boilover might lead to a multiple tank fire scenario.

1.2.6. Multiple Tank Fire

Many of the fire scenarios discussed above might evolve to cause a multiple tank fire scenario. Fire escalation to multiple tanks, also called ‘domino’ effect, is a big concern because it might cause considerably high economic, environmental and social negative consequences. Moreover, multiple tank fire scenarios are hard to extinguish and require a huge effort to control.

Although consequences of multiple tank fire might be large, recent efforts to prevent these events make domino scenarios not very likely events. Nevertheless, some recent events have put the topic into debate again. The enquiry about how well prepare the industry is to prevent and/or mitigate the event is still an open discussion. Some of the most disastrous recent events involving multiple tank scenarios are:

- Caribbean Petroleum Tank Terminal, Puerto Rico, 2009
- Indian Oil Company, 2009
- Buncefield, UK, 2005

1.2.6.1. Caribbean Petroleum Tank Terminal - CAPECO

One night of October of 2009, a large explosion occurred in a Caribbean Petroleum Corporation fuel storage facility in Bayamon, Puerto Rico. A tank overflowed light hydrocarbon during loading process, the liquid vaporised and ignited causing a large explosion. The blast affected 17 more tanks causing secondary fires that lasted for 60 hours. (U.S. Chemical Safety and Hazard Investigation Board 2015)

1.2.6.2. Indian Oil Company

Also in October of 2009, a large leak occurred during a product transfer process. The leak created a pool, vapours ignited and created an explosion that affected 11 tanks. The fire persisted for 11 days before being extinguished. As a result, 11 people died. (U.S. Chemical Safety and Hazard Investigation Board 2015)

1.2.6.3. Buncefield

In December of 2005, 300 tonnes of volatile hydrocarbon overfilled a storage tank in the Hertfordshire Oil Storage facility, also known as Buncefield, located in Herefordshire, England. Part of the fuel evaporated, spread and ignited causing a massive explosion which cause several damages on adjacent tanks. The consequent fire involved 23 storage tanks and lasted for 5 days before being extinguished. Although nobody was killed by the event, 43 people were injured and economic losses reached £800 million. Figure 6 shows the event aftermath, the total destruction of the storage tanks involved in the multiple tanks fire. (Buncefield Major Incident Investigation Board 2008)

Figure 6.Buncefield Aftermath

1.3.Fire Protection Measures

Fire events on storage tank farms represent a considerably high risk for life and property. Moreover, in recent years, storage facilities include very large tanks and a variety of different fuels, which increases the risk and difficulties its prevention and mitigation.

Industry has responded to the increasing risk with many protection measures that reduces either the probability of the event to happen or mitigate its consequences. These protection measures may be divided in:

- Passive fire protection
- Active fire protection
- Fire brigade intervention

These protection measures are further described below.

1.3.1. Passive Fire Protection

Passive fire protection is widely used in fire engineering to mainly prevent a fire event to occur and to limit its spread and escalation. The most common passive fire protection measures used in tank farms are the use of bunds and the use of heat insulation layer or fireproofing on the tank shells.

1.3.1.1. Bunds

Bunds are made around the tank or group of tanks to contain the flammable liquid in case of leakage. Additionally, bunds should protect other tanks for fire engulfment and heat radiation in case of a pool fire event.

Bund and tank layout is used as a measure to reduce the risk of fire escalation. For this reason, to put several tanks in the same bund increases the risk of a multiple tank fire event, nevertheless for many locations it is not feasible to put every tank in a separate bund. A practical solution is to locate lower and intermediate bunds between tanks and incline the bund floor to direct the spilled liquid far away from other tanks. Standards allow to locate bund walls close to the tanks shell, however, the arrangement should allow access to firefighters.

1.3.1.2. Fireproofing

Heat insulation is often used for either pressurised or refrigerated tanks. However, new developments make it feasible to partially insulate atmospheric tanks to prevent the shell from direct flames exposure. Different materials are used as heat insulators. Some materials require an external shell too and some others do not.

Partial heat insulation may be used in combination with water cooling systems, the insulation protects the low part of the tank shell from heat radiation and the water cooling systems protects the top.

1.3.2. Active Fire Protection

Active fire protection measures are designed mainly to reduce the consequences of a fire event and to limit its escalation. Active fire protection are the most common protection measures in storage facilities. The most used measures are water cooling systems and fixed foam systems.

1.3.2.1. Water Cooling System

The main objective of water cooling systems is to cool the tanks surface from external heat radiation. The cooling effect is achieved by a ring of nozzles mounted on the tank at the top of the shell. An additional ring of nozzles may be located along the tanks height depending on the size of the tank. Figure 7 (electrical4u.com 2017) shows a basic tank water cooling system.

Figure 7. Water Spray System

1.3.2.2. Foam System

Mayor storage facility incidents show that they cannot rely just upon portable or mobile firefighting devices. Thus, fixed foam systems are installed to counterbalance the time delay caused by the mobile systems to start operating.

The type of fixed foam system depends on the characteristics of the facility, but they can be grouped in to categories:

- Tank roof fixed foam system
- Bund fixed foam system

As the scope of this work is related to bund fires, just the bund fixed foam systems are considered. Fixed foam pourers have been used for many years to protect bund areas. In case a flammable liquid leaks and ignites, the bund pourer systems control and in some cases extinguish the fire. The foam layer limits the combustion process by absorbing heat and by reducing the oxygen level. Figure 8 (Fire Dust Control 2017) shows a basic bund pouring system.

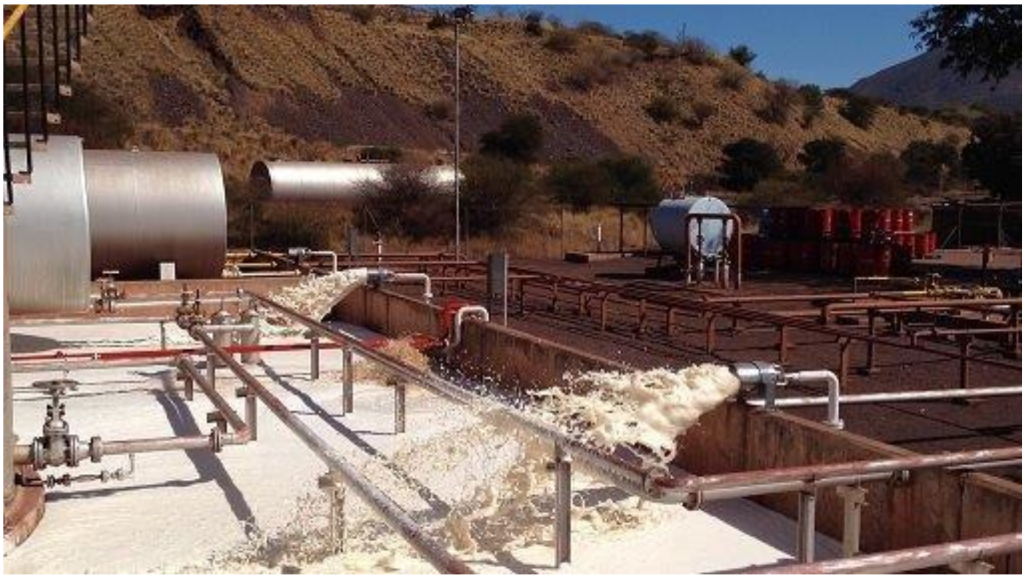


Figure 8. Bund Pouring System

1.3.3. Fire Brigade Intervention

In most of the tank fire incidents there is sufficient time to implement a firefighting strategy before the event escalates. The selection of the firefighting strategy is vital since it is very difficult to predict when the fire will escalate. The firefighting strategy strongly depends on the type of fire to deal with. The main type of firefighting strategies may be divided in:

- Rim seal firefighting strategies
- Roof spill firefighting strategies
- Bund firefighting stratifies
- Full surface firefighting strategies

All firefighting strategies are important. However, as the scope of this thesis is the bund fire events, only the firefighting strategies related to bund fires are mentioned.

In all bund fire events it is very important to avoid tanks to ignite. Time is critical since there might be multiple tanks inside the bund. In case of a bund fire, the surface should be covered by foam. The foam may be applied by either fixed or mobile systems. If the foam application requires time to start, all tanks and piping should be cooled down with a water cooling system.

For large bund areas or in case of a full tank collapse, the area should be split-up into manageable segments (for both fixed and mobile systems).

In these cases, portable foam monitors and/or pourers are recommended to fight a big bund fire, moving from controlled zones to uncontrolled zones. The strategy should be (Centrum Industriële Veiligheid 2017):

- Shutdown tank operations
- Isolate release source
- Actuate any fixed or semifixed foam system
- Actuate any rim seal foam system on exposed tanks
- Deploy portable foam monitors and pourers
- Maintain foam application until fire is extinguished and a foam blanked is developed

The bund level should always be monitored to avoid bund overfilling. The bund should be constantly drained off.

2. Objectives and Methodology

2.1. Objectives and Scope

The objectives of this work are divided into main and minor objectives. The main objective is:

- To perform a risk assessment and a cost-benefit analysis of some of most relevant protection measures against bund fire events in storage facilities

The main objective is then divided into minor objectives, which are:

- To define the risk scenarios and to design a methodology for estimating the likelihood and consequences of having a bund fire event in a storage facilities
- To identify and evaluate the effectiveness of the most relevant fire protection measures for bund fire events
- To design a methodology for assessing the cost effectiveness of every bund fire protection measure
- To illustrate the use of the methodology in a case study

The scope of this work is to evaluate the protection measures against bund fire events. Neither other tank fire events are considered in the analysis, nor any other protection measures against other risk analysed.

2.2. Methodology

The cost benefit analysis of the bund fire protection measures is based on the general framework for risk assessment methodology. The main steps of this methodology are:

- To define the risk scenarios (chapter 3)
- To calculate the likelihood and consequences of the risk scenarios (chapter 3)
- To select the most relevant protection measures against the risk (chapter 4)
- To evaluate the effectiveness of the protection measures against the risk (chapter 4)
- To estimate the risk with and without protection measures as annual economic loss (chapter 5)
- To estimate the cost of implementing every protection measures (chapter 5)
- To compare the cost of the protection measure vs the economic loss reduction (chapter 6)

Figure 9 shows the structure of the general framework for risk assessment. The risk assessment is divided in many sub-steps (Tehler 2015).

This framework is based on the standard ISO 31000 for risk management (International Starndards ISO 2009), which shares the core structure. However, this framework accounts for some additional social aspects that the ISO standard does not account and that are key for the bund fire assessment.

This risk assessment frameworks is explained in the oncoming chapters, specifically considering bund fires in the centre of the assessment.

Figure 9. General Framework for Risk Assessment

3. Bund Fires – Risk Based Analysis

One of the goals of this work is to assess the risk of bund fires. However, risk is not easy assessable. For instance, risk might be defined by either an objective or a subjective approach. The objective point of view determines risk by mathematical formulas and the outcome is a simple calculated value. On the other hand the subjective approach bases risk on social values and social perception (Hansson 2010).

To be able to assess the risk of a bund fire, it is essential to use an objective approach where the evaluation is based upon facts. However, the subjective social values should not be ignored since risk contains both subjective and objective components. To do so, a general framework for risk assessment is used to allow the different stakeholders, including the society, to use a common language (Tehler 2015). The following section explains the general framework to assess the tank fire risk.

3.1. General Framework for Risk Assessment

The following subsections define some of the features of the general framework for the field of interest. The first subsection describes the values and objectives of assessing the risk of having a bund fire. The second subsection is aimed to describe the system where bund fires might occur. Then, the next sections of the framework are analysed independently in different chapters.

3.1.1. Values and Objectives

Values are what the stakeholders care about. There are many values that might be of interest to the stakeholders. However, it is necessary to narrow down the values to a short list.

The main stakeholders interested in assessing the risk of having a bund fire are:

- Fire brigades
- Farm tank owning companies
- Farm tank operating companies
- Fire engineer (design and consultant) companies
- Risk regulation agencies

Different stakeholders might share some objectives and values but they might differ in some others. However the different objectives and values that different stakeholder care about may be grouped in:

- Prevent storage facility workers from any harm
- Prevent community members from any harm
- Limit economic losses due to damage of equipment
- Limit economic losses due to business interruption
- Limit the damage to stakeholders reputation
- Limit the harmful effect to the environment

Bund fires are of concern because of their potential to cause a domino effect where multiple tanks might fail resulting in an uncontrolled multiple tank fire which might have unwanted consequences to the above values and objectives.

3.1.2. System Description

Storage facilities play a key role in current industry. All liquid products are stored before being used or transported.

The risk awareness of storing flammable product has increased in the recent years. In the last decade several incidents involving multiple tank fires have changed the risk perception and bund fires are a big concern due to the difficulty to control this fire events. Moreover, a bund fire event might represent thousand million in losses.

Nowadays, the increase in tank capacities and number of tanks located in a single bund has caused a bund fire event to be further studied and analysed. Some risk reduction measures have been implemented to both prevent the event to happen and to mitigate the negative consequences. However, there is no certainty about their effectiveness or reliability. Thus, this risk based study will allow to analyse the risk of having a bund fire and the will allow to propose some risk management.

3.1.3. Risk Evaluation

The risk evaluation helps to quantify a risk, in this case a risk of having a bund fire scenario. The risk evaluation is divided in:

- Risk Scenarios definition
- Likelihood estimation
- Consequences quantification

The scenario definition represents a chain of events that may lead to an undesired event according to the values established beforehand.

The number of risk scenarios may be considerable. However, some practical methods facilitate their definition. A scenario for a bund fire might be a tank overfill during a loading operation and later ignition.

The likelihood estimation is about quantifying each risk scenarios probability. It is usually estimated in an annual basis and is given as an event frequency. The consequences quantification is about estimating how bad the scenario would be if it happens. It usually represent number of injuries and casualties or the total economic loss.

Once all these elements are together, the results are brought to an annual basis, which helps to interpret the results of the assessment. These results make the decision-taking task easier. The risk value is compared to the acceptance criteria. If the risk is not acceptable, the risk needs to be managed.

3.1.4. Risk Management

Once the risk has been evaluated, the decision maker needs to manage the risk. Depending on the risk evaluation, some measure might or might not be required. Risk management measures go from ignoring the risk to eliminate it. Risk management decisions consider some criteria such as social, economic or political criteria. For this work, the evaluation criteria for both risk management measures are based on a cost benefit analysis. The total cost of implementing the risk reduction measures is compared to the loss reduction according to the risk evaluation. The economic feasibility of the measure gives the final outcome of the analysis.

3.2. Risk Scenarios

The risk scenario definition is based upon statistical data. Many authors have reported statistical studies of industrial incidents and their main causes, called initiating events. These studies show that around **17% of all industrial incidents occur in storage facilities or tank farms** (Vilchez, et al. 1995). Moreover, **85% of these incidents are fires and/or explosions** (Chang 2006).

Some authors have reported that tank fire event frequencies are rather low. The tank fire frequency event might be around **1.5×10^{-4} to 3.6×10^{-4} per tank per year** (Thyer, et al. 2009) (Ryder 2017). This represents around **15 to 20 tank fires per year worldwide** (Persson and Lönnermark 2004). Nevertheless, there is very limited information regarding bund fires. Therefore, a statistical study is done below to estimate the risk scenarios that might lead to a bund fire.

3.2.1. Bund Fire Initiating Events

To estimate the initiating for a bund fire it is essential to identify first all the event that might lead to a tank fire. These initiating events can be divided in the following categories (Argyropoulos, et al. 2012):

- Lightning Strike
- Maintenance errors
- Operational errors
- Equipment/instrument failure
- Static electricity
- Tank crack/rupture
- Piping rupture/leak
- Miscellaneous
- Safety supporting systems

Among these categories, the **main fire initiating event is a lightning strike, with 33% of the total cases.** (Campbell 2014) (Chang 2006) (Rennia, Krausmanna and Cozzani 2010). Table 1 shows the probability for all the above described categories. All these categories and their influence on causing bund fires are explained below.

Table 1. Probabilities for initiating events.

Event	Probability %
Lightning strike	33.0
Maintenance Error	13.2
Operational Error	12.0
Equipment/Instrument Failure	7.9
Sabotage	7.4
Tank Crack/Rupture	7.0
Piping Rupture/Leak	6.2
Static Electricity	5.0
Others	8.3

3.2.1.1. Lightning Strike

Lightning is the major cause of tank fires. This is mainly due to poor and ineffective grounding and flammable vapours or liquid present on the rim seal

Tank fires due to lighting strikes happen more often in Oil &Gas and Petrochemical industry (around 90% of the cases). Atmospheric tanks, and floating roof tanks in special, are the most affected equipment in industry. After a strike, the probability of ignition might reach 82% (Rennia, Krausmanna and Cozzani 2010).

Incidents due to fire strikes are divided in three categories. (Wu and Chen 2016):

- <u>Fire on the rim seal.</u> The presence of flammable substances on the rim seal is unavoidable. The flammable substance is immediately ignited if the lighting strikes near the rim seal. This is the most common type of fire in the industry. The rim seal fire protection system is very likely to control the fire. Although fire escalation might occur causing a complete surface fire, it is very unlikely for a rim seal fire to cause a bund fire.
- <u>Fire on the tank roof.</u> Flammable liquid present on the tank roof is very likely to ignite if a lightning strikes on the tank roof. The presence of flammable liquid is a consequence of leakage. A lighting strike on the roof might also cause its partial or total failure (sunk). The roof perforation due to a lighting impact depends mainly on the roof thickness and surface area. It is less likely for this event to occur compared to a rim seam fire.
- <u>Bund fire due to a spillage.</u> A lighting impact on a tank wall might also cause a wall rupture and consequent leakage of flammable liquid and ignition. However, tank walls are much thicker than a floating roof. Furthermore, the relative perpendicular position of the wall makes it very unlikely for a lighting to strike directly. Wall perforation and, thus, bund fires due to lighting strikes are often neglected due to its very low probabilities.

As a result of the above discussion, lightings strikes are not considered as a relevant bund fire initiating event.

3.2.1.2. Maintenance Error

Main maintenance errors that cause tank fires are:

- Welding/cutting spark
- Use of non-explosion proof tools
- Circuit shortcuts
- Poor grounding of soldering equipment
- Improper maintenance of equipment (tanks)

Maintenance errors mentioned above contribute to the ignition of already present flammable vapours but they do not cause the spillage itself. However, poor maintenance might lead to tank or piping rupture, but these events are separately considered below. **Thereafter, maintenance errors mentioned above are not considered as a relevant bund fire initiating event.**

3.2.1.3. Operational Error

Main operational errors that cause tank fires are:

- Tank overfilling - human error in the loading procedure
- Drain valves left open inadvertently
- Oil leaks due to operators errors

- Drainage ducts to retention basin obstructed
- High inlet temperature in loading procedures
- Vent valve left closed during loading or unloading procedures

The first four events lead to a leakage and might cause a bund fire. The fifth event might cause a tank failure due to overpressure/underpressure. The sixth cause might lead to fuel evaporation and boil-over.

For this set of scenarios that can cause a bund fire, only the tank overfilling is to be considered as an initiating event. Drain and drainage valves are too small to cause a representative leakage that can fill the bund with fuel.

3.2.1.4. Equipment/Instrument Failure

Main equipment and/or instrument failure that cause tank fires are:

- Sinking of floating roof
- Tank overfill due to level control system failure
- Valves failures

Sinking of a floating roof might cause a full surface fire but not a bund fire. **Tank overfill is considered as a bund fire initiating event and is analysed below. Valves failure are not considered because the leak is too small to fill the bund in few minutes.**

3.2.1.5. Sabotage

In this category, main causes are:

- Terrorist or military attacks
- Arson or theft

This cases are not considered because they are very unlikely events.

3.2.1.6. Tank Crack/Rupture

Tank crack or rupture is often caused by:

- Poor soldering
- Shell distortion/buckling
- Shell corrosion and ground subsidence

Tank crack or rupture is considered as a main cause of bund spillage and consequent fire.

3.2.1.7. Piping Rupture/Leakage

Piping crack or rupture is often caused by:

- Valve or pump leaking
- Flammable liquid leak of gasket
- Piping material failure
- Pipe failure because of liquid expansion

These causes result in either smaller or larger liquid leakage. Piping failure is considered the only event that might cause a large liquid leakage. Gasket, valve or pump leakages are not considered to cause a large releases for an extended period of time.

3.2.1.8. Static Electricity

Static electricity can cause tank fires due to:

- Rubber seal cutting
- Poor grounding
- High fuel transfer rates during tank loading and unloading
- Improper sampling procedures

Static electricity is likely to cause the ignition of already present flammable vapours but they do not cause the spillage itself. **Thus, is not considered as an initiating event for bund fires.**

3.2.1.9. Other Fire Initiating Events

Other fire initiating events are not considered as bund fire initiating events:

- Natural disasters
- Open flames impingement
- Vehicles impacting
- Supporting safety systems failures like: electric power system, tank cooling, fire extinguishing system.

3.2.2. Frequency of Initiating Events

According to the discussion above, of all the initiating events that cause tank fires, only few events actually might cause a bund fire. The initiating events that are most likely to cause a bund fire are:

- **Overfilling due to operational error and instrument failure**
- **Tank shell rupture or leakage**
- **Piping rupture or leakage**

Each of these bund fire initiating events are discussed below.

3.2.2.1. Tank Overfilling Frequency

To estimate the overfilling frequency, there are two approaches. The first approach consist on take statistical data from literature. The second approach is to estimate the event frequency through failure analysis techniques, like fault trees.

According to statistical data recollected by LASTFIRE project, on overfill event is responsible for 19% of the total fuel leak events (Argyropoulos, et al. 2012). If it is considered that the frequency of having a liquid spill outside the tank is around $2.8x10^{-3}$/year/tank (OGP Risk Assessment Data Directory 2010), **it can be concluded that the frequency of having a tank overfill is approximately $5.3x10^{-4}$/year/tank.**

3.2.2.2. Tank Rupture Frequency

To estimate the frequency of tank rupture as an initiating event, it is easier to use literature data since this kind of events have been investigated extensively. There are many references that report tank failure frequencies. However, some of the references give a more complete description of the failure scenarios. Table 2 shows the tank leak/rupture frequencies for single shell tanks according to the Belgian authority’s statistics (Flemish Goverment 2009).

Table 2. Frequencies for tank shell failure and leakage according to Belgian authorities.

Event	Failure Frequency [$year^{-1}tank^{-1}$]
Small leak - d_{eq}=10mm	$2.4x10^{-3}$
Medium leak - d_{eq}=25mm	$2.2x10^{-4}$
Large leak - $d_{eq}=D_{max}$	$2.2x10^{-4}$
Rupture – Total Release (release in 10 min or immediate release)	$1.0x10^{-5}$

Furthermore, Table 3 shows the tank leak/rupture frequencies for single shell tanks according to the Dutch authority's statistics (Haag 1999).

Table 3. Frequencies for tank shell failure and leakage according to Dutch authorities.

Event	Failure Frequency [$year^{-1}tank^{-1}$]
Leak - d_{eq}=10mm	$1.0\ x10^{-4}$
Rupture – Total Release (release in 10 min or immediate release)	$1.0x10^{-5}$

Assuming that a bund should contain at least the total volume of the biggest tank inside the bund (and even more) (NFPA - National Fire Protection Association 2015) (European Committee for Standarization 2006), it is very unlikely for a small leakage to fill up the entire bund.

As the objective of this work is to estimate the consequences of having a bund fire that might escalate to a multiple tank fire, only the events that produce a large leakage or a total release are considered as an initiating event.

3.2.2.3. Pipeline Rupture Frequency

Similar to tank shell failure, it is easier to use literature data for pipeline failure frequencies. There are many references that report pipeline failure frequencies. However some of the references give a more complete description of the failure scenarios.

Table 4 shows the piping leak/rupture frequencies according to the Belgian authority's statistics (Flemish Goverment 2009).

Table 4. Frequencies for pipeline failure and leakage according to Belgian authorities.

Event	Failure Frequency [$year^{-1}$]
Small leak - d_{eq}=0.1D	$2.8x10^{-7}$ L/D[1]
Medium leak - d_{eq}=0.15D	$1.2x10^{-7}$ L/D
Large leak - d_{eq}=0.36D	$5.0x10^{-8}$ L/D
Rupture	$2.2x10^{-8}$ L/D

---

[1] L = Pipeline length (mm) (at least 10 m)
D = Inner pipeline diameter (mm)

Furthermore, Table 5 shows the piping leak/rupture frequencies for single shell tanks according to the Dutch authority's statistics (Haag 1999).

Table 5. Frequencies for above ground pipeline failure and leakage according to Dutch authorities.

Event	**Failure Frequency [year^{-1}]**
Leak or rupture - d_{eq}<75mm	6.0×10^{-6} L[2]
Leak or rupture - 75mm< d_{eq}<150mm	2.3×10^{-6} L
Leak or rupture - d_{eq}>150mm	6.0×10^{-7} L

As explained before in the section 3.2.2.2, a further analysis should be performed to narrow down events. **For this case it is also very unlikely for a small pipe leakage to fill up the bund. Thus, just the event that a total rupture (>150mm) is considered as an initiating event.**

3.2.3. Risk Scenarios Analysis

To summarise, according to what was discussed above, bund fire risk scenarios are based on the following initiating events:

- Tank overfill
- Tank leakage or rupture
- Piping leakage or rupture

To estimate the frequencies of the initiating events, the following criteria is followed:

- Tank overfill frequency is approximately 5.3×10^{-4}/year/tank
- Tank leakage and rupture frequencies are shown in Table 2 and Table 3. Just large leakages and total release events are considered as bund fire initiating events.
- Piping leakage and rupture frequencies are shown in Table 4 and Table 5. Just large piping leakages and rupture events are considered as bund fire initiating events.

---

[2] L=Pipeline length (m)

3.3. Likelihood Estimation

After estimating the initiating events that might cause a bund fire, the next step is to quantify the probability of having a bund fire.

Although the initiating events estimate the probability of having a fuel leak to the bund surrounding the tank, it does not estimate the chances of igniting it. To do so, an event tree analysis is performed to estimate the actual frequency of getting a bund fire from a bund leakage or spillage.

3.3.1. Event Tree Analysis

With the initiating events it is possible to quantify the frequency of having a bund fire. However, to do so it essential to quantify as well all the probable consequences that arise from the initiating event. An even tree analysis allows to estimate the frequency of all the final events that come up from the initiating event.

Assuming a fuel that produces sufficient flammable vapours to reach flammability limits when it is released, all the final scenarios may be grouped in the following events:

- No consequences
- Pool fire in the bund
- Flash fire + pool fire
- Explosion + pool fire

The consequences of a bund fuel spillage are shown in the Figure 10. This figure explains how the final consequences depend mainly on factors like having an immediate or delayed ignition, or the confinement of the flammable vapours. Every possibility should be analysed to estimate the final probability of having a bund pool fire.

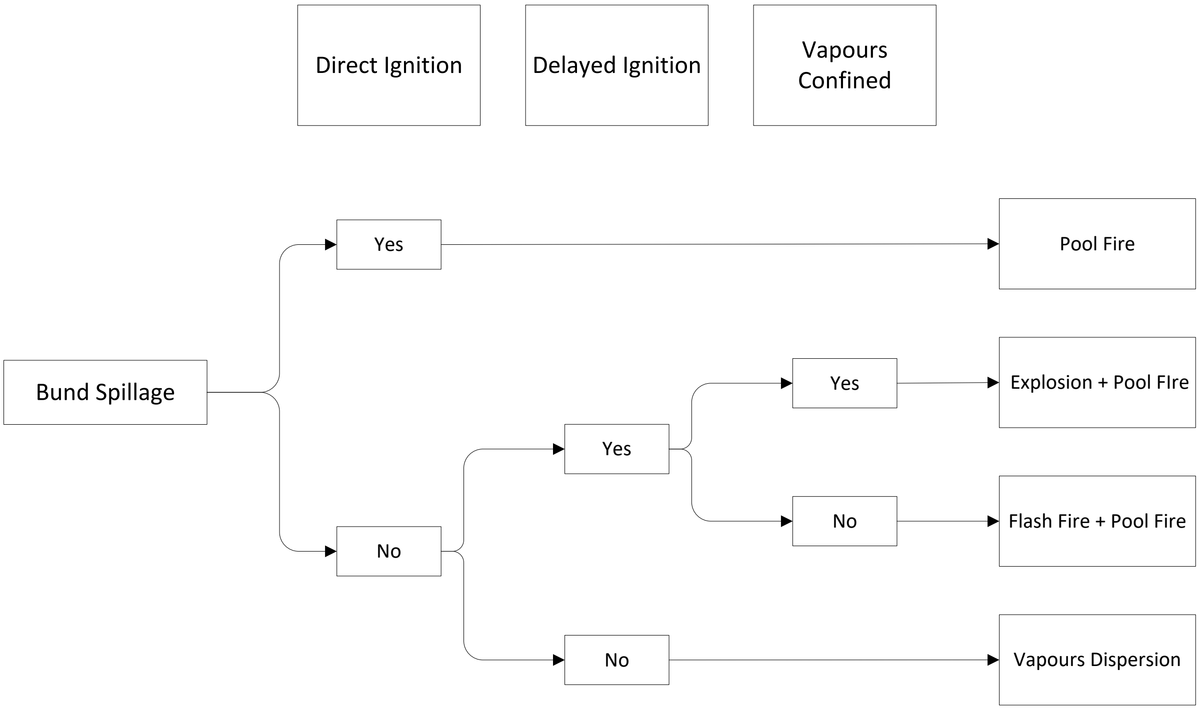


Figure 10. Bund spillage event tree

3.3.1.1. Ignition Probability

The product release does not necessary lead to a fire scenario. This depends upon the ignition probability. The probability of ignition must be quantified to estimate the likelihood of having a fire event. Ignition sources include (Shi, Shuai and Xu 2014):

- Hot surfaces (Auto ignition temperatures)
- Open flames (smoking, hot works)
- Electrical sparks (non-explosion proof equipment)
- Lightning
- Friction or Impact Sparks

According to the Purple Book (Haag 1999), the ignition probability depends mainly on three variables:

- Amount of fuel released
- Type of fuel
- Surrounding configuration (ignition sources in the area)

Table 6 shows the probabilities of direct ignition according to the Purple Book. It is important to remark that in case of liquid fuels the likelihood would not depend on the quantity released according to the source.

Table 6. Direct ignition probability according to Dutch authorities.

Source		**Probability**		
Continuous	**Instantaneous**	**Liquid**	**Low Reactive Gas**	**High Reactive Gas**
<10kg/s	<1000kg	**0.065**	0.02	0.2
10-100kg/s	1000-10000kg	**0.065**	0.04	0.5
>100kg/s	>10000kg	**0.065**	0.09	0.7

Moreover, the Purple Book states that the delay ignition depends on the ignition sources at the establishment. **Once a flammable vapour cloud has formed, the probability of having a delay ignition within a minute in sites are chemical plants and refineries is around 0.9.** Yet, the probability of forming the flammable vapour cloud from flammable liquids depends on the volatility of the substance and subsequently on the type of liquid.

On the other hand, the Handbook of Failure Frequencies (Flemish Goverment 2009) provides statistical information for both direct and delayed ignition. Table 7 shows the probabilities of direct and delayed ignition for different substances. It is important to remark that Table 7 also shows the probability of explosion, which will be discussed in the next section.

Table 7. Direct and delay ignition probability according to Belgian authorities.

Source		**Consequence**	**Probability**		
Continuous	**Instantaneous**	**Direct, Delay or Explosion**	**Liquid (over flash point)**	**Low Reactive Gas**	**High Reactive Gas**
<10kg/s	<1000kg	Direct	**0.065**	0.02	0.2
		Delay	**0.07**	0.02	0.06
		Explosion	**0.2**	0.2	0.2

Source		**Consequence**	**Probability**		
Continuous	**Instantaneous**	**Direct, Delay or Explosion**	**Liquid (over flash point)**	**Low Reactive Gas**	**High Reactive Gas**
10-100kg/s	1000-10000kg	Direct	**0.065**	0.04	0.5
		Delay	**0.07**	0.04	0.2
		Explosion	**0.2**	0.3	0.3
>100kg/s	>10000kg	Direct	**0.065**	0.09	0.7
		Delay	**0.07**	0.1	0.7
		Explosion	**0.2**	0.4	0.4

As expected, the data of the Purple Book matches with the data of the Handbook of the Flemish Government. **Other authors estimate that the ignition probability might vary from 0.03 to 0.1** (Shi, Shuai and Xu 2014) (Wang, Zhang and Chen 2013), which is consistent with data showed on Table 6 and Table 7.

3.3.1.2. Explosion Probability

When a delay ignition of flammable vapours occurs, there are two possible outcomes: a flash fire with no pressure effects, or an explosion with pressure effects. The final outcome depends mainly on how confined the flammable vapours are, and thus this depends on the configuration around the flammable vapours.

The Purple Book (Haag 1999) reports that the probability of having either and explosion or a flash fire splits with values of 0.4 and 0.6 respectively. On the other hand, the Handbook for Failure Frequencies (Flemish Goverment 2009) provides a probability of having an explosion of 0.2 (see above). In any case, the consequences include the consequent development of a pool fire.

However, as the explosion carries pressure effects, it is expected that the pressure wave would immediately cause product leakages and ignition on adjacent tanks.

3.3.2. Bund Fire Likelihood Analysis

To summarize the discussion presented above. The annual frequency of having a bund fuel spillage is estimated by adding the frequencies of all the initiating events:

$$\mathrm{FI}_{\mathrm{bund\ spillage}} = \mathrm{FI}_{\mathrm{overfill}} + \mathrm{FI}_{\mathrm{tank\ rupture}} + \mathrm{FI}_{\mathrm{pipe\ rupture}} \qquad (1)$$

Values for the frequencies FI are taken from the section 3.2.2. As multiple references are cited, the values used for this assessment are the most conservative one.

$\mathrm{FI}_{\mathrm{overfill}} = 5.3\mathrm{x}10^{-4}\mathrm{year}^{-1}\mathrm{tank}^{-1}$

$\mathrm{FI}_{\mathrm{tank\ rupture}} = 1.0\mathrm{x}10^{-5}\mathrm{year}^{-1}\mathrm{tank}^{-1}$

$\mathrm{FI}_{\text{pipe rupture}}$[3] $= 6\text{x}10^{-5}\text{year}^{-1}\text{tank}^{-1}$

Thus, $\mathbf{FI}_{\textbf{bund spillage}} = \mathbf{6.0\ x10^{-4}year^{-1}tank^{-1}}$

Using the probability values for the direct and delayed ignition obtained in the section 3.3.1.1 and the probability of explosion discussed in the section 3.3.1.2, the frequencies of the final events are calculated. Figure 11 shows the event tree for the bund spillage with the values of the frequencies of the final events.

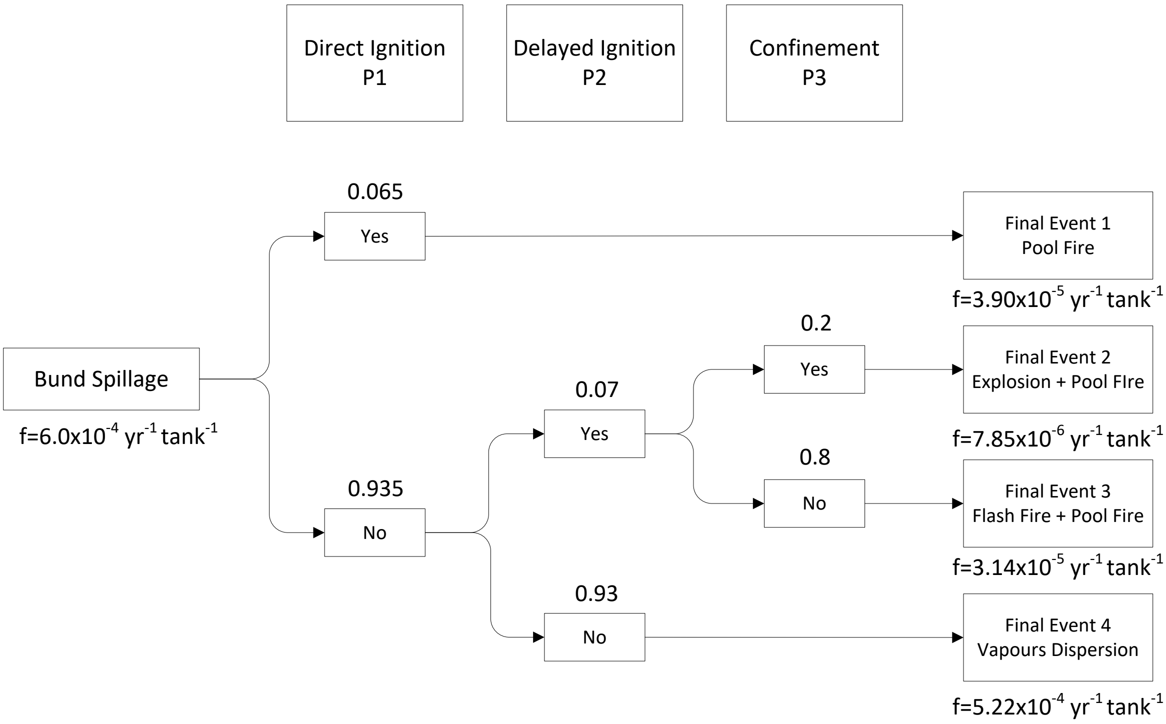


Figure 11. Bund fire event tree with frequency values of final events

The frequencies of the final events are estimated by the following set of equations:

$$\mathrm{FF}_1 = \mathrm{FI} * \mathrm{P1} \tag{2}$$

$$\mathrm{FF}_2 = \mathrm{FI} * (1 - \mathrm{P1}) * \mathrm{P2} * \mathrm{P3} \tag{3}$$

$$\mathrm{FF}_3 = \mathrm{FI} * (1 - \mathrm{P1}) * \mathrm{P2} * (1 - \mathrm{P3}) \tag{4}$$

$$\mathrm{FF}_4 = \mathrm{FI} * (1 - \mathrm{P1}) * (1 - \mathrm{P2}) \tag{5}$$

As a result it can be concluded that the overall frequency of having a bund fire is:

$$\mathrm{F}_{\mathrm{BF}} = \mathrm{FF}_1 + \mathrm{FF}_2 + \mathrm{FF}_3 = 3.90\text{x}10^{-5} + 7.85\text{x}10^{-6} + 3.14\text{x}10^{-5} = 7.83\text{x}10^{-5}\ \text{yr}^{-1}\ \text{tank}^{-1}$$

Then, the frequency of having a large bund fire is approximately 7.83x10^{-5} yr^{-1} tank^{-1}. In other words, for a facility with 100 tanks, a large bund fire is likely to occur once every 128 years.

These results agree well with the value reported by International Association of Oil & Gas Producers, which report a frequency value of having a large bund fire equal to 6.0 x10^{-5} yr^{-1} tank^{-1} (OGP Risk Assessment Data Directory 2010)**.**

---

[3] Assuming D>150mm and L=100m, according to the purple book.

3.4. Consequences Estimation

When performing a risk assessment, it is critical to estimate the potential consequences on the values and objectives. To do so, this section is divided in two parts. The first part qualitatively describes how the values are affected by the risk scenarios. Moreover, the second part explain the calculation method to quantify the consequences for the risk scenarios considered in this work.

3.4.1. Consequences on Values

The consequences vary depending on the risk value which is affected. The defined risk values or protection objectives are:

- Life Safety
- Property
- Business Interruption
- Environment
- Reputation

This section explains how all different values might be affected by a large bund fire.

3.4.1.1. Life Safety

Consequences on life safety are commonly assessed by considering the amount of fatalities and injuries. Life safety consequences are often reported as number of fatalities per year. A tank fire event might affect the life safety in the following ways:

- Heat radiation
- Toxic substances exposure
- Pressure effects (vapour gas explosion)

Since regulation is based on the probability of death, only lethal effects are considered. Probit functions are used to estimate the probability of death due to heat radiation or toxic effects. The Probit function is a mathematical expression that transforms the probability of death function, represented with a sigmoid type curve, to a straight line function (Haag 1999).

As the emphasis if this work is based on the effects of bund fires, pressure effects due to explosions and toxic effects due to substances dispersion are not considered in this assessment.

The Purple Book reports the Equation 6 that describes the probit function of the heat radiation and time of exposure effects on people (Haag 1999):

$$\mathrm{Pr} = -36.38 + 2.56\ln(\mathrm{Q}^{4/3} * \mathrm{t}) \qquad (6)$$

Table 8 shows the probability of death due to heat exposure for different heat radiation values and different exposure times.

Table 8. Probability of a person dying due to heat exposure.

Heat Exposure Condition (kW/m^2)	Probability	
	60 sec	20 sec
Inside a Fire Envelope	1.00	1.00
35.0 – 37.5	1.00	0.99

Heat Exposure Condition (kW/m^2)	Probability	
	60 sec	20 sec
20.0	1.00	0.54
12.5	0.90	0.065
4.0	$5x10^{-3}$	$>1x10^{-4}$
2.5	$>1x10^{-4}$	$>1x10^{-4}$

Although assigning value to life is controversial, it is required to find out a way to assess the life loss in term of monetary loss in order to compare its impact with other values loss (i.e. property loss).

Some studies made to estimate the cost-benefit analysis for counter terrorism protective measures assign values from $2 to $3 million USD per life according to US Federal Agencies (Stewart 2010)**. For this assessment, an average value of U$2.5 million per life (€2.32 million per life) is used.**

3.4.1.2. Property

Property losses due to bund fires are easier to assess since they are tangible values and can be assigned a monetary cost. After an incident, the damaged tanks and equipment require to be either repaired or replaced and this carries a price with it. Additionally, the product burned in the fire needs to be considered as part of the total economic loss. Both the equipment economic loss and the product economic loss are discussed separately in this section.

To be able to estimate the consequences on property it is important to calculate the economic cost of a possible property loss. The cost estimation is given by the Equation 7:

$$C(k€) = \sum T_i\,(k€) + \sum P_j(k€) \qquad (7)$$

Where the total cost C is the addition of the cost of all the partial (P) and total losses (T) accounted for all the equipment affected. The cost of a partial loss (P) as consequence of a small fire varies from 10% to 25% of the total value of the equipment (Mannam 2012). However, a more conservative perspective should be assumed. **For this assessment, the partial loss would represent a 50% of the total loss.**

To estimate the equipment monetary loss, the cost of the tanks needs to be estimated. The gross purchase cost of atmospheric tanks of different capacities are shown in the Table 9. Values are brought to current prices by using an industrial inflation index (Chemical Engineering Online 2017), also known as CE Index. Prices are for carbon steel tanks.

Table 9. Purchase cost for different atmospheric tanks

Type	Capacity (m^3)	Cost (kU$)	
		2010	2016
Floating Roof	100	180	188
	1000	400	418
	5000	940	982
	10000	1410	1473
	20000	2140	2236

Type	Capacity (m³)	Cost (kU$)	
		2010	2016
Cone Roof	100	50	52
	1000	210	219
	5000	630	658
	10000	1015	1061
	20000	1650	1725

Price values are obtained using the Equations 8 y 9 (Tolwer and Sinnott 2013), where T_p is us USD and V is the capacity of the tank in m^3:

$$T_{p-\mathrm{Floating}} = 13300 + 3250 * V^{0.65} \quad (8)$$

$$T_{p-\mathrm{Cone}} = 5800 + 1600 * V^{0.7} \quad (9)$$

Prices obtained from these equations were compared with real costs of tanks already constructed and the error margin is within 30%, which gives a good indication of the validity of the estimation method.

However, the equipment cost increases due to the following aspects:

- Equipment installation
- Piping
- Instrumentation and control
- Electric work
- Civil work
- Structure and building
- Lagging and painting

Furthermore, engineering, commissioning, contingency and working costs must be accounted. The equipment cost in case of total loss is represented by Equation 10.

$$T_i(k€) = (F + W) * T_{p_i}(k€) \quad (10)$$

To obtain the cost after commissioning and installation, the purchase cost is multiplied by a factor F, which for chemical plants and refineries is stablished to be around 3 to 4 (Tolwer and Sinnott 2013). Additionally, the purchase cost is multiplied by the work capital factor –W- which varies from 10% to 20% (Tolwer and Sinnott 2013). **For this assessment, a value of F equal to 4 and a value of W equal to 0.2 is used.**

Then, the below equation gives the final cost estimate for the property losses in case of a bund fire, where the subscript “i” represents all the equipment that suffered total damage and the subscript “j” represent all the equipment that suffered a partial damage.

$$C(k€) = 4.2 * \sum T_{p_i}(k€) + 2.1 * \sum T_{p_j}(k€) \quad (11)$$

The T_p value might be obtained using Equation 8 or 9.

Furthermore, the content of the tanks must be also included. Table 10 (Index Mundi 2017).shows some prices of common products that are stored in tanks. The total loss of the product may be estimated by multiplying the tank capacity by the unitary cost of the product.

Table 10. Commonly Stored Product Prices

Product	Price (€/litre)
Base Lube-Oils	0.82
Crude Oil	0.33
Diesel	0.41
Ethanol	0.37
Fuel Oil	0.30
Gasoline-Naphtha	0.39
Gasoil	0.39
Jet Kerosene	0.40

3.4.1.3. Business Interruption

While repairs of the damaged equipment are performed, the cost of the partial or complete operational interruption might considerably increase the total economic loss. This can be measured in terms of the amount of days lost or the volume of production lost. However, it is not easy to quantify the business interruption losses due to the amount of variables and uncertainties. The loss of production is easily quantified, but the lost opportunities, loss in competiveness, or damage to reputation are not easily quantified (Coppola 2011). Nevertheless, statistical data might, for a broad calculation, help to make some estimates.

According to the Loss Control Newsletter of 2007, an analysis from 119 events allowed to conclude that the business interruption losses are on average 2.7 times the property damage losses (Buncefield Major Incident Investigation Board 2008). **For this work, a conservative assumption is made and it is assumed that business interruption losses are 3 times the property damage losses.**

3.4.1.4. Environment

The environmental consequences of an event vary depending on the magnitude of the event, the location of the area affected, and the weather conditions, among others. Environmental consequences can be measured in terms of:

- Clean up cost
- Cost of repair damaged areas

On the other hand, long term consequences are not easy to quantify. It is hard to measure the loss of landscape enjoyment or the future environmental consequences. For this assessment, environmental consequences will be estimated according to the size of the event.

Different damage levels are to be set and different environmental loss values are to be assigned to these damage levels.

In case of a bund fire, environmental damage may be associated to two main aspects: environmental pollution and contamination of soil and/or water sources. Although pool fire events might cause an environmental loss/cost, in reality, the environmental loss is considerable smaller than the life and property/business losses.

For instance, according to the final report of Buncefield incident (one on the most catastrophic tank fire incidents in recent time) the environmental loss reached £2 million. Just 0.7% of the total cost of the losses. (Buncefield Major Incident Investigation Board 2008).

For this assessment, it is assumed that the environmental loss of a bund fire that is properly contained within the facility would represent the 1% of the sum of the property and business interruption losses.

3.4.1.5. Reputation

The common belief is that the damage to reputation would bring the most devastating consequences. When reputation is affected, is very likely that the company’s name will be related to the catastrophic event for years, which would destroys reliance on the brand. Reputation consequence is also related to business continuity cost.

However, it is very unlikely to affect the reputation of a company involved in a catastrophic event. None of Buncefield facility owners, Total S.A. and Chevron Texaco, suffered any reputation consequence after the incident. According to the European Stoke Exchange-EutoNext, on November 2005, one month before Buncefield incident, the Total S.A. price action was around €53 and on January2006, one month after the incident, the Total S.A. price per action was around €55. (Euronext 2017)

For this assessment, the consequences on reputation are included in the business interruption loss estimation.

3.4.2. Calculation Method

To assess the consequences it is necessary to estimate how the scenarios described in section 3.2 affect the values described above. Then, this subsection aims to explain the calculation method to quantify the physical consequences.

The consequences on the property depends on the severity of the event. Similar to life safety, a bund fire event might affect property by heat radiation or pressure effects (vapour gas explosion). However, as explained before, just heat radiation effects are considered when assessing the consequences on property values.

The following physical phenomena affect the values when a bund fires occurs:

- Distant radiant heat flux
- Direct flame impingement

The way in which these phenomena affect the values of interest and the method to quantify is explained below.

3.4.2.1. Distant Radiant Heat Flux

Heat radiation is one of the three ways of heat transfer (along with conduction and convection). Radiation is commonly associated with fire spread. In case of fire, flammable objects are heated at a distance of the fire source and they might ignite, spreading the fire. Thus, radiation is described as the main cause of fire spread and fire escalation.

When a tank catches fire, the adjacent tanks are exposed to heat radiation. If the product stored in the adjacent tank is close to its boiling point (e.g. gasoline), the heat transfer through radiation might cause product to start evaporating.

When the pressure increases to the point the flammable vapour exits the tank, the fuel may ignite and the fire escalates. To determine if an adjacent tank may ignite, the heat flux has to be determined.

Some references mention that if the radiant flux is equal or higher than 8kW/m^2, the tank cooling system should be activated (IP Model Code of Safe Practice, Part 19 1993). **Other authors mention that a heat flux between 8 to 12.5kW/m^2 is an acceptable value when assessing tank fire escalation events** (Mansour 2012)**.** At this heat flux value, the steel temperature rises to the point where the metal reaches the required auto-ignition temperature of a hydrocarbon flammable mixture.

3.4.2.2. Direct Flame Impingement

Similar to the distant heat radiation, the direct flame impingement represents one main cause for fire escalation in tank fires. However, it is a more complex phenomena and it is harder to model the response of a tank under fire engulfment.

In case of direct flame impingement, the external heat from the flames causes the layer of liquid next to the tank wall to warm up and to flow upwards to the top of the tank. This creates a strong temperature stratification.

Contrary to the case of distant heating, there is very little mixing inside the tank, which causes the hot liquid at the top to evaporate easier (since there is no heat dissipation to the bulk), which causes the pressure to increase faster and thus, fire escalation to occur rapidly (Mansour 2012).

Despite the complexity of the phenomena, simplified model for the estimation of the time to failure of tanks under flame impingement are available. This models relate the time to failure to the flames radiation intensity and make it feasible to estimate the fire escalation due to flame engulfment (Landucci, Gubinelli, et al. 2009). Besides, many studies have been performed around surface emissive power for large fire hydrocarbon pool fires.

Values for surface emissive power for liquid pool fires (kerosene) are reported to be around 35kW/m^2 with a very low chance to exceed 60kW/m^2 (Lees, Chapter 16 - Fire 2012)**.**

Additionally, a model developed by Mudan allows to estimate the maximum emissivity of the flames according to the fire diameter (Mudan 1984). Equation 12 shows Mudan’s correlation.

$$\mathrm{E} = \mathrm{E_{max}} * \mathrm{e}^{-\mathrm{sD}} + \mathrm{E_s} * \left(1 - \mathrm{e}^{-\mathrm{sD}}\right) \qquad (12)$$

Where:

E [kW/m^2]; average emissive power at flame surface - D [m]; equivalent pool diameter

$\mathrm{E_{max}} = 140\,\mathrm{kW/m^2}$; Equivalent blackbody emissive power (flames)

$\mathrm{E_s} = 20\,\mathrm{kW/m^2}$; Emissive power of smoke

$\mathrm{s} = 0.12\ \mathrm{m^{-1}}$; Extinction coefficient

3.4.2.3. Pool Fire Modelling

There are fire models that allow to quantify the radiant heat release rate of pool fires towards external objects. These models may be classified according to the calculation method used by these pool fire models. Main pool fire modelling methods are:

- Simple point model
- Solid flame model
- CFD Modelling

Single Point Model

A single point model is the simplest model that can be used to estimate the radiant heat flux. To predict the heat flux coming from a fire, the flames are modelled as a single point source. The single point model is based on the following assumptions (Mansour 2012):

- All the energy is emitted by a single point located at the centre of the flames.
- The radiant heat generated represent a specific fraction of the total heat release of the fuel burning
- The flame length and flame tilting angle effect the single point source location
- The radiant heat flux at a distant point varies proportionally to the inverse of the square of the radial distance from the fire point source

Solid Flame Model

Solid flame models use empirical correlations resulting from pool fire experiments. This type of model assumes flames as a combination of single geometric shapes. The resultant flame surface behaves as a radiative emission source. The main variables used to predict the heat radiation are the flame size and shape, the mass burning rate and the surface emissive power.

Solid flame models are well-suited for the estimation of heat radiation to sources far outside the flame. However, results are less reliable to predict heat fluxes at distances lower than one to half diameter of the pool fire (Mansour 2012).

As bund fires might affect adjacent tanks at lower distances than the mentioned above, a careful analysis of the data is to be done, even more where flame engulfment affects adjacent tanks.

CFD Model

CFD, or computational fluid dynamics, models solve the Navier-Stoke equations, which describe the turbulence phenomena of fluids. To solve scenarios where a combustion process is involved, CFD models incorporate sub-models that describe chemical reactions and heat radiation phenomena.

However, CFD modelling is time consuming and requires big effort (both human and computational).

For this assessment, the software PHAST®, developed by Det Norske Veritas (DNV), is used to predict the pool fire radiation on adjacent tanks. PHAST® uses empirical correlations to estimate the radiant heat flux. PHAST® may use either a single point model or a solid flame model. For this work, the solid flame correlation is used to evaluate the bund fire heat radiation.

3.4.2.4. Time to Failure Estimation

Failure of a tank can be ambiguous if it is not properly defined. From a catastrophic point of view, failure of a tank means the total collapse and release of the content instantaneously. From a realistic perspective, failure of a tank refers to the instant when the stress level exceeds the maximum allowable stress for the structure, which is dependent on temperature (ASME 1987).

Thus, time to failure is defined as the time when the stress level might lead to deformation with the potential of causing a leakage (size is not considered).

Landucci provides a simplified equation (refer to Equation 13) based on experimental data and finite element model validation, which relates the time to failure (ttf) of an atmospheric tank with the heat radiation intensity (I) (Landucci, Gubinelli, et al. 2009).

The time to failure "ttf" is given in seconds and the intensity "I" is given in kW/m^2. **This equation applies only for radiant heat values greater that 9kW/m^2.** It is considered that radiation intensities below 8kW/m^2 do not represent a risk of fire escalation during an atmospheric tank.

$$\ln(\text{ttf}) = -8.80 * (\text{I} - 9.0)^{-0.14} \tag{13}$$

Figure 12 is constructed upon the Equation 13 and shows the values of the correlation between the time to failure and the heat radiation intensity.

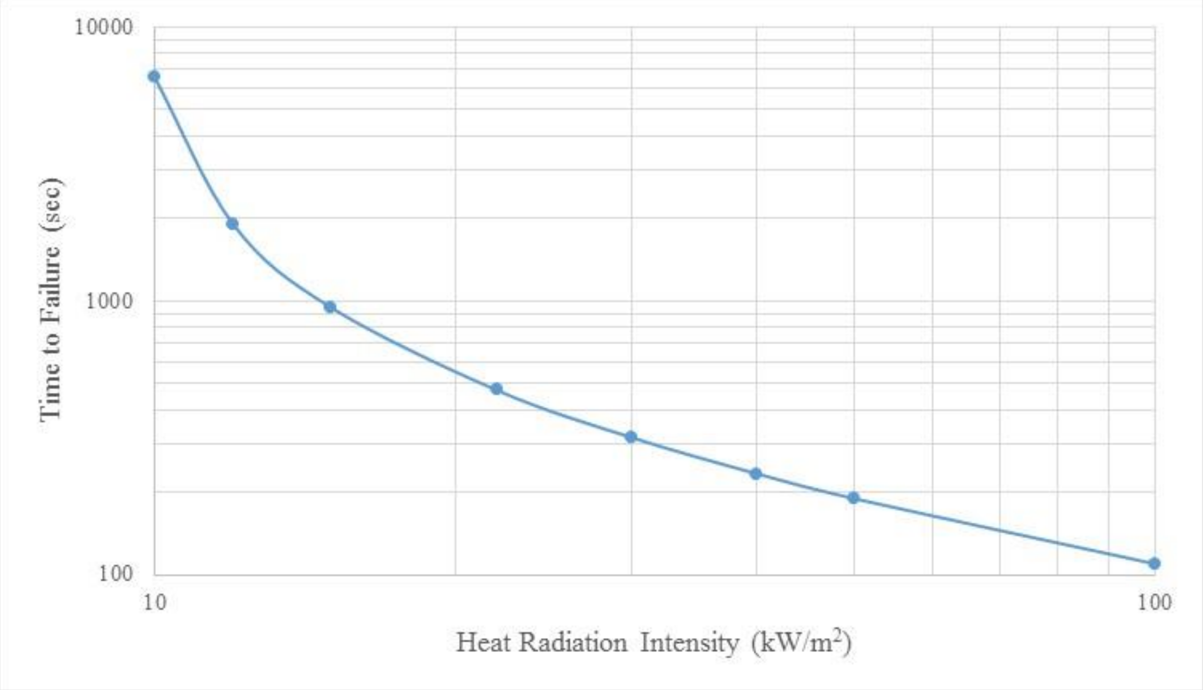


Figure 12. Time to failure of atmospheric tanks according to the intensity of the heat radiation

3.4.3. Consequence Estimation Analysis

To summarise what was discussed in section chapter, the following analysis is performed. The section 3.4.1 addresses how a bund fire event might directly affect all risk prevention objectives or values. As this is an economic assessment, all the consequences on the risk values are determined as an economic loss. The main conclusions of this section are:

- The life safety economic loss is estimated in €2.32 million per life. The probability of a person dying in a bund fire event depends on the heat radiation and time of exposure. This is calculated using Equation 6.
- The property loss is divided into equipment loss and product loss. The equipment loss depends only on the tank capacity and it is estimated using the Equations 8 or 9 and then Equation 11. The product loss can be estimated using Table 10.
- Business interruption loss represents 3 times the property loss
- Environmental loss represent only 1% of the sum of property loss and business interruption loss
- Reputation damage does not have an economic effect on the consequences

The section 3.4.2 presents a calculation method to predict the physical tank damage due to the fire event. The calculation method proposed, estimates the tank damage according to the thermal effects. The thermal effect are:

- Distant radian heat flux
- Direct flame impingement

The distant radian heat flux is calculated using the software PHAST®, an empirical solid flame model (pool fire model). Direct flame impingement effects are estimated using the surface emissive radiation flux, which is calculated using Equation 12. The damage on the storage tanks are evaluated according to its “time to failure”, which only depends on the heat radiation intensity. The model proposed to estimate the tank “time to failure” is summarised by Equation 13 and Figure 12.

4. Risk Reduction Measures

Once the risk has been well characterised and both likelihood and consequences have been estimated, the risk requires to be managed. The risk reduction measures are part of the risk management and they seek to reduce the likelihood and consequences of the risk to avoid a catastrophic event.

Risk reduction measures may be catalogued into passive reduction measures and active reduction measures. Every reduction measure that might be applied to reduce the bund fire risk is explained in this chapter. Even more, the reliance and feasibility of every protection measure is analysed.

4.1. Passive Fire Protection Measures

Many passive measures are implemented to reduce the risk of having an escalation event from a bund fire. Some of the most important measures used in industry are:

- Separation distances and Bunds
- Fireproof coating

Each of these measures is explained below.

4.1.1. Separation Distance and Bunds

The distance between tanks is a key aspect to avoid fire spread when a fire event occurs in a tank. However, in case of bund fires (multiple tank bunds), the distance between tanks inside the same bund becomes irrelevant since the fuel and flames would spread all around the bund.

Nevertheless, the bund configuration (i.e. number of tanks per bund), the type of fuel stored and the distance from tank-to-bund are important to predict the extent of the fire event. Tanks containing boilover products should be placed in separate bunds due to its risk to cause fire escalation. However, this is not always the case in practice. The presence of intermediate bunds separating tanks inside a bigger bund is used as a solution. In case the first fuel spillage is small enough to be contained inside the intermediate bund, the distance from tank to tank starts to be relevant for the assessment.

Table 11. Distances Tank-Tank and Bund-Tank according to different legislations

Configuration		**Distance (m)**		
		NFPA	**Eurocode**	**IP Code**
Tank - Tank	Fixed Roof	1/3 ΣDi[4]	1/2 D[5]	10-15
	Floating Roof	1/4 ΣDi	1/3 D	10-15
Tank - Bund	Fixed Roof	1/2D	No Requirement	2
	Floating Roof	Refer to Code	No Requirement	2

---

[4] Sum of the diameters of each pair of tanks that are adjacent to each other (tanks inside a bund).

[5] Diameter of the largest tank

Table 11 shows the different distance requirements between tank-to-tank and tank-to-bund according to different regulations, including the NPFA30, the European Model Code of Safe Practice and the Institute of Petroleum Model Code Safe Practice (Mansour 2012).

These different approaches make it difficult to standardise a method to estimate tanks separation distances. For instance, for a couple of floating roof tanks of 40m diameter each, the NFPA requires a minimum separation distance of 20m, the Eurocode requires 13.3m and the IP requires 10m. Differences in applying one code or the other are critical when evaluating the risk of having fire spread from one tank to the other.

Some authors argue that the distances stablished by the codes are insufficient to avoid fire spread in case of high wind speed scenarios (Mansour 2012) (Santos and Landesmann 2014). **Furthermore, Santos proposed that the minimum distance should be increased to around one diameter of the largest tank.** Although an increase in the separation distances might be recommendable to reduce the risk of fire escalations, it is not the case for existing facilities where distances are already fixed according to one standard or another.

4.1.1.1. Bund Overtopping Probability

Tanks may be placed in independent bund to reduce the risk of fire escalation. However, although bunds may be very effective at shielding adjacent tank from external heat radiation, they may not be that effective at retaining a total tank release.

Bund effectiveness is related with its capacity to retain the leaked substance when the primary containment fails. In some circumstances bunds may not be effective in retaining the spilled material. For instance, in the scenario of a catastrophic tank failure, the momentum of the released liquid would cause a portion of the liquid to overtop the bund which increase the risk of spreading the fire to other bund in case of ignition. Some other common causes for bund retention failure are:

- Bund overtopping due to the liquid surge
- Structural failure due to impact of collapsing pieces or due to the liquid force
- Firefighting water overfilling
- Drain valves open
- Holes or cracks in the bund walls
- Failure of two or more tanks
- Flying “missiles” product of a primary explosions

Due to the previous reasons it has been found that, for a total tank release, the bund failure probability reaches a value close 40%, which is considerable high for a protection measures. (Davies, et al. 1995)

4.1.2. Fireproof Coating – Double Shell Tanks

Heat insulation is a protection measure to reduce the heating stress of the material which contains the liquid in adjacent tanks. By locating a barrier between the tank primary wall and the radiant source (e.g. flames) it is feasible to increase the time to failure and, thus, to reduce the risk of fire escalation. There are two main options to insulate the tank wall from external radiation sources:

- Fireproof coating
- Double shell

A fireproof layer of insulation material (i.e., glass wool or rock wool) is usually applied to pressurised vessels to reduce the risk of a BLEVE event.

A layer of a few millimetres of an epoxy lining is able to double or even triple the time to failure of a pressurised vessel. (Landucci, Molag and Cozzani, Modeling the performance of coated LPG tanks engulfed in fires 2009)

Although fireproof coating is usually associated with pressurised vessels, it might be a feasible option to protect atmospheric tanks inside multiple tank bunds from impingement fires.

According to the standards, fireproofing installed should provide protection for 2h before the tank shell starts to weaken. Tanks can be thermally insulated in two ways. The first method is to use a single layer of insulation material, like polyurethane foam -PUF -, over the walls. The insulation layer is then exteriorly protected with a fire resistant vapour protection barrier. The second method is to use a double shell tank, with perlite insulation located in between the walls. Nevertheless, the perlite insulation barrier might collapse if the exterior shell fails due to high temperatures exposure. Other insulation material (rock wool, mineral wool, fibreglass, etc.) might be used as well. (Lees, Chapter 22 - Storage 2012)

Double shell tanks, without any insulation material in-between the shells, are also a suitable reduction measure to reduce the risk of fire escalation in multiple atmospheric tank bunds. The second shell undertakes two tasks: it reduces the frequency of having a fuel spillage out to the bund and it insulated the primary shell from the radiant source. **Besides, as the second shell reduces the probability of leaking the product to the exterior, bunds are not required anymore because the second shells acts as the second containment barrier.**

Heat insulating measures are not usually applied to big tanks because of the high cost involved in covering big surface areas. A further discussion on the economic aspect of heat insulation is presented in the next chapter.

4.1.2.1. Heat Insulation Failure Probability

The probability of failure of passive protection measures such as heat insulation may be determined by performing a Layers of Protection Analysis or LOPA. A layer of protection, also called a safety barrier, is a measure taken to reduce the risk of a non-desired event. It can be allocated as a prevention measure or as mitigation system. A passive barrier, such as heat insulation, has a lower probability of failing under demand because it lacks the need of any further action to 'operate'.

According to the LOPA analysis, a passive safety barrier has a probability of failure on demand of $1x10^{-3}$. (Landucci, Argenti, et al. 2015)

4.2. Active Fire Protection Measures

Active fire protection measures are widely used in industrial fields where flammable substances are stored. The Most commonly used active fire protection measures in flammable substances storage facility are:

- Safety Instrument Systems
- Water Cooling Systems
- Fixed Foam Systems

Each of these protection measures are further discussed below.

4.2.1. Instrumented Systems

Instrumented systems are preventive measures that act as a barrier against loss of containment and ignition of flammable liquids.

One of the most common causes of bund fires is the overfilling of tanks. Instrumented systems reduce the frequency of overfilling by implementing redundant alarm schemes and by triggering automatic shutdown protocols. Moreover, instrumented systems might include Fire&Gas systems which includes a broad set of flammable gas, heat and flame detectors. All instrumented applications that might reduce risk of overfilling and ignition are explained below.

4.2.1.1. Process Control Loop

The risk of overfilling is relatively high due to human intervention during the tank loading process. A simple level control loop reduces the risk of overfilling as consequence of human error. Figure 13 shows how the level control loop should be implemented in tanks. It also shows the automatic shutdown system described below.

4.2.1.2. Automatic Shutdown System

If the level control loop does not respond to a potential overfill, the automatic shutdown system will overtake the control on the filling process. If the level in the tank exceeds the limit, an independent and redundant level switch will detect it and trigger the shutdown response, which shall close the inlet valve and shall stop the filling pump automatically. The shutdown system also triggers an audio-visual alarm to notify the operator who shall be able to manually close an inlet valve, in case of a malfunction or delay in the automatic shutdown system. Figure 13 also shows how the automatic level shutdown system would operate.

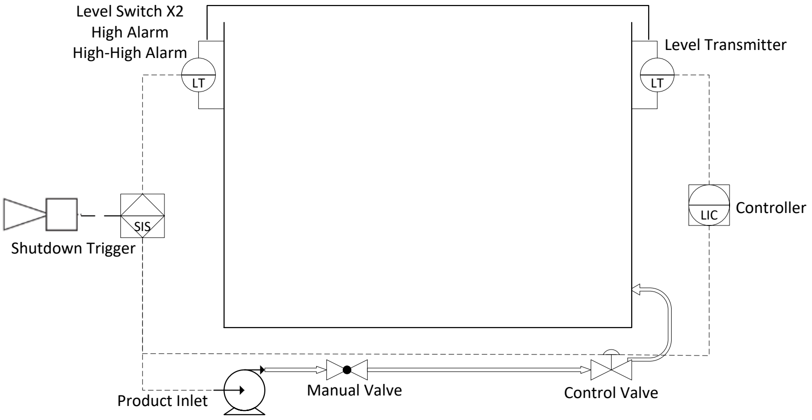


Figure 13. Instrumented System Scheme as a Protection Barrier for Tank Overfilling

4.2.1.3. Fire&Gas System

Fire and gas systems include a set of different detectors that alert in case of a release and ignition of a flammable liquid. Fire and gas systems include:

- Gas detectors
- Heat detectors
- Flame detectors
- CCTV footage

Fire and gas systems allow the operators of the facility to act during the early stages of the release and/or pool fire, which reduces the risk of fire escalation.

4.2.1.4. Instrument System Failure Probability

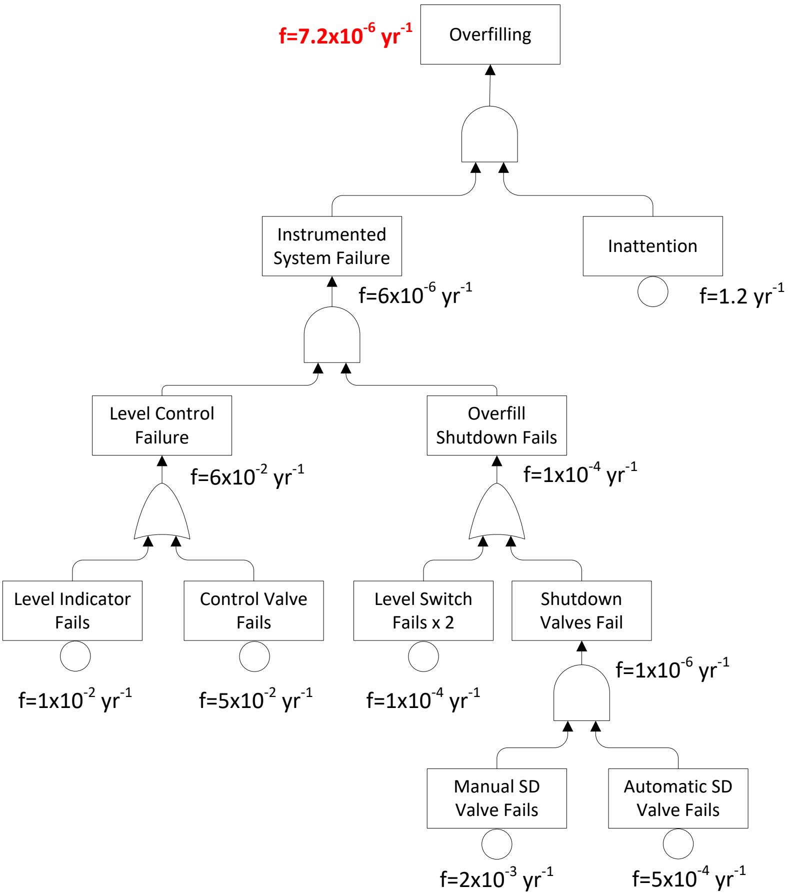
To estimate the probability of failure of an instrumented system it is necessary to estimate first the failure probability of the individual elements of the system. Assuming that the following protection measures are taken into account:

- Automatic level control system
- Overfill protection system – automatic shutdown
- Level switch redundancy (x2)

A fault tree is developed to estimate the frequency of having a tank overfill. Failure frequency of each individual element (Schüller 1997) and probabilities for human error (Lees, Chapter 14 - Human Factors and Human Errors 2012) are listed in the Table 12. To estimate the human error frequency, it is assumed that a loading process is perform once per month per tank, in average.

Table 12. Frequencies for overfill individual failures

Element	Failure Probability/Frequency
Human Error – Inattention	5-10% (1.2 yr^{-1})
Level Sensor/Transmitter Failure	$1x10^{-2}$ yr^{-1}
Control Valve Failure	5 $x10^{-2}$ yr^{-1}
Manual Valve Failure	2 $x10^{-3}$ yr^{-1}
Safety/Spring Valve Failure	5 $x10^{-4}$ yr^{-1}



/

Figure 14. Tank overfill fault tree

With the data of Table 12 a fault tree was constructed. The fault tree is shown in the Figure 14. To convert the human error probability in a frequency, it was assumed one loading operation per month per tank. **According to the fault tree analysis, there is a tank overfill frequency of $7.2\text{x}10^{-6}$ $\text{year}^{-1}\text{tank}^{-1}$, around 70 times lower than the frequency obtained for in section 3.2.2.1.**

4.2.2. Water Cooling Systems

The primary objective of water cooling systems, also known as water deluge or spray system, is to:

- Cool down tanks from engulfed fires
- Cool down tanks from radiant heat

The requirement of water depends on the end purpose of water deluge systems. For protection against **flame engulfment**, water density design value is **10 l/min.m^2**. For protection against **radiant heat** on adjacent tanks, water density design value is approximately **2 l/min.m^2** (NFPA - National Fire Protection Association 2017) (Mansour 2012) (Centrum Industriële Veiligheid 2017)

Companies do not have the habit to provide water cooling systems on storage tanks unless the distance between tanks is lower than required by the standards. The IP Model Code of Safe Practice recommend to use water cooling systems on tanks within just one diameter distance from the burning tank (two diameters downwind). Moreover, European regulation code suggest a water rate of 2 l/min.m^2 for adjacent tanks but does not mention any measure against engulfment fires (IP Model Code of Safe Practice, Part 19 1993) (European Model Code of Safe Practice 1981). The minimum distance requirement between tanks was discussed in section 4.1.1.

In industrial applications, it is more common to find water cooling monitors at ground level. In most of the cases, the reliance is put on mobile cooling systems rather than fixed systems. **The capacity of a mobile water monitor is considered from 2500 l/min upward. However there is no recognised international standard for water monitor application rates** (Centrum Industriële Veiligheid 2017).

4.2.2.1. Water Cooling System Effectiveness

The effectiveness of a water cooling system refers to its capacity to keep the tank walls cold enough to avoid their weakening. On a theoretical basis, a flowrate of around 2 l/min.m^2 would be able to absorb 60kW/m^2 ($20000\text{BTU/ft}^2\text{.h}$) (Lees, Chapter 16 - Fire 2012). However, real cooling systems are considerably less efficient.

It has been proven that a water film covering tank walls, with a flowrate of 11 l/min.m^2, is able to keep the tank cold at exposure rates of more than 130kW/m^2 (flame radiation without smoke obscuration) (Roberts, Effectiveness of an enhanced deluge systemto protect LPG tanks and sensitivity to blocked nozzles and delayed deluge initiation 2004). Nevertheless, the flowrate density flowing out of the nozzles does not correspond to the actual flowrate of the water film covering the tank walls. **It has been observed that the flowrate density is drastically reduced before being able to cool down the tank**. This is often called as the spray efficiency. The inefficiency is water spray systems can be attributed to (Roberts, Directed deluge system designs and determination of the effectiveness of the currently recommended minimum deluge rate for the protection of LPG tanks 2004):

- Spay angle application
- Distance from the nozzle to the tank wall
- Wind speed

As consequence of the water flow reduction, hot spots are created and the material wall starts to weaken.

Table 13 shows the efficiency of the nozzles according to the flowrate density. Extrapolating the efficiency data, it can be concluded that a nozzle with a flowrate density of 10 l/min.m^2 would have an efficiency of around 48% and that a nozzle with a flowrate density of 2 l/min.m^2 would have an efficiency of around 72%.

Table 13. Cooling water system efficiency according to the flowrate density

Water flowrate [l/min.m^2]	Nozzle Efficiency [%]
11.1	46.0
21.7	37.3
34.0	29.4
40.0	26.5

According to discussion above, **it is assumed that a water cooling system with a flowrate density of 10 l/min.m^2 has an effective heat reduction of around 60 kW/m^2** (~47% of flames emissive radiant heat - 130kW/m^2) (Lees, Chapter 16 - Fire 2012) **and that a system flowrate density of 2 l/min.m^2 has an effective heat reduction of around 14.5 kW/m^2** (~72% of smoke emissive radiant heat - 20 kW/m^2) (Lees, Chapter 16 - Fire 2012)**.**

4.2.2.2. Water cooling System Failure Probability

Similarly to the passive fire protection, the probability of failure of water cooling systems may be determined by performed a Layers of Protection Analysis or LOPA. An active protection barrier, such as water cooling systems, has a higher probability of failing on demand compared to passive barriers, because it depends further actions (either human or not) to operate. Additionally, a fault tree analysis may be performed to establish the probability of failure under demand.

According to the LOPA analysis, a water cooling system has a probability of failure on demand of 1x10^{-2}. Besides, according to the fault tree analysis, this probability is around 3x10^{-2} (Landucci, Argenti, et al. 2015). As the order of magnitude agrees independently on the method, any of both values might be used for the analyses.

4.2.3. Foam Systems for Tanks

Foam systems are widely applied as a supplementary protection measure. Foam system may be divided in three categories:

- Fixed systems
- Semi-fixed systems
- Mobile system

Fixed systems refer to equipment permanently fixed for the supply of foam solution. Semi-fixed systems refer to equipment which connection may only be made at the moment of the fire event. Mobile systems refers to monitors that may be moved according to the necessity. There are many types of fixed foam systems depending on the application. The main types of fixed foam systems are listed below (Centrum Industriële Veiligheid 2017):

- **Fixed foam pourer for bunds**
- Fixed foam pourer for cone roof tanks
- Subsurface protection of cone roof storage tanks

- Foam pourer of open top floating roof tanks
- Catenary system of open top floating roof tanks
- “Coflexip” system of open top floating roof tanks

As the scope of this work is bund fire events, only the fixed foam pourer for bunds is considered in the assessment. A further explanation of every system was given in section 1.3.2.

4.2.3.1. Fixed Foam Pourer System for Bunds

Fixed foam systems for bunds are useful when access for firefighting to multiple tank bunds is limited (minimum distances according to the standards). **The recommended application rate is 4.1 l/min.m^2** (NFPA - National Fire Protection Association 2016). Table 14 shows the number of pouring devices required for a specific bund area. This value comes from the experienced fixed foam systems industry advisors. For larger bund areas (more than 2820m^2), an additional device is required every 450m^2 (Centrum Industriële Veiligheid 2017).

Table 14. Fixed foam pouring devices according to the bund area.

No. of Pouring Devices	Maximum Bund Area (m^2)
1	450
2	1020
3	1380
4	1810
5	2290
6	2820

According to NFPA 11 (NFPA - National Fire Protection Association 2016), **the recommended discharge time for bund fires is 20 min for non-volatile hydrocarbons and 30 min for all other flammable liquids.**

4.2.3.2. Mobile Monitors and Semi-Fixed Foam Pourer System for Bunds

Monitors and semi-fixed foam systems should not be considered as the primary protection method because of its difficulty to ensure sufficient foam solution application on large tank bund fires. Monitors and semi-fixed systems require higher application flowrates and larger application periods because it takes more time for semi-fixed and mobile systems to start operating, compared to fixed systems. **Properly design fixed systems can be actuated within a few minutes whereas mobile/semi-fixed application can take even hours to start.**

This time difference is critical due to the potential of having fire escalation. Thus, application requirements for mobile systems are more demanding.

According to NFPA 11 (NFPA - National Fire Protection Association 2016), for mobile monitors in bund fires **the recommended minimum application rate is 6.5 l/min.m^2** and **the recommended discharge time is 50 min for non-volatile hydrocarbons and 65 min for all other flammable liquids.** However, for major incidents being fought with mobile foam systems, the application time might considerable increase, depending on the fire event.

4.2.3.3. Foam System Failure Probability

The probability of failure of the foam systems may be determined by performing a Layers of Protection Analysis or LOPA. A fixed foam protection barrier has a lower probability of failing on demand compared mobile foam systems, because of it depends further actions (either human or not) to operate.

According to the LOPA analysis, **a fixed foam system has a probability of failure on demand of $2x10^{-3}$. On the other hand, the probability of failure on demand for a mobile foam system, is around $2x10^{-2}$** (Landucci, Argenti, et al. 2015)**.**

4.3. Firefighting Intervention

In case of fire, the emergency response may be provided by either an internal or an external emergency team. It is assumed that in any circumstance the all the emergency team members are well trained, thus the effectiveness of the fire brigade intervention will depend only on the time of response and mitigation compared to the time of propagation (i.e. tanks time to failure – see section 3.4.2.4). Three time are defined to be able to quantify the total time of response and mitigation (Landucci, Argenti, et al. 2015):

- **Time to alert (ta):** maximum time for the fire to be detected and the alert to be given.
- **Time to start mitigation on-site (tsm):** maximum time to start the on-site response actions to contain the fire and mitigate its impact
- **Time to effective mitigation (te):** maximum time to achieve a constant and effective cooling operation on the target

The time to alert depends on the detection systems, the personnel on-duty present at the time of the event and the training of the personnel in emergency situations. The time to start mitigation depends on the distance from the fire station to the location of the facility, the location of the water sources and the plant lay-out. Lastly, the time of final mitigation depends on the firefighting strategy, the amount of water required and the availability of external water sources.

These times are defined according to the case study. The assessment requires the feedback from the internal emergency team or the external fire brigade that would respond in case of a fire event. **Once these values have been defined, the escalation threshold value for bund fires involving multiple tanks is estimated.**

4.3.1. Escalation probability

The probability of escalation may be estimated by using a model that compares the estimated time of effective mitigation to the time of tank failure. The probabilistic model considers the fire intervention success probability to avoid fire escalation (Landucci, Gubinelli, et al. 2009).

The simplified model proposes to use a probit function to estimate the probability of fire escalation. Equation 14 shows the probit function used for the escalation assessment.

$$\mathrm{Pr} = \mathrm{a} + \mathrm{b}\ln(\mathrm{ttf}) \qquad (14)$$

The variable ttf represent the time to failure in minutes, estimated using Equation 13. The constants “a” and “b” depend on the effective mitigation time. In the simplified model, it is assumed that the period of time between the start of the mitigation actions (tsm) and time to achieve effective mitigation (te) is negligible.

Although this is not entirely true, the transition time from “tsm” to “te” is considerably lower compared to the transition between “ta” to “tsm”. Thus, to neglect this transition from “tsm” to “te” would not cause a big impact in the final outcome. Nevertheless, this should be considered an uncertainty source.

Thus, the values of “a” and “b” will only consider the time to alert “ta” and the time to effective mitigation “te”. Equations 15 and 16 show how this constants are calculated.

$$a = \frac{3.718\log(\mathrm{ta}) - 6.283\log(\mathrm{te})}{\log(\mathrm{ta}) - \log(\mathrm{te})} \qquad (15)$$

$$b = \frac{1.114}{\log(\mathrm{ta}) - \log(\mathrm{te})} \qquad (16)$$

The times “ta” and “te” are in minutes. To exemplify, if “ta” has a value of 5 min and “te” has a value of 20 min, the constant “a” would be equal to 9.25 and the constant “b” would have a value of -1.85 (using Eq. 15 and 16). Assuming that the “ttf” value is 10 min, the probit value is 4.99 (using Eq. 14). Finally, by applying the error function to convert from probit value to a probability, the resulting escalation probability is approximately 50%.

4.4.Layers of Protection Scheme – Bow Tie Diagram

Bow-tie diagram is a tool that allows to assess the different risk reduction measures. Figure 15 (Rausand 2011) shows a general bow-tie diagram. The main hazardous event, a bund fire in this case, is placed in the centre. The risk prevention measures are placed on the left and the risk mitigation measures are places on the right. The prevention measures, usually related to maintenance and engineering activities, are aimed to avoid threats to evolve into a hazardous event. The mitigation activities, usually related to operations activities, are meant to reduce the negative consequences of the hazardous event, once this has occurred.

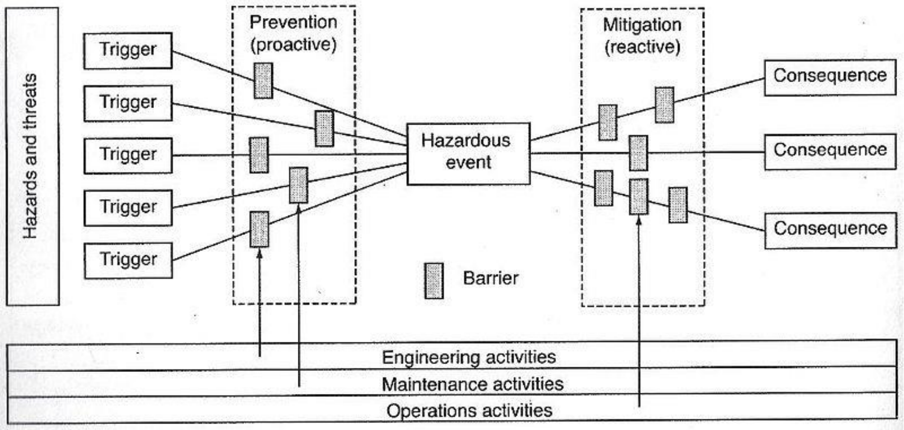


Figure 15. Bow-tie diagram

For tank fire events, the prevention measures are mainly aimed to prevent a loss of containment and ignition events. On the other hand, the mitigation measures are mainly aimed to reduce fire escalation.

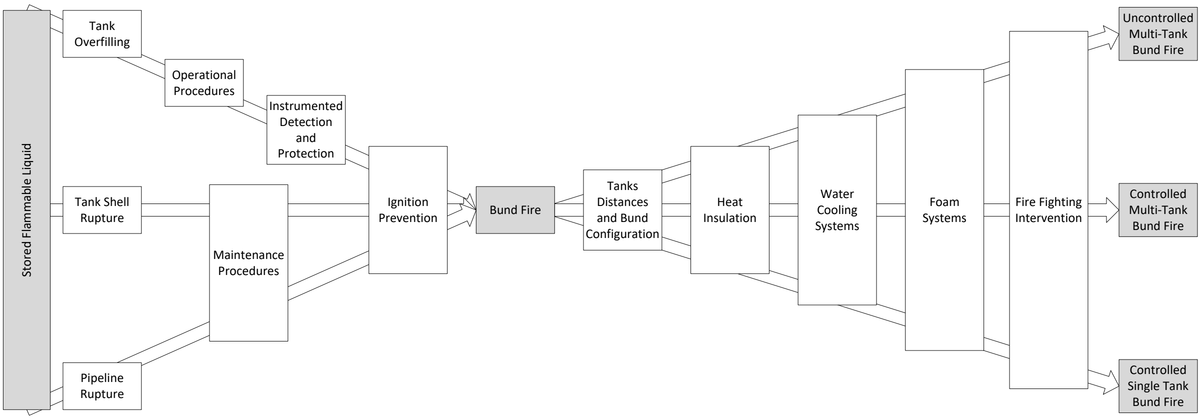


Figure 16. Bow-tie diagram for bund fire events

The Figure 16 shows how all the reduction measures analysed in this chapter may be placed in a bow-tie diagram. Every reduction measure reduces either the frequency of a bund fire event, which is in the centre of the diagram, or reduces the consequences of the final event, which would reduce the final frequency of having an uncontrolled multiple tank event. An event tree might be elaborated to estimate the final probability of having any of the final events. Every decision branch of the event tree would represent a failure probability of the layer of protection.

4.5.Risk Reduction Measures Analysis

Different risk reduction measures were discussed and analysed. This section aims to summarise the discussion presented above.

The first risk reduction measure discussed was tanks separation distances and the use of bunds. Nowadays, standards do now agree on the minimum safe distances between tanks. Moreover, bunds are allowed to contain multiple tanks. It was concluded that the best risk reduction strategy is to use independent bunds (e.g. one tank per bund) and to increase the tank separation distances.

The second reduction measure discussed was tank fireproofing. Although it is not a usual protection measure in atmospheric tanks, it would be a very efficient risk reduction measure, because it would delay the tank failure for hours.

The third risk reduction measure analysed is perhaps the simplest one. It consist in the use of instrumented systems to reduce the tank overfill probability, by including a robust monitoring system and a shutdown sequence. It is very efficient in preventing overfill events, it is reliable and it does not required a big equipment investment.

The forth risk reduction measure proposed is the use of water cooling systems. By cooling the surface of the tank, the walls weaken process is delayed and the risk of tank failure and fire escalation is reduced. Two water flow densities were analysed (2 and 10 $l/min.m^2$). It was found that the higher flowrate is very efficient in preventing fire escalation for flame impingement fires and the lower is widely used to prevent escalation from distant radiant heat fluxes.

The fifth risk reduction measured analysed is the use of bund fixed foam systems. It was concluded that the fixed foam systems are a supplementary protection measure and that the mitigation strategy should not rely just upon fixed foam systems.

The last protection measure contemplated is the fire brigade intervention. A model was presented to estimate the fire escalation probability based on the fire brigade intervention. This model describes how likely a bund fire is to escalate into a multiple tank fire. The model is based on the ‘time of alert’ and the ‘time of effective mitigation’ of the fire brigade intervention.

5. Cost-Benefit Analysis

A cost-benefit analysis is an important tool for decision makers. It contributes to counterbalance the cost of risk scenarios with low probabilities, but large consequences, with the cost of the reduction measures aimed to reduce the initial risk. In some cases, the reduction measures are more costly than the risk cost (in most cases due to its low likelihood).

One way to evaluate the risk scenarios and their consequences is by estimating the risk annualised cost. This is done by adding the consequences on all the affected values, translated to costs. The analysis is done on an annualised basis to facilitate comparison to the cost of reduction measures. In other words, a cost-benefit study determines if the risk reduction strategy is economically feasible.

5.1.Risk Annualised Cost

The risk annualised cost is defined as the cost of the negative effects of a risk scenario multiplied by 7the probability of such event. The final outcome is estimated on an annual basis. Equation 17 describes the risk annualised cost estimation.

$$\mathrm{RAC} = \sum_{\mathrm{i}} \mathrm{F_i} * \mathrm{C_i} \qquad (17)$$

Where F_i represent the frequency of every risk scenario and C_i represents the cost of the negative consequences of the scenario. The negative consequences on the different values are independently analysed below.

5.2.Risk Reduction Measures Cost

After estimating the annualised cost for a bund fire scenario without reduction measures, the next step is to estimate the annualised cost of the reduction measures. Thereafter, it is possible to perform a cost-benefit analysis in order to establish the best protection strategy.

In most of the cases, the cost is amortised to annualise to cost and to ease the comparison with the annualised consequences estimated above. **The amortisation period (or service life) of a fire protection systems is assumed to be 30 years for passive systems and 20 years for active systems. The amortisation period assumption is based on the conservative standpoint that the equipment installed would not require total replacement for the mentioned period of time.**

Nevertheless, a sensitivity analysis is presented at the end of the case study to evaluate the influence of the amortisation period in the final outcome of the cost-benefit evaluation. The cost breakdown of implementing every reduction measures for the simplified case proposed is shown below.

5.2.1.Bund and Separation Distances

One of the reduction measures to reduce the risk of having a multiple tank bund fire is to build an independent bund for every tank. However, this solution implies an additional cost due to the space required to build up bunds for every tank. The reduction on the space efficiency makes this option, in most cases, not feasible due to location limitations. Nevertheless, implementing this measure is analysed below. The cost of associated with the increase in the required area might fit in one the following categories:

- Cost of constructing additional bund, piping and additional expenses
- Cost of land (when land acquisition is not a constrain)
- Cost of profit loss (when land is not available and space needs to be optimised)

According to the cost estimation method for chemical plant designs**, the construction of additional bund and piping would represent a maximum 10% of the equipment cost (without installation). This value needs to be annualised. An amortisation period of 30 years is used for this study.**

Additionally, in most cases, the land is rented instead of purchased. **The cost of the land rent usually represents around the 6% of the tank cost.** This value is not amortized since rent is calculated on annual basis (Peters, Timmerhaus and West 2004).

In case of land limitation (e.g. no land available for rent), the profit loss due to the reduction of the number of tanks in the facility is considerably higher than the annualised consequences of bund fire, which makes this solution really hard to implement in practice.

5.2.2. Heat Insulation – Fire proofing

The cost of installing heat insulation may be broken down in the following items:

- Cost of the insulation material
- Cost of insulation cover/support
- Cost of the installation
- Fixed costs (e.g. maintenance)

The price of the main insulation materials might be found in Table 15 (Homewyse 2017). The cost of insulation cover or support depends on the material used as insulation.

Table 15. Average cost of insulation material

Material	**Cost (€/m^2)**
Rock wool	6.36
Fiberglass	4.11
Mineral wool	6.89
Perlite[6]	6.16
PUF	21.73
ProRox®[7]	58.00

On one hand, materials like perlite, fiberglass and rock wool require a steel jacket because of their lack of structural stability. The cost of a carbon steel shell 6mm thick (1/4 in), according to Dec. 2015 steel prices, is 35.5€/m^2 (Steel Industry Portal 2017). It is important to mention that this cost does not include construction and installation cost.

On the other hand, PUF and ProRox boards require just a simple fireproof cover or sealing material layer. It would be assumed that the cost of this layer is included in the installation cost. The construction cost is negligible for this type of solution.

Then, the installation cost needs to be estimated. The **installation cost** can be broadly estimated (Peters, Timmerhaus and West 2004) by assuming that its value represents around **35% of the materials or**

---

[6] Perlite layer is assumed to be 10cm thick

[7] ROCKWOOL® Product with reference ProRox SL 660

equipment cost. Additional **construction expenses** and contractor's fee represent an additional **50% of the material or equipment cost**. Finally, **the maintenance cost** varies around **3-5% of the equipment cost**. The calculated maintenance cost is already annualised, the remaining costs need to be converted to an annual bases using an **amortisation period of 30 years.**

5.2.3. Instrumented Systems

Instrumented systems might be the most cost-efficient way to reduce the tank overfilling risk. Similarly to the heat insulation, the cost of installing instrumented system in tanks may be broken down in the following values:

- Cost of the instruments
- Cost of the installation
- Cost of signalling and electrical cabling
- Fixed costs (e.g. maintenance)

The market price of all the instruments required per tank is shown in Table 16 (Alibaba Group 2017). The distributed control system, the Fire&Gas panel and the safety instrumented system processor are not contemplated in the price list since the new instruments might be connected to the current tank metering and safety system of the facility.

Table 16. Average market price of instruments per tank

Instrument	Units	Cost (€/unit)
Radar Level Transmitter	3	1000
Multiple Point Temperature Transmitter	1	1000
Control Valve	1	5000
Gas detector	4	250
Flame detector	2	2000
Linear Heat Detector	1	1000
Total	**-**	**15000**

Following the same criteria of the heat insulation, **installation and commissioning** would cost around the **35% of the equipment price**. The **cost of additional cabling** to/from the central control system, the electrical cabling and an extra piping rack would represent an additional **65% of the equipment price**. Additionally, **maintenance would represent an additional 5% of the equipment price**, on a year basis (Peters, Timmerhaus and West 2004).

Cost of equipment and installation are converted to an annual basis using an **amortization period of 10 years**, which would represent the service life of this alternative. Contrary to other systems, instrumented systems require to be updated or replaced more often to keep their reliability.

5.2.4. Cooling Water Systems

Cooling water system do have a big impact on the heat radiation reduction on adjacent tanks. Similarly to the instrumented system, the cost of installing cooling water system may be broken down in the following values:

- Cost of the equipment
- Cost of construction (i.e. pump house, underground piping, etc.)
- Cost of the installation
- Fixed costs (e.g. maintenance)

The costs of the equipment might vary depending on the water flowrate density to be used. As discussed above, there are two standard flowrates used in industry, $2\ \mathrm{l/min.m}^2$ and $10\ \mathrm{l/min.m}^2$.

To make an example, the area to cool one tank of 40m diameter, 20000m^3 capacity, is 2000m^2. This means that the water flowrate required are assure $2\ \mathrm{l/min.m}^2$ is 67 l/s and the flowrate required to assure $10\ \mathrm{l/min.m}^2$ is 333 l/s. Using a safety factor of 50%, the actual flow required is approximately 100 l/s (1600 GPM) for the first scenario and two pumps of 250l/s (4000 GPM) for the second scenario.

The cost of the pump is established by Equation 18, which relates the cost of the pump to its design flow. The cost C_e is given in U$ (2006) and the S value is the capacity of the pump (l/sec). This value needs to be adjusted using the CE Index correction (inflation correction) to bring the price to the current date (Towler and Sinnott 2008).

$$C_e = 3300 + 48S^{1.2} \tag{18}$$

Although the water pumps are the most import piece of equipment of the water cooling system, the remaining piping and accessories still need to be quantified. Some design premises to estimate quantities and prices are:

- Pumping requirements are calculated according to the bund with the largest tank surface area (e.g. number of tanks in the bund x individual tank surface area)
- An extra spare pump is required in all cases
- Spacing between nozzles is required to be less than 3m (10ft). (NFPA - National Fire Protection Association 2017)
- It is assumed that a water source is nearby the facility, otherwise a water tank should be considered in the price estimation
- One deluge valve is installed per tank
- One strainer is installed per bund and one flowmeter is installed in every pump room
- Underground piping is installed from the pump to, and around, every bund in the facility
- Aboveground piping is installed from the bund wall to every tank inside the bund
- One control panel is installed for the entire facility
- One pumping room is required for the entire facility

Once the list of required equipment has been obtained, the total cost should be estimated. A basic estimation of the unitary prices of items required for the water cooling systems is presented in Table 17 (Abdullah 2016).

Table 17. Average market price of a water cooling system.

Item	Cost (€/unit)
Water Centrifugal Pump	30000-50000
Deluge Valve	10000
Flowmeter	7700
Strainer	3500
Aboveground piping (per meter)	150

Item	Cost (€/unit)
Underground piping (per meter)	400
Water Spray Nozzle	50
Control Panel	10000
Prefabricated Pump Room	500000

Following the same criteria as above, **installation and commissioning** would cost around the **35% of the equipment price**. Additionally, the **piping installation** (civil and piping work) has and extra cost of **65% of the total price**. Additionally, **maintenance** would represent an additional **5% of the equipment price**, on a year basis. Cost of equipment and installation are converted to an annual basis using an **amortization period of 20 years**, which would represent the service life of the solution. (Peters, Timmerhaus and West 2004).

5.2.5. Fixed Foam Systems

Bund fixed foam systems are a very efficient measure to control the bund fire, however, the cost this solution might negatively affect its implementation. As described above, the cost of installing a fixed foam system in the bund may be broken down in the following items:

- Cost of the equipment
- Cost of construction (i.e. pump house, underground piping, etc.)
- Cost of the installation
- Fixed costs (e.g. maintenance)

As discussed above, there flowrate density for bund foam systems is 4.1 $\mathrm{l/min.m}^2$ and the application time is 30 min. The cost of the pump is establish by Equation 18 (see above), which relates the cost of the pump to its design flow. Although the water pump is the most import piece of equipment of the fixed foam system, the remaining piping and accessories still need to be quantified. Some design premises to estimate quantities and prices are:

- Pumping and foam requirements are calculated according the largest bund area. Tank area should be discounted from the total bund area
- The area covered by every foam pourer is 450m^2
- Foam concentrate is assumed to be AFFF 3% type. If any other foam type is required, the price should be modified
- It is assumed that a water source is nearby the facility, otherwise a water tank should be considered in the price estimation
- An extra spare pump is required for facility
- One deluge valve is installed per bund
- One strainer is installed per bund and one flowmeter is installed in every pump room
- One proportioner is installed for every foam system
- Underground piping is installed from the pump to, and around, every bund in the facility
- Aboveground piping is installed from the bund wall to every tank inside the bund
- One control panel is installed for the entire facility
- One pumping room is required for the entire facility

Once the list of required equipment has been obtained, the total cost should be estimated. A basic estimation of the unitary prices of items required for the fixed foam system are presented in Table 18 (Abdullah 2016).

Table 18. Average market price of a fixed foam system.

Item	Cost (€/unit)
Water Centrifugal Pump	30000-50000
Deluge Valve	10000
Flowmeter	7700
Strainer	3500
Aboveground piping (per meter)	150
Underground piping (per meter)	400
Pouring Device	100
Proportioner	3000-8000
Foam Concentrate (AFFF 3%)	13.5/l
Foam Tank	3.5/l
Control Panel	10000
Prefabricated Pump Room	500000

Following the same criteria as above, **installation and commissioning** would cost around the **35% of the equipment price**. Additionally, the **piping installation** (civil and piping work) has and extra cost of **65% of the total price**. Additionally, **maintenance** would represent an additional **5% of the equipment price**, on a year basis. Costs of equipment and installation are converted to an annual basis using an **amortization period of 20 years**, which would represent the service life of the solution. (Peters, Timmerhaus and West 2004).

5.3.Cost-Benefit of Risk Reduction Strategies

Cost benefit is a technique that balances the cost of implementing a specific risk reduction measure or combination of measures against the expected benefit that the measure(s) will return in terms of risk reduction. Equation 19 is used to express the cost benefit criteria (Crippa, et al. 2009).

$$(\mathrm{C_{without}} * \mathrm{F_{without}} - \mathrm{C_{with}} * \mathrm{F_{with}}) > \text{cost of implementation} \qquad (19)$$

Where:

$\mathrm{C_{without}}$: represents the cost of the fire event without any protection measure

$\mathrm{F_{without}}$: represents the final event frequency if the protection measures are not implemented

$\mathrm{C_{with}}$: represents the cost of the fire event with the protection measure

$\mathrm{F_{with}}$: represents the final event frequency if the protection measures are implemented

Cost of implementation: represents the cost of implementing the risk reduction measure

As every reduction measure may fail, the probability of failure shall be introduced. This is done using Equation 20, describing how the reduced annualised cost is estimated.

$$C_{\text{with}} * F_{\text{with}} = C_{\text{escalation}} * F_{\text{escalation}} + C_{\text{no escalation}} * F_{\text{no escalation}} \qquad (20)$$

$$C_{\text{with}} * F_{\text{with}} = C_{\text{escalation}} * F_{\text{bund fire}}\ (\text{PFD}) + C_{\text{no escalation}} * F_{\text{bund fire}}\ (1 - \text{PFD})$$

$$C_{\text{with}} * F_{\text{with}} = (C_{\text{escalation}} * \text{PFD} + C_{\text{no escalation}} * (1 - \text{PFD})) * F_{\text{bund fire}}$$

Where PFD means the probability of failure on demand. This equations apply for a single protection measure, in case of multiple protection measures, the PFD of every measure has to be considered.

Although this method of calculation seems rather simple, it is important to highlight that the estimation of the frequencies and consequences, with and without the protection measure should be estimated according the premises discussed in sections 3.3, section 3.4 and chapter 4. To clarify the use of this methodology, a simple example is shown below. This example do not take real information from any source, it aims only to exemplify the methodology.

It is assumed a case where two tanks are inside the bund. The following assumption are made:

- The bund fire is caused by the rupture of a tank, the total release and ignition of its content
- The economic consequences of a total loss is €75 million per tank
- The frequency of a bund fire 1x10^{-5} year^{-1} tank^{-1}
- According to a radiant heat simulation, the protection measure is able to partially protect the tank exposed to flame engulfment
- Fire escalation is avoided but the second tank still results affected (partial loss, e.g. 50%)
- Cost of the protection measure is 500 € year^{-1} tank^{-1}
- The probability of failure of the protection measure –PFD- is 1x10^{-2}

Then,

$$C_{\text{without}} * F_{\text{without}} = (€75\ \text{million.tank}^{-1} * 2\ \text{tanks}) * (1\text{x}10^{-5}\ \text{year}^{-1}\ \text{tank}^{-1} * 2\ \text{tanks})$$

$$\mathbf{C_{without} * F_{without} = 3,000\ €/year}$$

and,

$$C_{\text{with}} * F_{\text{with}} = C_{\text{escalation}} * F_{\text{bund fire}}\ (\text{PFD}) + C_{\text{no escalation}} * F_{\text{bund fire}}\ (1 - \text{PFD}), \text{ where}$$

$$C_{\text{escalation}} * F_{\text{bund fire}}\ (\text{PFD}) = 3{,}000\ €/\text{year} * 0.01 = 30\ €/\text{year}$$

$$C_{\text{no escalation}} * F_{\text{bund fire}}\ (1 - \text{PFD}) = €75\ \text{mill.tank}^{-1} * 1.5\ \text{tanks} * 2\text{x}10^{-5}\ \text{year}^{-1} * (1 - 0.01)$$

$$C_{\text{no escalation}} * F_{\text{bund fire}}\ (1 - \text{PFD}) = 2{,}228\ €/\text{year}\ , \text{ then}$$

$$\mathbf{C_{with} * F_{with} = 30\ €/year + 2,230\ €/year = 2,260\ €/year}$$

Finally,

$$\mathbf{cost\ of\ implementation = 500€\ year^{-1}\ tank^{-1} * 2\ tanks = 1,000\ €/year}$$

As a result,

$$(C_{\text{without}} * F_{\text{without}} - C_{\text{with}} * F_{\text{with}}) < \text{cost of implementation}$$

The protection measure is not economically beneficial.

A case study is analysed in the next chapter where, the entire cost benefit study is performed to illustrate the methodology described above.

6. Case Study

To perform a complete risk assessment and a cost-benefit analysis, it is important to assume a scenario beforehand. In order to make an accurate analysis, the assessment must be done using a real case scenario. The assumed scenario is based on a tank storage facility located in Antwerp, Belgium. It is important to mention that this case study does not aim to target any specific facility or company in particular. It is just an example to demonstrate how the cost benefit analysis is performed to a real case scenario.

The storage facility has several multiple tanks bunds. Intermediate bunds are in place to separate large tanks. Figure 17 shows the layout of the case study storage facility. There are three mayor bunds with six tanks located in every bund. Also, intermediate bunds separate the tanks in three subgroups of two tanks each. Tanks are labelled with numbers to ease their identification. The tank characteristics are presented in Table 19 and the bund characteristics are displayed in Table 20.

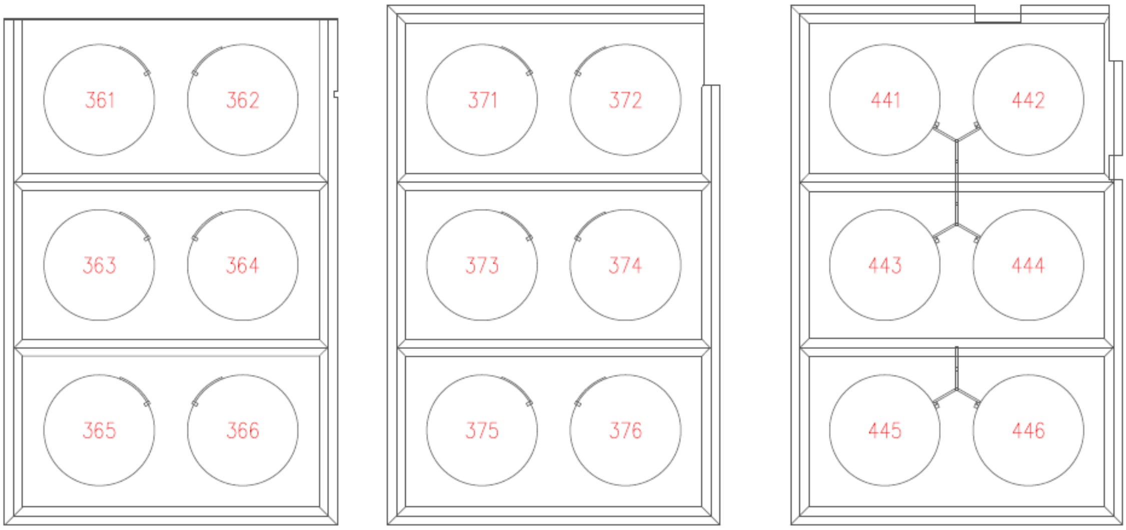


Figure 17. Tank Storage Facility Layout – Case Study

Table 19. Storage Facility Tank Description – Case Study

Tank	Type	Capacity [m^3]	Diameter [m]	Product
361-362	Fixed Roof	22150	44	Fuel Oil
363-364	Fixed Roof	22150	44	Fuel Oil
365-366	Fixed Roof	22150	44	Fuel Oil
371-372	Fixed Roof	22150	44	Fuel Oil
373-374	Fixed Roof	22150	44	Fuel Oil
375-376	Fixed Roof	22150	44	Fuel Oil
441-442	Floating Roof	24200	45	Gasoline
443-444	Floating Roof	24200	45	Gasoline
445-446	Floating Roof	24200	45	Gasoline

Table 20. Storage Facility Bund Description – Case Study

Tank	Dimensions [m x m]	Area [m^2]	Capacity [m^3]	Total Capacity[m^3]	Walls Height [m]
361-362	120x60	7200	3600	25000	2.0
363-364	120x60	7200	3600		
365-366	120x60	7200	3600		
371-372	120x60	7200	3600	25000	2.0
373-374	120x60	7200	3600		
375-376	120x60	7200	3600		
441-442	120x60	7200	3600	27000	2.1
443-444	120x60	7200	3600		
445-446	120x60	7200	3600		

The assumed scenario is defined with the following characteristics:

- One operator (on average) is present inside the bund when the event occurs. Evacuation time of the area inside the bund is assumed to be 20 sec
- All tanks are filled to their maximum capacity
- Distance between intermediate bund tanks (i.e. 361 and 363) is 20m
- Distance between adjacent bund walls is 30m
- Distance between the tank shell and the bund wall is 10m
- Loading/unloading piping inside every large bund is assumed to be 300m long
- The bund succeeds in retaining all the spilled liquid inside its walls

6.1.Risk Scenarios

Risk scenarios for this case study may be broadly categorised in:

- Spillage and immediate ignition inside an intermediate bund **(small bund fire)**
- Complete tank rupture and immediate ignition in the whole bund area **(large bund fire)**

For this case study, both the small and the large bund fires are considered. Additionally, some assumptions have to be made. **In order to consider the scenario with the worst consequences, it is assumed that the fire occurs due to a spillage in either tank 373 or 374.** This is considered the scenario with the worst consequences because it might escalate in all directions because the tanks are in the middle of the facility.

6.2.Likelihood

The next step is to estimate the likelihood of the scenarios. This is done using the frequency data discussed in section 3.2.2 and 3.3.2.

The assumption of a small bund fire requires the spillage not to overflow the intermediate bund. This means that the maximum quantity of fuel released is 3600 m^3.

However, the leak has to be large enough for the fuel to spread all over the area of the intermediate bund and to create a pool thick enough to sustain the pool fire for several minutes or hours. This type of spill can just be caused by a large leak (75-120mm).This result is obtained assuming that the leaks last for at least five minutes before being stopped. (Swinderen 2005)

On the other hand, a large bund fire can just be caused by either the tank rupture/total release of its content or by a large piping rupture (>150mm for more than 10 min).

Table 21 shows all the scenarios that might produce a small and large bund fire. **As result, the total frequency of having a small bund fire is equal to 2.0×10^{-3} $year^{-1}$ and the frequency of having a large bund fire covering the entire bund is equal to 9.3×10^{-5} year.** In other words, a small bund fire is expected to occur in the facility every 500 years in the facility and a large bund fire is expected to occur every 10000 years. **It is important to clarify that these frequencies are based on statistics and do not consider any prevention measure.**

Table 21. Frequencies of Bund Fire Scenarios– Case Study

Event	Type of Bund Fire	Event Frequency [$tank^{-1}$ $year^{-1}$]/[m^{-1} $year^{-1}$]	Event Frequency [$year^{-1}$]
Overfill	Small	6.9×10^{-5}	1.2×10^{-3}
Tank Leak (large)	Small	2.9×10^{-5}	5.2×10^{-4}
Pipe Leak (> 75mm)	Small	3.0×10^{-7}	2.7×10^{-4}
Total Release	Large	1.3×10^{-6}	2.3×10^{-5}
Pipe Leak (>150mm)	Large	7.8×10^{-8}	7.0×10^{-5}

6.3. Consequences

Once the frequencies and likelihood have been estimated, the next step is to calculate the consequences of the selected scenarios. The first step to estimate the consequences is to calculate the fire extent and whether or not the adjacent tanks are at risk of fire escalation.

As explained in section 3.4.2, the calculation method describes how the software PHAST® is used to estimate the radiative heat flux for adjacent tanks and how Equation 12 is used to estimate the average emissivity heat flux from the flames to tanks involved in the engulfing pool fire. The Table 22 shows the heat flux values according to the size of the bund fire. A wind category 1.5D is assumed for the case scenario.

Table 22. Heat Flux Values for Bund Fire Scenarios – Case Study

Distance From the Bund Wall [m]	Radiant Heat Flux [kW/m^2]	
	Small Bund Fire (D_{eq}=96m)	Large Bund Fire (D_{eq}=166m)
0	20.0	20.0
10	10.0	9.0

Distance From the Bund Wall [m]	Radiant Heat Flux [kW/m^2]	
	Small Bund Fire (D_{eq}=96m)	Large Bund Fire (D_{eq}=166m)
20	8.0	8.0
30	7.0	7.0
40	6.0	6.0

Now, with the radiant heat fluxes, it is possible to estimate the consequences on every item mentioned in section 3.4.1.

6.3.1. Life Loss

As stated before, it is assumed that just one operator is present inside the bund when the fire starts and that it takes 20 seconds for the operator to evacuate. The Equation 6 in the section 3.4.1.1 allows to estimate the effects on the people present inside the bund. **The outcome of the Probit function tells that there is a probability of 53.7% for the operator to die due to the hear radiation exposure.** By multiplying the cost associated to a casualty (€2.32 million), as discussed in the section 253.4.1.1, with the probability of the operator to die it is concluded that **the cost associated to life loss is around €1.24 million.**

6.3.2. Property Loss

The cost of the property loss is estimated adding the cost of the equipment damaged and the cost of the fuel burned.

To estimate the amount of equipment damaged by the fire it is necessary to estimate whether the adjacent tank would fail or not. This is done by using the time to failure Equation (13) found in the section 3.4.2.4. Table 23 shows the time to failure of every adjacent tank for both small and large bund fires.

Table 23. Time to failure of adjacent tanks – Case Study

Location of Adjacent Tank	Quantity of Tanks	Time to Failure [min]	
		Small Bund Fire	Large Bund Fire
Origin of the Leakage	1	NA	NA
Tanks inside the same intermediate bund	1	9.1	9.1
Tanks inside the same large bund	4	110.1	9.1
Tanks in adjacent bunds	12	No Failure	No Failure

As external fire brigade intervention is likely to control small bund fires within 100 min (see section 6.4.6). It is assumed that tanks with “time to failure” values above 100 minutes will not be affected by the fire. **Table 23 allows to conclude that in case of a small bund fire just two tanks will be affected and that in case of a large bund fire, six tanks will be affected. Tanks in adjacent bund would not be affected by the pool fire.**

Thus, it is assumed that when the fire escalates, all tanks involved in the fire are going be completely damaged and that all the product is burned out.

The economic equipment loss is estimated from Equations 8 and 11. Furthermore, the fuel burned loss is estimated using Table 10. Both losses are presented in Table 24. The tanks affected are fixed roof type and the fuel stored in the tanks is fuel oil.

Table 24. Economic property loss estimation – Case Study

Item	**Cost (million €)**	
	Small Bund Fire	**Large Bund Fire**
Equipment	17.8	53.4
Product	13.3	39.9
Total	**31.1**	**93.3**

The outcome of the estimation gives that the total property loss would reach €31.1 million in case of a small bund fire and €93.3 million in case of a large bund fire.

6.3.3. Business Interruption Loss

As explained in section 3.4.1.3, the business interruption loss may be estimated by multiplying the property loss by a factor of 3. **Then, the cost associated with business interruption loss is €93.3 million for the small bund fire and €280.0 million for a large bund fire.**

6.3.4. Environment Loss

As explained in section 3.4.1.4, the environmental cost is assumed to be 1% of the sum of the property and business interruption cost. **Thus, the environmental loss for a small bund fire is estimated to be €1.24 million for a small bund fire and €3.73 million for a large bund fire.**

6.3.5. Reputation Damage

As explained in section 3.4.1.5, the reputation is unlikely to be affected in the long term. The potential impact of a loss due to the reputation damage is assumed to be accounted for in the business interruption losses. **Thus, no additional economic loss is assumed to be related to the reputation damage.**

6.3.6. Annualised Consequences

The annualised cost of a bund fire event in the scenario proposed is estimated using the total economic consequences, which are shown in Table 25.

Table 25. Economic consequences according to the value affected – Case study

Value	**Cost Associated (millions €)**	
	Small Bund Fire	**Large Bund Fire**
Life	1.24	1.24
Property	31.1	93.3
Business Continuity	93.3	280.0
Environment	1.24	3.73

Value	**Cost Associated (millions €)**	
	Small Bund Fire	**Large Bund Fire**
Reputation	0.0	0.0
Total	**127.0**	**378.0**

Using Equation 14 and the event frequencies data obtained in section 6.2, it is concluded that the annualised cost of a small bund fire is €254.000 per year and the annualised cost of a large bund fire is €35.000 per year. **Then, the combined annualised cost reaches €289.000 per year, or €16.000 per year per tank** (counting all 18 tanks in the facility). It is important to highlight that these values are estimated without considering any prevention or mitigation measure.

6.4. Risk Reduction Measures

Risk reduction measures aim to reduce either the frequency or the negative consequences of a bund fire event. However, every reduction measure involves an implementation cost. This section is aimed to quantify these three aspects:

- Impact on the escalation frequency
- Impact on the negative consequences
- Cost of implementation

Every reduction measure analysed in section 4 is analysed below.

6.4.1. Bund and Separation Distances

As described in section 4.1.1, many authors recommend to locate storage tank in separate bunds. This is very important because it avoids fire escalation. **If every tank is located in an independent bund, the economic loss would decrease to the loss of just one tank.** On the other hand, bunds are not that efficient when a catastrophic release occurs (see section 4.1.1.1). Thus, it is assumed that fire will escalate if the bund fails to retain the fuel. Table 26 shows the impact on the modified annualised cost ($C_{with} * F_{with}$) according to the section 5.3.

Table 26. Impact on economic consequences of independent bunds– Case study

Event	**Annual Consequences [k€/year/tank]**
Small Bund Fire	7.2
Large Bund Fire	1.0
Total Loss	**8.2**

Now, the cost of the measure need to be estimated. According to the standards, the volume of the bund needs to be sufficient to store up to 110% the capacity of the biggest tanks.

The capacity of all the tanks is around 23000m^2, so a 2.0 m high bund would require an area of 12500m^2. Now, assuming that the tanks are provided with independent bunds, and discounting the area of the tank, the minimum bund dimensions that accomplish with the IP Code would be 119m x 119m. Thus, the total space used for this design option is 255000m^2. **The area required increases by approximately 400% for using independent bunds.**

The annualised cost of implementing independent bunds for each tank is calculated according to section 5.2.1 premises and the results are presented in Table 27.

Table 27. Cost of implementing independent bunds– Case Study

Item	Annual Cost [k€/year/tank]
Additional Construction	6.0
Additional Land Rent	324.0
Total Cost	**330.0**

6.4.2. Heat Insulation – Fireproofing

As explained in section 4.1.2, a fireproof insulation shall provide two hours protection if correctly installed on tank walls. This would give the fire brigade sufficient time to control the fire and avoid fire escalation to adjacent tanks. **Thus, if fireproofing is applied to every tank, the economic loss would be reduced to the partial to total loss of the tank that initially failed**. It is assumed that, for a small bund fire, the fireproofing also helps to protect the tank that failed. This would reduce the property loss to the half of the total loss if the tank and its content were completely destroyed. The Table 28 shows the impact on the modified annualised cost ($C_{with*}F_{with}$) according to the section 5.3.

Table 28. Impact on economic consequences of fireproofing - Case study

Event	Annual Consequences [k€/year/tank]
Small Bund Fire	3.6
Large Bund Fire	0.3
Total Loss	**3.9**

Now, the cost of the measure need to be estimated. The cost of implementing the fireproofing to the tanks is described in section 5.2.2. Table 29 shows the annualised cost of implementing insulation to the case scenario. The insulation is applied all over the tanks surface (2100m^2 per tank).

Table 29. Cost of implementing insulation – Case Study

Item	Annual Cost [k€/year/tank]		
	Perlite+ External Shell	ProRox®	Second Shell
Materials	2.9	4.1	2.5
Installation	1.0	1.4	0.9
Construction	1.5	0.0	1.3
Maintenance	2.6	3.7	2.3
Total Cost	**8.0**	**9.2**	**7.0**

6.4.3. Instrumented System

The analysis in section 4.2.1 showed how instrumented systems may reduce and prevent the overfill events. The event tree shown in Figure 14 allows to estimate how the event frequency is reduced. This is a key aspect since tank overfill frequency is the event which most influence in the overall small bund tree frequencies. **The frequency of small bund fires is reduces from $2.0x10^{-3}$ to $8.1x10^{-4}$.** On the other hand, the large bund fires frequency is not affected. The Table 30 shows the impact on the modified annualised cost ($C_{with}*F_{with}$) according to the section 5.3.

Table 30. Impact on economic losses of instrumented systems - Case study

Event	Annual Consequences [k€/year/tank]
Small Bund Fire	5.7
Large Bund Fire	1.9
Total Loss	**7.6**

The cost may be calculated using the data and premises in section 5.2.3. Table 31 shows the cost of implementing an automatic instrumented solution to the simplified case.

Table 31. Cost of implementing automated instrumentation. - Case study

Item	Annual Cost [k€/year/tank]
Equipment	1.5
Installation	0.5
Cabling and Tubing	1.0
Maintenance	0.8
Total Cost	**3.8**

6.4.4. Water Cooling System

Section 4.2.2 addressed how water cooling systems reduce the probability of escalation. Depending on the water flowrate, the radiant heat coming from the flames is reduced to the point that the failure of the tanks involved in the bund fire might be evitable. Table 32 shows the effects of the water cooling system on the radiation intensity level. A water flow density of 2 l/min.m^2 is seem to be sufficient to decrease the radiant intensity to levels where escalation is no longer possible.

Table 32. Impact on the time to failure of the water cooling systems - Case study

Tank Location	Radiation Flux [kW/m^2]	Time to Failure [min]	Heat Radiation Flux Reduced [kW/m^2]		Time to Failure Increased [min]	
			10 l/min.m^2	2 l/min.m^2	10 l/min.m^2	2 l/min.m^2
Engulfed in the flames	20	9.1	>3	5	No Failure	No Failure

Tank Location	**Radiation Flux [kW/m²]**	**Time to Failure [min]**	**Heat Radiation Flux Reduced [kW/m²]**		**Time to Failure Increased [min]**	
			10 l/min.m²	**2 l/min.m²**	**10 l/min.m²**	**2 l/min.m²**
Adjacent tank (10m)	10	110	>3	>3	No Failure	No Failure
Adjacent bund (30m)	7	No Failure	>3	>3	No Failure	No Failure

This plays a key role in the consequence estimation because it means that a low water flowrate density is able to control the fire escalation until the fire brigade arrives and puts the situation under controls. **As mentioned above, it is assumed that, for small releases, the water cooling system would also protect the tank where the leakage or overfill occurred and it would be just partially damaged. This would reduce the loss to a 50% of the total economic loss of the equipment and its content** (partial loss, see section 3.4.1.2). Table 33 shows the total economic loss after implementing a water cooling system of 2 l/min.m^2 on all the tanks according to the section 5.3.

Table 33. Impact on economic consequences of water cooling system. - Case study

Event	**Annual Consequences [k€/year/tank]**
Small Bund Fire	3.7
Large Bund Fire	0.4
Total Loss	**4.1**

The premises to estimate cost and quantities of a water cooling system are given in section 5.2.4. To cover all the tanks inside a bund (2100m^2 per tank), the amount of water that needs to be pumped is 25200 l/min (6700 GPM). Assuming a design safety factor of 1.5, the required flowrate is 37800 l/min (10000 GPM). This would require three pumps of 3500 GPM plus a spare pump.

Table 34. Average market price of a water cooling system – Case Study

Item	**Units required**	**Cost [€/unit]**
Water Centrifugal Pump	4	40000
Deluge Valve	18	10000
Flowmeters	1	7700
Strainers	3	3500
Aboveground piping	450	150
Underground piping	2100	400
Water Spray Nozzle	1700	50
Control Panel	1	10000
Pump Room	1	500000
Total	**-**	**1.86 million**

Following the same criteria explained in the section 5.2.4, all other associated costs are estimated. The total cost of Table 34 is divided by the amortisation period and by the number of tanks. Table 35 shows the cost of implementing a cooling water system of 2.0 l/min/m^2 to the facility in the case study.

Table 35. Cost of implementing fixed cooling systems – Case Study

Item	Cost [k€/year/tank]
Equipment	5.2
Installation and Commissioning	1.8
Piping and Construction	3.3
Maintenance	5.2
Total	**15.5**

6.4.5. Fixed Foam Systems

In section 4.2.3 it was explained how the fixed foam systems operate. It is assumed that, if the foam system work properly, just one tank would be affected (the tank where the event started). **Furthermore, it is assumed that, for small releases, the fixed foam system would quickly control the fire and protect also the tank where the leakage or overfill event started. This would reduce the loss to a 50% of the total economic loss of this specific tank and its content** (partial loss, see section 3.4.1.2). Table 36 shows the total economic loss after implementing a water cooling system of 2 l/min.m^2 on all the tanks according to the section 5.3.

Table 36. Impact on economic consequences of bund fix cooling system - Case study

Event	Annual Consequences [k€/year/tank]
Small Bund Fire	3.7
Large Bund Fire	0.4
Total Loss	**4.1**

Now, to estimate the cost of implementing a fixed foam system, quantities need to be estimated. The premises to estimate cost and quantities are given in section 5.2.5. To cover all the bund area (12500 m^2), the amount of foam solution that needs to be pumped is 51250 l/min (11300 GPM) for at least 30 min. The required amount of foam concentrate is 46.2 m^3 (AFFF 3%). This would require four pumps of 3500 GPM plus a spare pump. Table 37 shows the average prices for all the components required to install a bund fixed foam system.

Table 37. Average market price of a bund fixed foam system - Case study

Item	Units required	Cost [€/unit]
Water Centrifugal Pump	5	40000
Deluge Valve	3	10000
Flowmeters	1	7700
Strainers	3	3500

Item	Units required	Cost [€/unit]
Aboveground piping	450	150
Underground piping	2100	400
Pouring Device	84	100
Proportioner	1	8000
Foam Concentrate (AFFF 3%)	50000 l	13.5/l
Foam Tank	1 (60000 l)	3.5/l
Control Panel	1	10000
Prefabricated Pump Room	1	500000
Total	**-**	**2.57 million**

Following the same criteria explained in section 5.2.5, all other associated costs are estimated. Table 38 shows the cost of implementing a fixed foam system to the facility in the case study.

Table 38. Cost of implementing bund fixed foam systems - Case study

Item	Cost [k€/year/tank]
Equipment	7.1
Installation and Commissioning	2.5
Piping and Construction	4.6
Maintenance	7.1
Total	**21.4**

6.4.6. Fire Brigade Intervention

Fire brigade intervention plays a key role in preventing fire escalation. In many cases, the probability of controlling a tank fire only depends on the response time. As discussed in section 4.3, the probability of escalation may be quantified upon these variables:

- Time of alert
- Time to effective mitigation
- Time to equipment failure

According to the fire brigade of Antwerp, Belgium, the time to alert for a bund fire event might be around five minutes and the time to effective mitigation might be around 40 min (Interview to the the Major Verschueren from the Antwerp fire brigade 2017). Thus, using Equation 14, Table 39 shows the probability of fire escalation depending on the equipment time of failure.

Table 39. Probability of escalation with fire brigade intervention – Case Study

Time of failure [min]	Probability of Escalation [%]
5	90
10	67

Time of failure [min]	Probability of Escalation [%]
20	33
30	18
60	4
120	0

Table 39 shows that the fire brigade would be very likely able to control the bund fire event and prevent fire escalation if the time to failure of adjacent tanks is at least 60 min. If it is assumed that there is no other protection measure than the fire brigade intervention it can be assumed that the consequences would be reduced as well. Table 40 shows the annual economic loss of relying only upon fire brigade intervention. It is assumed that the tank where the fire event started has no chance to be saved for either small or large bund fires.

Table 40. Impact on economic consequences of fire brigade intervention - Case study

Event	Annual Consequences [k€/year/tank]
Small Bund Fire	12.0
Large Bund Fire	1.5
Total Loss	**13.5**

6.5.Cost-Benefit Analysis

After estimating the reduced consequences and the cost of implementing all risk reduction measures contemplated above, the cost benefit analysis is done. Figure 18 shows the outcome of the cost-benefit analysis.

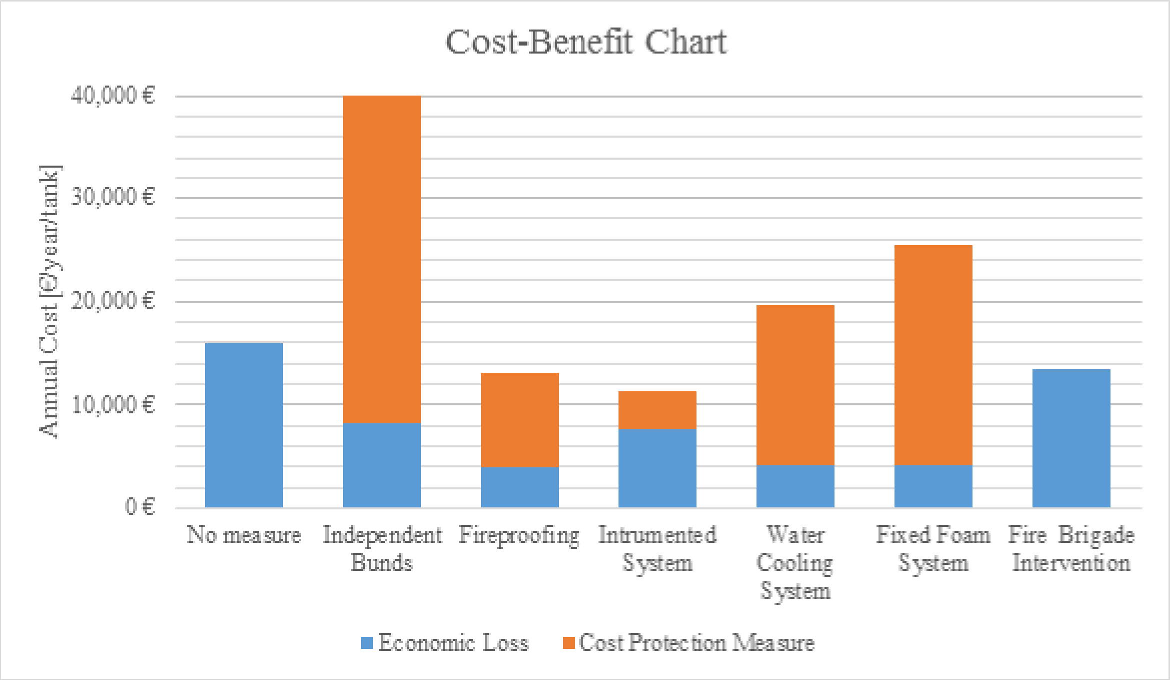


Figure 18. Cost benefit analysis chart of risk reduction measures –Case study.

The blue bar represents the annual economic loss associated with a bund fire event. The red bar represents the annual cost of the risk reduction measure.

It can be clearly seen that independent bunds for every single tank are too expensive. That measure does not even fit in the chart.

Additionally, it is clear that both water cooling systems and the bund fixed foam systems are so costly that they would not be economically beneficial to control or mitigate bund fires.

This is mainly due to both the low probability of a bund fire event to occur, what considerably reduces the annualised risk, and to the high cost associated to the pumps, piping and foam of active protection measures. In this case, it would be more economically advantageous to not take any active protection measure against bund fire events.

Protection measures like tank fireproofing or the installation of instrumented systems to prevent overfilling are less expensive and even more economically beneficial to prevent multiple tanks bund fire events.

On one hand, fireproofing not only counts with a larger service life time, but also does not require large pieces of equipment like a water pumping system (while active measures do).

On the other hand, instrumented systems to prevent overfills are a relatively cheap solution and are very effective in reducing the bund fire probability.

Finally, it can be seen that the intervention of the fire brigade reduces the annual economic loss to a point that it would be more effective to rely on the fire brigade rather than implementing any other measure.

However, there are some points that need to be analysed. Some of these points are:

- Other risks are not contemplated (full surface fires or explosions)
- The option to combine protection measures (e.g. passive and active systems)
- The analysis might differ from case to case
- The assumptions might considerably change the results and conclusions

6.5.1. Risks not Contemplated

Although it is true that this work does not contemplate other risks, a quick analysis might be done to estimate the influence of other risk like full surface fire on the results. To do so, some assumptions need to be done. Then, it is assumed that the other risks not contemplated justify the implementation of a fixed foam system located on the roof of every tank. This measure is meant to prevent full surface fires.

For fixed roof applications, the foam flowrate density required is 4.1 l/min.m^2 and the discharge time is up to 55 min. For floating roof applications, the water flowrate density is 12.2 l/min.m^2 (annular ring area) and a discharge time of 20 min (Centrum Industriële Veiligheid 2017). Foam quantities are defined upon the requirements for the largest tank.

Considering this, the area to cover for the case study is 1600 m^2 per tank. This would require a water flowrate of 6600 l/min (1750 GPM). Using a safety factor of 1.5, the pump requirement would be 10000l/min (2600 GPM). This would require single pump of 3000 GPM and an additional spare pump. The amount of foam concentrate would be close to 11000 l.

Table 41 shows the average prices for all the components required to install a roof fixed foam system.

Table 41. Average market price of a roof fixed foam system

Item	Units required	Cost [€/unit]
Water Centrifugal Pump	2	40000
Flowmeters	1	7700
Strainers	3	3500
Aboveground piping	450	150
Underground piping	2100	400
Pouring Device	72	100
Proportioner	1	8000
Foam Concentrate (AFFF 3%)	11000 l	13.5/l
Foam Tank	1 (13000 l)	3.5/l
Control Panel	1	10000
Prefabricated Pump Room	1	500000
Total	**-**	**1.72 million**

Following the same criteria explained in the section 5.2.5, all other associated costs are estimated. The total cost of Table 41 is divided by the amortisation period and by the number of tanks. Table 42 shows the cost of installing a roof fixed foam system to the facility in the case study.

Table 42. Cost of implementing roof fixed foam systems

Item	Cost [k€/year/tank]
Equipment	4.8
Installation and Commissioning	1.7
Piping and Construction	3.1
Maintenance	2.9
Total	**12.5**

Assuming that the tank roof fixed foam system is installed, the cost of both water cooling system and bund fixed foam system reduces because they would share the same piping and pumping system. The cost benefit chart of the active protection measures with the cost modification is shown in Figure 19.

It is clear that the installation of a roof fixed foam system reduces the cost of implementing a water cooling system to the point that it is now a feasible economic option to prevent tank fire escalation.

On the other hand, the bund fixed foam system is still too expensive. The main reason for this is the additional foam and the extra pumping capacity required to cover the area of a bund fire compared the area of a single tank roof.

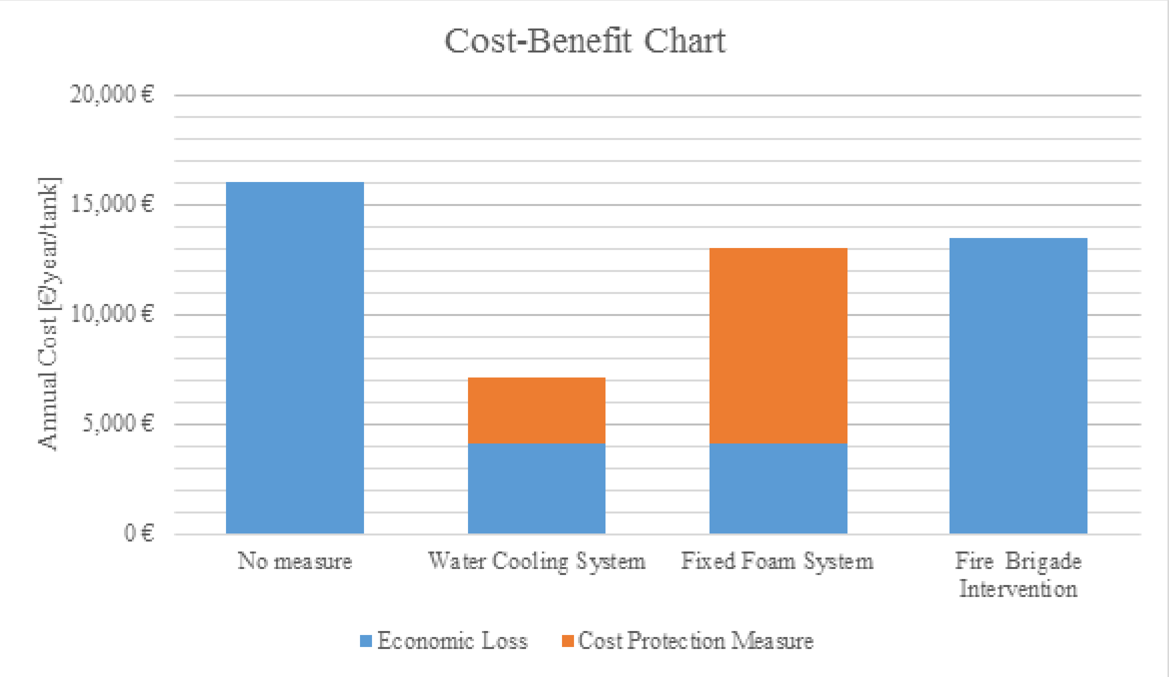


Figure 19. Cost benefit analysis chart with active protection systems cost reduction–Case study.

6.5.2. Combination of Protection Measures

Another aspect to analyse is the combination of protection measures. There is the possibility that combining protection measures would actually be more beneficial to manage the risk. Thus, the combinations analysed are:

- 1: No measure
- 2: Overfill protection + fire brigade intervention
- 3: Overfill protection + water cooling system
- 4: Overfill protection + fireproofing
- 5: Fireproofing + water cooling system (bottom with fireproofing and top with water cooling spray system)

For these scenarios, it is assumed that a roof fixed foam system is installed, so the water cooling system cost would require just the extra pieces of equipment required and extra maintenance.

Figure 20 shows the results of the cost benefit analysis. It can be seen how the combinations of risk reduction measures are even more cost effective. All the proposed combinations of measures are economically suitable.

The most effective measure to prevent escalation events from bund fire event is a combination of an overfill protection with a water cooling system (counting on an installed roof fixed foam system). It is important to highlight that the combination between the overfill protection and the fire brigade intervention might be a very attractive option, in case a roof fixed foam system is not installed.

At last, the fireproofing might work very well with other protection measures although this option has barely been analysed before on storage facilities.

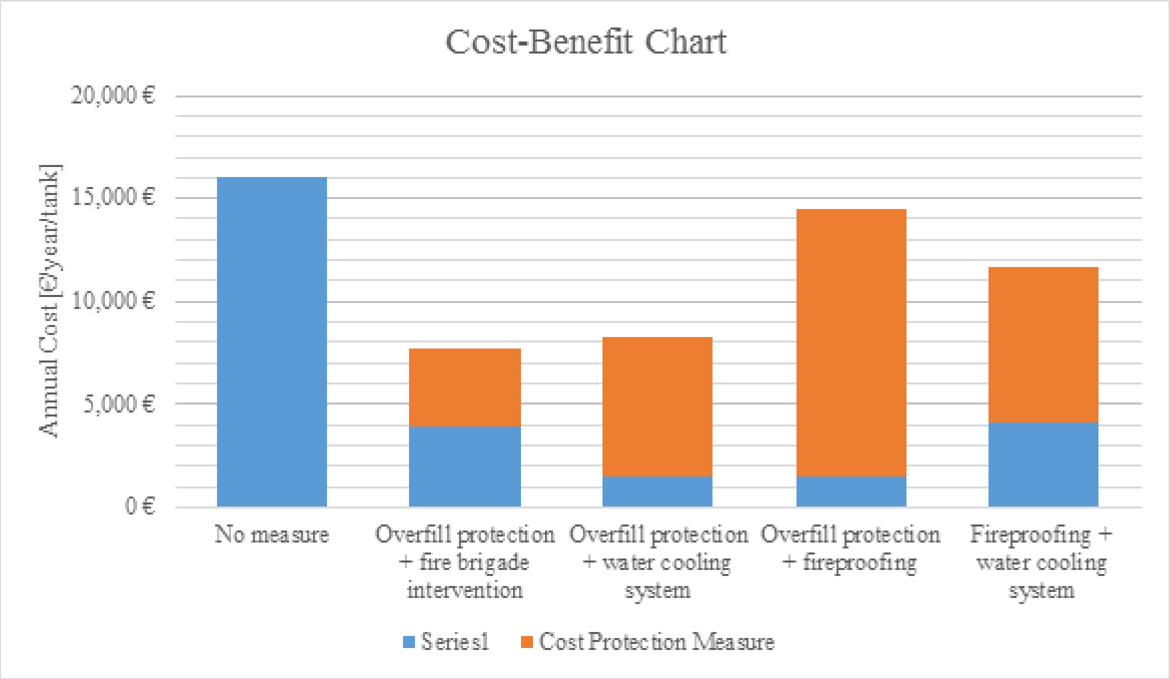


Figure 20. Cost benefit analysis chart for combined reduction measures–Case study.

A combination between an overfill protection system and a measure that protects the adjacent tanks from external heat radiation (e.g., water cooling system or fireproofing) is very effective because:

- The overfill protection considerably reduces the probability of causing a small bund fire and,
- The radiant heat protection measure considerably reduces the negative consequences of a large bund fire.

As a result, the protection measures complement each other in a very efficient way and the risk is reduced to a very low level (see measures 3 and 4 of Figure 20).

6.5.3. Uncertainty Analysis

To perform a risk assessment study and a later cost benefit analysis, a large number of assumptions need to be made. The more assumptions made, the larger the uncertainty involved in the results. Moreover, models used all along the methodology also carry some uncertainty. Thus, a brief sensitivity analysis is done below. Some of the main factors affecting the outcome of the analysis are:

- Initiating event frequency
- Loss estimation assumptions (i.e. relation business interruption/property loss)
- Radiant heat model
- Risk reduction measure cost assumptions (quantities and unitary prices)
- Amortisation period

Nevertheless, some other variables that only depend on the case study also might change the outcome of the study. The main variables that might affect the outcome are:

- Tank storage capacity and the type of product stored
- Number of tanks per bund
- Number of bunds in the facility

6.5.3.1. Sensitivity Analysis

All the variables and values either determined or assumed during the risk assessment and cost benefit analysis have an impact on the final outcome of the evaluation. The final outcome is basically composed of the annualised risk and the cost of the reduction measures.

The sensitivity analysis is separated in two sections. The first part analyses how changes in some of the most important assumptions affect the results on both annualised risk and annualised cost of the protection measure. The second part addresses how the changes in the case study would affect the cost benefit outcome.

6.5.3.2. Uncertainty of Assumptions

For the first part, a change of ±10% is made to the main variables mentioned above and the effects on the final outcome are presented in a tornado diagram. The base scenario for the annualised risk defined as the case study facility without any protection measure. The base scenario for the annual cost of the protection measures is defined as the annual cost to implement a water cooling system.

Figure 21 shows the effect of the change of some of the most important variables on the annualised risk. It is evident that all the variables analysed have a close proportional impact on the annualised risk. This means that a change, for instance, in the initiation event frequency would generate an impact almost “proportional” impact on the annualised risk. The only change in a variable that does not have a strong impact is the reduction on the heat radiation flux, because when adjacent tanks are at a certain distance not to be affected by the current radiation, a further reduction in this value does not generate any benefit.

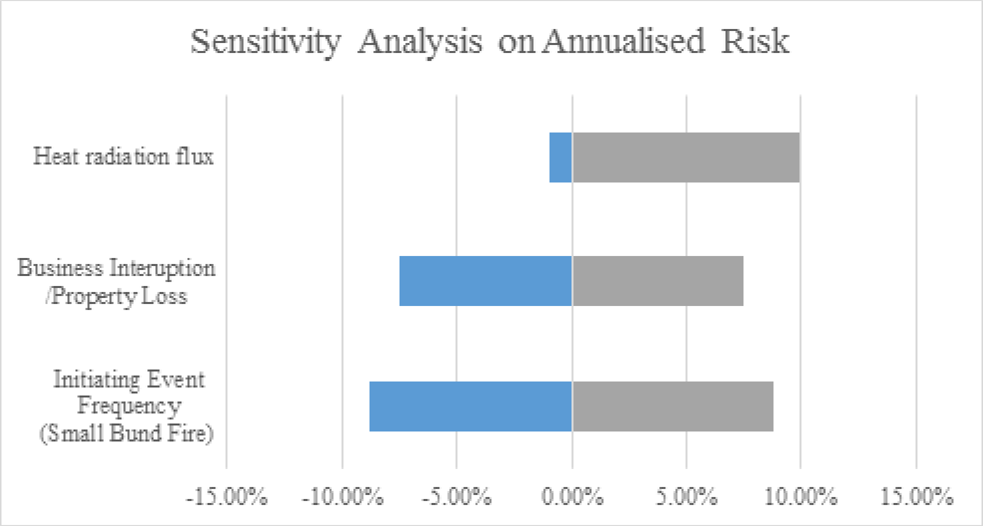


Figure 21. Sensitivity Analysis – Effect of assumption change in annualised risk (loss).

However, the most important conclusion is that the high uncertainty levels in the assumptions do considerably affect the final annualised risk. The negative consequence estimation (e.g., economic loss) is based on assumption with high level of uncertainty. **Thus, an assumption like the ratio between business interruption and the property loss need to be taken from a conservative perspective**. Consequently, the outcome annualised risk would consider the “worst case scenario”.

Figure 22 shows the effect of the change of some of the most important variables on the annual cost of a risk reduction measure (water cooling system). Contrary to the effect of the assumption on the annualised risk, assumptions because the made to estimate the protection measure cost have a lower impact on the result.

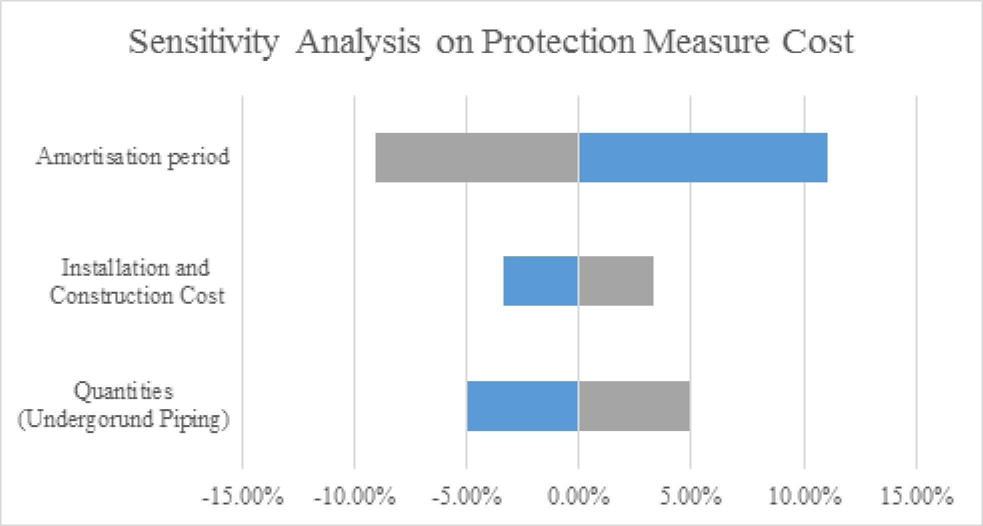


Figure 22. Sensitivity Analysis – Effect of assumption uncertainty on a protection measure cost.

The only variable that should be considered as a potential source of uncertainty is the amortisation period. A change in the amortisation period, or service life of the protection measure, does have a strong influence on the results. As mentioned above, the amortisation period assumption needs to be taken carefully. On one hand, an underestimated amortisation period (low value) might cause a beneficial protection measure to look too expensive. On the other hand, an overestimated amortisation period (high value) might cause a detrimental protection measure to look economically feasible.

6.5.3.3. Case Study Variables

For the case study, a change of ±10% is made to the main variables mentioned above and the effects on the final outcome are presented in a tornado diagram. The base scenario for the annualised risk is defined as the case study facility without any protection measure. The base scenario for the annual cost of the protection measures is defined as the annual cost to implement a bund fixed foam system.

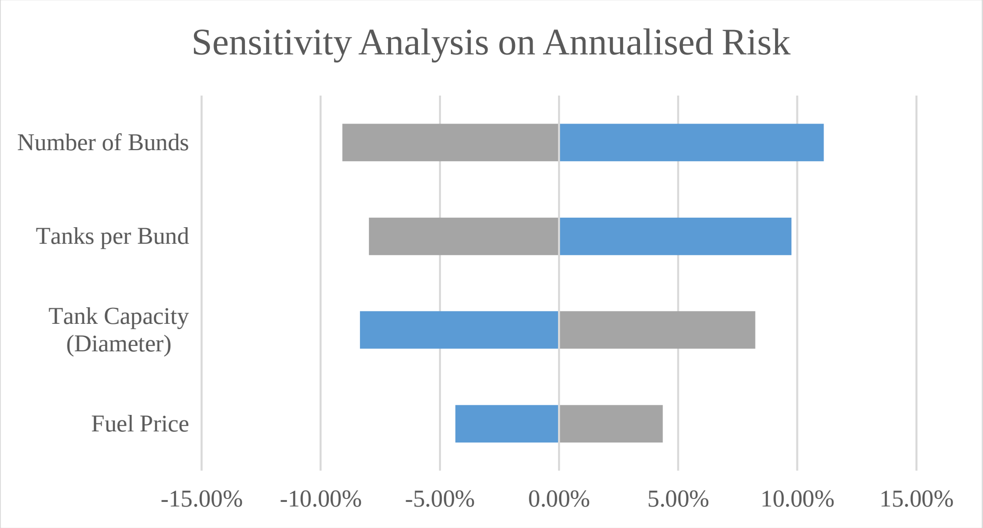


Figure 23. Sensitivity Analysis – Effect of case study specifications on the annualised risk.

Figure 23 shows the effect of a change in the case study parameters on the final annualised risk result. It is important to mention that the annualised risk in this analysis does not consider any protection measure. The first thing that calls the attention is the comparison between the influence of the type of fuel stored and the tank capacity.

Both variables have a direct impact on the annual economic loss. However the tank capacity has a stronger influence (almost double) in contrast to the fuel price on the final annual risk value.

The second notorious and surprising aspect is that both the number of tanks per bund and the number of bunds (e.g. size of the storage facility) have an inverse impact on the annual risk. This means that the more tanks per bund and bund in general, the lower the annualised risk. It is important to remark that the annual risk is expressed as economic loss per tank per year. This occurs because the risk depends upon the probability and consequences of both small and large bund fire events. However, small bund fires contribute substantially more to the overall risk than the large bund fires, which have a lower probability to occur. In the end, as the small bund fires are contained by intermediate bunds, the total amount of tanks inside the large bund does not increase the annualised risk per tank, but actually reduces it.

To compare the influence of the case study parameters on the annualised risk, to their influence on a protection measure cost, the same sensitivity analysis was done to the installation of bund fixed foam systems. Figure 24 shows the effect of the change of some of the most important variables on the annual cost of a risk reduction measure (bund fixed foam systems).

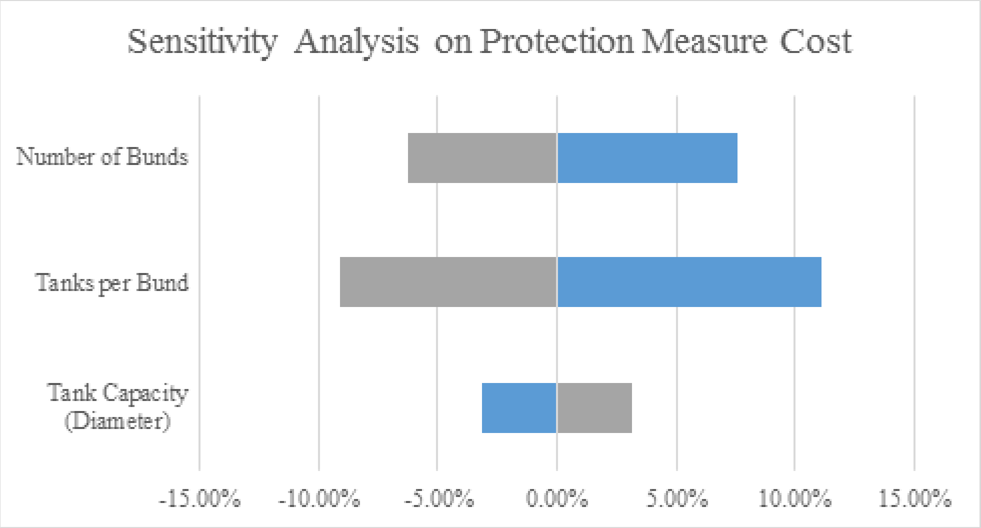


Figure 24. Sensitivity Analysis –Effects of case study specifications on a protection measure cost.

The first aspect to analyse is the tank capacity. As expected, the larger the tank capacity, the more expensive the protection measure becomes. Now, the relevant aspect is that the increase in the cost due to the increase in the capacity is lower than the increase in the annualised risk (see Figure 23). **This means that as the tank size is increased, at some point, measures that were not economic beneficial might become a feasible option**. As the trend in storage industry is to increase tank size, the trend in fire protection field should focus on innovation. Solutions that were not economically beneficial in the past might be potential solutions now or in the near future.

The second and final aspect to analyse is that similar to the annual risk, the cost of the protection measure decreases with the number of tanks per bund and bunds in general. This happens because the bund fixed foam system is designed for to the largest bund. The more bunds, and the more tanks per bund, the lower the cost per tank of the bund fixed foam system.

Nevertheless, it is important to highlight that the presence of intermediate bunds avoids the risk to proportionally increase with the number tanks per bund. This happens because intermediate bunds contain small spillages in a restricted area. Thus, thanks outside this area are not affected by the pool fire.

7. Conclusions

A risk assessment was performed on bund fire scenarios in large storage facilities. Then, different risk reduction measures were discussed and a cost-benefit analysis was performed to evaluate which risk reduction measure was the most cost-efficient. The conclusion of this assessment are presented ahead.

7.1.Risk Assessment

The first part of the risk assessment allowed to conclude that just a low number of initiating events might cause a bund fire to occur. These initiating events are reduced to tank and piping large leakages or rupture and tank overfills.

After calculating the leakage and ignition probabilities, it was established that the frequency of having a large bund fire event, without any prevention measure, is around 7×10^{-5} per year per tank. This means that a large bund fire might occur roughly every 130 years in a storage facility with 100 tanks.

The tank overfill events contribute with 88% to the total bund spillage event frequency. The piping rupture contributes with around 10% and the tank rupture with the remaining 2%.

Additionally, the bund fire consequences estimation was discussed. It was concluded that the total bund fire economic consequences depend mainly on the property loss and business interruption loss. Environmental or company reputation damages might be at some point negligible. Besides, life losses would only play an important role if the number of people inside the bund is high, what is very unlikely in current storage facilities.

7.2.Risk Reduction Measures

Different risk reduction measures were discussed and analysed. The first risk reduction measure discussed was tanks separation distances and the use of bunds. It was concluded that the best risk reduction strategy is to use independent bunds (e.g. one tank per bund) and to increase the tank separation distances.

The second reduction measure discussed was tank fireproofing. Although it is not a usual protection measure in atmospheric tanks, it would be a very efficient risk reduction measure, because it would delay the tank failure for hours.

The third risk reduction measure analysed is use of a tank overfill prevention system. Instrumented systems are very efficient in preventing overfill events, it is reliable and it does not required a big equipment investment.

The forth risk reduction measure proposed is the use of water cooling systems. It was found that a 10 $l/min.m^2$ flowrate is very efficient in preventing fire escalation from flame impingement fires and a 2 $l/min.m^2$ flowrate is widely used to prevent escalation from distant radiant heat fluxes.

The fifth risk reduction measured analysed is the use of bund fixed foam systems. It was concluded that the fixed foam systems are a supplementary protection measure and that the mitigation strategy should not rely just upon fixed foam systems.

The last measure contemplated is the fire brigade intervention. A model that describes bund fire escalation likelihood was developed. The model is based on the ‘time of alert’ and the ‘time of effective mitigation’ that the fire brigade intervention.

7.3.Cost-Benefit Analysis-Case Study

A cost-benefit analysis for bund fire protection measures cannot be performed if a case study is not considered. Thus, the results and conclusions of the cost-benefit analysis might vary depending on the case study characteristics. Consequently, the conclusions presented ahead are based in the case study analysed in this work.

Based on the case study presented in the Chapter 6, it can be concluded that just two risk reduction measures are economically feasible. These reduction measures are the fireproofing and the overfill protection system. Moreover, just to rely on the fire brigade intervention results more convenient that to apply many of the protection measures.

Active fire protection systems, such as water cooling and fixed foam systems are not economically advantageous because they require an enormous equipment and construction investment. Besides, the additional foam inventory cost makes fixed foam systems even less attractive. However, if the piping systems is already installed, these measures become feasible options.

Additionally, the combination of different protection measures showed to be an efficient and economically beneficial way to reduce the risk. The most economically advantageous strategy is the combination of overfill protection systems and the fire brigade intervention. However, the most effective strategy in reducing the risk is the combination of overfill protection with either water cooling system or fireproofing. If the water piping is already installed, the first option becomes the most attractive one, otherwise, the second one would have the advantage.

7.4.Uncertainty

To perform a risk assessment and a further cost-benefit analysis, many assumptions have to be done. All these assumptions carry a degree of uncertainty that, in the end, affects the outcome of the assessment. To evaluate the degree of uncertainty, a sensitivity analysis was performed.

The sensitivity analysis showed the assumption made do have a marked influence on the both the annualised risk estimation and the protection measures cost estimation. All variables assessed to determine the uncertainty of the annualised risk calculation (e.g. heat radiation flux, business interruption/property loss ratio and initiating event frequency) presented a direct and proportional influence on the final outcome.

On the other hand, just the amortisation period showed to have an inverse and proportional influence on the cost of the reduction measures. Thus, it is crucial to make all the assumption from a conservative perspective to avoid misleading results. If the uncertainty is not considered, a relatively low risk level and a relatively costly outcome (of a certain protection measure) might lead to a wrong interpretation of the results.

Additionally, it was proved that the results of the cost benefit analysis may vary depending on the case study characteristics. The results allow to conclude that the type of the fuel stored have a limited influence in the final outcome as long as the price of the product stays within a range of ±20%.

It is also concluded that the tank capacity variance has a greater impact on the annualised risk than on the protection measure cost. This means that for low tank capacities, certain protection measure might not be economically beneficial. But, for larger tank capacities the same protection measure may be a cost-effective solution. In any case, every scenario should be studied independently.

At last but not at least, the results showed that the total number of bund and the number of tanks per bund have an inverse influence on both the risk and the protection measures cost.

This means that both the risk and the protection measure cost (per tank) are reduced as the number of bunds, or number of tanks per bund is increased. This happens because at the risk and the cost of the protection measure do not proportionally increase with the number of tanks per bund or number of total bunds. Finally, this analysis also shows the importance of intermediate bunds because without them, the risk of small bund fires would not be kept "constant" when the number of tanks per bund in increased.

7.5.Limitations and Future Work

Unfortunately, there are many aspects that this work did not contemplate in its scope. The most important limitations of this work are:

- The methodology is not easily 'extrapolated' to other case studies. The complete evaluation has to be performed independently for every case.
- This study just contemplates the risk of having bund fires, other risk scenarios, such as full surface fires or explosions are not considered
- The degree of uncertainty does not allow to make definite conclusions when the results of the proposed risk protection strategies are similar (within a range of 10%)

For these reasons, it is recommended that future studies should be performed to analyse other risk scenarios that might lead to multiple tank fire events. Additionally, it would be stirring if these methodology is applied to different case studies with different configurations and characteristics. That would allow to compare the results of this assessments and make further conclusions.

8. References

Abdullah, Mert. 2016. *Evaluation of the Cost of Fire Safety: Development of a Framework to Improve Cost Transparency for Large Companies.* Ghent: International Master of Science in Fire Safety Engineering - IMFSE.

Alibaba Group. 2017. *Alibaba.* Accessed 04 05, 2017. https://www.alibaba.com.

Argyropoulos, C.D., M.N. Christolis, Z. Nivolianitou, and N.C. Markatos. 2012. "A hazards assessment methodology for large liquid hydrocarbon fuel tanks." *Journal of Loss Prevention in the Process Industries* 329-335.

ASME. 1987. *Boiler and Pressure Vessel Committee.* New York: American Society of Mechanical Engineers.

Buncefield Major Incident Investigation Board. 2008. *The final report of the Major Incident Investigation Board.* London, UK: ISBN.

Campbell, Richard. 2014. *Fires at Outside Storage Tanks.* Quincy, MA: National Fire Protection Association.

Centrum Industriële Veiligheid. 2017. "CIV 02 Brandveiligheid Opslagtanks - Technical Frame of Reference." *Veiligheidsregio Rotterdam-Rijnmond.* 02 03. http://vr-rr.nl/over/rc/iv/cursussen-workshops/beheersen-0/.

Chang, James I. 2006. "A study of storage tank accidents." *Journal of Loss Prevention in the Process Industries* 51-59.

Chemical Engineering Online. 2017. *CURRENT ECONOMIC TRENDS: CEPCI FOR MARCH 2016.* 10 February. http://www.chemengonline.com/current-economic-trends-march-2016/.

Coppola, Damon. 2011. "Risk and Vulnerability." In *Introduction to International Disaster Management,* by Damon Coppola. Butterworth-Heinemann.

Crippa, C., L. Fiorentini, V. Rossini, R. Stefanelli, S. Tafaro, and M. Marchi. 2009. "Fire risk management system for safe operation of large atmospheric storage tanks." *Journal of Loss Prevention in the Process Industries* 574–581.

Davies, T, A B Harding, I P McKay, R G J Robinson, and A Wilkinson. 1995. "Bund Effectiveness in Preventing Escalation of Tank Farm FIres." *Major Hazards Onshore and Offshore II - IChemE Symposium series no. 139* 237-251.

Drysdale, Dougal. 2011. "Chapter 5 - Steady Burning of Liquids and Solids." In *An Introduction to Fire Dynamics*, by Dougal Drysdale, 186. Wiley.

electrical4u.com. 2017. *Medium Velocity Water Spray or MVWS System for Fire Protection.* Accessed 04 04, 2017. https://www.electrical4u.com/medium-velocity-water-spray-(mvws)-system-for-fire-protection/.

EPA. 2006. "Chapter 7: Liquid Storage Tanks." In *Compilation of Air Pollutant Emission Factors, Volume 1: Stationary Point and Area Sources,* Chapter 7. U.S.: Environmental Protection Agency.

Euronext. 2017. *Total - European Stoke Exchange.* Accessed 04 04, 2017. https://www.euronext.com/en/products/equities/FR0000120271-XPAR.

European Commission. 2017. *Weekly Oil Bulletin.* European Commission.

European Committee for Standarization. 2006. *EN 1998-4 (2006) Eurocode 8: Design of structures for earthquake resistance – Part 4: Silos, tanks and pipelines.* Brussels, Belgium: The European Union.

European Model Code of Safe Practice. 1981. *The Storage and Handling of Petroleum Products.* Concawe Product Dossier.

Fire Dust Control. 2017. *Foam-based Fire Suppression on Surface Oil Storage Tanks.* Accessed 04 04, 2017. http://firedustcontrol.co.za/fire-dust-control-clients/.

Flemish Goverment. 2009. *Handbook of Failure Frequencies.* Brussels: Environment, Nature and Energy Department. Flemish Goverment.

Haag, Uijt de. 1999. "The Purple Book - Guideline for quantitative risk assessment." The Hague, Netherlands.

Hansson, Sven Ove. 2010. "Risk: objective or subjective, facts or values." *Journal of Risk Research* 231–238.

Homewyse. 2017. *Homewyse.* Accessed 03 2017, 23. https://www.homewyse.com/costs/index.html.

Index Mundi. 2017. *Index Mundi.* Accessed 03 21, 2017. http://www.indexmundi.com/commodities/?commodity=diesel&months=12&currency=eur.

International Starndards ISO. 2009. *ISO 31000 - Risk Management - Principles and guidelines.* Geneva, Switzerland: ISO.

2017. *Interview to the the Major Verschueren from the Antwerp fire brigade.*

IP Model Code of Safe Practice, Part 19. 1993. *Fire precautions at petroleum.* London, UK: John Wiley and Sons.

Landucci, Gabriele, Francesca Argenti, Alessandro Tugnoli, and Valerio Cozzani. 2015. "Quantitative assessment of safety barrier performance in the prevention of domino scenarios triggered by fire." *Reliability Engineering and System Safety* 30–43.

Landucci, Gabriele, Gianfilippo Gubinelli, Giacomo Antonioni, and Valerio Cozzani. 2009. "The assessment of the damage probability of storage tanks in domino events triggered by fire." *Accident Analysis and Prevention* 1206–1215.

Landucci, Gabriele, Menso Molag, and Valerio Cozzani. 2009. "Modeling the performance of coated LPG tanks engulfed in fires ." *Journal of Hazardous Materials* 447–456.

Lees, F.P. 2012. "Chapter 14 - Human Factors and Human Errors." In *Lees' Loss Prevention in the Process Industries,* by F.P. Lees. London: Elsevier Inc.

Lees, F.P. 2012. "Chapter 16 - Fire." In *Lees' LossPrevention in the Process Industries,* by F.P. Lees, 1262,1323. London: Elsevier Inc.

Lees, F.P. 2012. "Chapter 22 - Storage." In *Lees' LossPrevention in the Process Industries*, 1906-1940. London: Elsevier Inc.

Mannam, Sam. 2012. "Economics and Insurance." In *Lees' Loss Prevention in the Process Industries.*, by Sam Mannam. Texas, USA: Elsevier.

Mansour, Khalid Abusaieda. 2012. *Fires in large atmospheric storage tanks and their effect on adjacent tanks.* Loughborough, UK: Khalid Mansour.

MC Integ. 2017. *Cylindrical - Welded - Stainless Steel - Typical Arrangement Tank.* MC Integ. Accessed 03 07, 2017. http://www.mc-integ.co.uk/Item/Cylindrical-Welded-Stainless-Steel-Typical-Arrangement.

Mudan, K.S. 1984. “Thermal Radiation Hazards from Hydrocarbon.” *Progress Energy Combustion Science* 59–80.

NFPA - National Fire Protection Association. 2016. *NFPA 11: Standard for Low-, Medium-, and High-Expansion Foam.* Quincy, MA, USA: National Fire Protection Association.

NFPA - National Fire Protection Association. 2017. *NFPA 15: Standard for Water Spray Fixed Systems for Fire Protection.* Quincy, MA, USA: National Fire Protection Association.

NFPA - National Fire Protection Association. 2015. *NFPA 30: Flammable and Combustible Liquids Code.* Quincy, MA, USA: National Fire Protection Association.

OGP Risk Assessment Data Directory. 2010. “Storage indident frequencies.” *International Association of Oil and Gas Producers* Report No. 434 – 3.

Persson, Henry, and Anders Lönnermark. 2004. *Tank Fires, Review of fi re incidents 1951–2003.* Borås, Sweden: SP Fire Technology.

Peters, M. S., K. D. Timmerhaus, and R. E. West. 2004. *Plant design and economics.* McGraw-Hill.

Planas-Cuchi, Eulalia, Juan Antonio Vılchez, and Joaquim Casal. 1999. “Fire and explosion hazards during filling/emptying of tanks.” *Journal of Loss Prevention in the Process Industries* 479–483.

Rausand, Marvin. 2011. “A bow-tie diagram of risk management.” In *Risk Assessment: Theory, Methods, and Applications*, p.120, Figure 5.3. Hoboken, NJ, USA: John Wiley & Sons. Accessed 03 06, 2017. Risk Assessment: Theory, Methods, and Applications. Hoboken, NJ: John Wiley & Sons, 2011. p.120, Figure 5.3, FAL,.

Rennia, Elisabetta, Elisabeth Krausmanna, and Valerio Cozzani. 2010. “Industrial accidents triggered by lightning.” *Journal of Hazardous Materials* 42–48.

Rincon, Henry Eduardo Sanchez. 2015. *Risk Based Fire Protection Strategies for LNG/LPG Jetties.* Ghent: International Master of Science in Fire Safety Engineering.

Roberts, T.A. 2004. “Directed deluge system designs and determination of the effectiveness of the currently recommended minimum deluge rate for the protection of LPG tanks.” *Journal of Loss Prevention in the Process Industries* 103–109.

Roberts, T.A. 2004. “Effectiveness of an enhanced deluge systemto protect LPG tanks and sensitivity to blocked nozzles and delayed deluge initiation.” *Journal of Loss Prevention in the Process Industries* 151–158.

Roos, A.J. 1992. “The Green Book - Methods for the detennination of.” Voorburg, Netherlands.

Roos, Carl Johan, and Phil E. Myers. 2015. *The Engineer’s Guide to Overfill Prevention.* Emerson.

Ryder, Noah L. 2017. “Preparing For Large Atmospheric Storage Tank Fires.” *Fire & Risk Alliance.* 01 02. http://www.fireriskalliance.com/wordpress/wp-content/uploads/2014/09/2014-SFPE-SAC-Tank-Fires-Presentation.pdf.

Santos, Fernanda da Silva, and Alexandre Landesmann. 2014. “Thermal performance-based analysis of minimum safe distances.” *Fire Safety Journal* 57–68.

Schüller, J.C.H. 1997. “The Red Book - Methods for determining and processing probabilities.” The Hague, Netherlands.

Shi, Lei, Jian Shuai, and Kui Xu. 2014. “Fuzzy fault tree assessment based on improved AHP for fire andexplosion accidents for steel oil storage tanks.” *Journal of Hazardous Materials* 529–538.

Steel Industry Portal. 2017. *Price of steel 2001-2016 HRC CRC HDG & rebar prices.* Accessed 03 2017, 23. http://www.steelonthenet.com/steel-prices.html.

Stewart, Mark G. 2010. “Risk-informed decision support for assessing the costs and benefits of counter-terrorism protective measures for infrastructure.” *International Journal of Critical Infrastructure Protection* 2 9 ± 4 0.

Swinderen, Victor Van. 2005. “The Yellow Book- Methods for the calculation of physical effects.” The Hague, Netherlands.

Tehler, Henrik. 2015. *A general framework for risk assessment.* Lund, Sweden: Lund University.

Thyer, A. M., S. F. Jagger, W. Atherton, and J. W. Ash. 2009. “A review of catastrophic failures of bulk liquid storage tanks.” *Loss Prevention Bulletin* Issue 205.

Tianjin Anson International Co. Ltd. 2017. *Internal Floating Roof Tank.* Tianjin Anson International Co.,Ltd. . 20 03. Accessed 03 08, 2017. http://www.ansonindustry.com/resources/internal-floating-roof-tank.html.

Tolwer, Galvis, and Ray Sinnott. 2013. *Chemical Engineering Design.* Waltham, MA, USA: Elsevier.

Towler, Galvin, and Ray Sinnott. 2008. “Costing and Project Evaluation.” In *Chemical Engineering Desgin - Pinciples, Practice and Economics of Plant and Process Design*, Chapter 6. London, UK: Elsevier.

U.S. Chemical Safety and Hazard Investigation Board. 2015. *Final Investigation Report - Caribbean Petroleum Tank Terminal Explosion and Multiple Tank Fires.* U.S. Chemical Safety and Hazard Investigation Board.

Vilchez, Juan A., Sergi Sevilla, Helena Montiel, and Joaquim Casal. 1995. “Historical analysis of accidents in chemical plants and in the transportation of hazardous materials.” *J. Loss Prey. Process Ind.* Vol. 8, No. 2, pp. 87-96.

Wang, Daqing, Peng Zhang, and Liqiong Chen. 2013. “Fuzzy fault tree analysis for fire and explosion of crude oil tanks.” *Journal of Loss Prevention in the Process Industries* 1390-1398.

Wu, Dongyin, and Zhen Chen. 2016. “Quantitative risk assessment of fire accidents of large-scale oil tanks triggered by lightning.” *Engineering Failure Analysis* 172–181.