QRA with respect to domino effects and property damage

Leo Kardell
Mathias Lööf

Division of Risk Management and Societal Safety
Lund University, Sweden

Riskhantering och samhällssäkerhet
Lunds tekniska högskola
Lunds universitet

Report 5461, Lund 2014

The report was funded by Lloyds Register Consulting – Energy AB

QRA with respect to domino effects and property damage

Leo Kardell
Mathias Lööf

Lund 2014

Title: QRA with respect to domino effects and property damage
Titel: QRA med avseende på dominoeffekter och skada på egendom

Authors: Leo Kardell & Mathias Lööf

Report 5461
ISSN: 1402-3504
ISRN: LUTVDG/TVBB--5461--SE

Number of pages: 92
Illustrations: Leo Kardell & Mathias Lööf

Keywords
Domino effect, domino accident, QRA, DEA, cascade effect, property damage, vulnerability model, risk analysis

Sökord
Dominoeffekt, dominoolycka, QRA, DEA, kaskadeffekt, skada på egendom, sårbarhetsmodell, riskanalys

Abstract

In 1996 the European Union adopted the Seveso II Directive. The Directive stated actions to be taken in the process industry in order to prevent and limit the impact of serious chemical accidents. In the Directive it is clearly stated that domino effects shall be considered, but the level of detail required is not specified. Due to that fact and the high degree of complexity linked to domino effects, these aspects are mostly dealt with in a qualitative manner. Such approach leads to subjective assessments and is highly dependent on simplified assumptions, leading to results that may be questionable. Thus, it would be beneficial to develop a method that incorporates the risk of domino effects in a quantitative risk analysis (QRA), which has been the aim of this thesis. The method was developed based on a literature review of existing research. Focus was on integrating domino effects as a natural part of a QRA without compromising the timeframe associated to a QRA. The developed method has been applied in a case study of an oil refinery in order to evaluate how well it is applicable in practise. During the case study, the method has proven to enable the risk of property damage with regard to domino effects to be quantitatively analysed. The results from the case study, evidence the importance of taking domino effects into consideration in QRAs, as the risk may be underestimated if not.

Riskhantering och samhällssäkerhet
Lunds tekniska högskola
Lunds universitet
Box 118
221 00 Lund

http://www.risk.lth.se
Telefon: 046 - 222 73 60
Telefax: 046 - 222 46 12

Division of Risk Management and Societal Safety
Faculty of Engineering
Lund University
P.O. Box 118
SE-221 00 Lund
Sweden

http://www.risk.lth.se
Telephone: +46 46 222 73 60
Fax: +46 46 222 46 12

SUMMARY

Domino effects in industrial installations are complex phenomenon that may cause severe damage on property and life if not dealt with in a sufficient manner. As chain of accidents can be traced back to being the cause of major accidents occurring, domino effects have lately been given much attention and several research projects in the field have been conducted. The Seveso II Directive adopted in 1996 by the European Union states that domino effects should be included in risk analyses for chemical plants. However, the level of detail in which domino effects should be dealt with in analysis has not been stated. Due to that fact and the high degree of complexity linked with domino effects, these aspects are mostly dealt with in a qualitative manner. Such approach leads to subjective assessments and is highly dependent on simplified assumptions, leading to results that may be questionable. The objectives of recent projects have mainly been to develop and validate tools for the quantification of the risk associated with domino effects. Looking at existing approaches for analysing domino effects in a quantitative way, several models are available in literature. Common for these models are that they treat domino scenarios in a separate analysis, starting from the results gained from a conventional quantitative risk analysis (QRA). These models show that domino effects effectively can be integrated in a QRA, but do not provide any guidance of how these effects should be incorporated in an analysis. Thus, there is a need for comprehensive methods that clearly define how domino effects effectively can be implemented and analysed within the boundaries of a conventional QRA framework. With this said, the aim of the thesis has been to develop a comprehensive method for performing QRAs with respect to domino effects and property damage, based on the latest research on the area. During the development of the method, focus has been on achieving a logic incorporation of domino effects, thus making the analysis manageable within the timeframe of a QRA. To ensure the functionality of the method, criteria for what the method should be able to deal with are defined:

- The method should be applicable to well established analysis techniques and not dependent on complex algorithms for the analysis of the chain of events.
- The method should enable a risk profile for property damage to be computed with regard to all accident scenarios, including potential domino scenarios.
- The method should enable the risk of property damage with respect to domino effects to be analysed, both within a subsystem and between different subsystems.
- The method should enable site specific safety distances either to be established or validated with regard to property damage and domino effects.

The method has been applied in a case study of an oil refinery in order to evaluate how well it is applicable in practise; this with promising results, fulfilling the above defined criteria´s. During the case study, the method has proven to enable the risk of property damage with regard to domino effects to be quantitatively analysed. The results from the case study, evidence the importance of taking domino effects into consideration in QRAs, as the risk may be underestimated if not. During the evaluation of the method, it has been concluded that the chain of accidents should be delimited to only include first level of escalation. Such delimitation minimises the uncertainties linked to domino effects, thus making the results more reliable. It also enables the method to be more applicable when analysing larger systems, as the complexity and workload decreases. It has been concluded that computing risk contours with regard to property damage for all initial accident scenarios enables critical areas, where domino effects likely are to present themselves, to be identified in an early stage of the analysis. During the thesis, the need for a well established acceptance criterion with regard to property damage has been evidenced.

SAMMANFATTNING

Dominoeffekter inom processindustrier är komplexa fenomen som kan ge upphov till allvarliga skador på så väl egendom som människor om de inte tas i beaktande i säkerhetsarbetet. Medvetenheten om fenomenet har den senaste tiden ökat och flera forskningsprojekt har genomförts inom området, detta till följd av att allvarliga olyckor har kunnat härledas till dominoeffekter. År 1996 införde Europeiska Unionen Seveso II direktivet som fastslog att dominoeffekter skulle tas i beaktning i riskanalyser inom processindustrin, dock adresserades inte nivån på analyserna i direktivet. Detta faktum i kombination med den höga nivå av komplexitet som förknippas med dominoeffekter har lett till att dessa effekter framförallt behandlas på ett kvalitativt sätt, vilket leder till resultat baserade på subjektiva bedömningar och förenklade antaganden. Det huvudsakliga syftet med den senaste forskningen har varit att ta fram verktyg och modeller för att kunna kvantifiera riskerna associerade med dominoeffekter. Gemensamt för dessa modeller är att de behandlar dominoeffekter i en separat analys, med utgångspunkt från resultaten av en konventionell QRA. Modellerna visar att dominoeffekter kan analyseras kvantitativt, men de ger ingen vägledning om hur dessa effekter bör integreras och behandlas i en QRA. Det finns därmed ett behov av heltäckande metodiker som tydliggör hur dominoeffekter skall integreras och analyseras inom ramarna för en konventionell QRA. Målet med denna rapport har varit att utveckla en heltäckande metod för att genomföra en QRA med avseende på dominoeffekter och skada på egendom, vilken baseras på den senaste forskningen inom området. Under utvecklandet av metoden har fokus legat på att göra integreringen av dominoeffekter till en naturlig del av analysen och på så vis göra metodiken praktiskt tillämpbar inom tidsramarna för en QRA. För att säkerställa metodens funktionalitet har kriterier för vad metoden skall kunna hantera definierats:

- Metoden skall möjliggöra analys av kedjor av olyckshändelser med hjälp av väletablerade analystekniker och skall inte vara beroende av komplexa algoritmer.

- Metoden skall möjliggöra framtagande av en heltäckande riskbild för skada på egendom med hänsyn till samtliga olycksscenarier, där potentiella dominoscenarier är inkluderade.

- Metoden skall möjliggöra analys av risken för skada på egendom med hänsyn till dominoeffekter både inom en anläggningsdel och mellan olika anläggningsdelar.

- Metoden skall möjliggöra framtagande och validering av platsspecifika säkerhetsavstånd med hänsyn till skada på egendom och dominoeffekter.

Metoden har applicerats i en fallstudie, i vilken en del av ett oljeraffinaderi har analyserats, detta för att utvärdera hur väl den är applicerbar i praktiken. Under fallstudien har det visats att metoden är tillämpbar för kvantitativ analys av risken för skada på egendom med hänsyn till dominoeffekter och att ovannämnda kriterier har uppfyllts. Resultaten från fallstudien påvisar vikten av att inkludera dominoeffekter i kvantitativa riskanalyser, då risken annars kan underskattas. Utvärderingen av metoden ledde fram till slutsatsen att analysen bör avgränsas till att enbart behandla första ordningens eskalation. Avgränsningen minimerar osäkerheterna associerade med dominoeffekter och gör analysen mer tillförlitlig. Dessutom medför avgränsningen att metodens tillämpbarhet för analys av större system ökar, då komplexiteten och arbetsbelastningen minskar. En annan slutsats som har kunnat dras är att riskkonturer för skada på egendom möjliggör identifiering av kritiska områden, i vilka risken för dominoeffekter är betydande. Under arbetets gång har behovet av ett väletablerat acceptanskriterium för skada på egendom påvisats.

ACKNOWLEDGEMENTS

This master thesis was written in the spring of 2014 and is the final thesis in the master's programme of Risk Management and Societal Safety at Lund University.

The authors want to thank the following persons for valuable guidance and support throughout the writing of the thesis:

Alexander Cedergren – *Academic supervision*

Henrik Hassel – *Academic supervision*

Ulf Bergstrand – *External supervision at Lloyd's Register Consulting – Energy AB*

Ivar Hamrin – *External supervision at Lloyd's Register Consulting – Energy AB*

Marcus Abrahamsson – *Examination*

Bo Karlsson – *Contact person at Preemraff Lysekil*

As well as the staff in the Malmö and Gothenburg office at Lloyd's Register Consulting – Energy AB for guidance and feedback.

Lund 2014
Leo Kardell & Mathias Lööf

Table of Contents

1. INTRODUCTION

Several major accidents that have occurred in process plants are the results of unexpected domino effects (Darbra, 2010). When an accident occurs inside a process plant, its physical effects (including overpressure, heat radiation and impact of flying fragments) often damage the surrounding equipments, which can lead to a loss of containment and additional accident scenarios. The impact of a domino effect highly depends on the design and nature of the installations, as well as the presence of reliable safeguards.

Domino effects can be described as the cumulative effect from a chain of unwanted events, with severe consequences. Domino effects are often seen as synonym to a cascade of accidents, in which the consequences of a previous accident are increased by the following ones. Domino effects can be classified into two different categories: internal and external domino effects (Reniers, 2010). Internal domino effects are recognized as the escalation of an accident within the boundaries of an industry, whereas an external domino effect is recognized as the escalation outside the boundaries.

In 1996 the European Union adopted the Seveso II Directive. The Directive specifies actions to be taken to prevent and limit the impact of serious chemical accidents. In the Directive it is clearly stated that domino effects shall be considered. The members of the Union shall ensure that the concerned authority is informed of process industries that have an increased risk due to domino effects both within the plant and between different plants. It is important that the industries take these effects into account when dealing with safety issues, so that a high level of safety can be achieved. The industries shall also make sure that the public is informed of the risks and that the fire and rescue service has all the information needed to handle an accident in the most effective way (European Commission, 1996).

In Sweden the Seveso II Directive covers several different regulations, with the core in the regulations by Arbetsmiljöverket, AFS 2005:19. The regulations cover process industries that deal with specific hazardous substances in a greater amount than set values. In these regulations it is specified that the business operator is obligated to prevent serious chemical accidents and to limit the human and environmental impact if such an accident occurs. Process industries covered by the regulations shall establish a risk analysis, where domino effects are taken into account (AFS 2005:19).

The Seveso II Directive and the Swedish regulations by Arbetsmiljöverket have in common that they state that domino effects shall be analysed, but how this shall be done and the level of detail is not specified. Due to that fact and the high degree of complexity linked with domino effects, these aspects are mostly dealt with in a qualitative manner. Such approach leads to subjective assessments and is highly dependent on simplified assumptions, leading to results that may be questionable. The objectives of recent projects have mainly been on developing and validating tools for the quantification of the risk associated with domino effects. Looking at existing approaches for analysing domino effects in a quantitative way, several models are available in literature. Common for these models are that they treat domino scenarios in separate analysis, starting from the results gained from a conventional QRA. These models show that domino effects effectively can be integrated in a QRA, but do not provide any guidance of how these effects should be incorporated in an analysis. Thus, there is a need for comprehensive methods that clearly defines how domino effects effectively can be implemented and analysed within the boundaries of a conventional QRA framework. Recent research, as the studies by Cozzani et al. (2006) and Abdolhamidzadeh et al. (2010), have revealed that neglecting the risk of domino effect in QRAs leads to the risk being underestimated. Nowadays, no risk assessment can be considered complete without including analysis of domino effects (Reniers & Cozzani, 2013).

1.1 Purpose

The purpose of the study is to enable the risk of domino effects to be quantitatively analysed within the boundaries of a conventional QRA framework. The study should reveal the prerequisites and tools needed for the quantitative analysis of domino scenarios. The incorporation of domino scenarios in the QRA should not affect the way in which the analysis is carried out, nor affect the time needed for analysis in a substantially matter. By enabling the domino effect to be analysed quantitatively, the subjectivity of the analysis is lowered compared to a qualitative approach. By quantifying the risk of domino effects, vulnerable parts of the system can more easily be identified, and thus enables safety measures to be implemented where they contribute the most to the overall safety. The method enables acceptable safety distances between equipment within process plants to be analysed in more detailed way, which in turn contributes to the prevention of major accidents in process industries due to domino effects.

1.2 Objective

The objective of the study is to develop a comprehensive method for performing quantitative risk analysis with respect to property damage and domino effects in a process plant. The method shall guide and clearly define how domino scenarios can be incorporated in a QRA framework.

1.3 Research questions

Following questions are to be answered in the thesis, this to ensure that the objective is reached:

- How can a method for performing quantitative risk analysis with respect to property damage and domino effects in a process plant be developed?
    - What tools are needed for analysing the risk of domino effects?
    - To what extent does the level of uncertainty increase when including domino effects in the analysis?
    - Can such a method be used to determine site specific safety distances in the design phase?

- Is there a change in the overall risk when including domino effects in the quantitative risk analysis?

1.4 Delimitations

The study is delimited to only deal with the effects of mechanical and technical nature. The study does not deal with any economical or environmental effects due to domino effects. No natural hazards, e.g. floods, earthquakes etc. have been dealt with in the study.

1.5 Method

The study is divided into four parts: literature review, method development, case study and evaluation of the case study. The aim of the four parts is to fulfil the purpose and to reach the objective. How well the purpose and objective are met is then discussed and conclusions are drawn. Figure 1 presents a flowchart of the process and in the following sections the different parts of the flowchart are discussed.

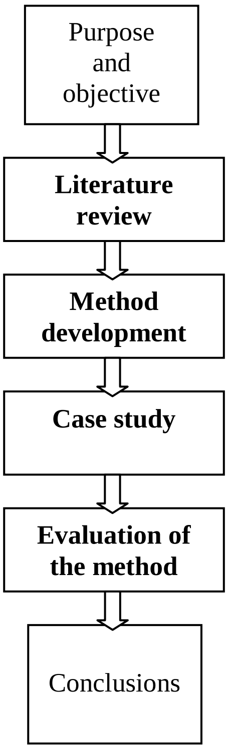

Figure 1. Flowchart of the methodology used in this study.

During the process, a halfway presentation of the thesis was given for persons with expertise knowledge in the risk management field. The aim of this presentation was to receive feedback and input for further improvements regarding the developed method, making the study more reliable.

1.5.1 Literature review

The report is based on a literature study, where relevant literature in the specific field is reviewed in order to get an up to date understanding of the existing research and to identify where new contribution is needed. Literature from different authors is studied and the material most applicable and relevant for this study is presented. The literature review begins with a presentation of the core elements associated with a quantitative risk analysis in process industries, presented in chapter 2. The characteristics of domino effects and how the chain of accidents may take form are presented in chapter 3. Existing models and tools enabling the quantitative analysis of domino scenarios are highlighted in chapter 3. Tools that are recommended in the method are then further elaborated on in chapter 4.

1.5.2 Method development

In this part of the study the method is developed and how it should be used is presented. The method can be seen as a framework, where the authors compile different existing approaches of domino effects analysis and make additions and modifications when needed. The focus of the method development is that the method should be manageable from a limited time perspective and that domino effects shall be taken into account in a QRA without having to make a separate analysis.

1.5.3 Case study

The objective of the case study is to test the method on an existing process plant, this in order to see how well it is applicable in practice. The focus of the case study is therefore not on the specific results, but if the method is manageable within a reasonable time span and whether the parts included in the method are sufficient and well suited for the purpose. Throughout the case study, the use of the methodology process is documented and further reviewed in the evaluation step. Although the focus of the case study does not lie on the specific results, it is still of some concern to evaluate the results gained to judge whether the results are realistic or not and whether domino effects have a significant impact on the overall risk.

1.5.4 Evaluation of the method

By evaluating how well the method is applicable in practice, gaps and weaknesses within the proposed method can be discovered and revised if needed. Prerequisites needed for the analysis and problematic aspects associated with the method are discussed and the need of further research in the area is presented.

2. QUANTITATIVE RISK ANALYSIS WITHIN PROCESS INDUSTRIES

In this chapter, based on a literature review, the conventional approach of quantitative risk analysis in process industries is elaborated on to give the reader understanding of the baseline which the method is built upon.

As stated in the introduction, an industry that handles hazardous material is by law forced to assess their risks to prevent that a major accident occurs. But what is risk? There are many definitions of risk and due to that fact, people from different academic areas often tend to misinterpret each other. The definition of risk used in this thesis is the combination of probability and consequence for an unwanted event to occur, that can bring harm to human beings, property or environment. By answering the following three questions, also known as the risk triplet by Kaplan and Garrick (1981), the risk profile can be determined:

1. What can go wrong?
2. How likely is it?
3. What are the consequences?

To answer these questions, one can perform a quantitative risk analysis (QRA), which is a systematic approach for analysing risk scenarios quantitatively. The QRA approach has mostly been adopted in the nuclear industry, but nowadays it is also commonly used within the process industry (Khan & Abbasi, 1998). A typical QRA contain four steps:

- Hazard identification
- Frequency analysis
- Consequence analysis
- Risk profile presentation

Initially in every QRA, the scope and context of which the analysis is based on is defined. For each of the four steps there are many different tools available, which serves to give practitioners guidance when performing risk analysis. In literature, the term QRA is often associated with the quantitative risk assessment which can lead to confusion, if not clearly defining whether the terms should be seen as synonyms or not. In this thesis a distinction is made between the terms, in line with the *Guidelines for engineering design for process safety* by CCPS (2012). A flowchart, illustrating how the risk management process is seen in this study is presented in figure 2.

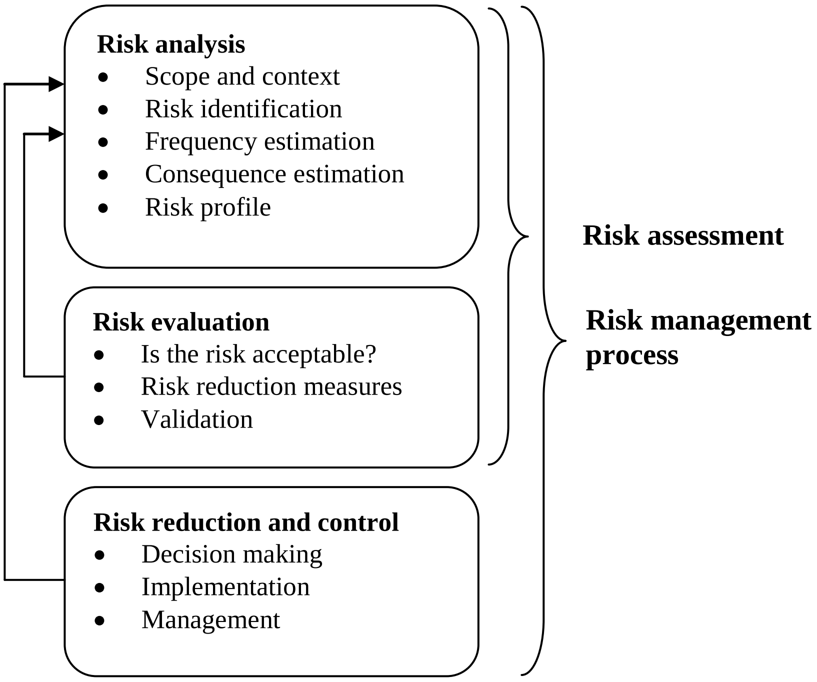

Figure 2. Flowchart of the risk management process (IEC, 1995).

2.1 Scope and context

All stakeholders involved in a project should reach an agreement of the area of interest and the level of detail in which the analysis is based on. A detailed description of the different parts within the system, giving information of what kind of hazardous material that is being used and in which amount, how it is processed and what kind of protection systems that are present are all important aspects that needs to be elaborated on in the context. Simplifying assumptions are always needed when analysing complex systems, such as a process industry, and it is important to clearly define the assumptions of which the analysis is built on so that these uncertain parameters can be evaluated in a later stage of the analysis. Another important aspect of defining the assumptions is to minimize the confusion that can arise when external evaluators interpret the results. All delimitations, factors that are completely discarded in the analysis should also be defined so that it is clear that the result reflects on the context of the analysis, which shall not be confused with the reality.

2.2 Risk identification

The risk identification step is probably the most crucial step in a QRA, due to the fact that it is where the foundation of the QRA is laid. If one of the most important hazards is overlooked, it is quite evident that the overall objective of the risk analysis cannot be satisfactorily achieved. The limited time associated with QRAs does not always allow every single risk source to be evaluated, therefore it is important to identify a number of representative risk scenarios that can cover a wide range of possible threats. This is often done through a preliminary risk assessment, were low severity and low frequency risk sources can be screened out. However, in complex systems it is time consuming just to perform a preliminary assessment and to do it with a high level of accuracy requires great expertise knowledge and tools that enable risks to be systematically mapped.

According to the Seveso II Directive, risks that do not fall under the category "major accident" potential can be screened out in a preliminary assessment (Kirschsteiger, 1998). "Major accident" is defined in the third article of the Directive as:

> *An occurrence such as a major emission, fire or explosion resulting from uncontrolled developments in the course of the operation of any establishment covered by this Directive, and leading to serious danger to human health and/or the environment, immediate or delayed, inside or outside the establishment, and involving one or more dangerous substances* (Commission of the European Communities, 1997, p.6).

Given this threshold it should be a straightforward approach to list all potential risks, however is the definition deemed as a bit vague which can lead to different interpretations being made. For example, it is not obvious what is significant for a *major* emission, fire or explosion and in what range *serious* danger should be considered. Disregarding the obvious obstacles, there are some tools available that enable the risk identification to be approached systematically with a high level of certitude (Kirschsteiger, 1998).

Several tools for risk identification are available; the most common techniques have been reviewed by the US Center for Chemical Process Safety (CCPS) in their *Guidelines for Hazard Evaluation Procedures (1992)* and are as follow:

- Checklists
- Safety review Indices (Dow F/EI & Mond)
- Preliminary hazard analysis
- "What if?" analysis
- Hazard and operability study (HAZOP) and Hazard identification study (HAZID)
- Failure modes, effects and criticality analysis (FMEA)

The selection of preferred technique should strongly be dependent on the complexity in the object analysed. For a process plant, which is not complex or innovating in the way they store and process hazardous material, a simple "expert review" may be sufficient (Kirschsteiger, 1998). For complex plants where significant processing of hazardous material takes place, the general approach is to use a more deep analysis technique, such as the HAZOP. Often are different techniques used in combination to ensure a satisfactory level of hazard identification. The *US Guidlines for Chemical Process Quantitative Risk Analysis* recommends a structured method, like HAZOP or FMEA, as a complement to more general methods, such as "expert review" (CCPS, 1989). For guidance of which technique that should be used and when, readers are referred to *Guidelines for Hazard Evaluation Procedures* by CCPS (1992) and *Lees´ third ed*. by Mannan (2005).

2.3 Frequency estimation

The next step in the QRA is to estimate the frequency in which the identified representative risk scenarios occur. Methods such as event and fault tree analysis are conventionally used to estimate these frequencies. By combining the two approaches, a bowtie analysis can be performed, which is also an established method. These approaches to system analysis can be used to model the failure behavior of process industries (Kirschsteiger, 1998). Regardless of choice of method, input in form of substantiated data for failure rates is crucial for any attempts to estimate a reliable hazard frequency (Nilsson, 2003). But due to the fact that it is hard to find statistical failure rate data for all components in a system, the estimation of failure frequencies often needs to be combined with some assumptions. Process industries are linked with a high degree of complexity and interdependencies are therefore a fact, thus simplifying assumptions can be seen as a prerequisite to enable analysis of such systems. However, every assumption made contributes to heightening the level of uncertainty and in turn may the reliability of the results be questioned. To take these uncertainties into account it is preferable to perform a sensitivity analysis of critical factors, which can have great influences on the results.

As stated above, frequency estimations are always linked to a level of uncertainty, which influence should be analysed. A well known method for taking uncertainties into account is the Monte Carlo simulation analysis. Monte Carlo simulations are often implemented in the framework for QRA and serve to analyse a variety of uncertainty permutations simultaneously (Rezaie et al., 2007). By asserting a proper distribution function (normal, log-normal, etc) for each uncertain variable, a stochastic permutation of the uncertainties can be created. Through intensive simulation (1000 – 10 000 runs) it is possible to analyse how the frequency differs as a function of the uncertainties in the input variables. The number of runs should be dependent on the project size and the importance of risk (ibid.). The method enables frequency rates to be estimated in a confidence interval instead of a fixed value, which can be assumed as a more accurate representation of the reality (ibid.).

2.4 Consequence analysis

When conducting a consequence analysis for a process plant the first step is to analyse the release scenario. Important inputs for this initial analysis are the release rate, leak duration, amount of fuel and the ambient conditions (CCPS, 1999). The next step in the analysis is dependent on whether the released substance is flammable or toxic. For toxic releases it is mainly the dispersion of the substance and the toxic effect that needs to be analysed to determine the consequences (ibid.). If the substance is flammable the release may result in either explosion or fire. For the calculation of overpressure effects due to an explosion either point source models, e.g. TNT models, or multilevel models, e.g. the Multi-Energy model and the Baker-Strehlow model, may be used (Mannan, 2005). When analysing the effects of a fire the consequences are mostly dependent of the radiation effects. Which method that should be used to analyse the emitted radiation is dependent of the type of fire; pool fire, jet fire, flash fire or fireball. There are several computational tools available for the consequence analysis, for example ALOHA, PHAST, HAZDIG, RIB- "spridning i luft". It is important to point out that these methods represent a simplification of reality and that the input data is linked with uncertainties. Therefore, as described in section, 2.3, it is beneficial to perform a sensitivity analysis.

2.5 Risk profile presentation

Quantitative risk measures are conventionally presented in either individual or societal risk. Both individual and societal risks are based on the same analysis parameters, the incident frequency and consequence; it is just different ways of presenting the risk. The individual risk is the risk that an individual is exposed to at a certain distance from the source of hazard and it is usually expressed as annual risk of death and presented as iso-risk contours (Renjith & Madhu, 2010), see figure 3 for a simplified example.

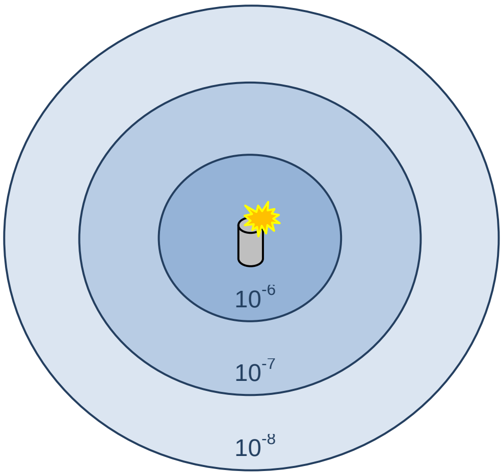

Figure 3. An example of individual risk presented by iso-risk contours.

The individual risk does not take into account if an accident may lead to an impact on several people, then the societal risk is better applied (AIChE, 2012). The individual risk is specified for a certain location, while the societal risk covers a whole area. Societal risk is the risk a group of people is exposed to and it is usually presented in an FN-curve, a fictive example is presented in figure 4. In the graph the expected annual frequency (F) of the number of casualties (N or more) are plotted (Wood, 2010).

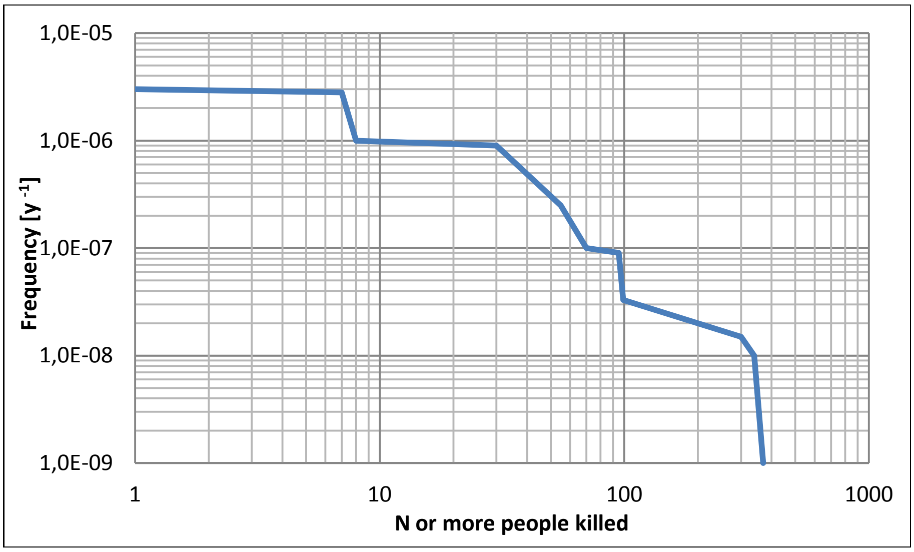

Figure 4. An example of a FN-curve.

The results from a QRA can also be presented in a risk matrix, where the consequences can be either environmental, economical or human. The advantage of the matrix approach is that it is easy to rank the different accidents, which can be the base to decide where risk reduction actions shall be taken (Tugnoli et al., 2011). The matrix contain frequencies on the y-axis and consequences on the x-axis. Each axis is divided into categories depending on the expected frequency of accurance and the severity. The categorisation can either be specificied by specific ranges or dependent on the order of presedence, an example of a risk matrix is presented in figure 5. Accidents in the upper right corner, with high frequency and severity, are the ones with the highest risk. If the risk is acceptable or not shall be decided by the risk criteria for the specific company, with a maximum risk acceptance according to relevant legislation (ibid.). The matrix approach is also often used in a preliminary assessment and is a good tool that enable risk scenarios to be screened out in an effective way (ibid.). The categorisation is then rather unspecified and the result, to a high extent, rely on expert judgements.

>Once a year	🟨	🟨	🟥	🟥	🟥
Once every 1-10 years	🟩	🟨	🟨	🟥	🟥
Once every 10-100 years	🟩	🟩	🟨	🟨	🟥
Once every 100-1000 years	🟩	🟩	🟩	🟨	🟨
<Once every 1000 years	🟩	🟩	🟩	🟩	🟨
Human	Temporary mild discomfort	Some people injured, enduring discomfort	Some serious injuries	Some fatalities and several serious injuries	Several fatalities and tens of injuries
Environmental	No sanitation, little dispersion	Easy sanitation, little dispersion	Easy sanitation, large dispersion	Severe sanitation, little dispersion	Severe sanitation, large dispersion
Economical	<0,01 EUR million	0,01-0,1 EUR million	0,1-1 EUR million	1-2 EUR million	>2 EUR million

Figure 5. An example of a risk matrix (Davidsson et al., 2003).

3. DOMINO EFFECTS IN THE QRA FRAMEWORK

Gaining understanding of the chain of events that may follow an initial accident is crucial for the integration of domino effects in a QRA. Therefore, it is of interest to review previous accidents and the characteristics that define the chain of events. Further, existing models that allow a quantitative assessment of domino effects are elaborated on, this to identify strength and further developing areas. Before moving on to the above sections, the term domino accident needs to be defined as it represents the foundation of which this study is based on.

3.1 Definition of domino accident

After a primary accident has occurred, there is a risk of surrounding equipments being damaged due to exposure of physical effects of the primary event, which in turn can cause secondary or tertiary events. This phenomenon is known as a domino effect and the physical effects responsible for setting it in motion, also known as escalation vectors, are: radiation, overpressure and fragment projection. Although there is no consensus regarding a universal definition of a domino effect, some elements that are required for a domino accident to take place have been identified. The elements needed for a domino accident to occur are presented in table 1, with the definitions proposed by Reniers and Cozzani (2013). For the simplicity, only primary and secondary scenarios are mentioned in table 1 but all of the features also apply to any tertiary or higher order of propagation.

Table 1. Elements needed for a domino accident (Reniers & Cozzani, 2013).

Element	***Definition***
Primary scenario	*An accident scenario that starts a domino effect propagating and escalating to other process or storage units, triggering one or several secondary accident scenarios* (Reniers & Cozzani, 2013, p.32).
Secondary scenario	*An accident scenario caused by the impact of an escalation vector generated by a primary accident scenario* (Reniers & Cozzani, 2013, p.32).
Propagation	*In case of a spatial domino effect, the propagation indicates the involvement of other units or equipment items, present at different positions with respect to that of the primary accident. In case of a temporally domino effect, there is propagation within the same unit or equipment item* (Reniers & Cozzani, 2013, p.32).
Escalation	*The intensification of the overall consequences of an undesired event* (Reniers & Cozzani, 2013, p.32).
Escalation vector	*A vector of physical effects (radiation, overpressure or fragment projection) generated by the primary accident scenario* (Reniers & Cozzani, 2013, p.32).

As stated earlier, domino effects are linked with a high degree of complexity and it is therefore difficult to unambiguously define a domino accident. Reniers and Cozzani (2013) state that defining what should be considered as a domino accident is not just an academic exercise, since several technical standards and the legislation require specifically that domino effects shall be analysed. Based on the elements needed for a domino accident to occur and by analysing fifteen different definitions, Reniers and Cozzani (2013) have compiled the following definition of a domino accident:

An accident in which a primary unwanted event propagates within an equipment (“temporally”), or/and to nearby equipment (“spatially”), sequentially or simultaneously, triggering one or more secondary unwanted events, in turn possibly triggering further (higher order) unwanted events, resulting in overall consequences more severe than those of the primary event (Reniers & Cozzani, 2013, p.35).

As the definition states; given that a primary accident occurs, the overall consequences need to be increased for a chain of events to be accounted for as a domino effect. In practice this means that secondary or higher events with lower escalation potential than of the primary event should be excluded from the analysis as these events do not increase the overall risk.

3.2 Review of statistical data

Due to the fact that full-scale experiments are very expensive and more or less impossible to conduct, researchers must make use of data from real life accidents (Reniers & Cozzani, 2013). Historical analysis of domino accidents can be useful to identify specific features for the domino effect: initiating events, materials most frequently involved, the causes and consequences and the most common chain of accidents (Darbra et al., 2010). This information can be used by practitioners as input in their risk assessments and thus making the results more reliable.

As seen in appendix A, most domino events have originated from fixed installations, where storage and process units are the most common ones. Looking at the substances most frequently involved in domino events, combustible substances represent a total of 89 percent. LPG, oil and gasoline represent the majority of substances associated with domino accidents. Fires and explosions are the hazards responsible for initiating the chain of accidents; based on the result from Darbra et al. (2010) and Abdolhamidzadeh et al. (2011), the two categories can approximately be seen as equal in numbers of initiating events. Comparing the different types of fires and explosions, one can see that vapour cloud explosions (VCE) and pool fires are the most frequent causes of initiating a domino sequence. Furthermore, Darbra et al. (2010) have performed an event tree analysis, by evaluating 225 domino accidents the characteristics of a chain of accident could be identified. The different chain of accidents and their relative frequency are presented in figure 6.

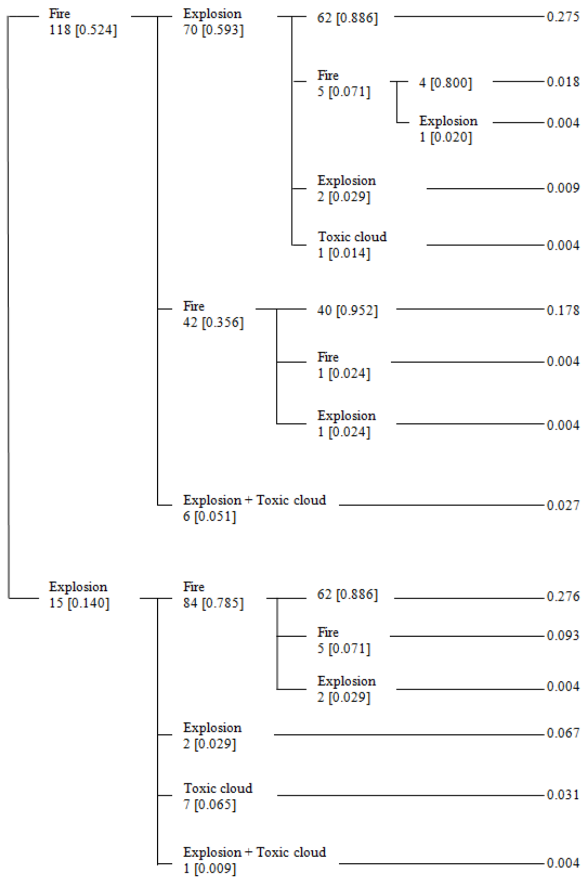

Figure 6. Event tree analysis of the chain of accidents and their relative frequency (Darbra et al., 2010).

The chain of accidents can be approximated with the knowledge of the expected escalation vector following the primary scenario. In a study by Cozzani et al. (2006), which was a revision of a previous study by the same authors conducted in 2004, more than 100 domino accidents gathered from the MHIDAS database were analysed. The study reveals how the expected secondary scenarios can be linked to escalation vectors following the primary scenario. Table 2 summarises the expected secondary scenarios that should be included in analysis for different primary scenarios and their escalation vector.

Table 2. Escalation vectors and expected secondary scenarios for different primary scenarios (Cozzani et al., 2006).

Primary scenario	*Escalation vector*	*Expected secondary scenarios*[a]
Pool fire	Radiation, fire impingement	Jet fire, pool fire, BLEVE, toxic release
Jet fire	Radiation, fire impingement	Jet fire, pool fire, BLEVE, toxic release
Fireball	Radiation, fire impingement	Tank fire
Flash fire	Fire impingement	Tank fire
Mechanical explosion[b]	Fragments, overpressure	All[c]
Confined explosion[b]	Overpressure	All[c]
BLEVE[b]	Fragments, overpressure	All[c]
VCE	Overpressure, fire impingement	All[c]
Toxic release	-	-

[a] Expected secondary scenarios also depend on the properties of target vessel inventory.

[b] Additional accident scenarios may take place simultaneously (e.g. pool fires, fireballs and toxic releases).

[c] All, any of the scenarios listed in column 1 may be triggered by the escalation vector.

3.3 The chain of accidents and different types of domino effects

When talking about domino effects, the distinction between internal and external domino effect is often made. If the escalation of an accident occurs inside the boundaries of a process industry it is classified as an internal domino effect and if the escalation of an accident occurs outside the boundaries of a process industry it is classified as an external domino effect (Reniers, 2010). As the statistical review shows, the chain of accidents can assume different forms, from a chain of single-level to a chain of multi-level accidents (Reniers & Cozzani, 2013). Principle structures for chain of accidents are presented in figure 7.

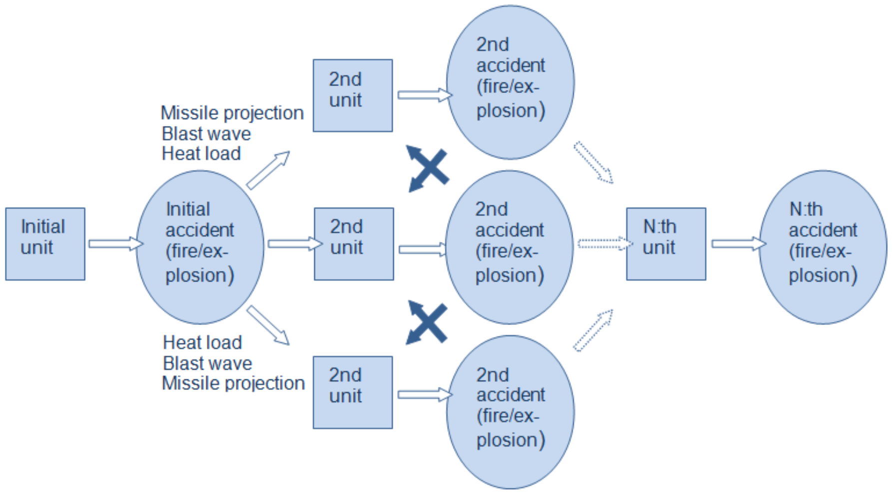

Figure 7. Principle structures for chain of accidents.

Looking at figure 7, it is obvious that a domino accident is linked with a high degree of complexity and that the chain of accidents can take many different forms. For example, as the dark blue arrows points out in figure 7, propagation to a secondary unit can both be influenced by the escalation vector from the primary event, as well as from another secondary event. To deal with the complexity issue Khan and Abbasi (1998) defined two main features for escalation that are linked to the characteristics of a domino accident:

- Direct escalation
- Indirect escalation

Direct escalation is caused by the immediate exposure of radiation, overpressure or fragment projection following an initiating event. Indirect escalation may occur if for example the control room is damaged by the primary scenario, leading to malfunctioning of a system or operators misreading system information, which in turn may lead to a secondary accident (Reniers & Cozzani, 2013). In order to achieve a more detailed identification of possible domino scenarios, two more categories of escalation have been defined (Reniers, 2010):

- Escalation of low-severity initiating events
- Interaction of different critical events

Escalation of low-severity initiating events is crucial to take into consideration when performing an assessment of possible domino scenarios. History has shown that these low-severity initiating events can have devastating consequences if they are not taken into consideration. Reniers and Cozzani (2013) describe an accident in an Italian plant for ethylene and propylene production. The chain of accidents was initiated by a minor rupture in a small-diameter (2 inch) ethylene pipe, which lead to a small jet fire. Further, a 600 mm pipe was exposed to heat radiation and suffered a full-bore rupture causing a large jet fire. In turn this large jet fire impinged a pressurised propane storage tank leading to a BLEVE. Further the BLEVE damaged and caused three other pressurised tanks to complete rupture, which resulted in the plant being almost completely destroyed. In an ordinary risk assessment, only focusing on the consequences of the primary event, it is likely that low-severity initiating events will not be taken into consideration. Because of the low propagation potential following these low-severity scenarios it is easy to delimit the escalation effect to an area close to the initiating events. The second type of escalation is based on the starting point that the consequence of the initiating event is high. Further, the propagation in space is the main factor to take into consideration when assessing these kinds of scenarios (Reniers & Cozzani, 2013). For this type of escalation, it is credible to assume that the propagation of the initiating event both can affect nearby units inside the boundaries of the plant as well as the surrounding buildings outside the plant boundaries.

3.4 Existing models for the integration of domino effects in QRA

Ever since the European Union adopted the Seveso II Directive in 1996, which requires the identification and assessment of domino hazards in the chemical industry, the phenomenon has been an important aspect for consideration in the field of major loss prevention. Since the early 1990s, efforts have been made to develop qualitative methods for the assessment of domino accidents (Reniers & Cozzani, 2013). However, more recently has relevant research been conducted in order to develop tools and models that enable domino scenarios to be analysed quantitatively (Antonioni et al., 2009; Cozzani et al., 2005, 2006; Landucci et al., 2009).

This research shows that three main categories of tools are needed for the quantitative analysis of domino events:

- Threshold values for the identification of potential targets of escalation
- Equipment damage models
- Specific tools and procedures for the assessment of frequency and consequences of the overall domino scenarios

Despite this up-to-date research, the most common approach for the inclusion of domino events in the risk assessment is still from a qualitative standpoint. Such approach leads to subjective assessments and is highly dependent on simplified assumptions, leading to results that may be questionable. Although QRA techniques have been widely used for the assessment of risk, its application to domino effects has been limited. The quantitative analysis of domino effects requires great computational resources, which have not been available until recent years (Reniers & Cozzani, 2013). These authors also state that a greater attention for developing methods that enable domino effects to be integrated in the QRA framework is needed.

Looking at existing approaches for analysing domino effects in a quantitative way, several models are available in literature. All of these models share common aspects, such as the tools used for the estimation of damage probability on target equipments and threshold values for the estimation of secondary accident scenarios. The typical differences between these models are found in the way that the chain of events is represented. Complex algorithms have been developed for this purpose, which have been programmed into computer codes in various software packages. Software packages that come with a user license cost. Common for these models are that they treat domino scenarios in separate analysis, starting from the results gained from a conventional QRA. These models show that domino effects effectively can be integrated in a QRA, but do not provide any guidance of how these effects should be incorporated in analysis. Thus, there is a need for comprehensive methods that clearly defines how domino effects effectively can be implemented and analysed within the boundaries of a conventional QRA framework. It is believed that such method can be developed starting from the baseline of a conventional QRA framework. By making use of the existing tools and models that have proven to deal with domino effects in a successfully way, the additional steps needed for the inclusion of domino effects can be implemented. To overcome the complexity concerning the inclusion of domino effects, as seen in existing models, the method should be applicable using well established tools and models that are likely to be accepted amongst practitioners.

4. METHOD DEVELOPMENT

By expanding the QRA framework and implementing additional steps for the analysis of domino scenarios, the overall contribution of domino effects can be assessed. As previously stated, the existing models for dealing with domino effects in a quantitative way treats domino scenarios in a separate analysis, starting from the results gained from a conventional QRA. If integrating the risk of domino effects in a QRA framework, such aspects are deemed to be more efficiently analysed, thus shortening the time needed for analysis. The integration of domino effects also leads to a better estimation of high severity scenarios, thus enabling a more realistic risk profile to be computed. As Reniers and Cozzani (2013) describe; threshold values, equipment damage models and specific tools and procedures for the assessment of frequency and consequences of the overall domino scenarios, should be seen as prerequisites for the quantitative analysis of domino scenarios. As a starting point, the four classical steps of QRA: risk identification, frequency analysis, consequence analysis and risk profile presentation, described in chapter 2, represent the baseline of which the additional steps for integrating the analysis of domino scenarios are built on. For the method to be effective, the additional steps required to analyse the domino effect must be integrated in a logical way so that a natural flow in the process can be achieved. To ensure the functionality of the method, criteria´s for what the method should be able to deal with are defined:

- The method should be applicable to well established analysis techniques and not dependent on complex algorithms for the analysis of the chain of events.

- The method should enable a risk profile for property damage to be computed with regard to all accident scenarios, including potential domino scenarios.

- The method should enable the risk of property damage with respect to domino effects to be analysed, both within a subsystem and between different subsystems.

- The method should enable site specific safety distances either to be established or validated with regard to property damage and domino effects.

4.1 The proposed method

By combining relevant information obtained in the literature study, a new method that allows domino scenarios to be integrated and analysed within the boundaries of a conventional QRA framework has been developed. The method is presented in a detailed flowchart describing each required step in the method, as shown in figure 8. The non highlighted boxes represent the core of a conventional QRA framework, whereas the blue highlighted boxes represent the additional steps added for the analysis of domino scenarios.

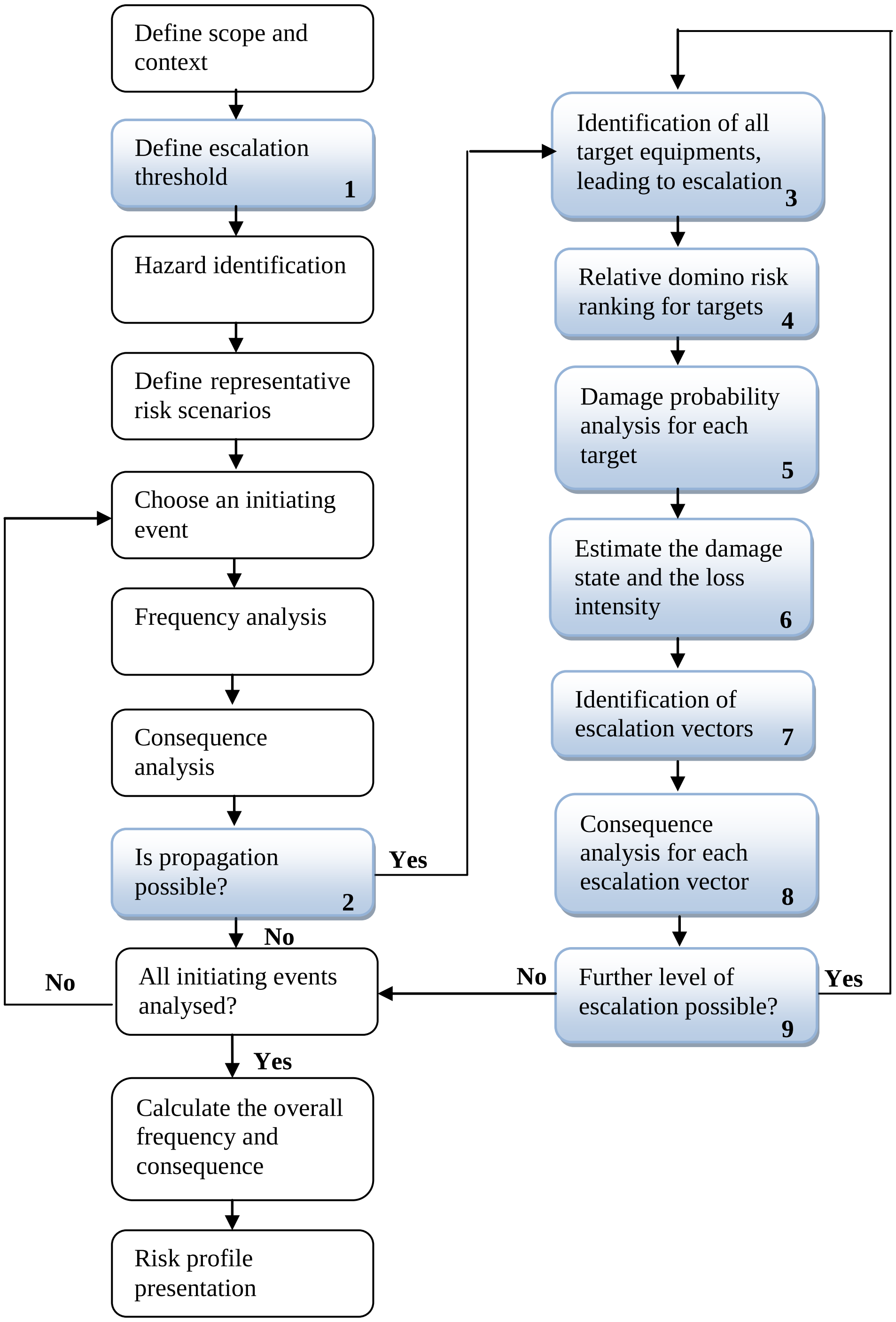

Figure 8. Flowchart describing the methodology process.

Depending on the scope and context of the analysis, the method aims to enable the analysis of domino effects to be accounted for in multiple ways. This means, the method should enable the risk of domino effects within a subsystem, between different subsystems and from one plant to another to be accounted for in a QRA. As domino effects are complex phenomena, it is crucial that the scope and context is clearly defined, stating the level of detail and delimitations that the analysis is based upon. The method is seen as flexible, as it can be used to achieve many different objectives and can be adapted to various methods and tools for frequency and consequence analysis. The most intuitive approach is to perform event tree analysis for each representative scenario, enabling the chain of events and the final outcomes to be identified. Thus, the impact of all events that can trigger escalation to nearby units can be accounted for, leading to a more realistic assessment of the accident scenarios. The event tree analysis can be conducted with the aid of specific tools, input from statistical data, procedures for the calculation of damage probability and the estimation of damage states and loss of containment, which are further described in this chapter. To keep the analysis of domino effects to manageable proportions, a cut off criteria delimiting scenarios to be included in the analysis is proposed. In literature, a cut off criterion of frequencies above $10^{-8}\ y^{-1}$ is often used, this can be seen as reference value but can be changed to better suit the aim of the analysis. The event tree analysis method is well known amongst risk and safety experts and thus likely to be accepted in this context, why it is recommended to be the choice of frequency analysis technique. To enable the risk profile to easily be compared to an acceptable risk criterion, risk contours with regard to property damage is seen as the most appropriate way to present the risk profile. Further, a more detailed description of the different steps, box 1-9, needed to incorporate the risk of domino effects in a QRA is presented.

Box 1: Define escalation threshold

After defining the scope and context of the analysis, the escalation threshold values for the specific process plant shall be estimated. An escalation threshold value defines the highest amount of inflicting load that target equipment may be exposed to before taking damage. Escalation threshold values for different equipment categories and damage states are available in literature and are further described in sections 4.2.2 and 4.2.3. A participatory approach, involving different actors of interest, is recommended when performing the hazard identification. Through workshop activities, hazards that pose the greatest threat of inflicting property damage can be identified. During the hazard identification, the threshold values can be used as support for the identification of critical areas with regard to domino effects, as these values can be converted into distances of impact. The advantage of taking domino sequences into consideration in the hazard identification step, rather than treating such effects in a separate step, is mainly that clusters of hazards with the potential to propagate into major consequences can be identified, which otherwise may have been overlooked. The representative scenarios should be chosen in a way that the risk of all potential accident scenarios is accounted for in the analysis.

Box 2: Is propagation possible? & Box 3: Identification of all target equipments, leading to escalation

From the base of the selected representative scenarios the first step in the analysis should be to calculate the frequency and consequence. By comparing the effect zone gained from the consequence analysis of the primary accident scenario with escalation threshold values for target equipments found within the zone, all targets that may suffer damage due to exposure of external loads may be identified. Box 2 and 3 represent this straightforward approach of identifying possible target equipments, and if propagation is deemed as possible the next step would be to analyse whether the target units can contribute to enhance the consequences of the primary accident, meaning is escalation possible?

Box 4: Relative domino risk ranking for targets

As the definition of a domino accident, see section 3.1, states; given that a primary accident occurs, the overall consequences need to be increased for a chain of events to be accounted for as a domino effect. In practice this means that secondary or higher events with lower escalation potential than of the primary event should be excluded from the analysis as these events do not increase the overall risk. Based on the fact that many units containing hazardous substances often are situated close to each other, it is easy to end up in a circular reference if not addressing domino effects with a systematic approach. For this purpose a relative domino risk ranking is recommended, meaning that all target equipments found within the effect zone should be ranked with regard to their potential to escalate the consequences. This is a terminology not to be found in any existing literature, why it is important to clearly define its purpose and how it should be implemented in frequency assessments, this is further elaborated on in section 4.3.1.

When ranking the escalation potential of scenarios, the recommended starting point is to investigate which units that have the largest amount of flammable substance, the flammability level and ignition point, and in what form it is being processed (gas or liquid, pressurised or atmospheric conditions). To avoid ending up in a circular reference, all potential chain of events that may follow a primary accident should be analysed starting from the unit having the greatest escalation potential and then working down the ladder to units with lower domino risk ranking. From a probabilistic point of view this means that escalation to the unit ranked next in line only is allowed in cases where the unit having the greatest escalation potential does not suffer damage. The same approach is applied when working down the relative domino risk ranking ladder. The risk of two or more units bursting simultaneously is preferably incorporated in the domino risk ranking as a separate scenario and treated in the same way as described above. However, the overall consequence of multiple units suffering damage simultaneously needs to be greater than the consequence of the involved unit with the largest escalation potential. Otherwise it should not be accounted for in analysis as damage to the unit having the greatest escalation potential can be seen to represent such scenario.

Box 5: Damage probability analysis for each target

After having determined the order in which the chain of events should be analysed, the next step is to estimate the probability of target equipments taking damage when exposed to external loads. This is preferably done with the aid of vulnerability models for different equipment categories. These models are based on multiple stress tests for different equipment categories exposed to various heat and overpressure loads, and are presented more in detail in section 4.2.2 and 4.2.3. The recommended vulnerability models have been correlated as probit functions and enable the probability of damage to be calculated in a time efficient way, in contrary to more detailed simulation methods. The vulnerability models proposed for the estimation of damage probability to target equipment have been developed without any regard to safety systems. Therefore, the impact of safety systems is recommended to be assessed separately, thus allowing the damage probability to be updated with regard to safeguards and protection barriers. There are several types of safeguards and protection barriers, which have different mitigation effectiveness depending of the hazard and the type of system. Furthermore, the limited time associated with QRAs does not allow detailed analysis for risk reduction measures to be performed. Due to that fact, the use of generic values for risk reduction factors in combination with expert judgements is recommended and deemed to be adequate in the QRA framework.

Box 6: Estimate the damage state and the loss intensity & Box 7: Identification of escalation vectors

In order to analyse which secondary accident scenarios that may follow target equipments suffering damage and in turn identify the following escalation vectors, the damage state and the loss intensity needs to be estimated. These classes describes the type of damage a unit may suffer due to exposure of external loads and the size of the subsequent loss of containment, these classes are presented in detail in section 4.2.1. The damage state and the loss intensity are estimated by comparing the received load to predefined escalation threshold values for different equipment categories. These classifications serve as input when secondary accidents and escalation vectors are estimated. With use of this input the release rate of the secondary loss of containment can be approximated. Having this information and knowing the properties of the substance and the conditions in which it is being processed, enables the secondary accident scenario to be estimated.

Box 8: Consequence analysis for each escalation vector & Box 9: Further level of escalation possible?

By performing a consequence analysis of the escalation vectors previously identified, additional effect zone can be computed for each secondary accident scenario. If additional units are found within these effect zones further level of escalation needs to be analysed, this is done by repeating the process described in boxes 3-9.

As figure 7 in section 3.3 shows, a target unit can be exposed to physical effects from different risk sources simultaneously. As stated before, domino effects are linked with a high degree of complexity and if one were to incorporate these kinds of synergetic effects to the analysis, it is likely that the complexity would escalate to an unmanageable proportion. Up to this day, there are no computational software programs that can manage such aspects to be taken into account. Reniers and Cozzani (2013) clearly state that there is a need for simplifying assumptions in order to carry out the consequence analysis in a manageable time span and with regard to the limited computational capacity present, thus it is acceptable to analyse the consequences of accidents separately, neglecting the assessment of possible synergetic effects.

The inclusion of domino effects, see the blue highlighted boxes in figure 8, requires understanding of the procedure in which the frequency and consequence of domino effects can be estimated. As stated earlier, the most intuitive and recommended approach to analyse the chain of events is to perform event tree analysis for each representative scenario. However, other approaches may be adopted as the method is not dependent of a certain analysis technique. Depending on the complexity and the objective of the analysis, other analysis techniques can be adopted to better suit the purpose of the analysis: fault tree analysis, bow-tie analysis, Bayesian network analysis and Monte Carlo simulations, are all examples of this and are further elaborated on in section 4.4.

The analysis of domino scenarios in this framework is strongly dependent on vulnerability models for damage on different equipment categories, why these are further elaborated on in this chapter. The physical effects that initiate escalation must also be elaborated on, this to give the reader understanding of which parameters that affect the consequences of domino accidents. The following sections aim to give the reader input and the knowledge needed to perform the additional steps, boxes 1-9, that enable domino scenarios to be incorporated in a QRA.

4.2 Physical effects of escalation vectors

Understanding of the physical effects of escalation vectors is particularly important when defining the relative domino risk ranking (box 4) and for the identification and consequence analysis of escalation vectors (box 7 and 8). As stated earlier, the physical effects due to exposure of escalation vectors (radiation, overpressure and fragment projection) are the initiating cause for setting a chain of accidents in motion. To give the reader understanding of which hazards that should be taken into account in the proposed method, how these hazards can be assessed and which parameters that have the greatest influence on the consequences, these physical effects are further described in the following sections.

4.2.1 Fire

As the statistical analysis described in appendix A shows, approximately 50 % of all domino accidents are caused by fires. The secondary targets are most frequently containments in terms of tanks, vessels and pipelines. The high temperature of the fires, typically between 800 and 1200 degrees Celsius, lower the resistance of the shelter and leads to an increase of the internal pressure of the containment (Reniers & Cozzani, 2013). Combustion of flammable gas-air mixture occurs if the concentration is within the flammability limits and conditions for ignition exist. A combustible gas-air mixture can be ignited by a local source, either a spark or a flame, or by the heating of the mixture to its ignition temperature. The local source needed to start a fire and the ignition temperature varies for different substances, as well as the flammability limit, which in turn is dependent of the pressure. Pressures below atmospheric pressure imply a narrow range of the flammability limit and overpressure implies a wide range (Mannan, 2005). The limits are also affected by the temperature, where a higher temperature equals a wider flammability range (ibid.).

The characteristics of a fire are influenced by leakage rates, the burning substance, storage conditions and wind conditions (Reniers & Cozzani, 2013). The heat developed by the fire can be transferred by: radiation, convection and conduction. Most of the heat from fires is transferred by radiation and convection, where convection represents about 75 % of the total transfer (Mannan, 2005). Even though radiation is corresponding to a lower percentage of the total heat transfer compared to convection, it is often the most significant heat transfer mechanism on an open plant (ibid.). This is mainly due to the fact that radiated heat is transferred directly to the objects nearby and crosses through open spaces, whereas convection mainly is transferred upwards. When analysing the consequences of a fire within a process plant it is therefore mainly the effects of radiation that should be analysed (Mannan, 2005).

4.2.1.1 Escalation caused by heat loads

The types of fires relevant for escalation are: jet fires, pool fires, flash fires and fire balls (Reniers & Cozzani, 2013). Jet fires may occur if pressurised vessels of flammable gas or flashing liquid bursts and ignition occur. The high kinetic energy of a jet fire implies a large flame length in the direction of the release. The duration and the characteristics of the flame are affected by the phase of the burning substance, either vapour, liquid or two-phase. Depending on the phase and the amount of fuel, a jet fire's duration can vary from seconds to hours (Reniers & Cozzani, 2013). A jet fire with long duration, several minutes to hours, can be modelled as a steady source of radiation (ibid.). The high heat load and temperature associated to jet fires implies a large amount of radiation, therefore jet fires are considered to have great escalation potential (ibid.). This fact, in combination with relatively high frequencies of occurrence, entails that jet fires are one of the most frequent causes of domino effects.

Jet fires may cause escalation either by direct flame impingement or distant radiation (Reniers & Cozzani, 2013). The effects of direct flame impingement of jet fires are well documented through past accidents and experiments. The escalation possibility from steady radiation is more specific for each scenario and has to be evaluated with models that not only take the intensity of radiation into account but also the features of the target equipment (ibid.).

Pool fires usually occur when a pool of flammable liquid is generated and ignited, often due to a loss of containment of a vessel. The combustion takes place in the vapours generated from the pool and the duration of the fire is usually longer than in the case of a jet fire. The generally long duration of pool fires implies that it can be modelled as a steady source of radiation in most of the cases. A pool fire may lead to escalation either by distant radiation or fire engulfment (Reniers & Cozzani, 2013). The modelling of pool fires are described in *Lees' Loss Prevention in the Process Industries* (Lees, 1996).

Flash fires, also called vapour cloud fires, is the term for a low-turbulent combustion of a vapour cloud. The difference from a vapour cloud explosion is that a flash fire is associated with slow reactions leading to a low flame speed (Reniers & Cozzani, 2013). The low reactivity may occur due to an inhomogeneous mixture of fuel and air, a concentration close to the flammability limits or a stratified cloud (ibid.). The duration of a flash fire is short, usually not longer than a few seconds, and therefore it is not likely to lead to secondary damage due to radiation. The possibility of escalation is instead dependent of the ignition of flammable material due to flame impingement (ibid.).

Fireballs are a phenomena caused by immediate ignition of a vapour cloud generated by a severe loss of containment (Reniers & Cozzani, 2013). The duration of a fireball is longer than of a flash fire, up to one minute, and associated with a high intensity of radiation (ibid.). Although the duration of a fireball is longer than in the case of a flash fire, it is still relatively short compared to the time to failure for the target equipment. This fact entails that the effect of fireballs often is neglected in domino effects analysis. Fireballs may however cause damage on atmospheric vessels due to the high intensity of radiation and shall in a detailed domino effects analysis therefore be included as a possible cause of escalation (Reniers & Cozzani, 2013).

Domino effects triggered by fire are typically delayed relative to the initial event, in contrary to escalation triggered by overpressure effects and missile projection where the escalation occurs rapidly (ibid.). The delay of escalation can be minutes up to hours and is calculated in the means of time to failure (ttf). The ttf can be used to estimate if mitigation efforts can be taken before escalation occurs. The ttf depends on the characteristics of the target equipment and the heat load transmitted to it. The key issue to protect a target from a fire hazard is therefore to prevent or mitigate the exposure of the target equipment, for instance by thermal coating.

The vessel wall temperature determines the strength of the wall and thus the pressure carrying ability. The increase in vessel wall temperature due to external heat load is highly dependent of the phase of the stored substance, where heating of a vessel containing gas entails a rapid increase of the vessel wall temperature due to the low cooling effect of the gas while the wall temperature of a vessel containing a liquid substance remains near the temperature of the liquid due to the high cooling effect (Reniers & Cozzani, 2013). If the vessel contains a liquid substance, the external heat load instead mainly causes a rapid increase of the internal pressure, causing an increased stress to the vessel shell. The vessel will burst when the hoop stress is greater than the strength of the vessel wall material (ibid.). Even if pressure relief valves are present and controlling the pressure at a level that is lower than the nominal burst pressure of the vessel, failure may occur due to decreasing burst pressure resulting from an increase of the vessel wall temperature (ibid.).

In the proposed method, flash fire is not considered as a credible accident scenario leading to escalation, this due to the short duration associated to the phenomenon. As stated, escalation due to equipments being exposed to fire can either be triggered by distant source radiation or flame engulfment/impingement. If target equipment is engulfed or impinged by fire, the heat load received by the target equipment should be estimated by considering both radiation effects and convective heat transfer effects.

4.2.2 Explosions

An explosion is defined as a rapid and violent release of energy (Mannan, 2005). The magnitude of the explosion is dependent of the velocity in which the energy is released. There are three main types of energy that can be released through an explosion: physical, chemical and nuclear energy. In the process industry it is mainly chemical explosions, in particular through combustion of flammable gas that is the main threat and thus should be prioritised in the QRA (ibid.). Explosions caused by combustion of flammable gas can either propagate through detonation or deflagration, where detonation is most severe and travels at speeds in the order of thousands of metres per second. In the process industries there are different types of explosions that can occur (Mannan, 2005):

- Physical explosion
- Condensed phase explosion
- Vapour cloud explosions (VCE)
- Boiling liquid expanding vapour explosion (BLEVE)
- Confined explosions with reaction
- Dust explosions

4.2.2.1 Escalation caused by overpressure loads

Damage on target equipment due to explosions can be correlated to the overpressure loads developed by the blast wave. Depending on the amount of energy and the velocity in which it is released, the overpressure load generated by an explosion may vary. Depending on the type of explosion there are different methods for the calculation of such overpressure effects. When considering point source explosions, for example BLEVE and condensed phase explosion, a TNT model is often used, which is conservative model that converts the energy released into TNT equivalents enabling a simplified approach for the consequence assessment of overpressure effects (Mannan, 2005). When analysing more complex phenomena, for example VCE, the models used shall be able to handle peak pressure and impulses in the near and far field. The Multi-Energy Model and the Baker-Strehlow method are used worldwide for these kinds of calculations. In recent years the application of Computational Fluid Dynamics (CFD) models for explosion analysis of complex systems has increased (Reniers & Cozzani, 2013). However, such modelling is very time consuming and thus not preferable when analysing domino effects in a QRA, as the time associated with such analysis most certainly would be exceeded. All type of explosions should be considered when analysing property damage with regard to domino effects. No explicit model is recommended for the proposed method, as the choice of model should be dependent on the software program at hand and the scope and context defining the level of detail in which the analysis is based on.

4.2.2.2 Escalation caused by missile projection

A possible secondary effect of explosions is projection of fragments, also referred to as missile projection. Missile projection is one of the most frequent causes of domino effects in process industries. A burst of a vessel is a typically accident that may result in missile projection (Reniers & Cozzani, 2013). The fragments can travel up to 1 kilometre, which implies that the possibility of secondary or tertiary levels of escalation must be considered for a long range, relative to the initial position (ibid.). Gubinelli and Cozzani (2009) have conducted a survey of more than 180 accidents that lead to missile projection to analyse the cause. The result was as follows:

- Fired BLEVE (62 %)
- Unfired BLEVE (12 %)
- Physical explosion (10 %)
- Confined explosion (10 %)
- Runaway reaction (6 %)

All causes to missile projection have in common that they are initialised by internal energy, most frequently in the form of high pressure, in the vessel (Reniers & Cozzani, 2013). The increase of internal energy can propagate cracks in the containment, resulting in fragmentation and transformation of the internal energy of the vessel into kinetic energy of the fragments (ibid.). Fragments can also be projected by rotating equipments, such as turbines and compressors. Missile projections caused by fragmentation due to a burst of a vessel or by projection from rotating objects are described as "primary missiles", due to the fact that they are directly generated from the failure of equipment (ibid.). "Secondary missiles" instead describes the case when a blast wave picks up objects in the surroundings of the accidental unit. When conducting an assessment of domino effects the focus is usually on primary missiles, since they are more likely to cause escalation (ibid.).

Assessment of missile projections can be divided into three steps: calculation of fragment velocity, estimation of fragmentation patterns and impact analysis. Different methods are available for the calculation of these three steps. The proposed method is not dependent on any explicit method, however it is important to have fundamental knowledge of the three steps needed for the assessment of missile projection, why these steps are further elaborated on.

The fragment velocity is generally significantly higher than normal wind velocities, thus making it reasonable to neglect the effect of wind direction and velocity when analysing this phenomenon (Reniers & Cozzani, 2013). The velocity of the fragments is dependent of the kinetic energy, which in turn is dependent of the scenario and the design of the vessel. There are several different methods for calculating the kinetic energy of the fragments, different models are presented and reviewed in *Lees' Loss Prevention in the Process Industries* by Mannan (2005). Some methods consider the efficiency of energy transformation from internal into kinetic, which is primarily affected by two parameters: the condition of the vessel when it bursts and the condition of the content in the vessel (Reniers & Cozzani, 2013). Other methods are based on the simplification that almost all of the energy is transferred or using a transfer ratio based on statistical data. There are also more complex methods based on the energy and momentum balance, where the Baker model, described by Baker et al. (1983), is the most frequently used. The models are often restricted to particular types of vessels, fragment geometries or chemicals, so it is important to choose a method that is representative for the situation that is analysed (Reniers & Cozzani, 2013).

The transformation ratio of energy differs in a large range depending on the model used. It has been validated against experimental data that the use of a kinetic energy model is suitable in case of BLEVEs and mechanical explosions (Mannan, 2005) and that an energy and momentum model is suitable for confined explosions (Baker et al., 1983). When considering missiles caused by rotating equipment the fragment velocity is often simplified as the maximum tangential velocity of the rotating part alternatively calculated by the conservation of kinetic energy of the rotor (Reniers & Cozzani, 2013).

The fragmentation patterns and the probable dimensions of the missiles are often based on statistical data for vessels or rotors similar to the one that is analysed (Reniers & Cozzani, 2013). There are some different models available to analyse the impact probability. Hauptmanns et al. (2001) have created a model based on trajectory analysis accompanied by Monte Carlo simulations, but the model focuses on human impact and is therefore not adaptable to property damage and domino effects. Another approach with emphasis on the probability of domino effects has been provided by Gubinelli et al. (2004). The method is based on ballistic analysis of the possible trajectories of the fragments and has been validated against accidental data (Reniers & Cozzani, 2013).

The target damage caused by a missile can be a perforation (the missile penetrates all the way through the shell), an embedment (the missile stop before complete penetration) or a ricochet (the missile bounces back against the shelter) (Reniers & Cozzani, 2013). There are many factors affecting the behaviour of the missile and the impact on the target, resulting in a large span of possible travel distances and damages. Parameters that affect the fracture propagation and secondary damage potential are: the velocity of the missile, the dimensions, density, elasticity and robustness of both the missile and the target (ibid.). The probability of perforation is higher for small missiles, often originated from rotating equipment, than in the case of large fragments (ibid.). Vessel failure often results in quite large fragments that travel in a relatively low pace, most frequently resulting in plastic deformation of the target (ibid.). The literature gives several calculation models for the penetration scenario, most frequently developed through fitting of experimental data, which are reviewed by Mannan (2005), but the plastic deformation is more difficult to model. There are models used in other fields that simulate impulse loads on structures by finite element analysis, but they have not been applied in the process industry to any great extent, mostly due to the variance of the conditions for different scenarios (Reniers & Cozzani, 2013).

The above described steps needed for the assessment of missile projections should be seen as guidance for how such aspects can be taken into account in the proposed method and which models that can be used. However, the information given in this section should only be seen as an overview of the existing models that can be used for such assessments. In order to gain more detailed knowledge concerning the models and the uncertainties associated with them, the reader is referred to the originating sources found in literature.

4.3 Damage assessment for equipments exposed to external loads

The proposed method is dependent of simplified tools that enable the probability of damage for target equipments exposed to external loads to be calculated (box 5) and escalation threshold values for the assessment of whether escalation is possible or not (box 1, 2 and 3). If target equipment suffers damage, different damage state and loss intensity classes can be used as support when estimating secondary accident scenarios (box 6). The following sections aim to give the reader the proper knowledge, enabling these steps to be performed.

When considering the risk of domino effects it is not only the external loads received by target equipments that are of interest to analyse. The characteristics of target equipments also have great impact on the escalation probability and the severity of sequential accident scenarios. After the escalation vectors have been calculated the next step is therefore to analyse how it will affect the target equipment. Different models are available for the analysis of the impact on target equipments, static methods or simple analytical methods such as the Single Degree Of Freedom (SDOF) or Multi Degree Of Freedom (MDOF) are two commonly used models used for such analysis (Reniers & Cozzani, 2013). In recent years computational codes for Finite Element Analysis (FEA) have been developed, which enables a more detailed structural analysis. When taking domino effects into account during a QRA even the most simplified methods for impact analysis, like the SDOF, are generally too time-consuming (ibid.).

To overcome the limits concerning the time available for impact analysis, a threshold based approach is often used when analysing domino effects. From historical accidental data, threshold values for different types of equipment categories have been estimated. Several attempts in defining thresholds have been made, see table 3, however, the proposed values are associated with a high degree of uncertainty, which in turn leads to results with large variation. More specifically, this has lead to safety distances that vary from tens of meters to several hundred meters (Cozzani et al., 2006). The origin of the threshold values showed in table 3 is presented in Appendix B.

Table 3. Escalation thresholds reported in literature (Cozzani et al., 2006).

Escalation Vector	*Threshold*	*Equipment Category*	*Reference*
Radiation (kW/m2	9.5	All	Tan (1967)
	12.5	All	DM 151/2001
	15.6	All	API RP 510 (1990)
	24.0	All	Bagster and Pitblado (1991)
	25.0	All	Van den Bosh et al. (1989)
	37.0	All	Khan and Abbasi (1998)
	37.5	All	HSE (1978)
	37.5	All	BS 5908 (1990)
	37.5	All	Mecklenburgh (1985)
	38.0	All	Kletz (1980)
Overpressure (kPa)	7.0	Atmospheric	Gledhill and Lines (1998)
	10.0	Atmospheric	Barton (1995)
	10.0	Atmospheric	Bottelberghs and Ale (1996)
	10.0	Atmospheric	Kletz (1980)
	14.0	Atmospheric	Gugan (1979)
	20.3	Atmospheric	Brasie and Simpson (1968)
	20.7	Atmospheric	Clancey (1972)
	23.8	Atmospheric	Glasstone (1980)
	30.0	All	DM 151/2001
	30.0	Pressurized	Bottelberghs and Ale (1996)
	35.0	All	Wells (1980)
	35.0	All	Gledhill and Lines (1998)
	38.0	Pressurised	Bagster and Pitblado (1991)
	42.0	Pressurised	Cozzani and Salzano (2004c)
	55.0	Pressurised	Glasstone (1980)
	65.0	Pressurised	Brasie and Simpson (1968)
	70.0	All	Khan and Abbasi (1998)
Fragments (m)	800.0	All	DM 151/2001
	1150.0	All	Tan (1967)

The escalation threshold values are easy to use, but such approach leads to a deterministic estimation and does not consider that different load intensities are more or less likely to lead to escalation. Another approach is the use of simplified vulnerability models correlated as probit functions. The advantages of these vulnerability models compared to the threshold based approach are that the probability of escalation can be quantified and that the characteristics of the specific equipment can be taken into account (Reniers & Cozzani, 2013). Based on the fact that the proposed method has been developed to enable the risk of domino effects to be analysed quantitatively within the timeframe associated with a QRA, vulnerability models are recommended for the calculation of damage probability for target equipments exposed to overpressure.

The probit function is an analytical equation, based on the sigmoidal shaped dose-response curve. The function is used to make dose-response relationships more practical to use, this by converting the curve into a straight line. Probit functions can be used for a variety of exposure, including the exposure of pressure and radiation (CCPS, 1999). Probit functions for the probit variable,Y, based on the dose of exposure, D, can generally be described as the following:

$$Y = a + b \ln D \qquad \text{(Eq. 1)}$$

Where a and b are the probit coefficients used to fit the function against experimental data. To transfer the probit variable gained from the function to a probability value either conversion tables or equation 2 can be used (CCPS, 1999).

$$P = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Y-5} exp\left(-\frac{u^2}{2}\right) du \qquad \text{(Eq. 2)}$$

Where P is the probability, Y is the probit variable and u is an integration variable. Y is normally distributed with a mean value of 5 and a standard deviation of 1. When analysing domino effects, probit functions can be used to assess the vulnerability of equipments due to the exposure of overpressure and radiation (CCPS, 1999). In 1975 Eisenberg et al. (1975) defined a probit function that correlated equipment damage to the peak static overpressure. Ever since then, research on developing better correlated probit functions has been performed. Nowadays, probit functions for the assessment of vulnerability for a various range of process equipment due to exposure of radiation and overpressure are available in literature.

Damage to process equipment is due to the exposure of different escalation vectors: heat radiation, overpressure and fragments projection. The escalation is both influenced by the specific features of the escalation vectors and by the design features of the target equipment (Cozzani et al., 2006). In order to obtain reliable vulnerability models and a set of escalation threshold values, these specific features need to be analysed. By taking different levels of exposure intensities into account when estimating the damage probability on target equipment, it is possible to quantify the consequence that follows escalation. Different levels of loss intensities are strongly linked to the damage state of the target equipment, why it would be beneficial to define a correlation between the two.

4.3.1 Damage states and loss intensity classes

Different intensities of loss of containments are associated with different damage states (DS). Defining different damage states and how they are linked to different classes of loss of containment enables the consequences of the secondary scenario to be assessed quantitatively. Thus, the definition of loss intensity classes (LI) and their association to respective DS category are an important element in the framework for risk assessment of domino effects (Reniers & Cozzani, 2013). It also enables an easier estimation of the cost associated to damage on equipment, which in turn can be used to assess process downtime. In literature, damage state categories are often defined as:

- DS1: light damage to the structure or to the auxiliary equipment.

- DS2: intense or catastrophic damage, which is certainly followed by an intense loss of containment.

As stated earlier, different types of loss of containment may follow DS1 and DS2. There are many factors affecting the severity of a loss of containment, mainly the release flow, which in turn is influenced by the physical properties and the condition of the fluid in the vessel. Following the approach described in the *Purple book* (2005), three classes of loss intensities can be defined:

- LI1: minor loss, defined as the partial loss of inventory or total loss of inventory in a time interval of more than 10 min.

- LI2: intense loss, defined as the total loss of inventory within 10 min.

- LI3: catastrophic loss, defined as the instantaneous loss of inventory.

When defining LI classes caution should be taken, especially when a high number of LI classes are proposed, this because a more detailed analysis demands actual damage data or structural modelling to be justified (Reniers & Cozzani, 2013). The correlation between LI classes and DS categories is defined in table 4, the definitions presented are commonly used in various literature and are based on research of previous accidents.

Table 4. Loss of intensities classes and damage states categories (Cozzani et al., 2006).

Structural damage	***Loss of containment***	***Secondary events for flammable materials***			
		Equipment			
		Atmospheric	Pressurized	Elongated	Small
DS1	LI1	Minor pool fire	Minor jet fire	Minor pool fire Minor flash fire	Minor pool fire Minor flash fire
DS2	LI2	Pool fire Flash fire VCE	Jet fire Flash fire VCE	Pool fire Flash fire VCE	Minor pool fire Minor flash fire
DS2	LI3	Pool fire Flash fire VCE	BLEVE/fireball Flash fire VCE	Pool fire Flash fire VCE	Minor pool fire Minor flash fire

4.3.2 Heat loads

Cozzani et al. (2006) state that three factors, except from the radiation intensity, should be taken into account when defining escalation thresholds due to exposure of heat loads: the possible specific effect of fire impingement and engulfment, the time evolution and the characteristics of the secondary target. The straightforward approach is to compare the heat load and duration generated by the primary scenario with the time to failure (ttf) of the target equipment. The ttf in turn depends on the target equipment design: shell thickness, atmospheric or pressurized vessel, volume of the tank, etc. The presence of active and passive protection system is also a contributing factor, water deluges, thermal insulation and relief valves for example. The position of the primary accident relative to the target equipment is also of importance; the targeted equipment may be partially or fully engulfed by a fire, a flame impingement may be present or heat radiation may come from a distant source (Cozzani et al., 2006).

Extensive research on the time to failure for different process equipments is available in literature. The research conducted by Cozzani et al. (2006) constitute one example; these authors defined an extensive set of representative scenarios, using input vessel data from well recognized standards and codes. The authors simulated the vessel wall temperature and internal pressure build up for different heat loads, which allowed them to estimate the ttf for each representative scenario. The simulations were conducted using a lumped-parameters model, and a sensitivity analysis of all factors affecting the escalation possibility was also conducted. The research allowed the authors to correlate representative vulnerability models for the estimation of damage to different equipment categories. For detailed information regarding the reference vessels and scenarios, readers are referred to Cozzani et al. (2005, 2006). Further, Landucci et al. (2009a) revised the study of Cozzani et al. (2006) and validated the lumped-parameters approach by comparing the ttf values from the lumped model with ttf values from a finite element model (FEM) and real life experiments. The validation shows that the lumped model gives credible and conservative values, with a 15 % average relative error on the safe side. These authors also introduced a dependency of vessel volume to improve the estimation of the ttf, which resulted in updated vulnerability models, as presented in table 5.

Table 5. Probit functions for the calculation of damage probability of equipments exposed to radiation; ttf [s]; I [kW/m^2]; V [m^3] (Landucci et al., 2009a)

Equipment category	***Probit function***
Atmospheric vessel (25 – 17 500 m^3, 0.1 MPa)	$Y = 9.25 - 1.85 \cdot \ln\left({}^{ttf}/_{60}\right)$
	$\ln(ttf) = -1.13\ln(I) - 2.67 \times 10^{-5} \cdot V + 9.9$
Pressurized vessel (5-250 m^3, 1.5-2.5 MPa)	$Y = 9.25 - 1.85 \cdot \ln\left({}^{ttf}/_{60}\right)$
Distant source radiation	$\ln(ttf) = -0.95\ln(I) + 8.845 \cdot V^{0.032}$
Engulfed by flames	$\ln(ttf) = -1.29\ln(I) + 10.971 \cdot V^{0.026}$

The above correlations are based on Landucci et al. (2009a) method for making the probit function more site-specific. These authors state that the probability of damage is dependent on the time to failure (ttf) and that the probit coefficients, a and b, are dependent of the time required to start emergency operations (tte_1) and the maximum time required to start mitigation actions (tte_2). Based on a survey conducted on multiple oil refineries, the time needed for the arrival of the internal emergency team and for them to start mitigating actions could be estimated. A rough distribution could be derived showing that only in 10 % of the cases the cooling could start in less than 5 minutes and in 90 % in less than 20 minutes (Landucci et al., 2009a). This information enabled the authors to derive the probit constants, a and b, using equation 5 and 6. These probit constants can be seen as generalised values and may be adapted if site-specific information is missing (ibid.).

$$a = \frac{\Pr(10\%)\cdot\log(tte_1) - \Pr(90\%)\cdot\log(tte_2)}{\log(tte_1) - \log(tte_2)} \qquad \text{(Eq. 3)}$$

$$b = \frac{\Pr(90\%) - \Pr(10\%)}{\log(tte_1) - \log(tte_2)} \qquad \text{(Eq. 4)}$$

Readers should note that the above correlations shall be seen as a conservative estimation of the actual ttf, as the vulnerability models are based on the lowest ttf for each analysed scenario. However, they are still useful in a QRA framework because they allow the possibility for escalation to be calculated within a reasonable timeframe. The results show that the ttf of any atmospheric vessel exposed to distant radiation intensity lower than 15 kW/m^2 was higher than 10 minutes and for radiation intensity lower than 10 kW/m^2 the ttf was higher than 30 minutes. In the case of pressurised vessels, the ttf resulted in higher than 10 minutes for a distant radiation intensity of 60 kW/m^2 and higher than 30 minutes for radiation intensity lower than 45 kW/m^2. Readers should note that the ttf for pressurised vessel is dependent on the design pressure, which was between 1,5 and 2,5 MPa. The authors did not include any active or passive protection systems in their analysis so these results should be considered rather conservative, especially for pressurised vessels, where thermal protections as fireproofing material and active mitigation systems as water deluges often are present (Reniers & Cozzani, 2013).

Recently, real life experiments have been made to see how thermal protective coatings affect the time to failure for pressurised vessels. The results from experiments made by Landucci et al. (2009b) evidence that thermal protective coating has a significant impact on the time to failure. The ttf resulted in over 100 minutes when a pressurised vessel 3m^3 with thermal protective coating was fully engulfed to fire with a flame emissive power of 110 kW/m^2 (Landucci et al., 2009b). Reniers and Cozzani (2013) have compiled the results from different experiments with coated pressurised vessels, showing a minimum ttf of 94 minutes. This can be compared to ttfs ranging from 4 up to 30 minutes for unprotected pressurised vessels (Reniers & Cozzani, 2013). Based on these experimental results the impact of radiation on pressurised vessels with thermal coating can be neglected when analysing the possibility of domino effects. Atmospheric tanks have considerably lower shell thickness compared to pressurised vessel, which make them more vulnerable to exposure of heat loads. The results from Cozzani et al. (2006) study shows that atmospheric vessels are likely to burst within times varying from 100 – 200 seconds when exposed to radiation levels between 60-90 kW/m^2. Based on this fact and that pool fires often have flame surface emissive powers ranging from 120 – 170 kW/m^2, depending on the substance, atmospheric tanks impinged or engulfed by fire are assumed to have an escalation probability of 1.

As stated before, different loss intensities (LI) may follow different damage states (DS). To enable a domino sequence to be analysed in a quantified way, both the probability for escalation (vulnerability models) and the consequences (DS and LI) that may follow escalation need to be evaluated. In studies by Cozzani et al. (2006), Landucci et al. (2009a) and Antonioni et al. (2009), efforts have been made to evaluate the consequences due to the exposure of different kinds of escalation vectors and heat loads. Which LI classes that should be addressed due to different levels of radiation intensities are presented in table 6.

Table 6. Threshold values for different equipment categories associated to DS and LI classes due to the exposure of heat loads (Antonioni et al., 2009; Cozzani et al., 2006; Landucci et al., 2009a).

Scenario	*Escalation vector*	*Threshold values (kW/m^2)*		*Consequence*
		Pressurised tanks	Atmospheric tanks	
Fireball	Radiation	$I \geq 100$	$I \geq 100$	DS1LI 1
		$I \leq 100$	$I \leq 100$	No consequence
	Flame engulfment	$I \geq 100$	$I \geq 100$	DS1LI 1
		$I \leq 100$	$I \leq 100$	No consequence
Jet fire	Fire impingement	$d_j \geq d$	$d_j \geq d$	DS2LI 3
	Radiation	$I \geq 60; t_j \geq 10$	$I \geq 15; t_j \geq 10$	DS2LI 2
		$I \geq 40; t_j \geq 10$	$I \geq 8; t_j \geq 10$	DS1LI 1
		$I < 40$	$I < 8$	No consequence
Flash fire	Fire impingement	Unlikely	Unlikely	No consequence
Pool fire	Flame engulfment	$d_p \geq d$	$d_j \geq d$	DS2LI 3
	Radiation	$I \geq 60; t_p \geq 10$	$I \geq 15; t_p \geq 10$	DS2LI 2
		$I \geq 40; t_p \geq 10$	$I \geq 8; t_p \geq 10$	DS1LI 1
		$I < 40$	$I < 8$	No consequence

d_j; jet length, d_p; pool diameter, d; distance between tanks, t_j; duration of jet fire [min], t_p; duration of pool fire [min]

However, these threshold values have been asserted to cover a big range of vessel volumes and shell thicknesses, as reported in the study by Cozzani et al. (2006). Looking at the proposed threshold value of radiation intensities equal to or higher than 15 kW/m^2, the time varies from 585 s to 940 s with vessel volumes ranging from 25 m^3 to 17 500 m^3. This indicates that the ttf varies significantly with specific vessel volumes and that one should verify that the duration of exposure is longer than the specific ttf.

4.3.3 Overpressure loads

For each primary scenario that may cause an explosion, the expected damage due to overpressure on the target equipment is mainly dependent on the peak static overpressure and of the features of the equipment. Other influential factors are: the dynamic overpressure, the rise time of the positive phase of the wave and the total impulse, as well as reflections of the pressure wave, flow separation, the geometry and relative position of the loaded equipment (Baker et al., 1983). These factors are though often neglected in analyses. An analysis of the effect of an explosion is linked with a high degree of complexity, and the consequences are hardly predictable by a deterministic approach (Cozzani et al., 2006). However, when far field interactions between the explosion source and the targeted equipment are of concern, or when relatively low pressure explosion with a maximum peak static overpressure lower than 50 kPa are considered, the damage caused by a blast wave can be effectively correlated to the peak static overpressure (Cozzani et al., 2006).

In a study by Cozzani et al. (2006), which is a revision from Cozzani and Salzano (2004a,b,c) previous work, the authors have analysed a wide range of damage threshold for the peak static overpressure, which allowed them to correlate probit functions and define threshold values for a number of category equipment. For detailed information concerning the input that has been used, the reader is referred to Cozzani and Salzano (2004a,b,c). The available data, allowed damage threshold values to be defined for four representative equipment categories: atmospheric vessels, pressurized vessels, elongated equipment and small equipment. It should be remarked that the reported structural damage threshold may not be correspondent to threshold values related to the escalation of accidental scenarios. Although any damage to equipment can result in a domino effect, the likelihood of escalation is strongly dependent on the intensity of damage and of the construction of the target equipment (ibid.). Hence, the features of potential secondary scenarios must be analysed and taken into account when defining escalation thresholds. By dividing the reference data into different damage states (DS) and different classes of loss of containment (LI), as described earlier in this chapter, Cozzani et al. (2006) could perform a more accurate analysis of the escalation thresholds. However, the authors only assigned four damage probability values (1%, 10%, 30% and 99%) on the entire probability range (0-100 %). This approach lead to damage values with great deviation being assigned to the same damage probability, which of course is not optimal. Mingguang and Juncheng (2008) have revised the study by Cozzani et al. (2006), taking into account the whole probability range. With the same categories of damage states and classes of loss of intensity that are described in section 4.3.1, the probability range could be divided in three correspondent probability ranges:

- The range of 0-30% was assumed to correspond to DS1LI1
- The range of 30-70% was assumed to correspond to DS2LI2
- The range of 70-100 % was assumed to correspond to DS2LI3

This approach allowed the deviation between overpressure values and probability values to be greatly mitigated, which can be observed in table 7.

Table 7. Comparison of mean square error and regression coefficients (Mingguang & Juncheng, 2008).

Category of equipment	***Cozzani et al.***		***Mingguang and Juncheng***	
	Regression coefficients	Mean square error (%)	Regression coefficients	Mean square error (%)
Atmospheric	0.573	55.9	0.905	14.1
Pressurized	0.852	52.5	0.844	13.9
Elongated equipments	0.690	5.3	0.786	9.4
Small equipments	0.776	42.8	0.826	11.2

The better fitted model allowed new probit functions to be derived by a least square regression analysis and escalation thresholds values to be determined, which are presented in table 8 and 9.

Table 8. Probit functions derived for four different equipment categories (Mingguang & Juncheng, 2008).

Equipment category	***Probit function***
Atmospheric	$Y = -9.36 + 1.43\ln(\Delta\mathrm{Pa})$
Pressurized	$Y = -14.44 + 1.82\ln(\Delta\mathrm{Pa})$
Elongated equipments	$Y = -12.22 + 1.65\ln(\Delta\mathrm{Pa})$
Small equipments	$Y = -12.42 + 1.64\ln(\Delta\mathrm{Pa})$

Table 9. Threshold values for different equipment categories associated with DS and LI classes due to exposure of overpressure (Mingguang & Juncheng, 2008).

Escalation Vector	***Threshold values (kPa)***				***Consequence***
	Pressurised tanks	Atmospheric tanks	Elongated equipments	Small equipments	
Overpressure	ΔPa>58	ΔPa>33	ΔPa>46	ΔPa>56	DS2LI3
	58≥ΔPa>32	33≥ΔPa>15	46≥ΔPa>24	56≥ΔPa>29	DS2LI2
	32≥ΔPa≥18	15≥ΔPa≥8	24≥ΔPa≥16	29≥ΔPa≥22	DS1LI1
	ΔPa<18	ΔPa<8	ΔPa<16	ΔPa<22	No consequence

4.3.4 Impact of fragment projection

All types of mechanical explosions and BLEVEs can lead to fragment projections, the fragment number, shapes and weights are in turn mainly dependent on the characteristics of the vessel that undergoes fragmentation (Cozzani et al., 2006). It is the availability of internal energy, usually in the form of internal pressure, which can propagate cracks in the vessel shell, leading to fragmentation, and be partly converted into kinetic energy of the fragments (Reniers & Cozzani, 2013). Damage and escalation caused by fragment projection require two conditions: the distance of the target equipment must be lower than the maximum credible projection distance and the impact must be followed by a loss of containment. Historical analysis shows that projection and impact of fragments is a credible cause of escalation. The escalation mechanism is complex, involving three main phases: fragment formation, fragment ejection and flight and damage from fragment impact (Reniers & Cozzani, 2013). By a probabilistic approach Cozzani et al. (2006) analysed the phenomena, and stated that the impact probability could conservatively be estimated to $2.5 \cdot 10^{-1}$ at 100 meters and $2.5 \cdot 10^{-2}$ at 300 meters. The deterministic safety distance for escalation due to fragment projection of a BLEVE or a mechanical explosion may be higher than 1000 meters (Cozzani et al., 2006). The suggested safety distance can be compared with the distance of 900 meters, which has been observed in past accidents involving commonly used storage vessels.

Due to the fact that fragment projection is linked with such a high degree of complexity, it is almost impossible to draw any generalised conclusion regarding the impact of the phenomenon and how often it is likely to occur. Looking at the statistical analysis in appendix A, fragment projection can be correlated as an effect from a BLEVE. In 84 percent of the cases where fragment projection occurred, BLEVE was the initiating event. Based on that fact, it seems reasonable to neglect fragment projection from the analysis if BLEVE is not deemed as a credible scenario. As defined in table 4, a BLEVE is deemed possible to occur only in the case of secondary consequences in form of a total collapse of structure followed by a complete loss of inventory in less than a minute (DS2LI3).

4.4 Approaches to the frequency analysis of domino accidents

The following sections serve to give the reader understanding of how the frequency assessment of domino scenarios should be performed accordingly to the proposed method. Two methods developed for the analysis of complex systems, which more recently have been recognised to be applicable for the frequency analysis of domino scenarios are: Bayesian network analysis and Monte Carlo simulations, and are described in sections 4.3.2 and 4.3.3. Two more conventional approaches are the event and fault tree analyses, which are elaborated on in the next section. Regardless of which analysis technique that is being adopted, the process in which domino effects can be accounted for in a QRA is still the same. It all boils down to investigate if there are any target equipments that may be damaged by an escalation vector following an initial accident, estimate the probability of damage for each target equipment and the potential secondary accident scenarios that may follow. For higher levels of escalation, this process is repeated and continues until all final outcomes have been identified.

The conventional QRA process leads to the identification of relevant final outcomes and an assessment of their frequency (f_{pe}). The given frequency can be used to calculate the frequency of single escalation events (f_{de}) (Reniers & Cozzani, 2013):

$$f_{de} = f_{pe} \cdot P_d \qquad \text{(Eq. 5)}$$

Where f_{de} and f_{pe} are measured in events per year and P_d is the escalation (E) probability given that the primary event (PE) occurs (ibid.):

$$P_d = P(E|PE) \qquad \text{(Eq. 6)}$$

The probability of escalation can be assessed using relevant probit functions for equipment damage. A condition for the validity of the presented equations is that the primary and secondary event can be assumed to be mutually exclusive from a probabilistic viewpoint, meaning that they only occur at the same time if an escalation takes place (Reniers & Cozzani, 2013).

4.4.1 Frequency assessment based on event or fault tree analysis

In a conventional QRA framework, the frequency is often calculated through fault tree analysis, event tree analysis or a combination of the two approaches, called bow-tie analysis. These approaches are also applicable to the frequency analysis of domino scenarios, however increases the workload substantially when including probabilities for escalation. In a complex system a single starting event may lead to several secondary events and every secondary event can lead to events on a higher level. Thus, really large event trees for each primary scenario can be anticipated and given the fact that a substantial number of primary scenarios can be expected within process industries, it is easy to grasp that the frequency analysis of domino scenarios can get out of proportion. These kinds of analyses have earlier been difficult or even impossible to perform due to lack of computer capacity, but in recent years the computational development has made it possible to analyse the frequency of domino scenarios with these kinds of analysis techniques (Reniers & Cozzani, 2013).

As stated, the most intuitive and recommended approach for frequency analysis of the chain of events is to perform event tree analysis for each representative scenario, enabling all final outcomes to be identified. Thus can the impact of all events that can trigger escalation to nearby units be accounted for, leading to a more realistic assessment of the accident scenarios. To avoid ending up in a circular reference, scenarios are only allowed to propagate to units that poses a greater threat to the surrounding area. This means that the overall consequences following propagation needs to be increased compared to the consequence of the initial accident scenario. In cases where multiple units can be exposed to external loads simultaneously it is important that all potential chain of events that may follow the primary accident are analysed, starting from the unit having the greatest escalation potential and then working down the ladder to units with lower domino risk ranking. Otherwise, the risk may be overestimated. From a probabilistic point of view this means that each chain of events should be analysed starting with the unit having the highest domino risk ranking (DRR), as shown in figure 9.

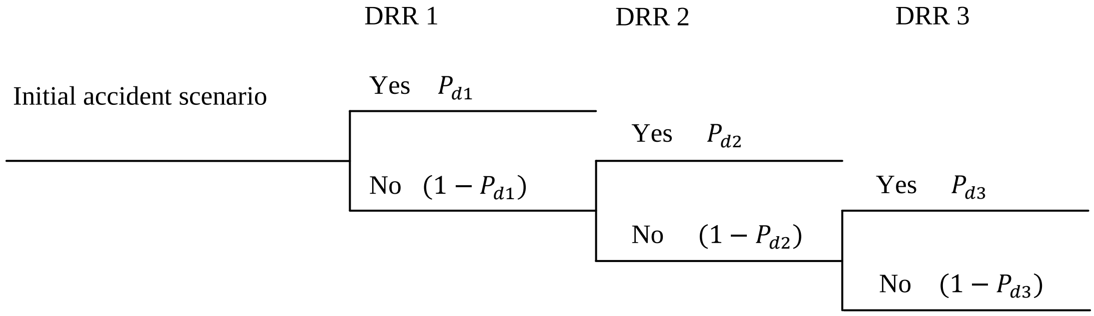

Figure 9. The probabilistic approach for the event tree analysis of each chain of event with regard to the domino risk ranking (DRR).

An alternative approach to the event tree analysis would be to identify critical units that if involved in an accident would lead to severe consequences. By performing fault tree analysis, where each critical unit are seen as a top event, the frequency of these high severity accidents can be updated with regard to the risk of domino effects. Further, the risk of escalation to other parts or plants can be estimated by event tree analysis. The overall risk associated to each chain of events can thereby be estimated by bow-tie analysis.

4.4.2 Frequency assessment by Bayesian network analysis

Bayesian network analysis is a tool for reasoning under uncertainty and to model a system of dependencies (Bobbio et al., 2001). One of the advantages of the Bayesian network approach is that it is flexible and that it is easy to update the initial values if new information is obtained, this by using the Bayes theorem (Reniers & Cozzani, 2013). By mapping fault trees into a Bayesian network, the dependencies between the different units and the uncertainties in the system can be better captured than in a conventional fault tree analysis. This is mainly due to the fact that the Bayesian network is built on probabilistic dependencies while the fault tree analysis only can handle deterministic dependencies (Bobbio et al., 2001).

When mapping process plants into the Bayesian network, the plant is modelled as a system of variables; usually each unit or equipment item is seen as a variable defined as a node. The different nodes are connected by directed arcs which represent their dependencies.
The different nodes are divided into child and parent nodes, where child nodes are nodes to which arcs are directed and parent nodes are nodes from which arcs are directed. A node can be both a child and a parent node at the same time. Nodes without any parent nodes are called root nodes and nodes without any children are called leaf nodes.

The Bayesian network estimates the probability distribution for the system by multiplying the probabilities of connected parents for each node (Reniers & Cozzani, 2013). A schematic sketch of a Bayesian network is presented in figure 10.

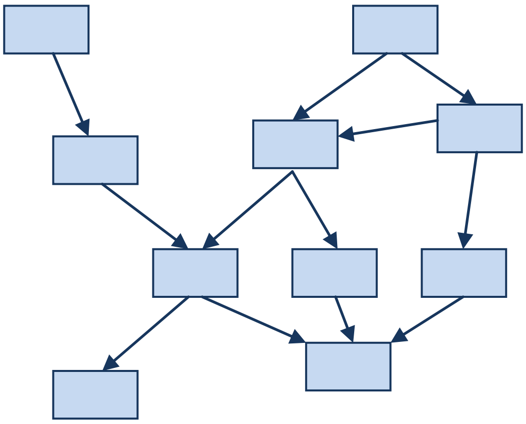

Figure 10. A schematic sketch of a Bayesian network

4.4.3 Frequency assessment by Monte Carlo simulation

Monte Carlo simulations have had a great influence on the computational fields the latest years. These types of simulation are often used when the underlying probabilities are known but the interactions in the system are hard to specify (Abdolhamidzadeh et al., 2010). When dealing with domino effects in the process industry this is often the case, due to the complexity of the system, and the method is therefore suitable also in this field according to Abdolhamidzadeh et al. (2010). The simulation technique is an iterative process where the inputs are sets of random numbers. Two kinds of probabilities need to be set before doing the simulation, the primary accident probabilities and the escalation probabilities (Abdolhamidzadeh et al., 2010).

The primary accident probability can be obtained by performing an event tree or fault tree analysis, alternatively from generic data. The probability of escalation is often obtained by probit models. These probabilities are set as inputs to the model. Depending on the complexity of the system that is examined the number of runs, normally in the order of thousands, can be set, where a system associated with a large amount of uncertainties should be analysed by a large amount of runs (Rezaie et al., 2007). For each variable a distribution is assigned and every run results in a stochastic value for each variable, which is assigned within the boundaries of the distribution (ibid.). The underlying utility amount is then based on these values. In addition to the mentioned strengths of the approach, a weakness is that it does not consider dependencies between the uncertainties, which in the case of domino effects are an important factor (ibid.). Abdolhamidzadeh et al. (2010) have developed an algorithm for multi-unit systems under influence of domino effects, called FREEDOM. The outcome from the algorithm is the failure frequency and it is based on hypothetical experiments containing domino effects.

4.5 Summary of the proposed tools and models

With aid of the tools presented in the previous sections, damage probability and secondary accident scenarios can be analysed for target equipments found within the effect zone of a primary accident. The escalation threshold values reported in this chapter may represent a starting point for the quantitative analysis of domino scenarios in a QRA framework. The failure of equipment is dependent on the conditions at hand and as seen in literature, there are many different proposed threshold values. Therefore, it is important to state that the threshold values described in this chapter only represents guiding values, which may be updated to be more site-specific if such information is available. The threshold values for different damage state and loss intensities should be seen as input when defining accident scenarios following escalation. However, it is crucial to have knowledge of the physical aspects concerning the different phenomena giving rise to escalation and the parameters affecting the final outcome, as described in above sections.

The vulnerability models used for the calculation of damage on equipment are simplified correlations of a much more complex process, thus the results should be seen as a rough representation of the reality. Due to the conservative approach that has been used when correlating these models they provide results on the safe side, which makes them suitable for a QRA. The results may even be seen as over conservative as no safety systems, active or passive, have been taken into consideration when developing the models. Due to that fact, the impact of safety systems needs to be analysed separately, allowing the damage probability to be updated with regard to these results so that a more realistic risk profile can be compiled.

The proposed method has been developed to be applicable, regardless of which consequence and frequency analysis models that are being used. Therefore, the models can be chosen depending on the purpose and the complexity of the analysis.

5. CASE STUDY

The objective of the case study is to apply the developed method on a real case and to evaluate how well it is applicable in practice. The present case study has its baseline in analysing a part within the Preemraff plant located in Lysekil. During a site visit a guided tour around the premises and relevant input data, such as process conditions and dimensions, was given. This information represents the baseline of the analysis. When analysing the chain of events, the computational software program Phast Risk version 6.7 has been applied. In order to easy the workload, some steps of the proposed method have been incorporated into the program, why it may be difficult to follow every step of the method described in the flowchart. However, during the case study three accident scenarios will be presented in detail in order to give the reader a deeper understanding of how the proposed method has been applied. For all other accident scenarios, only the results from the analysis of the chain of events will be presented, this in order to keep the magnitude of the report within the defined limits, given by the Division of Risk Management and Societal Safety. Readers should note that if nothing else is stated, all assumptions made in the following sections are based on the authors own reasoning.

5.1 Scope and context

The area of interest is the Vapour Recovery Unit (VRU) and the pipe bridge, as shown in figure 11 the two parts are situated close by each other why the risk of domino effect is interesting to analyse. The VRU and the pipe bridge are seen as two separate subsystems. The analysis has its base on investigating if domino effects can occur between the different parts of the VRU. The risk of propagation to other parts of the plant following accidents within the VRU is also analysed. Finally, it is of interest to analyse if equipments outside the subsystem of the VRU can inflict damage to any of the parts of the VRU, for this purpose accident scenarios that originate from the pipe bridge are analysed.

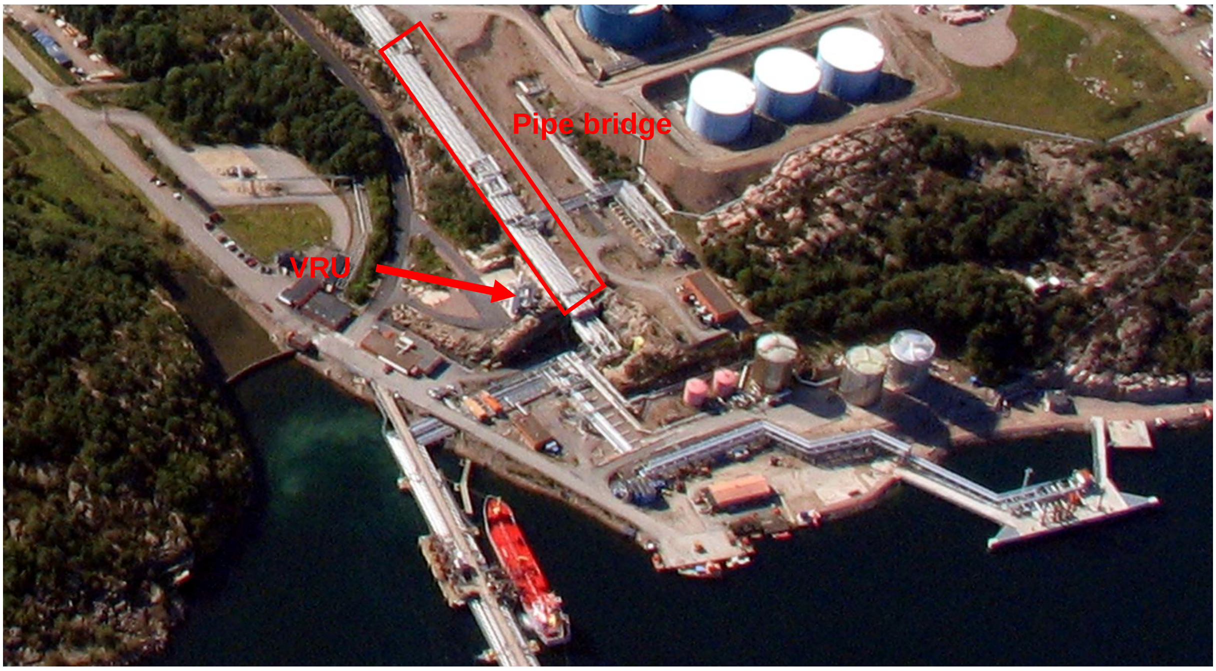

Figure 11. Overview of the area chosen for the case study.

The risk of domino effects is highly influenced by the relative distance between the primary accident and the different target equipments. The relative distances between the different parts of the VRU and to the pipe bridge are presented in figure 12.

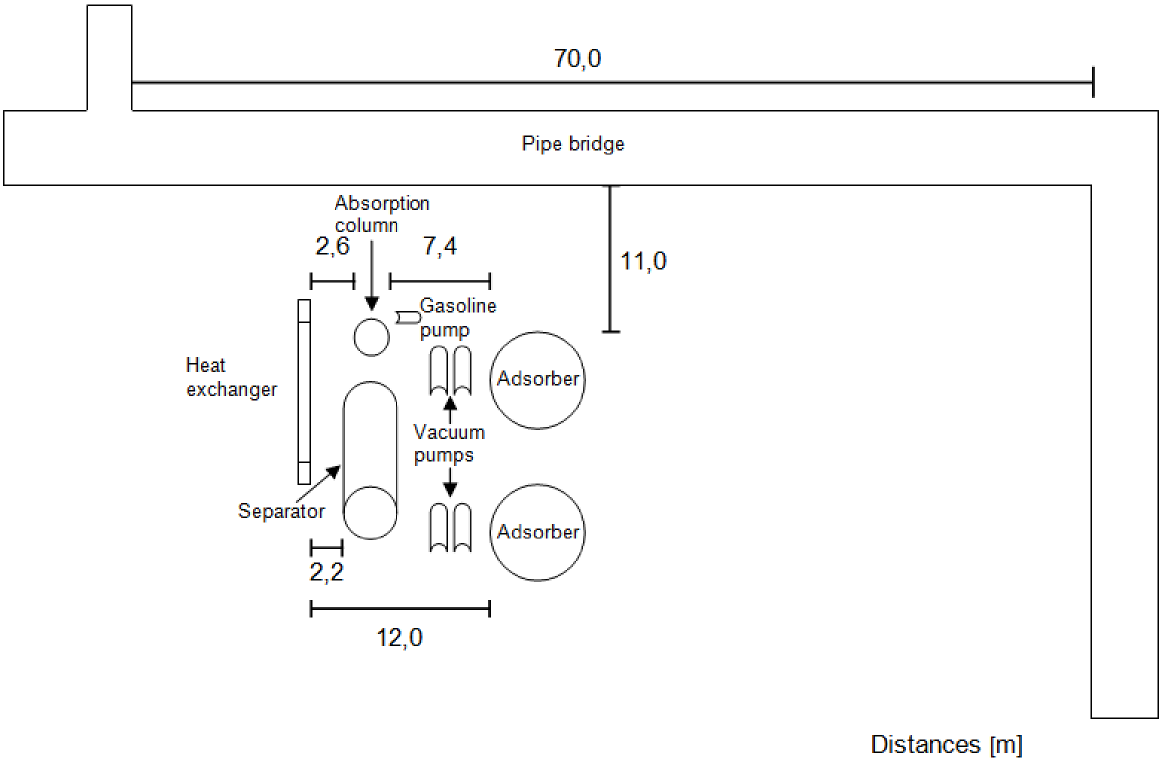

Figure 12. Relative distances for the parts of the VRU.

5.1.1 VRU

The purpose of the VRU is to recover vapour emissions generated during ship loading. The VRU reduces the emissions of green house gases significantly and regenerates gasoline at a low cost. A simplified flowchart describing this regeneration process is presented in figure 13.

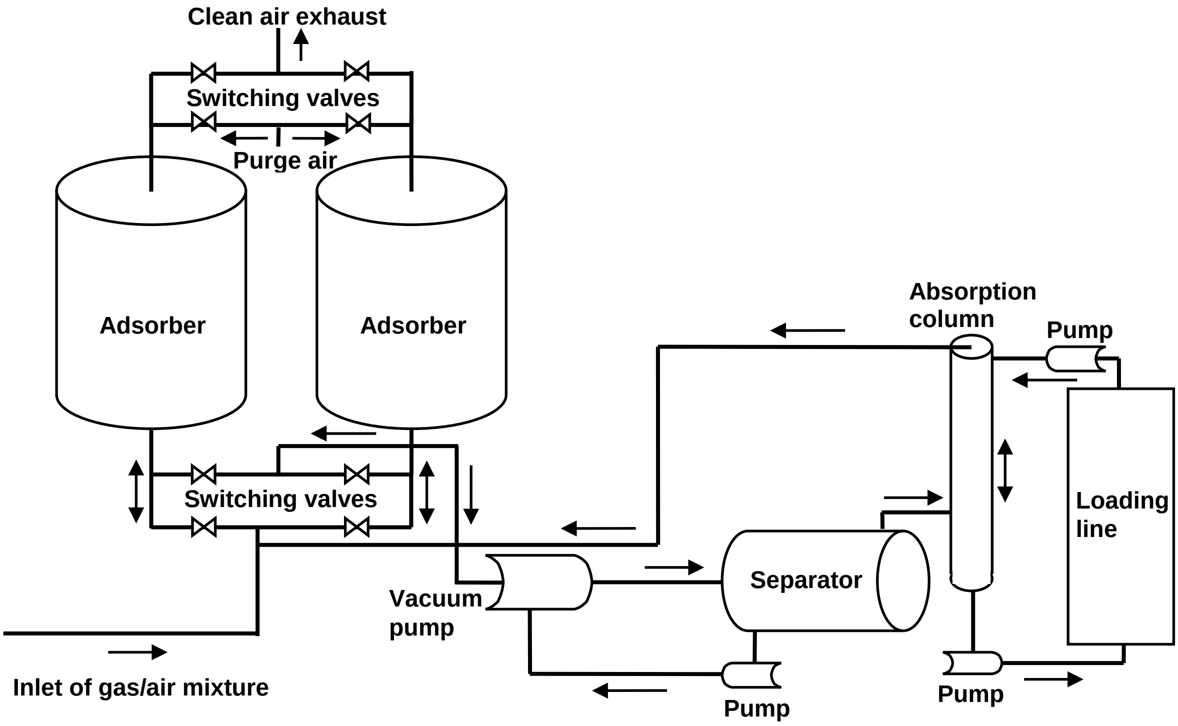

Figure 13. Simplified flowchart describing the vapour recovery process.

The first step in the process is that the gaseous emissions produced during loading are gathered by an unloading arm and further transported to the VRU by pipelines. At every loading arm there is a detonation arrester installed and further, another detonation arrester is located at the entry point to the VRU. These arresters do not affect the frequency of accidents, they rather mitigate the consequences and the risk of escalation to other installations. The piping between the ships and the VRU is also equipped with shut off valves, drains and safety valves. In the VRU the incoming flux is led to an adsorption tank containing a bed of activated carbon, which adsorbs the hydrocarbon vapour onto its surface while the clean air passes through and is vented to the atmosphere by an exhaust. Adsorption of the incoming hydrocarbon vapour continues until the bed of activated carbon is completely saturated. The adsorption vessel operates at pressures slightly above atmospheric pressure, with temperatures close to ambient temperature. As figure 13 describes, the system contains two adsorption tanks. The reason for this is that the process shall be able to continue while one of the tanks is saturated. Therefore the system is controlled by switching valves, which are set to direct the flow to the unsaturated tank while the other one is regenerated.

During the regeneration mode the tank pressure is lowered by four vacuum pumps in order to make the conditions favourable for desorption of the hydrocarbon vapour. To modulate the highest vacuum level, a small amount of purge air is added to the tank during the last part of the regeneration phase. The desorbed vapour is then led to a separator by a stream of seal fluid needed for the vacuum system to operate. The seal fluid, hydrocarbon liquid that may have condensed while going through the vacuum system and the hydrocarbon vapour is then stratified in the separator. The seal fluid is heavier than the condensed liquid and settles to the bottom of the tank, where it is re-processed through the vacuum system. The hydrocarbon vapour and the condensed liquid then pass through the absorption column, where the hydrocarbon vapour is recovered by absorption into a reverse stream of gasoline that is added in the top of the absorption column. The gasoline is then pumped back to the loading line, while the hydrocarbon vapour that is not absorbed into the gasoline is transferred back to the adsorption tanks where it is re-processed.

Within the VRU there are multiple alarms installed, these alarms indicate if the temperature, pressure, flow or fill level is lower or higher than in normal operating conditions. Two different types of alarm levels are present; high/low level alarm and high high/low low level alarm. The two different types of alarms have different set values, where the high high and the low low level alarm are set as trip level alarms and if triggered the process will automatically shut down, while if the high/low level alarm is triggered it will result in a warning signal. The adsorber vessel, separator vessel and the absorption column all have safety vents installed, which activates automatically if the pressure rises to a level higher than 6.6 bar. A bund is present, separating the adsorber vessels from the other process units. There is also a runoff drain with a capacity of 3000 l/min installed in the VRU.

The gasoline vapours, which are being processed in the VRU, are a mix of hydrocarbons including alkanes, cycloalkanes, alkenes, and aromatics. Looking at the results from a study of emission of gasoline vapours at gas stations in Sweden by Berglund and Petersson (1989), alkanes such as methylpropane, butane and methylbutane represent more than 66 percent of the vapour percentage weight. The vapour mix is highly combustible and the risk of fire and explosion is present during operation mode of the VRU. The gas mixture is within the flammability range during the adsorption phase until the moment that the carbon bed has been completely saturated. Although the hydrocarbons are outside the flammability range inside the adsorber vessel during the regeneration mode, the risk of fire in the carbon bed is still present. This due to the fact that spontaneous ignition can occur if air is allowed into the adsorber vessel during this phase.

In all other units, the gas mixture is above the flammability level, meaning that there is no risk for internal explosion in these units. However, any sort of loss of containment is thus likely to initiate an accident. As input for the consequence analysis, the characteristics of the units within the vapour recovery process are described in table 10. These values were given during the site visit.

Table 10. Characteristics of the units within the vapour recovery process.

Unit	Vessel type	Volume [m^3]	Substance property	Overpressure [bar]	Temperature [°C]	Fill level [%]
Adsorber vessel	Pressurised	126	Gas	0.1	20	100
Separator vessel	Pressurised	19	Gas	0.1	20	100
Absorption column	Pressurised	22	Liquid	0	20	40
Heat exchanger	Pressurised	6	Liquid	0	20	30

5.1.2 Pipe bridge

Many transporting pipelines are present within the industry, this to enable effective linkages between the different parts of the system. The pipe bridge situated close to the VRU consists of 19 pipes, many of which transporting flammable substances, which can cause domino effects if leak or rupture scenarios occur. The close relative position implies that damage to units in the VRU cannot be excluded from scenarios originating in the pipe bridge, and there is also risk of damage to the pipes if an accident occurs in the VRU. The three pipelines situated closest to the VRU contain liquefied natural gas (LNG). Due to the fact that the purpose of the case study is to examine how well the method is applicable in practice, not the specific results, and that the LNG pipelines will partly shelter the VRU if accidents occur in one of the other pipes, the case study is delimited to only analyse the VRU and the LNG pipelines. The characteristics of the LNG pipelines, which were given during the site visit, are presented in table 11.

Table 11. The LNG pipelines analysed.

Pipe	*Substance property*	*Diameter [mm]*	*Length [m]*
1	Liquid	300	1000
2	Liquid	50	1000
3	Gas	300	1000

5.1.3 Escalation threshold values used in the analysis

As the method states, it is crucial to define escalation threshold values to enable analysis of damage on target equipments. All potential damage states and loss intensity classes are of interest in this case study, why threshold values for DS1LI1, DS2LI2 and DS2LI3 are used in the analysis. These classes are defined as:

- DS1LI1: light damage to the structure or to the auxiliary equipment, followed by a partial or total loss of inventory within a time interval of more than 10 minutes.

- DS2LI2: intense or catastrophic damage, which is followed by a total loss of inventory within 10 minutes.

- DS2LI2: intense or catastrophic damage, which is followed by instantaneous loss of inventory.

As seen in table 12 and 13, when analysing the risk of domino effects, the threshold value should be chosen depending on the characteristics of the target equipment of concern.

Table 12. Threshold values for different equipment categories associated to DS and LI classes due to the exposure of heat loads (Antonioni et al., 2009; Cozzani et al., 2006; Landucci et al., 2009a).

Scenario	***Escalation vector***	***Threshold values (kW/m^2)***		***Consequence***
		Pressurised tanks	Atmospheric tanks	
Fireball	Radiation	$I \geq 100$ $I \leq 100$	$I \geq 100$ $I \leq 100$	DS1LI 1 No consequence
	Flame engulfment	$I \geq 100$ $I \leq 100$	$I \geq 100$ $I \leq 100$	DS1LI 1 No consequence
Jet fire	Fire impingement	$d_j \geq d$	$d_j \geq d$	DS2LI 3
	Radiation	$I \geq 60; t_j \geq 10$ $I \geq 40; t_j \geq 10$ $I < 40$	$I \geq 15; t_j \geq 10$ $I \geq 8; t_j \geq 10$ $I < 8$	DS2LI 2 DS1LI 1 No consequence
Flash fire	Fire impingement	Unlikely	Unlikely	No consequence
Pool fire	Flame engulfment	$d_p \geq d$	$d_j \geq d$	DS2LI 3
	Radiation	$I \geq 60; t_p \geq 10$ $I \geq 40; t_p \geq 10$ $I < 40$	$I \geq 15; t_p \geq 10$ $I \geq 8; t_p \geq 10$ $I < 8$	DS2LI 2 DS1LI 1 No consequence

Table 13. Threshold values for different equipment categories associated with DS and LI classes due to exposure of overpressure (Mingguang & Juncheng, 2008).

Escalation Vector	***Threshold values (kPa)***				***Consequence***
	Pressurised tanks	Atmospheric tanks	Elongated equipments	Small equipments	
Overpressure	ΔPa>58	ΔPa>33	ΔPa>46	ΔPa>56	DS2LI3
	58≥ΔPa>32	33≥ΔPa>15	46≥ΔPa>24	56≥ΔPa>29	DS2LI2
	32≥ΔPa≥18	15≥ΔPa≥8	24≥ΔPa≥16	29≥ΔPa≥22	DS1LI1
	ΔPa<18	ΔPa<8	ΔPa<16	ΔPa<22	No consequence

5.2 Hazard identification

The hazard identification mainly focuses on identifying risks situated within the VRU. The only risk sources except from these, included in the analysis, are the ones located in the pipe bridge which are deemed to have the potential to inflict damage on the VRU. Due to the fact that the case study mainly is conducted in order to evaluate how well the method is applicable in practice, a simplified hazard identification has been performed, why no stakeholders have been involved in the process. All potential leak scenarios that may follow a loss of containment have been included in the hazard identification. Generic loss of containment scenarios have been adopted for this purpose, which is based on the well established RIVM (2009) guideline. Readers should note that if nothing else is stated, all assumptions and conclusions made in the following sections are based on the authors own reasoning.

5.2.1 VRU process

Looking at the process flow described in figure 13, a large amount of combustible vapour mix is located in the adsorber vessel, separator vessel and absorption column. A loss of containment in either one of these vessels is deemed to inflict great damage to property situated in the area. If the adsorber vessel is exposed to external heat loads, the hydrocarbons will rapidly separate from the active carbon bed, thus leading to a pressure build up and an increased temperature within the vessel. The risk of a mechanical explosion in the adsorber vessel is thus always deemed as possible in the case of external exposure of heat load, due to the fact that one of the two adsorber vessels always is in adsorption mode, meaning that there is a flammable gas air mixture present. In scenarios where the separator vessel is being exposed to external heat loads, the pressure will increase with the temperature rise. However, the gas mixture is not within the flammability range in this vessel, meaning that ignition only can occur after a loss of containment where the mixture gets diluted with air. Thus, the secondary scenario following exposure of external heat loads is likely to be a fireball or a flash fire. The absorption column, which mostly contains gasoline, is likely to burst when exposed to external loads, resulting in a pool fire. Malfunctioning of the gasoline pump may lead to leakages, thus this pump is recognized as a threat to the safety and included in the analysis. Heat exchangers, in the same way as pumps can malfunction, and therefore this unit should also be included in the analysis.

The initial scenarios chosen for further analysis have been selected with guidance from RIVM (2009), which is a reference manual for risk assessment of chemical industries based on the *Purple book* (2005). As the RIVM states, when the lengths of pipelines are below 10 meters, the risk of pipe rupture and leakage can be assumed as included in the accident scenarios for the connecting equipments. Within the VRU, there are no pipelines with lengths over 10 metres, thus no pipe leak and rupture scenarios are treated separately in the analysis. The scenarios of interest and their estimated frequencies according to RIVM (2009) are presented in table 14.

Table 14. Representative scenarios chosen for further analysis.

Unit	***Scenario***	***Frequency***
Adsorber vessel	1. Instantaneous loss of the complete inventory of vapour mixture to the atmosphere.	$5 \cdot 10^{-7}\ y^{-1}$
	2. Continuous release of the complete inventory of vapour mixture to the atmosphere in 10 minutes.	$5 \cdot 10^{-7}\ y^{-1}$
	3. Continuous release from a hole with an effective diameter of 10 mm.	$1 \cdot 10^{-5}\ y^{-1}$
Separator vessel	4. Instantaneous loss of the complete inventory of vapour mixture to the atmosphere.	$5 \cdot 10^{-7}\ y^{-1}$
	5. Continuous release of the complete inventory of vapour mixture to the atmosphere in 10 minutes.	$5 \cdot 10^{-7}\ y^{-1}$
	6. Continuous release from a hole with an effective diameter of 10 mm.	$1 \cdot 10^{-5}\ y^{-1}$
Absorption column	7. Instantaneous loss of the complete inventory of gasoline to the atmosphere.	$5 \cdot 10^{-6}\ y^{-1}$
	8. Continuous release of the complete inventory of gasoline in 10 minutes.	$5 \cdot 10^{-6}\ y^{-1}$
	9. Continuous release from a hole with an effective diameter of 10 mm.	$5 \cdot 10^{-5}\ y^{-1}$
Gasoline pump	10. Catastrophic failure, continuous release of gasoline through the largest connecting pipe (6 inches).	$1 \cdot 10^{-5}\ y^{-1}$
	11. Leakage from a hole with an effective diameter of 10 % of the largest connecting pipe.	$5 \cdot 10^{-5}\ y^{-1}$
Heat exchanger	12. Instantaneous release of the complete inventory of gasoline to the atmosphere.	$5 \cdot 10^{-5}\ y^{-1}$
	13. Continuous release of the complete inventory of gasoline to the atmosphere in 10 minutes.	$5 \cdot 10^{-5}\ y^{-1}$
	14. Continuous release from a hole with an effective diameter of 10 mm.	$1 \cdot 10^{-3}\ y^{-1}$

5.2.2 Pipe bridge

As stated above, whenever there are pipelines with lengths over 10 meters, the risk of rupture and leak should be included in analysis as separate accident scenarios. For each of the three pipes, both leak and rupture scenarios will be analysed. The accident frequency for the pipeline containing natural gas is set according to the RIVM (2009) guideline, while the frequencies for the pipelines containing LNG are calculated depending on the operating hours. The scenarios originating in the LNG pipelines are analysed in the means of one accident scenario during circulation of LNG in the pipes and one scenario during loading of a ship. The operating pressure of the pipes containing LNG is 3 bars during circulation and 6.7 bars during loading, while the gas pipeline operates near atmospheric pressure. Based on the information gained from an existing QRA, performed by Lloyd´s Register Consulting, it was concluded that LNG is circulated in the pipelines for approximately 8760 operating hours per year, while unloading is approximated to be carried out for 481 hours per year. The pipelines are equipped with emergency shutdown (ESD) systems and the calculations are conducted with both functioning and malfunctioning systems. The reliability of the emergency shutdown system is deemed as 97 %, with regard to the RIVM (2009) guidelines. The accident frequencies are estimated according to the guidelines in RIVM (2009), making use of the operating hours and the reliability of the emergency shutdown system. The different accident scenarios, which are further analysed, and their estimated frequencies are presented in table 15.

Table 15. Frequency of pipeline accidents.

Scenario	***Frequency [$y^{-1}m^{-1}$]***		
	Pipe 1 (300 mm)	Pipe 2 (50 mm)	Pipe 3 (300 mm)
Circulation scenario			
- Rupture in the pipeline (functioning ESD)	$1.05 \cdot 10^{-6}$		
- Rupture in the pipeline (malfunctioning ESD)	$3.27 \cdot 10^{-8}$		
- 10 % leak (functioning ESD)	$4.59 \cdot 10^{-7}$	$4.85 \cdot 10^{-6}$	
- 10 % leak (malfunctioning ESD)	$1.42 \cdot 10^{-8}$	$1.50 \cdot 10^{-7}$	
Unloading scenario			
- Rupture in the pipeline (functioning ESD)	$4.73 \cdot 10^{-7}$		
- Rupture in the pipeline (malfunctioning ESD)	$2.75 \cdot 10^{-8}$		
- 10 % leak (functioning ESD)	$2.67 \cdot 10^{-8}$		
- 10 % leak (malfunctioning ESD)	$8.25 \cdot 10^{-10}$		
Gas pipe scenario			
- Rupture in the pipeline (functioning ESD)			$9.70 \cdot 10^{-8}$
- Rupture in the pipeline (malfunctioning ESD)			$3.00 \cdot 10^{-9}$
- 10 % leak (functioning ESD)			$4.85 \cdot 10^{-7}$
- 10 % leak (malfunctioning ESD)			$1.50 \cdot 10^{-8}$

5.3 Analysis of the identified hazards

All accident scenarios are simulated in DNVs commercial software package, Phast Risk version 6.7. The program uses conventional consequence models and enables multiple accident scenarios to be analysed simultaneously. The program enables the overall risk profile to be computed in form of individual risk contours and FN-curves in a GIS-based environment. For detailed information concerning the Phast Risk software, the reader is referred to DNVs homepage. For every loss of containment scenario, the program simulates the consequence and frequency of every possible outcome with regard to delayed or immediate ignition for different wind speeds and directions. In all simulations, stationary material reactivity is used for the calculation of immediate ignition. In line with the suggested simulation parameters described in RIVM (2009), a constant delayed ignition probability of 0.5 is assumed for all calculations and in areas where explosion can occur under turbulent conditions, the multi-energy curve number is set as 8.

Further, the consequence and frequency analysis is divided into three parts. First, it is of interest to analyse the risk of domino effects within the VRU, this to enable additional accident scenarios to be identified and included in further analysis. Secondly, the risk of propagation from the VRU to other parts of the system is analysed. Finally, it is of interest to analyse the risk of damage to the VRU with regard to accident scenarios in the pipe bridge. Each part is analysed with the approach described in the developed method, without delimiting the analysis to any specific level of escalation. In order to evaluate the impact of taking domino effects into consideration, the risk of propagation to other parts of the system is both analysed with and without the inclusion of domino scenarios. To relate back to the developed method, described in the flowchart in figure 8 in section 4.1, the first step of analysing the chain of accident is to estimate the heat and overpressure loads following an accident at the given distances of which target equipment is located. If escalation is possible, the probability of damage is estimated with the aid of vulnerability models. The consequence that may follows target equipments being exposed to external loads is estimated by comparing the heat and overpressure loads to given threshold values for different damage state categories and loss intensity classes. This classification and relevant statistical data of previous accidents are used as input and enables secondary accident scenarios to be determined and further levels of escalation to be analysed.

5.3.1 Domino effects within the VRU

As a starting point, damage probabilities for different levels of radiation intensity and overpressure values for pressurised vessels with various sizes were defined. This was done with aid of the defined escalation threshold values and the vulnerability model for pressurised process equipments, described in section 4.2.2 and 4.2.3. Next, the consequences following all of the representative loss of containment scenarios were simulated. To enable an early overview of where domino effects most likely are to present themselves and which equipment that is of concern, a risk contour with regard to property damage for pressurised vessels was computed. The volume of interest was set to 125 m^3, this with regard to the volumes of the adsorber vessels. The frequency of interest was chosen to $1 \cdot 10^{-5}\ y^{-1}$ and as figure 14 shows, propagation within the area including the heat exchanger, separator vessel and absorption column, can be expected to occur with a frequency of $1 \cdot 10^{-5}\ y^{-1}$.

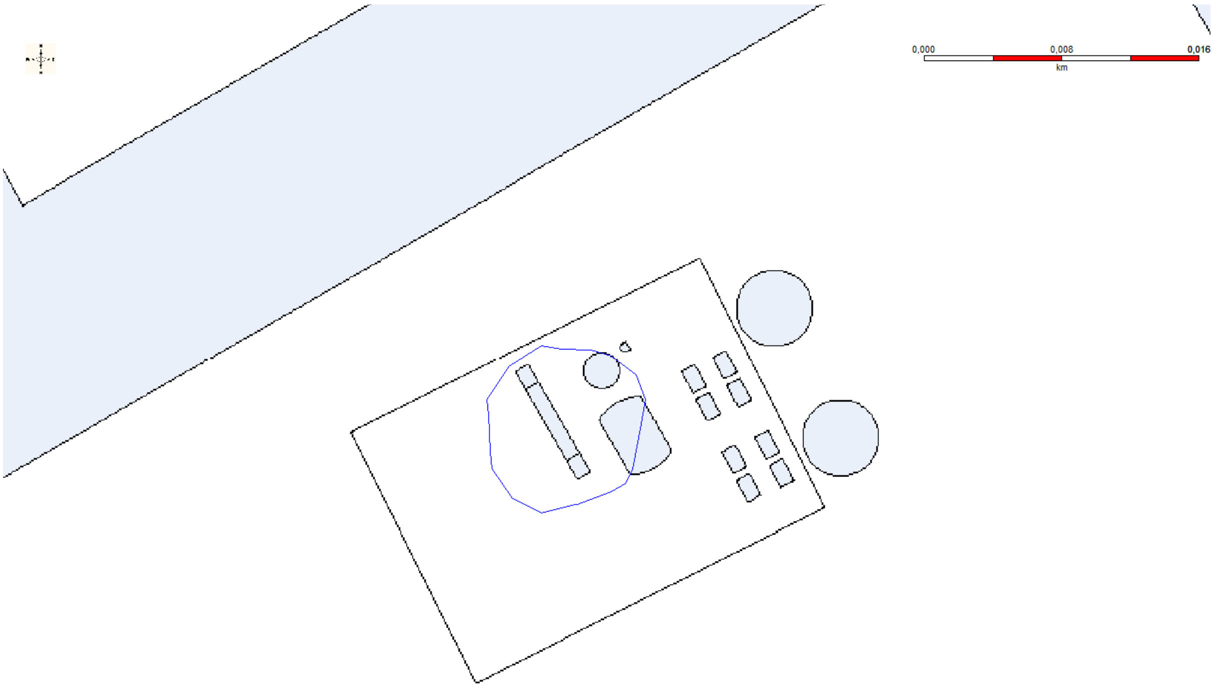

Figure 14. Risk contour with regard to property damage for pressurised vessels with a volume of 125 m^3.

As figure 14 evidence, pressurised vessels with a volume of 125 m^3 can be estimated to suffer damage with a frequency of $1 \cdot 10^{-5}\ y^{-1}$ due to exposure of external loads. By comparing the estimated frequency of $1 \cdot 10^{-5}\ y^{-1}$ in which the separator vessel and the absorption column may be inflicted by damage to the generic frequencies for loss of containment scenarios presented in table 14, it is not hard to grasp the substantial risk contribution if including domino effects in the analysis. Thus cannot the risk of domino effects occurring between the different parts of the VRU be disregarded as the chain of accident is likely to have great impact on the overall risk profile. Readers should note that the risk contour presented in figure 14, is without any regard to the risk of units being fully engulfed by fire. This because the Phast Risk software is limited to calculating the maximum heat flux at the border of the pool, thus neglecting the fact that target units situated within the borders of the pool are being exposed to considerably higher heat fluxes. Therefore, the risk of units being damaged due to exposure of external heat loads may in fact be higher than the risk contour in figure 14. Thus the heat load for scenarios of units being fully engulfed in fires must be dealt with in an alternative way, as shown later in this chapter.

The conclusion that can be drawn is that a more detailed analysis of the potential chain of accidents that may follow each representative scenario is needed to enable a more realistic risk profile to be computed. Before starting such analysis, a relative domino risk ranking including all units within the VRU is defined.

5.3.1.1 Defining a relative domino risk ranking

To avoid ending up in a circular reference, scenarios are only allowed to propagate to units that pose a greater threat to the surrounding area than the initial accident scenario. This means that the overall consequences following propagation need to be increased compared to the consequence of the initial accident scenario. In cases where multiple units can be exposed to external loads simultaneously it is important that all potential chain of events that may follow the primary accident are analysed, starting from the unit having the greatest escalation potential and then working down the ladder to units with lower domino risk ranking. Otherwise the risk may be overestimated.

In line with the proposed method, such ranking should be based on investigating which unit that have the largest amount of flammable substance, the flammability level and ignition point, and in what form it is being processed (gas or liquid, pressurised or atmospheric conditions).

Due to the fact that the adsorber vessel has the greatest explosion potential and as described in the hazard identification, is vulnerable for external exposure, damage on this unit is deemed as the final worst credible event. Comparing the amount of substance that may follow a loss of containment in the heat exchanger or due to pump failure, the consequences concerning these accident scenarios can be seen as equal in severity. Based on that and due to the fact that the equipments are positioned at the same relative distances from the separator vessel, absorption column and the adsorber vessel these units are deemed as equally likely to cause propagation to either one of these objects. Escalation between the gasoline pump and the heat exchanger is thus neglected from the analysis. Looking at the adsorption column and the separator vessel, these units are positioned at the same relative distance from the adsorber vessel. However, the secondary event that may follow a loss of containment in the column is likely to be a pool fire and due to the short distance to the adsorber vessels the risk of this unit being exposed to heat loads that can damage the vessel. The separator vessel can cause an explosion if exposed to external loads, however due to the fact that the vessel is equipped with safety valves and that the gas is handled near atmospheric pressure the risk of explosion is considered low. The more likely secondary scenario is therefore a jet fire that is being vented through the safety valve or a fireball that emerges when the vessel bursts. Therefore, a loss of containment in the absorption column is ranked as having greater domino risk potential than a loss of containment in the separator vessel.

From the reasoning above, the probability of damage to target equipment should be estimated from the starting point that damage to the adsorber vessel is analysed first, followed by the absorption column and lastly the separator vessel, as shown in figure 15.

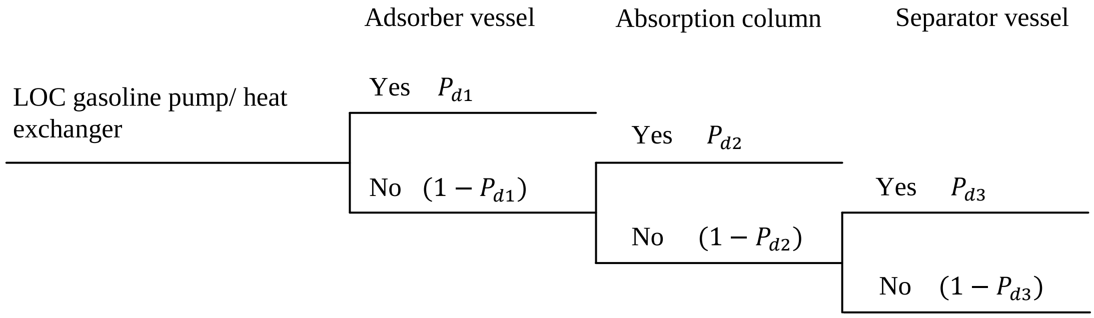

Figure 15. The process in which the frequency analysis of chain of events is based upon within the VRU.

5.3.1.2 Detailed analysis of the chain of events

To give the reader understanding of how the method is applied when analysing the chain of accidents, a more detailed description of the chain of events following accident scenarios originating in the heat exchanger (scenario 12, 13 and 14) is presented.

After having stated how the different equipments are ranked relative to each other, it is a straightforward approach to analyse the chain of accidents following the different representative accidents scenarios. First, it is of interest to identify all possible outcomes/escalation vectors following the loss of containment scenarios. The possible outcomes following flammable liquids being released to the atmosphere are presented in figure 16.

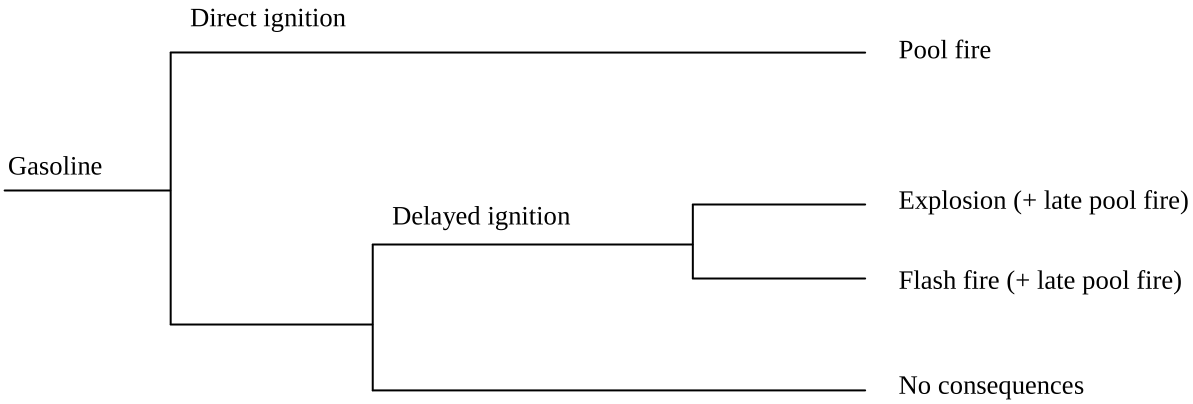

Figure 16. Outcomes of flammable liquid being released to the atmosphere (RIVM, 2009).

The next step is to analyse if any of the outcomes can exceed the escalation threshold values for pressurised equipments defined in section 5.1.3. Simulations in the Phast Risk software show that for the three losses of containment scenarios, the only outcome that exceeds the escalation threshold values and thus can lead to a domino effect is a pool fire. For scenario 12, the risk of a vapour cloud explosion is also present. However, the frequency of overpressure exceeding escalation threshold values is approximately $1 \cdot 10^{-10}\ y^{-1}$, which is lower than the cut off criteria $1 \cdot 10^{-8}\ y^{-1}$ and thus this effect is neglected from the analysis. By analysing the different pool fire scenarios in detail, the radiation intensity to target equipments can be estimated. In the case where the radius of the pool fire exceeds the distance to target equipment, the unit is assumed to be engulfed by fire and the heat load to target equipment is approximated to 160 kW/m^2. This calculated with a maximum flame surface emissivity of 140 kW/m^2 and a convective heat transfer of 20 kW/m^2. The probability of domino effect, P_d, is then calculated by converting the probit value, Y, into a value of probability, which have been estimated by using the vulnerability model for pressurised equipments described in section 4.2.2 with regard to each target vessels volume. The probability of damage is estimated by using equation 5, which is a simplified correlation with a fitting error of $1 \cdot 10^{-3}$ in comparison to the numerical approach, why it is deemed as suitable for this purpose.

$$P_d = \frac{1.005}{1+e^{\left(-\frac{Y-5.004}{0.612}\right)}} \qquad \text{(Eq.5)}$$

For each of the three scenarios, the heat load at the position of target equipments where converted to a probability of damage, P_d. A summary of the results gained from the analysis is presented in table 16.

Table 16. Results from the analysis of first level of escalation for scenario 12, 13 and 14.

Accident scenario	Outcome	Target equipment	Heat load [kW/m^2]	P_d
12	Pool fire	Absorption column (22 m^3)	160 (Engulfed)	0,95
	$f_{\text{Pool fire}}$	Separator vessel (19 m^3)	160 (Engulfed)	0.95
	$= 7.5 \cdot 10^{-6}\ y^{-1}$	Adsorber vessel (125 m^3)	30	0
13	Pool fire	Absorption column (22 m^3)	160 (Engulfed)	0,95
	$f_{\text{Pool fire}}$	Separator vessel (19 m^3)	160 (Engulfed)	0.95
	$= 7.5 \cdot 10^{-6}\ y^{-1}$	Adsorber vessel (125 m^3)	30	0
14	Pool fire	Absorption column (22 m^3)	45	0.15
	$f_{\text{Pool fire}}$	Separator vessel (19 m^3)	45	0.16
	$= 1.5 \cdot 10^{-4}\ y^{-1}$	Adsorber vessel (125 m^3)	0	0

When analysing the chain of events that can lead to the final worst credible scenario, it is important to first analyse the probability of direct propagation to this scenario. If this is deemed possible, escalation to other units is only allowed according to the approach described in figure 15, otherwise the overall risk may be overestimated. The damage target equipments may suffer due to exposure of heat load are estimated by comparing the amount of heat load at the position of target equipments to the escalation threshold values for the damage state and the loss intensity classes, defined in section 5.1.3. From reasoning with regard to these classifications, statistical data of previous accidents, see table 4 in section 4.2.1, and the physical aspects concerning escalation vectors, the secondary accident scenario is estimated. Because of the absorption column and the separator vessel being engulfed in fire in scenario 12 and 13, the damage state and the loss intensity following these scenarios are deemed as DS2LI3. The expected secondary scenarios are therefore assumed to be a complete loss of inventory within 1 minute that gives rise to an additional pool fire and a fireball, respectively. In both of the pool fire scenarios the bund limits the spread of the additional pools, limiting the heat load on the adsorber vessel. By comparing the amount of heat load that the absorption column and the separator vessel are exposed to with the escalation threshold for scenario 14, these vessels can be assumed to suffer minor damage, DS1LI1, giving rise to an additional small pool fire and a small jet fire, respectively.

When analysing further levels of escalation, all secondary accident scenarios are simulated in the Phast Risk software program, providing sequential effect zones, which enable third level of escalation to be analysed accordingly to the above described approach. To illustrate how the amount of heat load to target equipment is estimated, the radiation intensity following the additional small pool fire scenario, initiated by the absorption column suffering damage in scenario 14, is presented in figure 17.

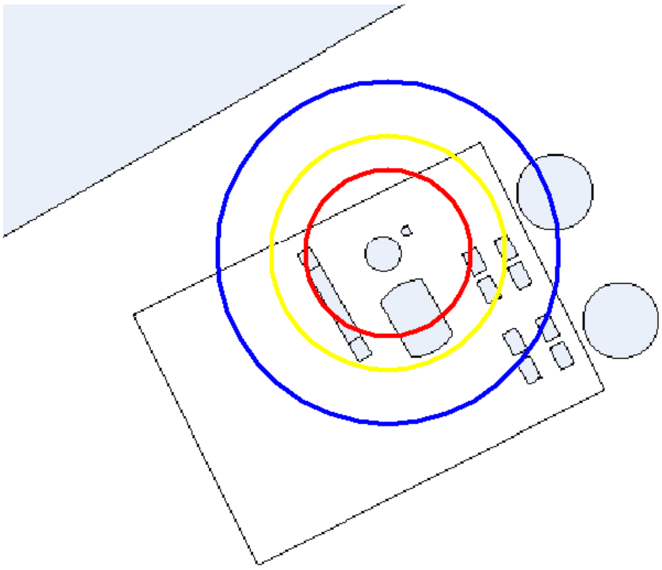

Figure 17. Heat radiation levels following a small leak scenario in the absorption column, red = 100 kW/m^2, yellow = 30 kW/m^2 and blue = 15 kW/m^2.

As shown in figure 17, the adsorber vessel is likely to be exposed of a heat load of 30 kW/m^2 when a small leak scenario in the absorption column occurs. The result for scenarios leading to a catastrophic rupture of the absorption column shows that the additional pool fire will spread to the existing bund, exposing the adsorber vessel to a radiation intensity of 45 kW/m^2. These results show that the radiation intensity for a small leak in the absorption column not will reach the set escalation threshold value for pressurised vessels (40 kW/m^2), while a catastrophic rupture of the adsorption column leads to a pool fire that exceeds this threshold and therefore can cause damage on the adsorber vessel. As for the fireball and the jet fire scenarios that may occur if the separator vessel is exposed to external heat loads, the consequences in these scenarios are lower than the set escalation threshold for a pressurised vessel. Thus, damage on the adsorber vessel is only possible when the absorption column suffers a catastrophic rupture. The probabilities of the final outcomes are calculated by event tree analysis, as shown in figure 18, 19 and 20.

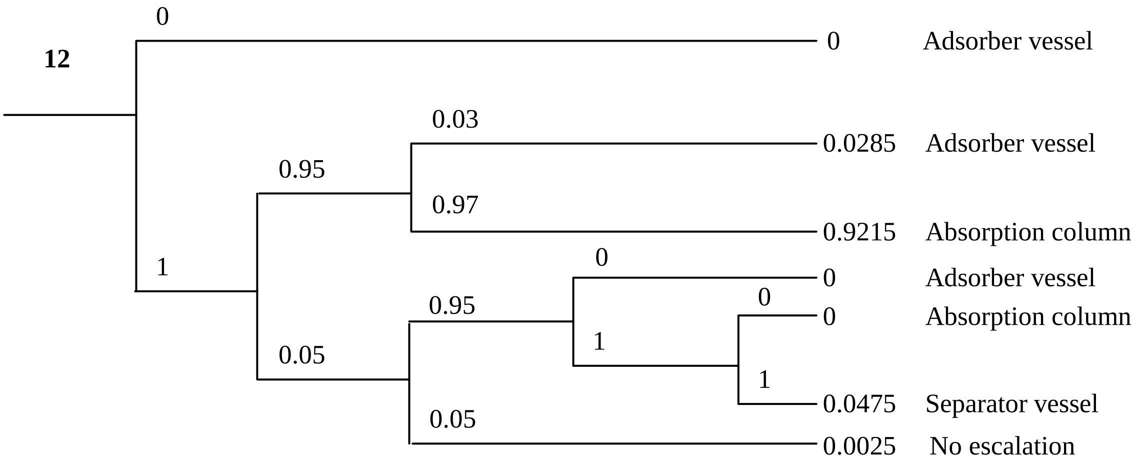

Figure 18. Event tree analysis of scenario 12.

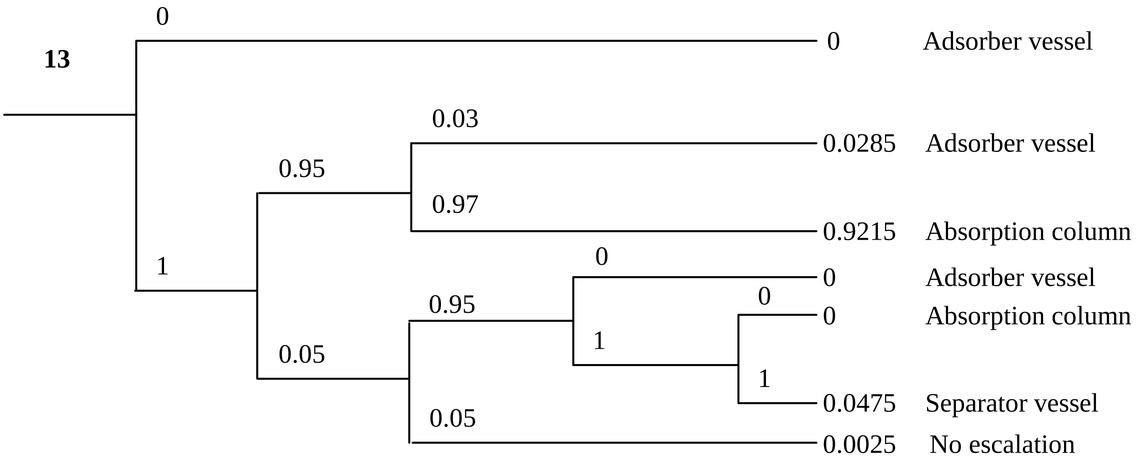

Figure 19. Event tree analysis of scenario 13.

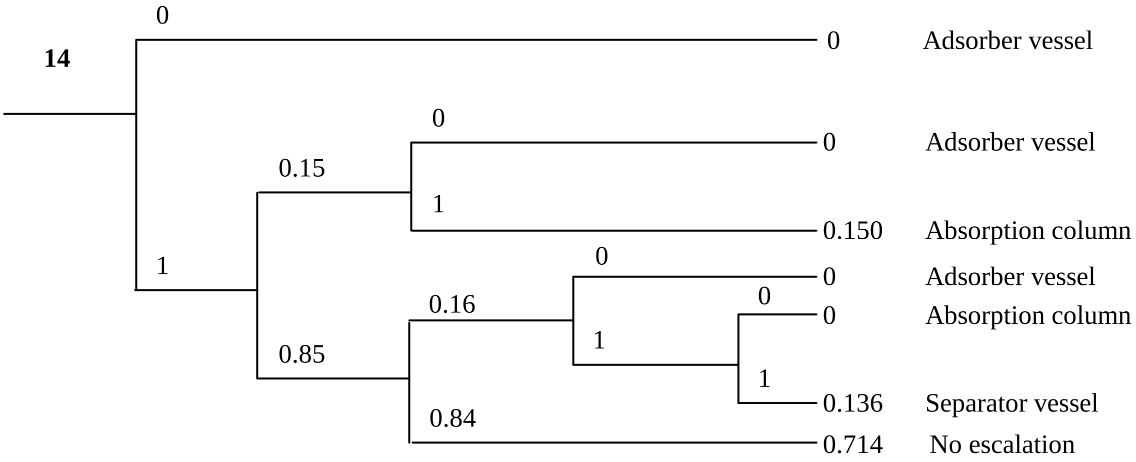

Figure 20. Event tree analysis of scenario 14.

The frequency for every final outcome is calculated with equation 3 and 4.

$$f_{de} = f_{pe} \cdot P_d \tag{Eq. 3}$$

$$P_d = P(E|PE) \tag{Eq. 4}$$

Where f_{de} is the expected frequency of domino effect, f_{pe} is the expected frequency of the primary event and P_d is the escalation (E) probability given that the primary event (PE) occurs.

For each of the primary accident scenarios defined in table 14, the chain of accidents is analysed with the above described procedure shown for scenario 12, 13 and 14. Further, only the results gained from the analysis of the other accident scenarios (4-11) are presented. Note that accidents originating from the adsorber vessel do not contribute to any domino effect within the VRU as this unit is defined to have the most severe consequences. A summary of the frequencies for all final outcomes is presented in table 17.

Table 17. Results from the analysis of chain of events within the VRU.

Accident scenario	*Final outcome*	*Damage state and loss intensity class*	*Frequency [y^{-1}]*
4- Separator vessel	Adsorber vessel	DS2LI3	$f_{de} < 10^{-8}$
	Absorption column	DS2LI3	$f_{de} < 10^{-8}$
5- Separator vessel	Adsorber vessel	DS2LI3	$f_{de} < 10^{-8}$
	Absorption column	DS2LI3	$f_{de} < 10^{-8}$
6- Separator vessel	No escalation	-	-
7- Absorption column	Adsorber vessel	DS1LI1	$2.3 \cdot 10^{-8}$
8- Absorption column	Adsorber vessel	DS1LI1	$2.3 \cdot 10^{-8}$
9- Absorption column	No escalation	-	-
10- Gasoline pump	Adsorber vessel	DS1LI1	$4.3 \cdot 10^{-8}$
	Absorption column	DS2LI3	$1.4 \cdot 10^{-6}$
	Separator vessel	DS2LI3	$7.1 \cdot 10^{-8}$
11- Gasoline pump	Adsorber vessel	DS1LI1	$2.1 \cdot 10^{-7}$
	Absorption column	DS2LI3	$6.9 \cdot 10^{-6}$
	Separator vessel	DS2LI3	$3.6 \cdot 10^{-7}$
12- Heat exchanger	Adsorber vessel	DS1LI1	$2.1 \cdot 10^{-7}$
	Absorption column	DS2LI3	$6.9 \cdot 10^{-6}$
	Separator vessel	DS2LI3	$3.6 \cdot 10^{-7}$
13- Heat exchanger	Adsorber vessel	DS1LI1	$2.1 \cdot 10^{-7}$
	Absorption column	DS2LI3	$6.9 \cdot 10^{-6}$
	Separator vessel	DS2LI3	$3.6 \cdot 10^{-7}$
14- Heat exchanger	Absorption column	DS1LI1	$2.4 \cdot 10^{-5}$
	Separator vessel	DS1LI1	$2.0 \cdot 10^{-5}$

By summarising each of the final outcomes, the annual frequency of accident scenarios that originate from exposure of external loads can be computed. Looking at the results presented in table 17, there is a substantial risk of the absorption column and the separator vessel taking damage from accident scenarios originated in the heat exchanger and the gasoline pump. It is mainly the pool fire scenarios that give rise to initiating a chain of events, however the consequences of these kind of scenarios are limited by the existing bund that are present in the VRU. This safety installation has been incorporated in the Phast Risk software program during simulations, showing that it protects the adsorber vessels from being fully engulfed in fire and limit the exposure of heat radiation from distance source, thus lowering the risk of potential explosion scenarios occurring. However, as seen in the result, there is a small risk of the adsorber vessel taking damage when exposed to distance radiation. Although the damage state and the loss intensity class is DS1LI1, meaning that the vessel is likely to suffer minor damage, the risk of a confined explosion is still present. This due to the fact that the vessel contains a combustible mixture of air and butane gas during a large part of the process and that the temperature rise in the steel can ignite this mixture before the vessel suffers damage. Readers should note that the existing runoff drain situated between the absorption column and the adsorber vessel, most likely is able to hinder the gasoline released from ever reaching the bund border. However, as no calculations regarding the capacity of the runoff drain have been included in the analysis the runoff drain cannot be guaranteed to manage these kinds of leak scenarios, thus has this safety measure been left out from the simulations. When analysing the risk of domino effects to other subsystems, the scenario of a confined explosion in the adsorber vessel is thus included.

5.3.2 The risk of domino effect to other parts of the system

From the results gained in the analysis of escalation potential within the VRU, the additional domino scenarios from analysing the chain of events (see table 17) can be incorporated in the analysis of domino effects to other subsystems. This enables a more realistic presentation of the risk profile within the VRU. By simulating the initial accident scenarios and the final outcomes for each chain of events identified in the VRU, the overall risk of propagation to other subsystems can be analysed. By implementing vulnerability models for damage on equipment in the Phast Risk software, individual risk contours showing the annual frequency of damage to different equipment categories can be computed. As damage on the pipe bridge is of interest to analyse, threshold values and vulnerability models for overpressure and heat radiation have been selected for elongated respectively smaller pressurised equipments in the simulations. The results from the simulations are presented in figure 21 and as shown, damage on the pipe bridge can be expected with a frequency approximately of $1 \cdot 10^{-8}\, y^{-1}$.

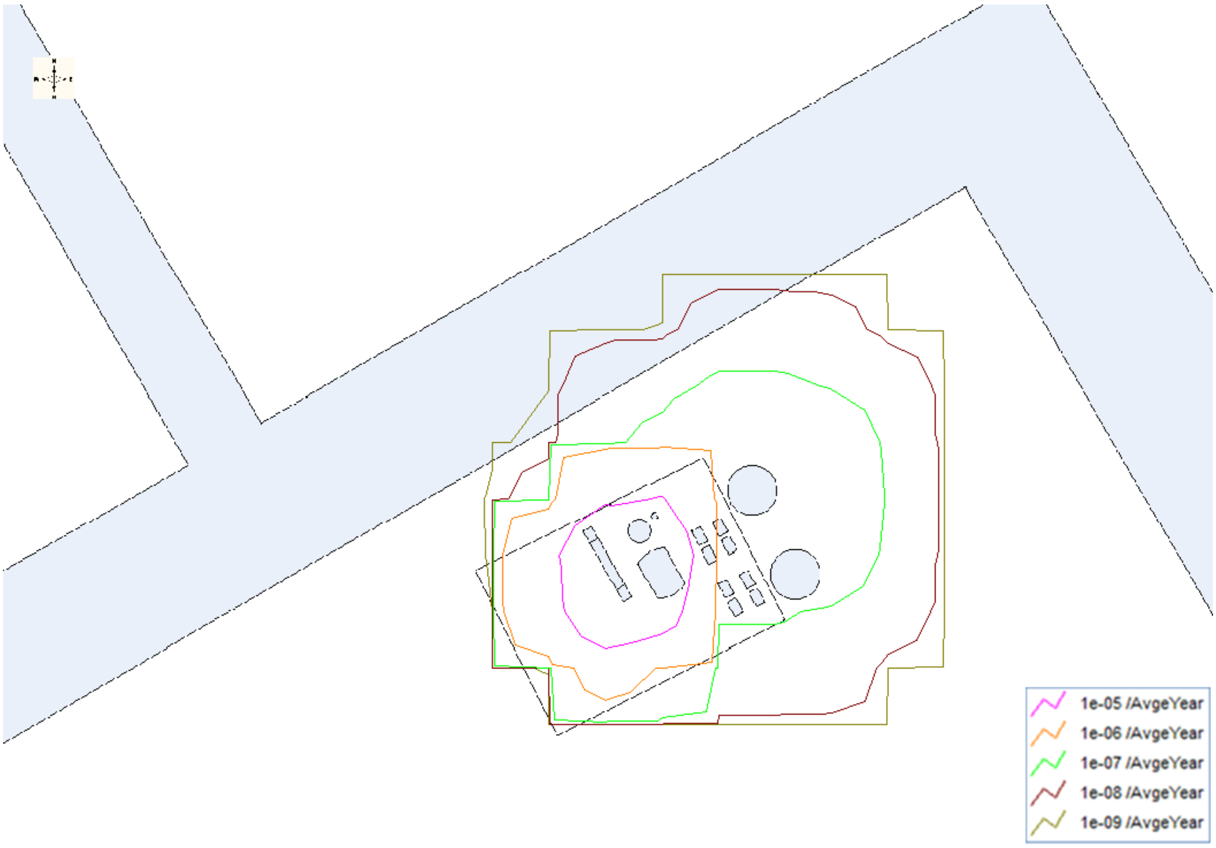

Figure 21. The risk that the pipe bridge suffers damage due to exposure of heat and overpressure loads from the representative accident scenarios with regard to escalation within the VRU.

To see how much the accident scenarios due to domino effects within the VRU contribute to the overall risk, a simulation without these scenarios has also been conducted. The results from this simulation are presented in figure 22.

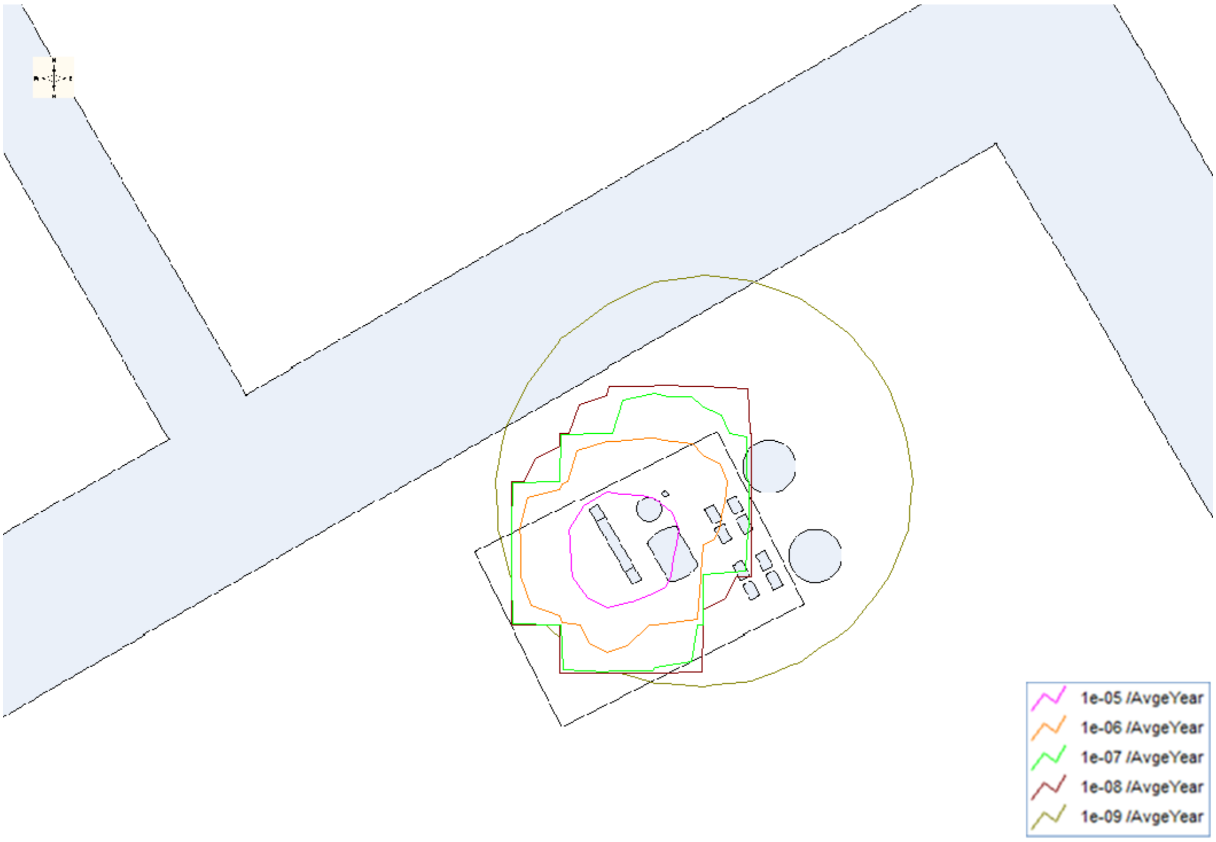

Figure 22. The risk that the pipe bridge suffers damage due to exposure of heat and overpressure loads from the representative accident scenarios without regard to escalation within the VRU.

Comparing the two results, the main contribution to the risk is found at the $1 \cdot 10^{-7}\ y^{-1}$ and the $1 \cdot 10^{-8}\ y^{-1}$ contours. The annual frequency in which the LNG pipeline is estimated to suffer damage can be approximated to $1 \cdot 10^{-8}$ when including domino scenarios, which can be compared to $1 \cdot 10^{-9}$ if not including such scenarios. The increased risk is mainly due to the additional overpressure effects from the confined explosion scenario in the adsorber vessel. To enable a more detailed comparison of the risk with and without the inclusion of domino effects, risk ranking points were implemented in the simulations. These risk ranking points enables a detailed point estimation of the risk of property damage for the equipment category of interest, such risk ranking point were defined in the middle of the LNG pipeline situated closest to the VRU. This point estimation shows that the risk of LNG pipelines suffering damage is approximately $4.4 \cdot 10^{-8}\ y^{-1}$ taking into account the risk of domino effects and approximately $1.1 \cdot 10^{-9}\ y^{-1}$ without the inclusion of accident scenarios originating from domino effects. These results evidence that domino effects can have a significant impact on the overall risk profile and thus these kinds of aspects should not be neglected from a QRA. Otherwise, the risk may be underestimated.

5.3.3 The risk of external domino effects impacting the VRU

As stated in the risk identification, there is a risk that accidents in the LNG pipelines may propagate and damage units within the VRU. By simulating all leak and rupture scenarios with regard to property damage for pressurised vessels with a volume of approximately 150 m^3, representative risk contours for damage on units within the VRU can be computed. In simulations, the location of accident scenarios is set in intervals of maximum 25 meters between two scenarios. The vulnerability model is set for pressurised vessels 150 m^3 for the purpose of investigating the frequency in which the adsorber vessel is likely to take damage. The results from these simulations are shown in figure 23.

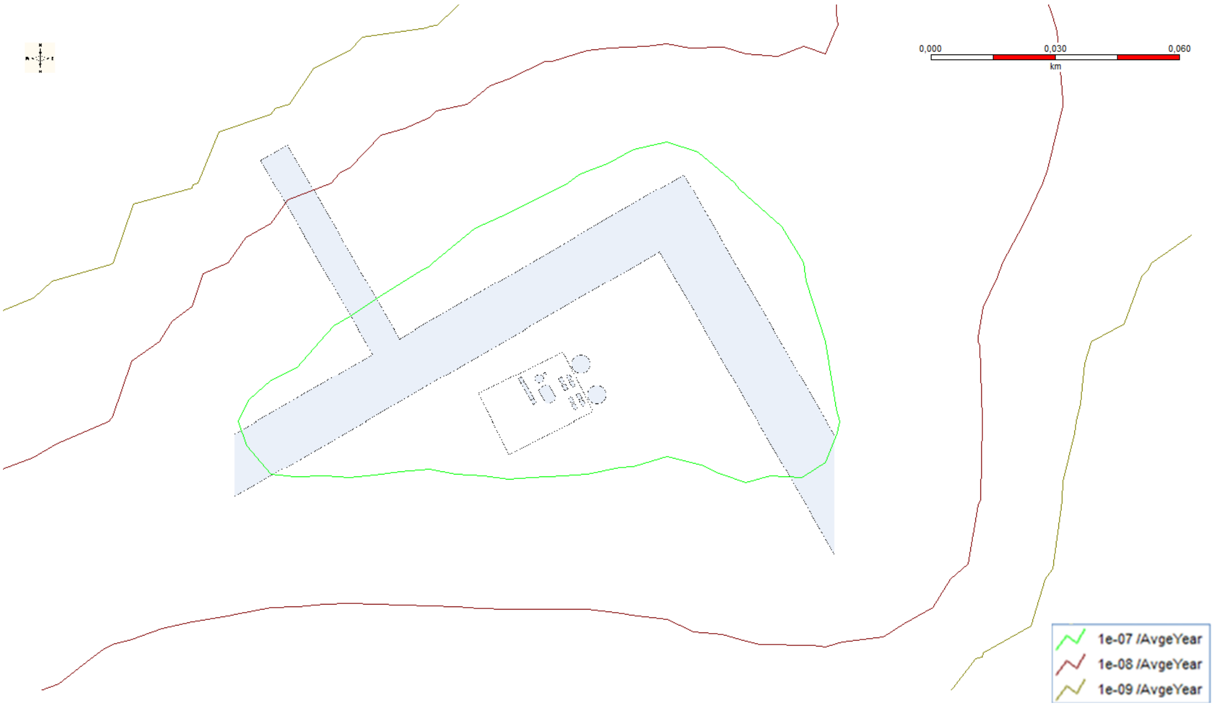

Figure 23. The risk associated to accident scenarios in the LNG pipelines.

As shown, units within the VRU are likely to take damage if leak or rupture scenario occurs in the LNG pipelines. However, the consequences from accident scenarios in the pipelines are far worse than those originating in the VRU, thus propagation to any of the units in the VRU is not of interest for further analysis. This because no secondary accident scenarios in the VRU can escalate the consequences. Readers should note that the risk profile is computed without regard to any cooling effects that the liquefied LNG gas may have on target equipments.

5.4 Conclusion of the results

As shown in the risk contours in figure 21, the risk of accidents originating from the VRU propagating to the LNG pipelines is low, approximately $1 \cdot 10^{-8}\ y^{-1}$. Thus, with the safety measures installed, the safety distances from the units in the VRU to other parts of the system are deemed to be sufficient. Mostly, it is potential explosion scenarios in the adsorber vessels that can cause propagation to the pipelines, thus it is assuring that these vessels are separated from the rest of the units within the VRU system, protecting them from external loads. Looking at the chain of events that can lead to an explosion scenario in the adsorber vessel, they all involve the absorption column taking severe damage. As seen in the event tree analysis presented in figure 18 and 19 the probability of the column taking severe damage is associated to the vessel being fully engulfed in pool fires. This indicates that pool fires have great escalation potential if short distances between units are present and the installation lacks separating bunds. Thus, it is important to ensure that no units with great escalation potential (e.g. large pressurised vessels containing liquefied gas) are allowed to be fully engulfed by fire to avoid severe accident scenarios like BLEVEs.

6. EVALUATION OF THE PROPOSED METHOD

The objective of the study has been to develop a comprehensive method for performing quantitative risk analysis with respect to property damage and domino effects in a process plant. The method should guide and clearly define how domino scenarios can be incorporated in a QRA framework. To ensure the functionality of the method, criterions for what the method should be able to deal have been defined:

- The method should be applicable to well established analysis techniques and not dependent on complex algorithms for the analysis of the chain of events.
- The method should enable a risk profile for property damage to be computed with regard to all accident scenarios, including potential domino scenarios.
- The method should enable the risk of property damage with respect to domino effects to be analysed, both within a subsystem and between different subsystems.
- The method should enable site specific safety distances either to be established or validated with regard to property damage and domino effects.

From the baseline that all potential leak scenarios were defined as representative scenarios and included in the analysis from the beginning, it was a straightforward process to analyse the different chain of events following the proposed methodology. Looking at the process in which the risk of domino effects has been analysed in the case study, the chain of events has successfully been analysed with the aid of event tree analysis, which is deemed as a well established analysis technique. As shown during the case study, the method allows the consequence and frequency of each final outcome, identified during the analysis of the chain of events, to be estimated, which allow each final outcome to be seen as a separate scenario. This enables the additional domino scenarios to be dealt with in the same way as the initial accident scenarios and thus can risk contours with regard to all accident scenarios be computed. As shown in the case study both domino effects within a subsystem and domino effects between subsystems have been effectively analysed. It also indicates that the method is flexible and can be adapted for different kinds of domino risk analysis, depending on the scope and the level of detail that is of concern. As shown in the case study, the overall risk computation of property damage with regard to domino effects enables existing safety distances between different subsystems to be validated. With the above reasoning, the proposed method is considered to be well applicable in practise, as all defined criterions were fulfilled during the case study.

However, some pitfalls were encountered during the case study, which can hinder an effective analysis of domino risks if not dealt with in a proper manor. In the next section, the pitfalls and the procedures to avoid them are further elaborated on.

6.1 Problematic aspects concerning domino effects

As stated in chapter 4, it is important to start the analysis by defining a relative domino risk ranking to avoid ending up in a circular reference. As the case study shows, this is a critical aspect when analysing the chain of events for units situated close to each other. However, defining such ranking is not a simple task as many parameters should be taken into account in the decision making. The risk ranking should at least take into account which flammable substances that are present, the amount, the likelihood, the relative position to target equipments, which safety measures that are present and how these affect different accident scenarios. For example, a unit containing gasoline may have a great escalation potential if there is no delimiting bund protecting target equipment from being fully engulfed in fire, but if a bund is present the same unit may not even pose an escalation threat.

In the case study, secondary accidents have been determined on the basis of the proposed damage state and loss of containment classes for different external load intensities and statistical data of previous accidents. However, there are several factors except for the given load intensity that decide what the final outcome will be and the severity of the consequences. Take a pressurised vessel exposed to distant radiation for example, the pressure rise in the vessel is dependent on the radiation intensity which in turn decides when the pressure relief valve opens. Depending on the thickness of the vessel shell, the time lapse between the opening of the pressure relief valve and the time to failure may vary a lot. This time span decides the amount of substance remaining when the vessel bursts, which can participate in a secondary accident scenario. The amount of substance available with regard to the internal pressure and temperature as well as the mix of fuel and air affects the characteristics of the final outcome. All these variables make it difficult to unambiguously define the final outcome of units exposed to external heat loads and by involving a lot of uncertainties in the analysis the results can be questionable.

Another problematic part of the analysis is to consider synergetic effects, which has been delimited from the proposed method. Depending on the level of detail chosen for the analysis the influence of these effects will vary. When including multiple levels of escalation, these effects are more likely to present themselves as the level of detail increases and therefore also the risk of several units taking damage at the same time. The increased number of accident scenarios will in turn heighten the risk of a unit being exposed to external loads from different sources at the same time. By delimiting the analysis to only include first level of escalation, the influence of synergetic effects will therefore decrease.

It is believed to be a difficult task to get plant managers to pay extra in order to get a quantitative analysis of the risk of domino effects instead of a qualitative analysis when it is not required by the legislation. When developing the method focus has been on making use of simplified tools to keep the analysis within a manageable timeframe, thus limiting the extra cost associated with the inclusion of domino effects in a QRA. As seen in the case study, when integrating escalation effects the time needed for the analysis increases compared to a conventional QRA. However, the additional domino scenarios initiated by equipments being exposed to external loads have been analysed within a reasonable timeframe, showing the effectiveness of the proposed method. If the same approach with equal level of detail was to be adopted when analysing a whole plant it is however not certain that this would be the case. It is deemed more likely that the time needed for analysis would increase beyond the timeframe associated with a QRA, making such analysis unmanageable in practise. Therefore, before drawing any conclusion of this concern, the method needs to be applied and evaluated for analysis of a large system. If the method would have been applied for a larger part of a system or a whole plant, not only would it be uncertain if the analysis would be manageable within the timeframe associated with a QRA, it would also be difficult to define which risk sources that have the greatest escalation potential.

This as a large amount of units most certainly would have the potential to initiate a chain of accident in such system. When analysing larger systems, it would be beneficial to have a holistic view of the overall risk of property damage. This can be achieved by computing risk contours for all initial accident scenarios with regard to property damage, such approach would enable critical areas with regard to the risk of domino effects to be identified in an early part of the analysis. If having a predefined criterion, stating which annual frequency domino effects can be seen as acceptable, the critical areas not fulfilling the criterion can be identified and further analysed in detail to identify the scenarios with the largest contribution to the overall risk. By delimiting the analysis to critical areas, the complexity and the workload is deemed as more likely to be held within reasonable proportions.

Many of the problematic areas concerning the analysis of property damage and domino effects can be dealt with if delimiting the analysis of property damage to only include first levels of escalation. Not only would the method be more applicable to larger systems, the risk of ending up in a circular reference and the uncertainties associated with the estimation of the secondary accidents would also decrease. The influence of synergetic effects and the time needed for analysis also decreases due to this delimitation. If narrowing the analysis to only deal with first level of escalation it is important to define a conservative acceptance criterion that takes into consideration that damage on equipment in reality may lead to further levels of escalation. As seen in the case study, it is the initial high frequency accident scenarios that have the potential to fully engulf target equipments that are the largest contribution sources in changing the overall risk profile when including domino scenarios in the analysis. Taking that fact into account, if delimiting the analysis to only consider first level of escalation it seems reasonable to state that the results gained from such approach only should be seen as reliable if the risk of target equipments being fully engulfed by fire can be seen as negligible. As bunds and runoff drains to a high extent are present within process industries, such conditions are likely to be found. However, before neglecting the risk of target equipments being fully engulfed by fire the functionality and the capacity of such installations should be validated.

6.2 Tools used in the method

The proposed method is to a great extent dependent of the use of vulnerability models for overpressure and heat radiation effects. These models are simplified correlations based on statistical analysis, experimental data and finite element analysis. Although these correlations are simplified and may not represent a realistic estimation of equipments taking damage from external loads, these models are still deemed as the best available tools for quantifying the risk of property damage within the timeframe of a QRA. Looking beyond the fact that these models may be seen as over conservative, as no regard to safety installations has been taken into account when developing the models, they show great advantages when computing the overall risk profile. Due to the simplicity of these models they may be integrated into existing computer programs, as shown in the case study where the Phast Risk software package was used. This ability allows risk contours for the overall risk of property damage for different equipment categories to easily be computed, which in turn serves as useful support for decision making.

With regard to the limited time associated with QRAs, the quantitative analysis of domino effects requires the aid of computer codes for the consequence and frequency estimation. This as the integration of domino effect leads to a more complex analysis. Software packages like the Phast Risk program are beneficial to use, as these kinds of packages enable the consequences and the frequencies of multiple accident scenarios to be calculated simultaneously. If not having such tools available, the proposed method most certainly would be difficult to perform within a reasonable timeframe. However, when using computational programs in the analysis it is up to the user to be aware of the limitations of the program. For example Phast Risk cannot calculate the heat load within the flame and this effect must therefore be treated separately outside the program, otherwise the risk may be under estimated. During the case study the use of Phast Risk lead to inter linkages of some of the boxes in the flowchart, indicating that the method is not dependent on every step being performed separately.

The vulnerability models used for the calculations of damage probability on target equipments have been correlated to take into account the time needed before mitigating actions can be taken. However, in the case where tertiary or higher levels of escalation is possible it could be argued that the elapsed time causing first level of escalation should be seen as a preparation time for additional mitigating actions. For example, if a unit is exposed to distance radiation causing that unit to rupture after an exposure time of 8 minutes, which in turn leads to an additional pool fire exposing a secondary unit, it can be argued that the rescue service has a shorter response time for dealing with the consequences of the additional pool fire scenario. When estimating the probability of damage on the third unit, the elapsed time of 8 minutes causing the secondary unit to suffer damage may be included and seen as preparation time for mitigation actions to be taken on the third unit. Meaning, the probability of mitigation actions increases with the level of escalation as the elapsed time of previous accidents should be included as preparation time. How such aspects should be dealt with in analysis is undefined, which serves as another argument for the analysis of domino effects being delimited to only include first levels of escalation. This to keep the uncertainties to a minimum, making the results of the analysis more reliable.

6.3 Pros and cons associated with the method

In comparison to the qualitative approach, which to this day is the most adopted way of analysing domino effects, there are several benefits with the proposed method. As it enables a quantitative analysis of the risk of property damage with regard to domino effects the subjectivity which the qualitative approach is linked with is substantially decreased, making the results more reliable. During the case study it has been showed that the inclusion of domino effects may have a substantial impact on the overall risk profile, and that the computation of risk contours with regard to property damage is a good way of revealing such effects. By computing such risk contours, risk based decisions of whether the risk of domino effects is acceptable or not can with more confidence be made compared to a qualitative assessment of such effects. The method can also be used in order to estimate site specific safety distances and to make cost effective layouts with regard to the risk of property damage, which in comparison to more generalised safety distances can prove to be economically favourable for the plant owner.

One negative aspect concerning the incorporation of domino effects in the QRA is that the degree of uncertainties increases in the analysis. If not clearly expressing which uncertainties that the analysis is based on and how they have been dealt with throughout the process, the results of the analysis should be questioned. Therefore, it is crucial that the risk agent whom is performing the QRA have proper knowledge and understanding of the underlying theory of the tools used in the analysis.

6.4 Further research needed

Something that has been disregarded in this study is how the risk profile with regard to property damage gained from the QRA should be assessed to determine whether the risk is acceptable or not. One approach would be to incorporate the results from the QRA in a cost benefit analysis, taking into account the cost for replacing damaged units, abruption costs and other potential losses in the supply chain. However, such analysis is time consuming and it may be hard to convince stakeholders to pay the extra cost associated with such analysis. Another approach, which is deemed as the most useable, is to define an acceptance criterion based on the annual frequency. A comparison can be drawn to the oil and gas industry where an acceptance criterion of $1 \cdot 10^{-4}\ y^{-1}$ for damage on critical structures has been defined. If such criterion where to be established and accepted amongst stakeholders, it would enable an easy assessment of whether the risk contours with regard to property damage gained from the QRA can be seen as acceptable or not. For such criterion to be defined, research involving different stakeholders needs to be conducted.

7. CONCLUSIONS

The objective with this thesis has been to develop a comprehensive method for performing quantitative risk analysis with respect to property damage and domino effects in a process plant. In order to achieve the objective and to ensure the applicability of the method, criteria for what the method should enable were defined. The drawn conclusions are based on how well these criteria´s were fulfilled and the results from the case study.

During the case study, the method has proven to enable the risk of property damage with regard to domino effects to be quantitatively analysed. The results from the case study, evidence the importance of taking domino effects into consideration in QRAs, as the risk may be underestimated if not. During the evaluation of the method, it has been concluded that the chain of accidents should be delimited to only include first level of escalation. Such delimitation minimises the uncertainties linked to domino effects, thus making the results more reliable. It also enables the method to be more applicable when analysing larger systems, as the complexity and workload decreases. It has been concluded that computing risk contours with regard to property damage for all initial accident scenarios enables critical areas, where domino effects are likely to present themselves, to be identified in an early stage of the analysis. During the thesis, the need for a well established acceptance criterion with regard to property damage has been evidenced. To relate back to the criteria´s for what the method should enable and whether these have been fulfilled or not, this is further elaborated on:

- The method should be applicable to well established analysis techniques and not dependent on complex algorithms for the analysis of the chain of events.

As shown during the case study, the chain of events were analysed with the aid of event tree analysis, which is deemed as a well established method and well known amongst practitioners. It should be stated that the Phast Risk software served as a great support, as it enables multiple accident scenarios to be analysed simultaneously and the overall risk profile to be computed. Without any aid of computational resources, it would be difficult to perform such analysis.

- The method should enable a risk profile for property damage to be computed with regard to all accident scenarios, including potential domino scenarios.

The case study shows that the risk contours with regard to property damage enables a holistic view of the overall risk profile, including identified domino scenarios.

- The method should enable the risk of property damage with respect to domino effects to be analysed, both within a subsystem and between different subsystems.

The risk of property damage with respect to domino effects was analysed both within a subsystem and between different subsystems during the case study. In both cases, the method was applied in coherence and the analysis of each chain of events could be performed with a straightforward approach.

- The method should enable site specific safety distances either to be established or validated with regard to property damage and domino effects.

During the case study it has been validated that the distance between the two subsystems analysed is sufficient. Due to that fact, the method is deemed to be applicable when establishing site specific safety distances, if used iteratively in the design phase.

REFERENCE LIST

Abdolhamidzadeh, B., Abbasi, T., Rashtchian, D. & Abbasi, S.A. (2010). A new method for assessing domino effect in chemical process industry. *Journal of Hazardous Materials 182,* 416–426.

Abdolhamidzadeh, B., Abbasi, T., Rashtchian, D. & Abbasi, S.A. (2011). Domino effect in process-industry – an inventory of past events and identification of some patterns. *Journal of Loss Prevention in the Process Industries 24,* 575–593.

Antonioni, G., Spadoni, G. & Cozzani, V. (2009). Application of domino effect quantitative risk assessment to an extended industrial area. *Journal of Loss Prevention in the Process Industries 22.* 614-624.

Arbetsmiljöverket (2005). *Förebyggande av allvarliga kemikalieolyckor.* Arbetsmiljöverkets författningssamling, AFS 2005:19.

Baker, W.E., Cox, P.A., Westine, P.S., Kulesz, J.J. & Strehlow, R.A. (1983). *Explosion Hazards and Evaluation,* Elsevier, Amsterdam.

Berglund, P.M. & Petersson, G. (1989). Hazardous petrol hydrocarbons from refuelling with and without vapour recovery. *The Science of the Total Environment 91,* 49-57.

Bobbio, A., Portinale, L., Minichino, M. & Ciancamerla, E. (2001). Improving the analysis of dependable systems by mapping fault trees into Bayesian networks. *Reliability Engineering and System Safety 71,* 249–260.

CCPS, Center for Chemical Process Safety (1989). *Guidelines for Chemical Process Quantitative Risk Analysis*. AIChE, New York.

CCPS, Center for Chemical Process Safety (1992). *Guidelines for Hazard Evaluation Procedures,* 2nd Edn AIChE, New York.

CCPS, Center for Chemical Process Safety (1999). *Guidelines for Consequence Analysis of Chemical Releases.* AIChE, New York.

CCPS, Center for Chemical Process Safety (2012). *Guidelines for Engineering Design for Process Safety.* AIChE, New York.

Commission of the European Communities (1997). *Directive 96/82/EC on the control of major accident hazards involving dangerous substances*. The Official Journal of the European Communities, No L 10, pp 13-33.

Cozzani, V. & Salzano, E. (2004a). The quantitative assessment of domino effects caused by overpressure. Part I: Probit Models. *Journal of Hazardous Materials 107,* 67–80.

Cozzani, V. & Salzano, E. (2004b). The quantitative assessment of domino effects caused by overpressure. Part II: Case studies. *Journal of Hazardous Materials 107,* 81–94.

Cozzani, V. & Salzano, E. (2004c). Threshold values for domino effects caused by blast wave interaction with process equipment. *Journal of Loss Prevention in the Process Industries17,* 437–447.

Cozzani, V., Gubinelli, G., Antonioni, G., Spadoni, G. & Zanelli, S. (2005). The assessment of risk caused by domino effect in quantitative area risk analysis. *Journal of Hazardous Materials A127*, 14–30.

Cozzani, V., Gubinelli, G. & Salzano, E. (2006). Escalation thresholds in the assessment of domino accidental events. *Journal of Hazardous Materials 129, 1–21.*

Darbra, R.M., Palacios, A. & Casal, J. (2010). Domino effect in chemical accidents: main features and accident sequences. *Journal of Hazardous Materials 183*, 565–573.

Davidsson, G., Haeffler, L., Ljundman, B. & Frantzich, H. (2003). *Handbok för riskanalys.* Räddningsverket, Karlstad.

Eisenberg, N.A., Lynch, C.J., Breeding, R.J. (1975). *Vulnerability Model: A Simulation System for Assessing Damage Resulting from Marine Spills*. Rep. CG-D-136-75, Enviro Control Inc., Rockville, MD.

Frederickson, A. (2001). *The Layer of Protection Analysis (LOPA) method.* Retrieved from http://www.jlab.org/accel/ssg/safety/lopa.pdf

Gubinelli, G., Zanelli, S. & Cozzani, V. (2004). A simplified model for the assessment of the impact probability of fragments. *Journal of Hazardous Materials A116*, 175–187.

Gubinelli, G. & Cozzani, V. (2009). Assessment of missile hazards: identification of reference fragmentation patterns. *Journal of Hazardous Materials 163*, 1008–1018.

Hauptmanns, U. (2001). A Monte Carlo-based procedure for treating the flight of missiles from tank explosions. *Probabilistic Engineering Mechanics 16*, 307–312.

IEC, International Electrotechnical Comission (1995). *International Standard - Dependabiliy management part 3*. Application guide - section 9, Risk Analysis of technological systems.

Kaplan, S & Garrick, B. J. (1981). On the quantitative definition of risk. *Risk analysis 1*, 11-27.

Khan, F. I. & Abbasi, S.A. (1998). Techniques and methodologies for risk analysis in chemical process industries. *Journal of Loss Prevention in the Process Industries 11*, 261-277.

Kirchsteiger, K. (1998). *Risk Assessment and Management in the Context of the Seveso II Directive.* Industrial Safety Series, vol. 6, Elsevier, Amsterdam.

Landucci, G., Gubinelli, G., Antonioni, G. & Cozzani, V. (2009a). The assessment of the damage probability of storage tanks in domino events triggered by fire. *Accident Analysis and Prevention 41,* 1206-1215.

Landucci, G., Molag, M., Reinders, J. & Cozzani, V. (2009b). Exerimental and analytical investigation of thermal coating effectiveness for 3 m^3 LPG tanks engulfed by fire. *Journal of Hazardous Materials 161,* 1182-1192.

Lees, F.P. (1996). Loss prevention in process industries, vol. 1–3. Butterworths, London.

Liu, A., Wu, C. & Peng, X. (2012). Research on area risk assessment for Chemical Park based on domino effect model. *Procedia Engineering 45,* 47–52.

Mannan, S. (2005). Lees' Loss Prevention in the Process Industries, third ed. Elsevier, Oxford.

Mingguang, Z. & Juncheng, J. (2008). An improved probit method for assessment of domino effect to chemical process equipment caused by overpressure. *Journal of Hazardous Material 158,* 280-286.

Nilsson, J. (2003). *Introduktion till riskanalysmetoder*. Brandteknik, LTH, Lund.

Purple Book (2005). *Guidelines for Quantitative Risk Assessment.* Directorate General for Social Affairs and Employment,The Hague, Netherlands.

Reniers, G.L.L., Dullaert, W., Ale, B.J.M. & Soudan, K. (2005). Developing an external domino accident prevention framework: Hazwim. *Journal of Loss Prevention in the Process Industries 18,* 127–138.

Reniers, G. (2010). An external domino effects investment approach to improve crossplant safety within chemical clusters. *Journal of Hazardous Material 177,* 167.

Reniers, G. & Cozzani, V. (2013). *Domino Effects in the Process Industries; Modeling, Prevention and Managing.* Elsevier, Bologna.

Renjith, V.R. & Madhu, G. (2010). Individual and societal risk analysis and mapping of human vulnerability to chemical accidents in the vicinity of an industrial area. *International Journal of Applied Engineering Research 1,* 135-148.

Rezaie, K., Amalnik, M.S., Gereie, A., Ostadi B. & Shakhseniaee M. (2007). Using extended Monte Carlo simulation method for the improvement of risk management: Consideration of relationships between uncertainties. *Applied Mathematics and Computation 190*, 1492–1501.

RIVM, National Institute of Public Health and the Environment. (2009). *Reference Manual Bevi Risk Assessments version 3.2 – Introduction.* Centre for External Safety, Netherlands.

Summers, A. (2002). *Introduction to Layer of Protection Analysis.* Retrieved from https://www.jlab.org/accel/ssg/safety/LAYER%20OF%20PROTECTION%20ANALYSIS.pdf

Tugnoli, A., Cozzani, V., Di Padova, A., Barbaresi, T. & Tallone, F. (2011). Mitigation of fire damage and escalation by fireproofing: A risk-based strategy. *Reliability Engineering and System Safety 105,* 25–35.

Wood, R. (2010). *Third Party Risk around airports.* Retrieved from http://www.aef.org.uk/downloads/AW+Third+Party+Risk+-+revised+Nov2010.pdf .

APPENDIX A – STATISTICAL ANALYSIS

Darbra et al. (2010) has studied the features of 225 domino accidents in process/storage plants and in the transportation of hazardous material. Of these accidents 25 % had occurred in The European Union, 56 % in Australia, Canada, Japan, New Zealand, Norway and the United States and 19 % had occurred in the rest of the world. More than 80 % of the accidents involving a domino effect occurred in developed countries, which have conditions of process plants comparable to Sweden. Other historical analyses have been conducted, Chen et al. (2012) is one example but their analysis is more focused on accidents in developing countries and therefore the results are not suitable to integrate in the study at hand. Abdolhamidzadeh et al. (2011) published an inventory of 224 major process industry accidents involving domino effects, where most of the accidents had occurred in process plants and some in transportation. Further in this chapter follows a detailed description of the findings in the analyses of Darbra et al. (2010) and Abdolhamidzadeh et al. (2011).

A.1 Types of hazardous material involved

Flammable substances are the most common ones involved in major accidents with domino events. Looking at Abdolhamidzadeh et al. (2011) findings, they concluded that flammable substances were associated with 89 % of all domino events. The same fraction was identified by Darbra et al. (2010), whom also present a more detailed list of the substances that had been most frequently involved in domino events, see table 18. Miscellaneous and toxic substances correspond for seven respectively four percent of the substances involved in domino events (Abdolhamidzadeh et al., 2011).

Table 18. The substances most frequently involved in domino events (Darbra et al., 2010).

Substance	Number of accidents	%
LPG	60	26,7
Oil	25	11,1
Gasoline	24	10,7
Naphtha	14	6,2
Diesel oil	12	5,3
Toluene	9	4
Vinyl chloride	9	4
Ethylene	8	3,6
Ethylene oxide	7	3,1
Natural gas	7	3,1
Chlorine	7	3,1
Methanol	6	2,7

A.2 Origin

As shown in figure 24, the area in which most domino accident originates from is storage facilities, followed by process plants and transportation. The different areas have been divided according to the Major Hazardous Incident Data Service database (MHIDAS database), which are as following: process, storage, transportation, transfer, commercial and warehouse (Darbra et al., 2010).

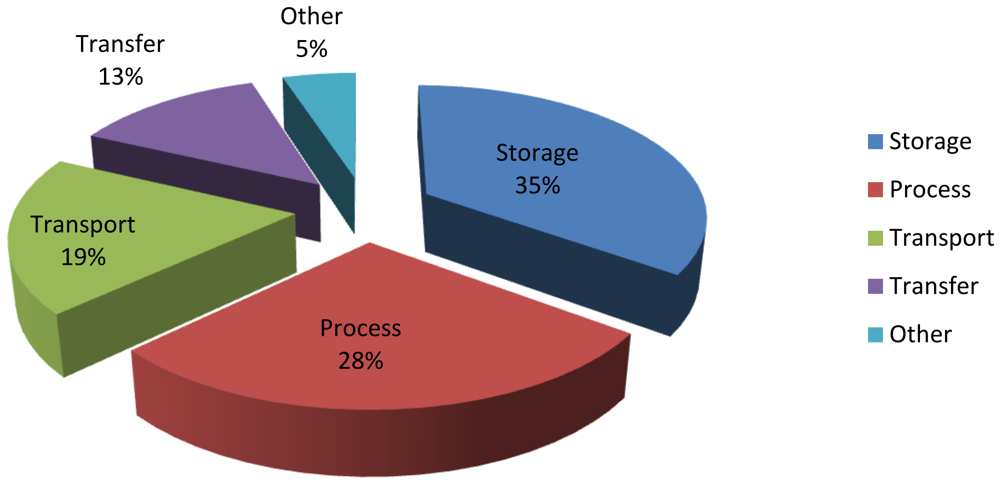

Figure 24. Origin of domino accidents, accidents in loading/unloading operations are included in *Transfer* (Darbra et al., 2010).

Figure 24 shows that 68 percent of all domino accidents have originated from fixed installations and 32 percent from different kind of transportation modes, including transfer. Looking at Abdolhamidzadeh et al. (2011) results, they have identified that 80 percent of all domino accidents have originated from fixed installations and 20 percent have occurred during transportation. Readers should note that there is a lack of accuracy regarding pipelines being included in transportation or not. This is believed to be one of the main reasons why there is such a substantial spread among the results from different authors. Abdolhamidzadeh et al. (2011) have also analysed how the distribution among different transportation modes looked like, these results are shown in figure 25.

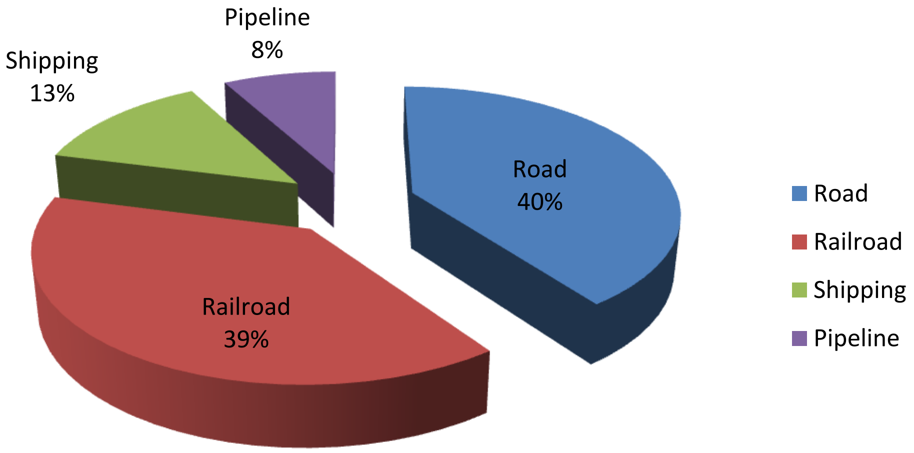

Figure 25. Different modes of transportation where domino events have been encountered (Abdolhamidzadeh et al., 2011).

A.3 Causes

Darbra et al. (2010) have from a variety of sources, divided according MHIDAS database, gathered information regarding the general causes of primary accidents, this information is presented in table 19. Readers should note that the total percentages goes beyond 100, this because some accidents were triggered by more than one general cause. There is also a lack of accuracy regarding accidents triggered by human factors. In the study made by Darbra et al. (2010), only accidents with specific references to human error were classified in that category. In reality, accidents that in the study have been classified as mechanical failure could very well be the consequence of an initial human error. Based on that fact it is likely that the percentages for human failure shown in table 19 is lower than it is in reality (ibid.).

Table 19. General causes of the initial event (Darbra et al., 2010).

Cause	Number of events	%
External Events	69	30,7
Mechanical failure	65	28,9
Human factor	47	20,9
Impact failure	40	17,8
Violent reaction	21	9,3
Instrument failure	8	3,6
Upset process condition	5	2,2
Services failure	3	1,3

A.4 Initiating events and domino sequences

A critical aspect for improving our understanding of domino effect accidents is to analyse the length and the events involved in domino sequences. 53 % of all accidents involved in the study by Abdolhamidzadeh et al. (2011) had secondary events and 47 % included a tertiary or even higher level of escalation. Looking at which accidents that is most likely to trigger one or more sequential accidents, it is revealed that explosions are the most frequent cause of domino effects (57 %), followed by fires (43 %) (ibid.). Among domino events initiated by fires, see figure 26, pool fires were the main type of fire that was involved in the initiation of domino accidents.

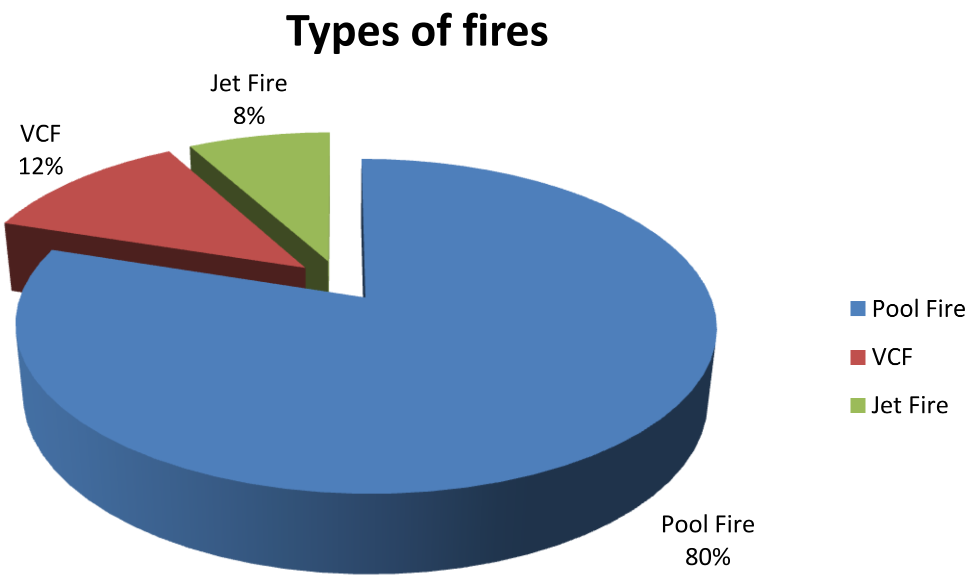

Figure 26. Types of fires involved in initiating domino effect (Abdolhamidzadeh et al., 2011)

Among the events initiated by an explosion, see figure 27, VCE (Vapor cloud explosion) has been the most frequent cause, followed by physical explosion and dust explosion (Abdolhamidzadeh et al., 2011).

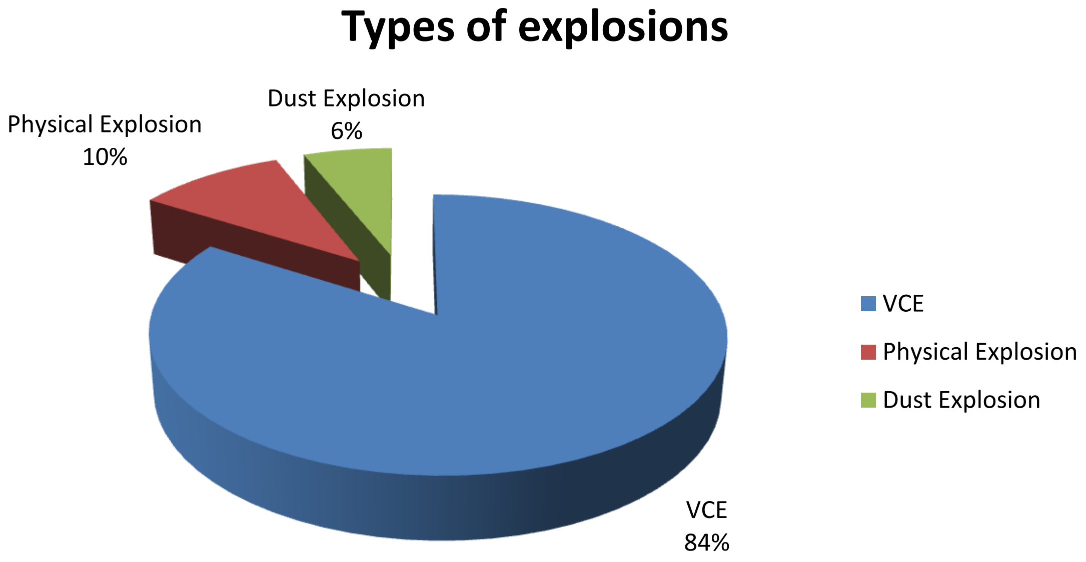

Figure 27. Types of explosions involved in initiating domino effect (Abdolhamidzadeh et al., 2011).

Comparing the different types of fires and explosions, one can see that VCE/VCF are the most frequent cause of initiating domino sequences and are followed by pool fires.

By asserting relative probabilities, Darbra et al. (2010) analysed domino sequences by using an event tree analysis. The initiating events were divided into four categories: release, fire, explosion and gas cloud. The event tree was later redeveloped, now only including fire and explosion as the primary events, see figure 28. The event release is often not registered in databases and therefore it can be seen as misleading to include that category. Regarding the gas cloud; if the gas cloud was made of flammable substances and ignited, it was considered an explosion; if the flammable cloud was ignited but did not involve any mechanical effects, it was considered a fire; and if it was a toxic non flammable gas cloud it would not cause any secondary events (Darbra et al., 2010).

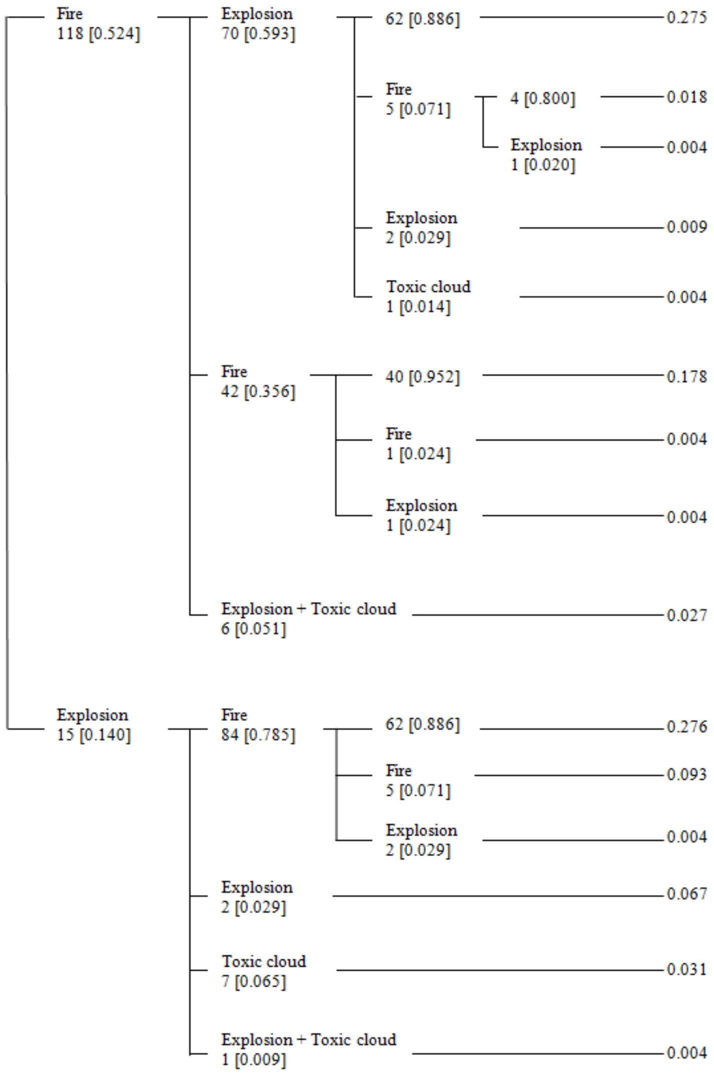

Figure 28. Relative probability tree showing the diverse domino effect sequences (Darbra et al., 2010).

Of the 225 accidents studied in by Darbra et al. (2010), 193 involved one domino effect (a primary event followed by secondary accidents), whereas 32 involved at least two domino effects. As following these results, the ratio between first-level and second-level domino effects sequences can be calculated to 6, which is significantly higher than Abdolhamidzadeh et al. (2011) ratio of 1,13. If the release factor were to be included in the relative probability tree the ratio would be 1,4, which is much closer with values given by other authors. The difference could also be traced back to the lack of accuracy in the description of accidents in databases, which often leads to different interpretations (Reniers & Cozzani, 2013). Readers should note that the physical effect known as fragment projection, which have been defined as an escalation vector is included in the percentages the explosion category. This is based on the fact that flying missiles are hard to correlate to any specific accident when interpreting data from historical domino events.

APPENDIX B – REFERENCES FOR THRESHOLD VALUES PRESENTED IN TABLE 3

API RP 510 (1990). Pressure Vessel Inspection Code: Maintenance, Inspection, Rating, Repair, Alteration. American Petroleum Institute, Washington D.C.

Bagster, D.F. & Pitblado, R.M. (1991). The estimation of domino incident frequencies: an approach. Process Safety and Environmental Protection 69, 196.

Barton, R.F. (1995). *Fuel gas explosion guidelines – practical application*. In: Proc. IChemE Symposium Series No.139. IChemE, Rugby, pp. 285–286.

Bottelberghs, P.H. & Ale, B.J.M. (1996). *Consideration of domino effects in the implementation of the Seveso II directive in the Netherlands*. In: Proc. European Seminar on Domino Effects, Leuven, pp. 45–58.

Brasie, W.C. & Simpson, D.W. (1968). Guidelines for estimating damage from chemical *explosions*. In: Proc. 2nd Loss Prevention Symposium, p. 91.

BS 5908 (1990). *Code of Practice for Fire Precautions in Chemical Plant*. British Standards Institution, London.

Clancey, V.J. (1972). *Diagnostic features of explosion damage*. In: Proc. 6th Int. Meeting of Forensic Sciences, Edinburgh.

Cozzani, V. & Salzano, E. (2004). Threshold values for domino effects caused by blast wave interaction with process equipment. *Journal of Loss Prevention in the Process Industries 17*, 437–447.

DM 151/2001, Decreto Ministeriale 9/5/2001 n.151, Official Journal of Italian Republic (Gazzetta Ufficiale), Rome.

Glasstone, S. (1980). *The Effects of the Nuclear Weapons*. Atom. Energy Comm., Washington, DC.

Gledhill, J. & Lines, I. (1998). Development of Methods to Assess the Significance of *Domino Effects from Major Hazard Sites*. CR Report 183. Health and Safety Executive, London.

Gugan, K. (1979). *Unconfined Vapour Cloud Explosions*. IChemE, Rugby.

HSE, Health and Safety Executive (1978). Canvey: An Investigation of Potential Hazards from Operations in the Canvey Island/Thurrock Area. HM Stationary Office, London.

Khan, F.I. & Abbasi, S.A. (1998). Models for domino effect analysis in chemical process industries. Process Safety Progress 17, 107.

Kletz, T.A. (1980). Plant layout and location: method for taking hazardous occurrences into account. *Journal of Loss Prevention in the Process Industries 13*, 147.

Leeuwen, D.V. & Blom-Bruggerman, J.M. (1989). *Methods for the Calculation of Possible Damage (Green Book).* Committee for the Prevention of Disasters, The Hague.

Mecklenburgh, J.C. (1985). *Process Plant Layout*. George Goodwin, London.

Tan, S.H. (1967). Flare system design simplified. *Hydrocarbon Processing 46*, 172.

Van Den Bosh, C.J.H., Merx, W.P.M., Jansen, C.M.A., De Weger, D., Reuzel, P.G.J. & Wells, G.L. (1980). *Safety in Process Plant Design*. Wiley, Chichester.