Safety professionals in the Netherlands

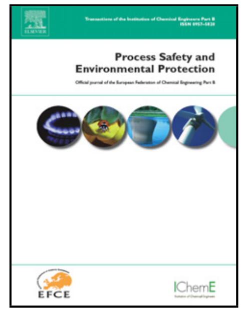
Swuste, Paul; Zwaard, Walter; Groeneweg, Jop; Guldenmund, Frank

DOI
10.1016/j.ssci.2018.12.015

Publication date
2019

Document Version
Accepted author manuscript

Published in
Safety Science



Title: Domino effects in chemical factories and clusters: An historical perspective and discussion

Authors: Paul Swuste, Karolien van Nunen, Genserik Reniers, Nima Khakzad

PII: S0957-5820(18)31247-3
DOI: https://doi.org/10.1016/j.psep.2019.01.015
Reference: PSEP 1634

To appear in: *Process Safety and Environment Protection*

Received date: 22 November 2018
Revised date: 13 January 2019
Accepted date: 16 January 2019

Please cite this article as: Swuste P, van Nunen K, Reniers G, Khakzad N, Domino effects in chemical factories and clusters: An historical perspective and discussion, *Process Safety and Environmental Protection* (2019), https://doi.org/10.1016/j.psep.2019.01.015

Domino effects in chemical factories and clusters: An historical perspective and discussion

Paul Swuste[1], Karolien van Nunen[2,3,4] Genserik Reniers[1,4,5] Nima Khakzad[1]

1. Safety Science Group, Delft University of Technology, the Netherlands
2. Research Chair Vandeputte, Universiteit van Antwerpen, België
3. Law Enforcement, Rechtenfaculteit, Universiteit van Antwerpen, België
4. Antwerp Research Group on Safety and Security (ARGoSS), Faculteit toegepaste Economie, Universiteit van Antwerpen, België
5. National Institute for Public Health and the Environment, Bilthoven, the Netherlands

Highlights

- Review of knowledge development on complex domino accident processes
- Research is dominated by quantitative risk analyses, and models to calculate probabilities
- Research is closely related to political, and private decision making
- Research on barrier quality and quality of risk management is in its infancy
- Research on initiating scenarios as a starting point for domino-effects is necessary

ABSTRACT

Major accidents in Western countries, receiving a lot of media attention in the 1970s, are starting point for research into internal and external domino effects in the chemical and petrochemical sectors and clusters. Initially, these reports are published by government institutions and government-related research centres. With the upcoming quantitative risk analyses in the 1970s and 1980s, the so-called 'coloured books', published in the Netherlands, play a prominent role in quantifying these domino effects. Since the mid 1990s, the second European Seveso Directive encourages scientific research on domino effects, shown in substantially growth of academic publications on the topic. Research in Western countries is dominated by risk assessments, probabilities, and failure mechanisms are calculated for the complex phenomenon of domino effects and its consequences. Previous works are closely related to political, official and private decision-making. A transition towards risk management is still in its infancy. A future transition is necessary to understand initial scenarios as starting points for domino effects.

In India a wake-up call for domino effects occurs in the mid-1990s. Chinese publications on domino effects in the international scientific press appear from the mid-2000s onwards. Due to a rapid industrialisation, the numbers in China country are overwhelming, versus chemical companies, as versus of many major accidents in this sector.

This article will discuss results of research on domino effects, conducted in the period 1966-2018, as well as major determinants of these accident processes. Also present, and future transition in this research domain will be discussed.

INTRODUCTION

Literature on domino effects shows quite a few review articles. Some papers present an analysis of major accidents in the chemical and process industries, including domino effects (Kourniotis et al., 2000; Ronza et al., 2003; Gómez-Mares et al., 2008; Darbra et al., 2010; Abdolhamidzadeh et al., 2011). One article reviews the state of the art or research on this phenomenon (Necci et al., 2015).
The present paper provides an historical overview on research, and development of knowledge of accident processes conducted for the last 50 years. Historical overviews are not only a source of anecdotes, and of chronology, but give insight in transitions in knowledge on domino effect, justifying this approach. This article focusses on these transitions in our knowledge, and determinants of complicated accident processes, leading to domino effects.

The Netherlands has a favourable business climate for the chemical sector. There are direct lines between the most important chemical centres in the Netherlands, Belgium, Germany and northern France. Six of those chemical clusters are active (Figure 1).

Rotterdam-Rijnmond, Moerdijk, Zeeland and Chemelot are also part of the so-called ARRRA cluster, the cooperation within the chemical industry with Antwerp and the Rhine-Ruhr area. The ARRRA (Antwerp-Rotterdam-Rhine-Ruhr Area) cluster is integrated via pipelines, roads and water and railways (EPCA, 2007a). A chemical cluster is a geographically defined area within which various chemical equipment and installations are located, whether or not surrounded by non-chemical devices. The cooperation between these institutions can be absent, lightly, or intensively organised. Collaboration creates opportunities, such as the efficient use of energy and raw materials. ‘Supply chain management’ is such an option, with associations between multiple partners that are active in different parts of the supply chain. This is known as vertical cooperation, and prevents unnecessary logistical costs. Cooperation can also be horizontal, referring to the exchange and sharing of information, facilities or resources, like incident and disaster management. This will reduce costs between companies that operate as competitors in the same market or are active in very different markets cooperation (Reniers, 2009, 2010a).

Proximity to and connections between companies do not necessarily have a positive effect on safety. The chain integration and the complexity in these sectors are increased by gradual growth and further automation. Combined with a further outsourcing of tasks and components, the processes and dependencies become more complex in a cluster, creating increased risks of major accidents, with, or without escallation effects. Major accidents and incidents, explosions, fires, emissions of hazardous substances via leaks, occur with some regularity in the Netherlands. Till now these major accidents have been limited to damage to installations with costs up to several tens of millions of euros. For example, the material damage of a major accident in 2011 at the Chemie-Pack company in Moerdijk, near Rotterdam, resulting in a large fire, has cost € 71 million (RIVM, 2016).

A domino effect is a relatively complex event. In the last two decades these events have attracted increasing attention in scientific literature. There are a number of definitions for domino effects. The simplest definition comes from Lees: 'an event in one unit that causes a follow-up event in another unit' (Lees, 1996). Reniers and co-authors describe a domino effect as 'a cascade of events in which the consequences of a previous accident increase through successive events, both spatially and sequentially and lead to a major accident' (Reniers et al., 2005a). These two definitions describe the process of domino effects. The American Centre for Chemical Process Safety (CCPS) of the American Institute of Chemical Engineers (AIChE) defines 'an incident that starts in one unit and affects nearby units through a thermal effect, an explosion or an impact of fragments' (CCPS, 2000). In this definition, attention is paid to the mechanism of a domino effect, heat radiation, the pressure wave and the projection of debris. This is further elaborated in a definition by Cozzani and co-authors where four stages are distinguished:

1. a primary accident scenario, the starting point of the domino effect;
2. the propagation following the primary event, caused by physical effects - the escalation vectors factors - of the primary scenario and resulting in damage to at least one secondary unit;
3. one or more secondary accident scenarios, involving the same or another plant units, or establishment;
4. an escalation effect is the result, an increase of the domino effect in relation to the primary scenario (Cozzani et al., 2006, 2007).

This latter definition is more detailed in mechanisms, and distinguishes between an 'internal domino effect', an effect within one establishment and an 'external domino effect' between several establishments. The above four definitions show that there is a poor agreement in the literature on a universally accepted definition of domino events (Reniers, 2010a; Abdolhamidzadeh et al., 2011; Necci et al., 2015). Despite the fact that the effects of domino accidents can be disastrous, the subject has received little attention from safety managers. Only the last decade's attention from science is raised. After all, domino effects are complex and, comparable to major accidents its probability of occurrence is very low. This article is structured along the following research questions:

- What are the results of research conducted between 1966 and 2018 on domino effects in the process industries?
- What was the focus of research related to primary scenarios, barriers, models to calculate domino effects, and risk management?
- Are major transitions in research detectable during this period?

MATERIALS AND METHODS

For this review, scientific bibliographic databases are used, *Web of Science* and individual scientific journals, including *Accident Analysis and Prevention, Journal of Hazardous Materials, Journal of Loose Prevention in the Process Industries, Journal of Safety Research, Process Safety Progress, Reliability Engineering and System Safety, Safety Science, Transactions of industrial Chemistry*, using search terms as *industrial park, chemical park, industrial area, chemical area, chemical cluster, multiplant, domino*. Relevant articles from these journals are consulted, as well as references to other scientific journals. Also so-called grey literature is reviewed; research reports and available government documents. The search has resulted in more than 100 articles and documents.

After the Second World War a massive upscaling of the chemical industry takes place in Western countries. The production capacity, storage and transport of hazardous materials increases significantly during this period. This leads to major accidents, which are discussed extensively in media and scientific literature since the 1970s. At that time the reliability of installations in the process industry is a matter of great concern and several 'loss prevention' studies are started (Pasman and Snijder, 1974, Coevert et al., 1974; Vörös and Honti, 1974; Grim, 1974; TNO, 1983; Pasman, 1999; Spoelstra et.al. 2015, for an overview see Oostendorp et al., 2016).

Research of domino effects can be divided into different time periods. Li and co-authors have made the relationship plausible between Seveso regulations and the production of articles from Western countries (Li et al., 2017). The Seveso I directive from 1982 (Council Directive 82/501 / EEC) mentions domino effects as an important phenomenon within the process industry. These effects will be the subject of presentations at international conferences and research reports on major accidents or research into the risks of chemical industrial parks. Publications in scientific journals appear little by little after 1982. The first period starts a major accident in Feyzin, France in 1966, an internal domino effect, and continues until the early nineties. The second period coincides with the publication of the European Seveso II directive from 1996 (Council Directive 96/82 / EC). This guideline contains rules for spatial planning and the requirement for the identification and prevention of domino effects. This period ends in 2011 and shows an increase in publications in the scientific press. The third period starts with Seveso III (Council Directive 2012/18 / EU). This guideline states that owners of chemical sites must exchange information intensively to prevent these escalating scenarios. All Seveso guidelines only speak of external domino effects between establishments. Internal domino effects within one establishment are left out. The third period shows a sharp increase in scientific articles, and continues in this literature review until 2018. This period can also be characterized by the development of methodologies for dynamic modelling and risk assessment of domino effects (e.g., via Bayesian network and Petri nets), modelling and assessing the impact of safety barriers on the probability and severity of domino effects, and cost-benefit risk management of domino effects in the past decade. In addition to research in Western countries, quite a few articles on domino effects have been published by authors from Central and Southeast Asia. This research is difficult to classify in time periods mentioned above and will be discussed in a separate section. This manuscript is written in ‘praesens historicum’

RESULTS

The first documented domino accident dates from 1947. In the port of Texas City a ship with ammonium nitrate detonates due to a fire. This results in a chain reaction, and other ships and an oil storage on land explode. Despite the fact that this major industrial accident in America is the largest, measured by the number of fatalities, almost 600, it was a not a trigger for research into domino effects (Khan and Abbasi, 1998a).

First period, 1966-1995

The first period is dominated by major accidents with internal domino effects: Feyzin-1966 France, Flixborough-1974 UK and Mexico City-1984 Mexico. Analyses of these accidents provide an overview of accidental processes with domino effects and stimulate a risk approach, introduced in the safety domain in the 1970s. It is the start for prospective research in Great Britain, the Netherlands and Italy. In the scientific literature there is a focus on research of escalating factors of these accident processes.

Major accidents with internal domino effects in Europe and mexico

In 1966 a large fire started in the tank storage of the Feyzin refinery in France, 10 km below Lyons. This major accident is only referred to sparingly in literature. An LPG emission has created a gas cloud, which has been ignited by a passing car from the adjacent road (Figure 2).

The second major accident happens one day after the conclusion of the 1st International Loss Prevention Symposium in Delft-The Hague (Buschmann, 1974). A heavy blast hits the Flixborough Works of Nypro Limited in North Linconshire, UK. A just-made bypass between two reactors bursts open during start-up and a large amount of cyclohexane escapes, which explodes. As a secondary effect, fires at many locations in the factory and subsequent explosions blow up a large part of the factory (Figure 3). This major accident too, is an internal domino effect (Parker, 1975; Lees, 1980; Høiset et al., 2000; Venart, 2004).

A third major disaster of an internal domino effect takes place ten years after Flixborough at the Pemex LPG storage of the state-owned oil company Petroleo Mexicana in San Juan Ixhuatepec, a northern district of Mexico City. An LPG leak on the site leads to a fireball, BLEVE, which torns LPG pipelines. The resulting flames generate a number of subsequent explosions and LPG cylinders are shot as projectiles, partly ending up in an adjacent residential area (Figure 4) (Pietersen, 1988; Lees, 1996). This is the worst ever recorded domino effect, some 650 people lost their lives.

Another disaster, four years later with the platform Piper Alpha, once again draws attention to domino effects and escalation due to fire and explosion on platforms and factory sites. This leads to the design strategy 'Layers of Protection Analysis', LOPA in short, at the end of the 1980s. This concept originates from the military sector and is first used in the nuclear sector in the 1950s (Swuste et al., 2017). In the late nineties the 'Safety Integrity Levels (SILs)' are added (Charlwood et al., 2004).

Prospective risk-research in Great Britain, the Netherlands and Italy

In the early seventies, the concept of risk makes its appearance in safety science, also initiated by the Flixborough disaster. In the Netherlands the so-called 'coloured books' are published, providing guidance for the design of the quantitative risk analysis method, the QRA (for an overview see Oostendorp et al., 2016). Another important publication is the WASH-1400 report, including for the first time probabilistic risk analysis methods (PRA) for nuclear power plants (Rasmussen, 1975). The quantification of the risks of chemical installations has first been applied in Great Britain, and is triggered by a proposal to reject of a permit for the construction of a second oil refinery at the chemical industrial park on the North Sea estuary of the Thames, Canvey Island. The British Health and Safety Executive calculates potential risks of installations, activities and possible consequences for local residents (HSE

1978, 1981; Lees, 1980). At this industrial park several hazardous companies are located, including an LNG and an LPG terminal, storage of petroleum products, toxic and flammable liquids and ammonia, an oil refinery, an ammonium nitrate plant and transport of hazardous materials over water, roads, rails and pipelines. Based primarily on historical data, probabilities are calculated for emissions of liquids, gases, explosions. Internal and external domino effects for a number of scenarios:

- interactions within and between companies/establishments, the influence of an LPG emission on the oil storage and the ammonia bulb storage;
- an LNG fire that causes a rupture in an adjacent tank;
- storage tanks or reactor vessels affected by objects originating from fire or explosions at the site or an adjacent location, or by fragments of a rotating machine, or of an exploding pressure vessel;
- a derailment of a tank wagon with an effect on a nearby ammonia storage globe.

Following the British Canvey study, the so-called COVO study is been initiated in the Netherlands. COVO stands for Contactgroep Veiligheid Omwonenden Rijnmond (Committee on Safety for the Residents of Rijnmond) (Cremer and Warner, 1982; Lees, 1996). For six industrial installations, the risks are calculated: the acrylonitrile storage of Pakhoed, the ammonia storage of UFK, the chlorine storage of Akzo, the LNG storage of Oxirane and the hydrodesulferiser of Shell. Domino effects are not included in this study.

Following the British Canvey survey and the Dutch COVO study, the ARIPAR project is launched in Italy, the first major risk survey in this country. Risks are calculated at a large chemical industrial park in the vicinity of Ravenna, including transport activities. In this park, companies including petrochemicals, agricultural products, inorganic chemistry, coal transhipment, food and storage are active. Nine companies are subject to Seveso regulations, and for 38 other companies 2000 possible accident scenarios are developed using expert assessments and historical data.
The scenarios result in emissions of chlorine, ammonia, acrylonitrile, inorganic acids, LPG and high flammable liquids. According to results internal domino effects are negligible and distances of fixed installations are far enough from the city and therefore do not contribute significantly to the risks of citizens of Ravenna.The nine Seveso companies, and road transport of hazardous substances has made a significant contribution to the risk contours (Figure 5). The risk contribution is limited to locations where the road is close to inhabited areas (Egidi et al., 1995).

A presentation of an accident process of domino effects, the domino effect bowtie

In this period the main determinants of accident processes leading to domino effects are known, coming mainly from case descriptions of past major domino accidents. One way to visualise these accident processes is a so-called double bowtie (Figure 6). This bowtie illustrates on the left-hand side the onset of an accident process, starting from a hazard. Several accident scenarios are shown as the arrows from left to right. These scenarios can lead to the central point of the domino effect: the primary central event. This is a situation where the hazard has become uncontrollable, leading to escalating factors. This is the yellow rectangle in the middle of the figure. According to the above definition of Cozzani and co-authors (2006, 2007), the propagation of dominos starts with these escalating factors, physical effects, provide a follow-up trajectory with the domino scenarios and a secondary central event. This secondary central event may lead to consequences on the right side of the figure, which are greater than the consequences of the primary accident process. The figure shows the accident process of a single domino. In principle, the primary accident process can result in multiple secondary central events. The strength of the model concerns the influencing parameters. These parameters can prevent primary and secondary central events, the circles in the figure, or limit the consequences, the yellow rectangles. Two types of influencing parameters can be identified. Firstly, the safety barriers, represented as the black rectangles in the figure. These are physical or technical entities, interrupting accident scenarios. Secondly there are management factors, the green rectangles at the bottom of the figure, influencing the quality of barriers, scenarios, and hazards through the blue vertical arrows. The blue lines represent non-physical or organizational and human aspects. To manage domino effects adequately, both primary, and secondary domino scenarios should be controlled.

QRA and domino effects (1)

From the outset, a risk approach and the associated risk calculation is dominant in publications. This is partly due to the increased focus on a risk approach from the 1970s and partly due to the complexity of the major accident processes that can happen, or have occurred. Major accidents in these industrial parks are very complicated. Despite difficulties in modelling failure mechanisms in this period (see Necci et al., 2015), a risk approach seems to give some way out.

It is mentioned in articles that domino effects are not accounted for in a QRA analysis. A start is made to describe the central events of the accident process and its consequences, including escalating factors. It concerns a pool fire, an explosion, release of a toxic chemicals, projected fragments by a fireball, BLEVE, a jet fire and an explosion after material breakdown. The escalating factor in fires are fire impingement, in case of jet fires, engulfment, in case of fire balls and flash fires, and heat radiation (Bagster and Ritblado, 1989, 1991). These authors have developed a program to calculate the frequency of domino effects caused by these primary accident processes.

In articles in the scientific press during this period, some of the uncertainties that are inextricably linked to quantitative risk analyses are discussed. It concerns the data on which the analysis is based upon; the mismatch between data through assessment by experts and historical data, the uncertainties in toxicity data of chemicals and the completeness of the analysis (Cremer and Warner, 1980; Paté-Cornell, 1987; Ronza et al., 2003). In the process of legislation and regulations, results of a risk analysis can support communication about risks and stimulate consensus among decision-makers. There is also a downside: expertise is needed to interpret risks. Local authorities, making decisions, often lack this expertise as do local residents living close to a chemical industrial park. The quantification of risks as arguments is rather counter-productive (Macgill and Snowball, 1983; Quarantelli, 1984; Swuste et al., 2016a).

Second period, around Seveso II, 1996-2011

In the second period, five large overviews are published of retrospective research into major accidents in the process industry and in port areas. Open literature and a number of databases have been used for these overviews, including the Major Hazard Incident Data Service (MHIDAS) of the British Health and Safety Executive (HSE), the Major Accident Reporting System (MARS) of the European Union, the Failure and Accident Technical Information System (FACTS) of the Dutch organization of Applied Scientific Research (TNO), and the Analysis, Detection and Information on the Accidents (ARIA) of the French Ministry of Regional Planning and the Environment. These articles provide an overall picture of accident processes, including accidents with single, or multiple, internal and external domino effects. In contrast to case reports, context information in databases is usually limited, differences are often not, or difficult to interpret. In addition to this research, with the number of major accidents running into hundreds, two prospective case studies are published in this period, both from Italy including risk calculations of industrial parks. Furthermore articles are published about primary central events, escalating factors, barriers and measures, methods for calculating domino effects and how safety in industrial chemical parks can be managed.

Retrospective research on domino effects

The first study provides an overview of 207 chemical major accidents between 1960 and 1998, using the MARS database. Characteristic patterns are found between the various hazards; flammable liquids (oil, naphtha, gasoline, kerosene), gaseous hydrocarbons and toxic substances (Cl_2, NH_3, pesticides). The highest domino frequency is found with the gaseous hydrocarbons and the lowest with the toxic substances, although the effect range for toxic substances is the greatest (Kourniotis et al., 2000). The second investigation, using MHIDAS as a source, discusses 828 chemical incidents in ports from a time period not specified. The Seveso II Directive does not apply to these transports of hazardous substances. Accident processes start with an 'loss of containment' (LOC), leading to an explosion, or a fire with or without an explosion. These fires are not very frequent in manoeuvre and approach operations, and more common during land operations, like process, and transport. 5% of the accidents happening during (un)loading have an LOC sequence (Ronza et al., 2003). MHIDAS is the main source of information of the third study. Also information from the MARS, FACTS, and ARIA databases have been consulted. This survey investigates 225 chemical accidents with domino effects in the period 1961-2007 with the categorization of the MHIDAS database as escalation factors: external events, mechanical failure, human error, collisions and violent reactions such as a runaway reaction. Here the first two categories, external event and mechanical failure are the most important factors for domino effects in storage, production process and transport. The accident processes starting with an explosion, followed by a fire and vice versa, are by far in the majority (Darbra et al., 2010). The last two studies discuss 224 domino accidents between 1917 and 2009 (Abdolhamidzadeh et al., 2011), and 84 jet fires (Gómez-Maris et al., 2008). An overwhelming majority of 89% is caused by flammable substances. But also non-flammables, like CO_2, Cl_2, and overheated water have created explosions and subsequent domino effects

Prospective risk-research in Italy

Fifteen years after the first ARIPAR study, a second prospective analysis is been initiated, based upon 300 scenarios from the official safety reports of companies in the park. The conclusions are not different from the 1995 study. Again a number of hot-spot locations are designated, caused by transport (Antonioni et al., 2009). A second prospective study is conducted in Sicily, Italy at the Augusta-Mellilli-Priolo industrial park near Siracusa, on the east side of the island. The article is rather scarce on specification of its data sources and results, except that the method of the ARIPAR project has also been applied (Bartolozzi et al., 2010).

QRA and domino effects (2)

There is a lot of attention in the scientific press for methods to calculate probabilities of domino effects and their consequences. The QRA analysis is supplemented with a damage probability model, a probit, for various escalation factors and categories of damage to process equipment as a result of overpressure, or with information from the 'yellow book', from the Dutch series of coloured books (CPR 14E, 1979). Despite the scarcity of historical data, the consequences of a domino effect with equipment are accurate to calculate with specific probes (Cozzani and Salzano, 2004a,b; Salzano and Cozzani, 2005; Antonioni et al., 2009). If the primary central event is an explosion, creating a blast wave as an escalating factor, for overpressure threshold values range from 7-70 kPa, depending on the consequences considered, like vessel rupture, vessel displacement, connection displacement, etc. (Cozzani et al., 2006; Necci et al.,2015). Primary central events as stationary, pool, or jet fires create radiation as an escalating factor. Target equipment, for instance a steel vessel, will rapidly weaken at temperatures above 700°K (Gómez-Maris et al., 2008).

To calculate probabilities of domino effects, and consequences user-friendly software is developed. DOMIFFECT (Khan and Abbasi, 1998b), and DomPrevPlanning (Reniers and Dullaert, 2007, 2008) are examples. This software determines, the relative importance of installations based upon distances between installations with (highly) flammable substances, the failure scenarios of installations and the changes, both qualitatively and quantitatively, to installations over the past five years. The 'purple book' and the Dutch Instrument Domino Effect (RIVM, 2003) are the sources for the calculations. The assessment is relatively simple, gives a first screening of domino hazards and, unlike a QRA analysis, requires a limited input to data (CPR 18E, 1999).

Safety management and prevention

The emphasis of the Seveso II directive on the identification and prevention of external domino effects generates a number of safety management articles transcending individual companies. This causes problems, since companies in industrial chemical parks are not prepared in advance to share information with other companies. The horizontal cooperation is not self-evident (EPCA, 2007b). In an industrial park, whether dominant or not, the joint responsibilities for safety, environment and health are not always clear (Gaucher and Dolladille, 2010; Heikkila et al., 2010). Information from chemical companies, relevant to external domino effects, is quickly regarded as confidential. In literature a so-called 'cluster council' is proposed. This is a body of representatives of the participating companies, supplemented with independent participants who take care of confidential information. This creates an open, non-confidential part of the board and a confidential part. In this constellation, a Cluster Safety

Management System can be set up with the standard activities of each management system, including possible external domino effects, and prevention (Reniers et al., 2005b,c, 2009a). Decision making, certainly in the context of a cluster council, can be complicated, especially if risk management over several companies does not provide a clear economic advantage. Publications about a game-theoretical approach for strategic cooperation are published to facilitate this process of decision making. Game theory is a mathematical discipline within the economic sciences to investigate strategic choices and financial benefits for those involved (Reniers et al., 2009b; Reniers 2010b, Pavlova and Reniers 2011).

Articles on prevention of domino effects appear in this period, on type of barriers, distances and inherently safe design (Cozzani et al., 2009). Barriers are divided into passive, active, and procedural barriers. Passive barriers are physical in nature and have a direct impact on scenarios. An example is thermal insulation of process components. This measure is frequently used and can be costly. Active barriers also directly influence scenarios, but require, other than passive barriers, an external intervention to be activated. A sprinkler system above a storage under pressure is an example. This barrier is found to be less reliable due to failure probabilities of interventions. Beyond these measures, distance and inherently safe design are very effective to control the consequences or the occurrence of primary scenarios (Gleshill and Lines, 1998; CPR 18E, 1999). With inherently safe design (Kletz, 1984) reference is made to process intensification, with key words: reduction, intensification, substitution and simplification. This design approach leads to less hazardous substances and ditto conditions (Hendershot, 1997; Cozzani et al., 2007, for an overview see Swuste et al., 2018). In Figure 6 inherent safe design represents the blue arrow leading directly from the management factors to the hazard.

For safe distances for external domino effects, RIVM has developed an instrument, mentioned before, to support inspection tasks of competent authorities. The so-called ‘Instrument Domino effect’ is based on a number of primary scenarios, on substance categories and on the vulnerability of exposed installations (RIVM, 2003). Safe distances are also a subject for spatial clustering of transport lines of infrastructures. Corridors of roads, railways, waterways and pipelines have arisen of transport flows due to an increased intensity of use and lack of space in the Netherlands. The distances between these transport lines are in many places less than 100 meters, while 300 meters are advised. This clustering can imply an increased risk of accidents and domino effects with major consequences in terms of property damage and fatalities. However, the FACTS database does not support this assumption on the basis of historical data (Rosmuller and Heijden, 2002).

In this period, the articles are predominantly focussing on primary central events (conflagration, explosions and toxic emissions), escalating factors (radiation, fire, fragments and overpressure) and consequences. Especially calculation of probabilities of these domino effects are a major topic in literature.

Third period around Seveso III, 2012-2018

The major accident in Mexico City from 1984 is often cited in the introduction of articles in this and the previous period, most likely due to its consequences. To a lesser extent, reference is made to the major accidents at Flixbourough in 1974 and Buncefield in 2005. Similar to the second period, research lines of quantitative assessments of dominos and their effects are dominant. One retrospective survey is reported. Pipelines receive attention again, as well as a dynamic modelling of domino effects, and software is developed to calculate the likelihood of accident processes and their effects. Seveso III is putting more emphasis than Seveso II on managing these domino accident processes, which is reflected in the number of articles on this topic.

Quantitative assessments of dominos

Again problems are identified with quantitative assessment methods. Domino effects are very complex, the same applies to models and likelihood estimates, the spread in data and uncertainties of analyses conducted are still considerable (Kardell and Lööf, 2014). There is still too little development in integrated software, which can take into account geographical information and provides an assessment of consequences. A second point is the lack of knowledge about structural damage leading to failure of equipment and installations. This concerns the initial scenarios leading to the primary central even, and primary and secondary domino scenarios (Cozzani and Reniers, 2013).

The results of retrospective research (Hemmatian et al., 2014), a form of descriptive domino epidemiology, is a repetition of the conclusions of similar research in the previous period. The difference is the period considered, which has been extended from 1961-2007 up to 2011. The study provides a geographical comparison of EU countries, other Western countries and the rest of the world, thus again indicating the importance of domino effects. In the rest of the world, an increase in frequency is observable, while the EU and other Western countries show a slight decrease.

An overview of the already known primary and secondary scenarios, including the escalating factors, is published (Table 1) (Salzano and Cozzani, 2012). Toxic emissions as the primary domino scenario are not held responsible in this overview for an escalation, although toxic release in combination with a fire, or an heat source might ignite (Necci et al., 2015).

As in the second period, modelling of domino effects is performed using several different approaches. There are examples of QRA analyses supplemented with probit functions (Kadri et al., 2013, Kardell and Lööf, 2014). The aforementioned purple book is an important source of failure frequencies and effects. This also applies to models for domino effects of primary emissions, followed by overpressure and heat radiation. A proposed model is based on an event tree, where the topography of the industrial area, the characteristics of vulnerable installations and the existing barriers are included in probability calculations (Alileche et al., 2017). Other research goes deeper into primary scenarios for gas cloud explosions.

It is a common believe these explosions can only occur following emissions of highly reactive chemicals, like H_2 or C_2H_2. Now it appears that many more combustible chemicals can detonate under the right conditions, whereby an emission can accelerate into a detonation. This phenomenon has been known among scientists for a long time (Kolbe, et al., 2017). Also new approaches have been used for modelling special evolution of domino accidents triggered by fire, using a Domino Evolution Graph (DEG) model in combination with a Minimum Evolution Time (MET algorithm (Chen et al., 2018), or a flexible matrix-based model (Zhou and Reniers, 2018a). A recent approach to domino effects is based on the dynamic environment in which these effects take place. The effects should not be calculated with binomial or linear approaches. Dominos are dynamic events of mutual dependencies. A Markov chain approach fills this need and provides a better model of the time and space within which domino effects develop (Khakzad et al., 2017a).

Pipelines and dominos

Another point are domino effects in parallel pipelines. These effects are different than in chemical plants. Corrosion is a very important factor here and a domino effect can occur if an adjacent pipeline lies in the hole or crater created by the primary scenario. Adjoining pipelines are protected by the ground, so that a distance of 10 meters between parallel pipelines appears to be sufficient (Ramirez et al., 2015; Silva et al., 2016).

Risk management

In this third period, more attention is paid to barriers that can influence or control primary, and secondary domino scenarios and to risk management. (Figure 7). Risk analysis has already attracted considerable attention from researchers. Now topics such as risk reduction become important. Risk management in industrial chemical parks starts with information exchange. The planning of a cluster council is proposed in the second period. This call is repeated again (Reniers and Amyotte, 2012), as is game-theoretical approach for decision-making (Reniers et al., 2012). Emergency responses and efficiency of safety barriers in preventing or delaying the propagation of domino effects are important elements of risk management, and a rather new line of research of domino effects. Modelling these responses and efficiencies in fire induced domino effects are tested using Timed Coloured Hybrid Petri-nets (TCHPN) (Zhou and Reniers, 2018b). Also a decision model based on Bayesian networks with indexes for potential domino installations and equipment, including an inherent safety approach, is introduced (Khakzad et al., 2013, 2014; Khakzad, 2015). This model supports decision-makers where barriers need to be placed (Janssens et al., 2015). It creates a need for a classification of measures and barriers. In line with the focus on quantification, the probability of failure of present barriers is addressed, including its effectiveness. The classification used is the same as in the second period: inherently safe designs, passive, active barriers, and procedural barriers. This last group are the management factors in the bow tie model in Figure 6.

Active barriers are part of a larger system, where failure probabilities are known. There must be a detection of the danger, of fire, gas, or smoke, followed by a notification, like an alarm in a control room, and an activation. This activation can be mechanical or instrumental. Examples of active barriers are emergency stops, blocking systems, pressure and/or temperature reduction, supply of inert gas, sprinklers, water deluge and foam systems (Khakzad et al., 2017b, 2018a). Examples of passive barriers are applications of refractory material, or fire-resistant walls, or panels. These topics are quantitatively assessed in a model and calculated for a number of scenarios including extreme weather conditions on oil platforms (Landucci et al., 2015-2017, Alileche et al., 2017). Safe design usually comes down to a distance between domino sensitive equipment, or installations. An article has been published to allow domino effects to be part of the design of a factory, or a chemical cluster. Till now results of a quantitative analysis are used in decisions on the expansion of chemical plants near residential areas, or of extensions of a residential area near chemical companies. These calculations often ignore domino effects. With a Bayesian network analysis, where the nodes consist of domino-sensitive installations or equipment, spatial planning can become part of the initial design of a chemical plant, or cluster (Khakzad and Reniers, 2015).

A rather recent trend is research to security issues in relation to domino effects in the process industry (Argenti et al., 2018; Casson et al., 2018; Hossainnia et al., 2018; Khakzad et al., 2017; Landucci et al., 2015; Reniers et al., 2015; Reniers, 2014; Zhang en reniers, 2018; Zhang et al., 2018)

Central and South East Asia

Research into domino effects in Central and Southeast Asia is from a more recent date. The major accident in Flixborough is the tipping point for research on domino effects in Western countries in the seventies. In India a major accident at a refinery near Vishakhapatnam in the late 1990s plays a similar role in Central and South East Asia. The neighbouring country China has a more rapidly growing chemical and petrochemical sectors, compared to other countries in the region. These sectors are organized in chemical clusters, mainly in coastal areas and near large population centres. Despite major accidents in these sectors, these accidents did not seem to play a similar role as the domino accident in Vishakhapatnam, India.

Major accidents with internal domino effects in India

In India a major accident with internal domino effects has occurred in 1997 at the 40-year-old Hindustan Petroleum Corporation Limited (HPLC) refinery near Vishakhapatnam, a metropolis in the Andrah Pradesh province on the Bay of Bengal. A leak in a pipeline next to an LPG storage tank, caused by corrosion, generates a gas cloud. The gas cloud explodes, a large fire develops and 15 minutes later an adjacent storage tank explodes, followed by several tanks (Figure 8).

The consequences are enormous in terms of injury, fatalities and damage. Several shortcomings are found during the analysis of the accident. There is panic and management inertia, such as failed actions on corrosion reports from the maintenance department and on previous large emissions of combustible substances. The affected buildings are located 30 meters from the tank farm and the reporting of the initial leak one hour prior to the explosion is not followed by any action. The accident in the HPLC refinery has been the start of the setup of a Domino Effect Analysis (DEA) method. This method combines threshold values from literature for various escalation factors, overpressure, fragments and heat radiation with characteristics of vulnerable installations: used construction materials, properties and quantities of chemicals, distances between units and the wind direction. Two articles deal extensively with the major accident at Vishakhapatnam, and other industrial accidents in India and provide a list of internationally registered major accidents, with or without domino effects, from 1947 to 1997 (Khan and Abbasi, 1998a, 1999). Five years before the major accident at the HPLC refinery, a first overview of an Indian risk analysis agency about domino effects, risk analysis models and barriers appears (Latha et al., 1992).

Major accidents with internal domino effects in China

For Chinese authors, it takes longer for their publications to appear in the international scientific press. The numbers are overwhelming in this country, rapid industrialization creates many major accidents (Huang et al., 2011; Wang et al., 2018). Between 2000 and 2003, 400-600 accidents involving chemical substances are registered every year, with every year between 800 and 1100 deaths. Which contribution comes from industrial chemical parks cannot be traced. After 2003 these numbers have been halved, or reduce even further. Authors attribute this drop to newly introduced legislation and another organization of the Chinese Labour Inspectorate, which from that year reports directly to the Central State Council (Duan et al., 2011; Wang et al., 2018). A number of authors report on risk analyses carried out in industrial chemical parks in the vicinity of Shanghai, Nanjing. These authors adapt QRA analyses for domino effects (Wang and Ma, 2009, Yu et al., 2009, Sun et al., 2010), or Monte Carlo simulations for multiple domino scenarios caused by exploding tank fragments (Sun et al., 2016). Just like in Western countries, there is attention for a risk management approach, which goes broadly back to general management principles (Zhou, 2013, Zhou and Zhang, 2017). Finally, a remarkable publication from Iran, in combination with Indian authors. A Monte Carlo Simulation is used to estimate frequencies of domino effects. An algorithm is introduced on a hypothetical combination of domino-sensitive installations, in this case four tanks with naphtha, LPG and xylene that are at different distances from each other. During many simulations with different starting conditions each time, the failure or non-failure for each installation is determined. The simulation provides a domino frequency. A simulation technique, has the advantage that statements can be made about, in this case failure frequencies, for systems that are mathematically too complex or where too much knowledge is lacking on the behaviour of the system (Abdolhamidzadeh et al., 2010).

DISCUSSION AND CONCLUSIONS

An internal domino effect, within a single plant, is a rare event, let alone external domino effects. Nevertheless, in dense chemical clusters with inadequate safety distance between the hazardous units of two adjacent plants, a primary fire or explosion in one is likely to trigger secondary ones at the other exactly the same way it may occur in a single plant. Thus, the scale of safety distance adequacy will be the same for the installations of a single plant as for the installations of two adjacent plants, obviously depending on the type and size of the installations and the type and magnitude of escalation vectors.

This overview discusses a period of 1966-2018 with respect to the history of domino effects in the process industry. In science this is still a relatively short period, which is reflected in the lack of a generally accepted definition of domino effects. Before the first Seveso directive no articles are traced, and knowledge on domino effects are published in reports of governments and research institutions, providing detailed case studies of major domino disasters. These reports already give insight into hazards, primary and secondary central events, a rough description primary, and secondary domino scenarios, and into consequences as early as the 1970s. The risk concept in the safety domain is still fairly fresh and QRA is the emerging analysis model. It is difficult to discount domino effects in this model, and influence of barriers are not included yet.

In the second period, scientific production starts, with overviews of escalation factors and primary and secondary central events. But once again, influences of barriers are not included in the models. Information about the development of primary scenarios is virtually absent in the literature. While the majority of the articles are dealing with risk assessment, later in this period a transformation in the direction of risk management, cluster safety management, decision making, and barriers takes place. The physical barriers will have a direct effect on all scenarios. An extensive list is presented (Faes and Reniers, 2013). Frequently mentioned barriers are:

- emergency stop (active)
- blocking systems (active)
- pressure and / or temperature reduction (active)
- supply inert gas (active)
- sprinklers (active)
- water deluge and foam system (active)
- refractory material (passive)
- fire-resistant walls or panels (passive)
- distance (passive)
- inherent safe design (process intensification)

Management factors, which have not yet been reported in the literature, relate to indicators and actions that keep the presence and quality of the barriers on the ball (Swuste et al., 2016b).

In the third period again there is a main focus on mathematical models to calculate domino probabilities. But there is also criticism of the quantified approach, which was also expressed in the first period. It concerns the uncertainties of the probability calculations and it is suggested that the calculated probabilities seem to say more about the vision of the analyst, the eye of the beholder, than about reality (Khakzad et al., 2018b). The influence of the Seveso guidelines is remarkable, as science usually has its own dynamic. In an applied discipline such as safety science, this may be somewhat less the case. But it can be concluded that research on domino effects is closely connected to political, official and private decision-makers.

The cornerstones for decision-making are the results of the quantified models, which no longer lead to results solely based on QRA's. Amongst others, indexes are created, Monte Carlo simulations are carried out and analyses with Bayesian networks and influences of barriers are included in the models. In decision making, a shift has occurred. This, for instance, is visible in the Netherlands in discussions about risks associated with chemical installations, where establishments are organized in clusters or not. Unlike in the first period, when safety was mainly a topic of companies, attention is now socially driven. Citizens are concerned and a transparent and understandable risk management process has become a serious subject for companies (Raaijen, 2018). This is also evident from a recent British proposal (COMAH, 2018). Discussions on hazards and risks between companies, scientists and citizens do not always go smoothly, as is shows a Norwegian article (Lindøe and Kringen 2015). At two locations near Stavanger and Oslo a conflict arises about the risk assessment between citizens, companies and government. The environmental risks of LNG storage are found to be negligible and an urban expansion near a petrochemical cluster is planned without consulting close living residents. The results of the risk analysis are difficult to communicate with the public and an interested company donates a large sum of money to the university. A professor who has commented on the results of the analysis is first dismissed and later recruited at a lower position.

A transformation yet to come is a better understanding of primary scenarios. Domino effects all start with one or more hazards, and primary scenarios leading to a primary central event. The lack of knowledge on these events create quite some uncertainty in probabilistic calculations of escalation factors. This part requires far more attention than it receives. Databases of past accidents are not a reliable source due to the lack of context information. Most likely these scenarios and central events are company specific. Research on this topic requires a thorough investigation in possible scenarios coming from literature, and discussions with plant managers and operational staff. The approach is not probabilistic, but deterministic, providing detailed information on existing barriers, and mechanical and instrumental warning systems. For managers and operational staff, probabilistic information is difficult to comprehend. They need instruments to track down progress of disaster scenarios, and management tools to ensure quality of barriers. Such an approach has been developed recently, both in the occupational and in the process safety domain, generating scenario specific indicators (Nunen et al, 2018, 2019; Schmitz et al., 2019; Swuste et al., 2019).

A major accident occurring in Central and Southeast Asia as in Feyzin, only thirty years later, has stimulated further research into domino effects. Whether this has led to an improved control of these effects cannot be deduced from the literature. In China, the numbers on major accidents and related mortality have played a role. There is a fairly constant production of articles about dominoes from this country.

REFERENCES

Abdolhamidzadeh B Abbasi T Rashtchian D Abbasi S (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 (2011). Domino effect in process-industry accidents. An inventory of past events and identification of some patterns. Journal of Loss Prevention in the Process Industries 24:575-593

Alileche N Olivier D Estel L Cozzani V (2017). Analysis of domino effect in the process industry using the event tree method. Safety Science 97:10-19

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 2: 614-624

Argenti F Landucci G Reniers G Cozzani V (2018). Vulnerability assessment of chemical facilities to intentional attacks based on Bayesian Network. Reliability Engineering and System Safety 169:515-530

Bagster D Ritblado R (1989). Thermal hazards in the process industry. Chemical Engineering progress 85:69-75

Bagster D Ritblado R (1991). The estimation of domino incident frequencies. Process Safety and Environmental Protection 69:195-199

Bartolozzi V Bajardi S Vasile F Marino S (2010). Safety Integrated Area Analysis, a recent case study. Chemical Engineering Transactions 19:457-462

Buschmann C (Ed.) (1974). Loss prevention and safety promotion in the process industry. Proceedings of the 1st International Loss Prevention Symposium, The Hague, May 28th-30st

Casson Moreno V Reniers G Salzano E Cozzani V (2018). Analysis of physical and cyber security-related events in the chemical and process industry. Process Safety and Environmental Protection 116:621-631

CCPS (2000). Centre for Chemical Process Safety. Guidelines for Chemical Process Quantitative Risk Analysis, second ed., AIChE, New York

Chen C Reniers G Zhang L (2018). An innovative methodology for quickly modelling the spatial-temporal evolution of domino accidents triggered by fire. Journal of Loss Prevention in the Process Industries 54:312-324

Coevert K Groothuizen Th Pasman H Trense R (1974). Explosions of unconfined vapour clouds. In Buschmann C (ed.) (1974). Loss prevention and safety promotion in the process industry. Proceedings of the 1st International Loss Prevention Symposium, The Hague, May 28th-30st, p. 145-157

COMAH (2018). How to work together Collaboration in the high hazard sector. A guide to join industry, regulators and union groups that work in the high hazard process sectors. COMAH Strategic Forum, version 1.0 12th February

Council Directive 82/501/EEC of June 24, 1982. On the major accident hazards of certain industrial activities (Seveso I). Official Journal of the European Communities, L230/25, Brussels, 5.8.82

Council Directive 96/82/EC (Seveso II) of 9 December, 1996, January 14, 1997. On the control of major-accident hazards involving dangerous substances. Off. J. Eur. Communities 0013e0033. L 10/13, Brussels

Council Directive 2012/18/EU (Seveso III) of 4 July 2012, July 24, 2012. On the control of major-accident hazards involving dangerous substances. Off. J. Eur. Communities. L 197/1, Brussels

Cozzani V Gubinelli G Salzano E (2006). Escalation thresholds in the assessment of domino accidental events. Journal of Hazardous Materials A129:1-21

Cozzani V Reniers G (2013). Historical background and state of the art on domino effect assessment. In: Reniers and Cozzani (Eds). Domino effects in the process industries. Modelling, prevention and managing. Elsevier, Amsterdam

Cozzani V Salzano E (2004a). A quantitative assessment of domino effects caused by overpressure Part I probit models. Journal of Hazardous Materials A107:67-80

Cozzani V Salzano E (2004b). A quantitative assessment of domino effects caused by overpressure Part II case studies. Journal of Hazardous Materials A107:81-94

Cozzani V Tugnoli A Salzano E (2007). Prevention of domino effects: From active and passive strategies to inherent safer design. Journal of Hazardous Materials A139:209-219

Cozzani V Tugnoli A Salzano E (2009). The development of an inherent safety approach to the prevention of domino accidents. Accident Analysis and Prevention 41:1216–1227

Cremer & Warner (1980). An analysis of the Canvey report. Oyez Intelligence Reports, London

Cremer and Warner (1982). Risk analysis of six potentially hazardous industrial objects in the Rijnmond Area. Londen (the so-called COVO-study)

CPR 14E (1979). Commission for Prevention of Disasters. Methods for the Calculation of Physical Effects of the Release of Dangerous Materials (Liquids and Gases. Yellow Book. Directorate General of Labour, The Hague, the Netherlands

CPR 18E (1999). Commission for Prevention of Disasters. Guidelines for quantitative risk assessment. Purple Book. National Institute of Public Health and the Environment (RIVM), Ministry of Transport, Public Works

and Water Management, Ministry of Housing, Spatial Planning and the Environment, The Hague, The Netherlands
Darbra R Palacios A Casal J (2010). Domino effects in chemical accidents: main features and accident sequences. Journal of Hazardous Materials 183:565-573
Duan W Chen G Ye Q Chen Q (2011). The situation of hazardous chemical accidents in China 2000-2006. Journal of Hazardous Materials 186:1489-1494
Egidi D Foraboschi F Spadoni G Amendola A (1995). The ARIPAR project: analysis of the major accident risks connected with industrial and transportation activities in the Ravenna area. Reliable Engineering and System Safety 49:75-89
EPCA (2007a). The European Petrochemical association. A Paradigm Shift: supply chain collaboration and competition in and between Europe's chemical clusters. Brussels
EPCA (2007b). European Petrochemical Association. The Role of Clusters in the chemical industry. 41st Annual meeting. Brussels
Faes R Reniers G (2013). Managing domino effects in a chemical industrial area. In: Reniers G Cozzani (2013) (Eds). Domino effects in the process industries, modelling, prevention and managing. Elsevier, Amsterdam
Gaucher R Dolladille O (2010). Conventions on multi-operator sites: An effective risk management tool. Process Safety Progress 29(1):32-38
Gledhill J Lines I (1998). Development of methods to assess significance of domino effects from major hazard sites. Contract Research Report 183/1998. Health and Safety Executive, Her majesty's Stationary Office, Norwich
Gómez-Mares M Záratev L Casal J (2008).Jet fires and the domino effect. Fire Safety Journal 43(8):583–588
Grim W (1974). Case studies of fires in refineries and petrochemical plants. In Buschmann C (ed.) (1974). Loss prevention and safety promotion in the process industry. Proceedings of the 1st International Loss Prevention Symposium, The Hague, May 28th-30st, p. 355-361
Heikkila A Malmen Y Nissila M Kortelainen H (2010). Challenges in risk management in multi-company industrial parks. Safety Science 48:430-435
Hemmatian B Abdolhamidzadeh B Darbra R Casal J (2014). The significance of domino effect in chemical accidents. Journal of Loss Prevention in the Process Industries 29:30-38
Hendershot D (1997). Inherently safer chemical process design. Journal of Loss Prevention in the Process Industries 10(3):151-157
Høiset S Hjertager B Solberg T Malo K (2000). Flixborough revisited – an explosion simulation approach. Journal of Hazardous Materials A77(1-3):1-9
Hosseinnia B Khakzad N Reniers G (2018). Multi-plant emergency response for tackling major accidents in chemical industrial areas. Safety Science 102:275-289
HSE (1978). Health and Safety Executive. Canvey: An investigation of potential hazards from operations in the Canvey Island/Thurrock Area. Her Majesty's Stationary Office, London
HSE (1981). Health and Safety Executive. Canvey: A second report. A review of the potential hazards from operations in the Canvey Island/Thurrock Area three years after publication of the Canvey report. Her Majesty's Stationary Office, London
HSE (2010). Health and Safety Executive. Refinery fire at Feyzin. 4th of January 1966. http://www.hse.gov.uk/comah/sragtech/casefeyzin66.htm consulted March 19th 2018
Huang L Wan W Li F Li B Yang J Bi J (2011). A two-scale system to identify environmental risk of chemical industry clusters. Journal of Hazardous Materials 186:247-255
IChemE (1987). The Feyzin Disaster. Loss Prevention Bulletin 077, October p 1-4
Janssens J Talarico L Reniers G Sorensen K (2015). A decision model to allocate protective safety barriers and mitigate domino effects. Reliability Engineering and System Safety 143:44-52
Kadri F Chatelet E Lallement P (2013). The assessment of Risk Caused by Fire and Explosion in Chemical Process Industry: A domino effect-based study. Journal of Risk Analysis and Crisis Response 3(2):66-76
Kardell L Lööf M (2014). QRA with respect to domino effects and property damage. Report 5461, Lund University, Sweden
Khakzad N (2015). Application of dynamic Bayesian network to risk analysis of domino effects in chemical infrastructures. Reliability Engineering & System Safety 138:263-272.
Khakzad N Amyotte P Cozzani V Reniers G Pasman H (2018b). How to address model uncertainty in the escalating of domino effects. Journal of Loss Prevention in the Process Industries doi 10.1016 j.jlp.2018.03.001
Khakzad N Khan F Amyotte P Cozzani V (2013). Domino effect analysis using Bayesian networks. Risk Analysis 33(2):292-306
Khakzad N Khan F Amyotte P Cozzani V (2014). Risk management of domino effects considering dynamic consequence analysis. Risk Analysis 34(6):1128-1138

Khakzad N Landucci G Reniers G (2017b). Application of dynamic Bayesian network to performance assessment of fire protection systems during domino effects. Reliability Engineering & System Safety 167:232-247
Khakzad N Landucci G Cozzani V Reniers G Pasman H (2018a). Cost-effective fire protection of chemical plants against domino effects. Reliability Engineering & System Safety 169:412-421
Khakzad N Naderpour M Reniers G (2017a). A Markov chain approach to domino effects in chemical plants. Journal of Safety Health and Environmental Research 13(2):360-369
Khakzad N Reniers G (2015). Risk based design of process plants with regard to domino effects and land planning use. Journal of Hazardous Materials 299:289-297
Khakzad N Reniers G van Gelder P (2017). A multi-criteria decision making approach to security assessment of hazardous facilities. Journal of Loss Prevention in the Process Industries 48:234-243
Khan F Abbasi S (1998a). Models for domino effect analysis in chemical process industries. Process Safety Progress 17(2):107-123
Khan F, Abbasi S (1998b). DOMIFFECT (DOMIno eFFECT): user-friendly software for domino effect analysis. Environmental Modelling & Software 13 (1998) 163–177
Khan F Abbasi S (1999). The world's worst industrial accident of the 1990s. Process Safety Progress 18(2):135-145
Kletz T (1984). Cheaper, Safer Plants, or Health and Safety at Work. The Institution of Chemical Engineers. Rugby, UK
Kolbe M Simoes V Salzano E (2017). Including detonations in industrial safety and risk assessments. Journal of Loss Prevention in the Process Industries 49:171-176
Kourniotis S Kiranoudis C Markatos N (2000). Statistical analysis of domino chemical accidents. Journal of Hazardous Materials 71:239–252
Landucci G Argenti F Tugnoli A Cozzani V (2015). Quantitative assessment of safety barrier performance in the prevention of domino scenarios triggered by fire. Reliability Engineering and System Safety 143:30-43
Landucci G Argenti F Spadoni G Cozzani V (2016). Domino effect frequency assessment: The role of safety barriers. Journal of Loss Prevention in the Process Industries 44:706-717
Landucci G Bonvicini S Cozzani V (2017). A methodology for the analysis of domino and cascading events in oil & gas facilities operating in harsh environments. Safety Science 95:182-197
Landucci G Reniers G Cozzani V Salzano E (2015). Vulnerability of industrial facilities to attacks with improvised explosive devices aimed at triggering domino scenarios. Reliability Engineering and System Safety 143(5252):53-62
Latha P Gautam G Raghavan K (1992). Strategies for quantifying of thermally initiated cascade effects. Journal of Loss Prevention in the Process Industries 5(1):18-27
Lees F (1980). Loss Prevention in the Process Industries. Butterworth-& Co, London, UK
Lees F (1996). Loss Prevention in the Process Industries, second ed. Butterworth-Heinemann, Oxford, UK
Li J Reniers G Cozzani V Khan F (2017). A bibliometric analysis of peer-reviewed publications on domino effects in the process industry. Journal of Loss Prevention in the Process Industries 49:103-110
Lindøe H Kringen J (2015). Risk governance of hazardous industrial ports and areas: a case study of industrial areas and harbours in Norway. Journal of Risk Research 18(7):931-946
Macgill S Snowball (1983). What use risk assessment? Applied Geography 3(3):171-192
Necci A Cozanni V Spadoni G Khan F (2015). Assessment of domino effect State of the art and research needs. Reliability Engineering and System Safety 143:3-18
Nunen K van Swuste P Reniers G et al. (2018). Improving Pallet Mover Safety in the Manufacturing Industry: A Bow-Tie Analysis of Accident Scenarios. Materials 11(1955):1-19
Nunen K van Swuste P Reniers G Schmitz P. (2019). Developing leading safety indicators for occupational safety based on the bow-tie method. Chemical Engineering Transactions (submitted)
Oostendorp Y Lemkowitz S Zwaard W Gulijk C van Swuste P (2016). Introduction of the concept of risk within safety science in The Netherlands focussing in the years 1970-1990. Safety Science 85:205-219
Parker R (1975). The Flixborough Disaster - Report of the Court of Inquiry. Department of Employment, Her Majesty's Stationary Office, London
Pasman H (1999). Risicobeheersing. Chemical risk management. Naar processen en producten veilig voor mens en milieu. Intreerede, TU Delft (Risk control. Chemical risk management. Processes, and products safe for humans and environment. Inaugural speech TUDelft)
Pasman H Snijder G (1974). Schadepreventie en veiligheidsbevordering in de procesindustrie (Damage control and safety promotion). De Veiligheid 50(5):211-212
Pate-Cornell E (1987). Probabilistic risk analysis and safety regulation in chemical industry. Journal of Hazardous Materials 15:97-122
Pavlova Y Reniers G (2011). A sequential-move game for enhancing safety and security cooperation within chemical clusters. Journal of Hazardous Materials 186:40-406
Pietersen C (1988). Analysis of the LPG disaster in Mexico City. Journal of Hazardous Materials 20:85-107

Pietersen C (2009). 25 jaar later. De twee grootste industriële rampen met gevaarlijke stoffen LPG ramp Mexico City, Bhopal tragedie (25 years later. The two biggest industrial disasters with dangerous substances LPG disaster Mexico City, Bhopal tragedy). Gelling Publishing, Nieuwekerk aan de IJsel, the Netherlands.
Quarantelli E (1984). Chemical disaster preparedness at the local community level. Journal of Hazardous Materials 8:239-249
Raaijen W (2018). Industriële veiligheid staat voor een fundamentele verandering, interview Genserik Reniers (Industrial safety is facing fundamental changes, interview Genserik Reniers). Petrochem 2, February 20st
Ramirez J Pastor E Casal J Amaya R (2015). Analysis of domino effect in pipelines. Journal of Hazardous Materials 298:210-220
Rasmussen N et al., (1975). Reactor safety study. An assessment of accident risks in U.S. commercial nuclear power plants. Executive summary. WASH-1400 (NUREG-75014). USA Nuclear Regulatory Commission, Rockville, MD
Reniers G (2009). How to increase multi-plant collaboration within a chemical cluster and it impact on external domino effect cooperation initiatives. Safety and Security Engineering III:379-388
Reniers G (2010a). Multi-pant safety & security management in the chemical process industries. Wiley-Vch, Weinheim
Reniers G (2010b). An external domino effects investment approach to improve cross-plant safety within chemical clusters. Journal of Hazardous Materials 177:167-174
Reniers G (2014). Safety and security decisions in times of economic crisis: Establishing a competitive advantage. Chemical Engineering Transactions 36:1-6
Reniers G Ale B Dullaert W Soudan K (2009a). Designing continuous safety improvement within chemical industrial areas. Safety Science 47:578-590
Reniers G Amyotte P (2012). Prevention in the chemical and process industries: Future directions. Journal of Loss Prevention in the Process Industries 25:227-231
Reniers G Cuypers S Pavlova Y (2012). A game-theory based multi-plat collaboration model for cross plant prevention in a chemical cluster. Journal of Hazardous Materials 209-210:164-176
Reniers G Dullaert W Ale B Soudan K (2005a). The use of current risk analysis tools evaluated towards preventing external domino effects. Journal of Loss Prevention in the Process Industries 18:119-126
Reniers G Dullaert W Ale B Soudan K (2005b). Developing an external domino accident prevention framework: Hazwim. Journal of Loss Prevention in the Process Industries 18:127-138
Reniers G Dullaert W Soudan K (2005c). Preventing external domino accidents: a framework for enhancing cooperation in Chemical Process Industry (CPI). Safety and Security Engineering 721-735
Reniers G Dullaert W (2007). DomPrevPlanning: user-friendly software for planning domino effects prevention. Safety Science 45:1060-1081
Reniers G Dullaert W (2008). Knock-on accident prevention in a chemical cluster. Expert System with Applications 34:42-49
Reniers G Dullaert W Karel S (2009b). Domino effects within a chemical clusters: a game-theoretical modelling approach by using Nash-equilibrium. Journal of Hazardous Materials 167:289-293
Reniers, G Van Lerberghe P Van Gulijk C (2015). Security risk assessment and protection in the chemical and process industry. Process Safety Progress 34 (1):72-83
RIVM (2003) Rijksinstituut voor Volksgezondheid en Milieu. (National Institute for public health and the environment). Instrument Domino effect. RIVM, Bilthoven
RIVM (2016). Rijksinstituut voor Volksgezondheid en Milieu (National Institute for public health and the environment). Nationaal Veiligheidsprofiel 2016. Een all hazard overzicht van potentiële rampen en bedreigingen die onze samenleving kunnen ontwrichten (National safety profile 2016. An all hazard overview of potential disasters, and threats capable to disrupt our society) Analistennetwerk Nationale Veiligheid, RIVM Bilthoven
Ronza A Félez S Darbra R Carol S Vílchez J Casal J (2003). Predicting the frequency of accidents in ports areas by developing event trees from historical analysis. Journal of Loss Prevention in the Process Industries 16:551–560
Rosmuller N Heijden R van der (2002). The impact of spacial clustering of transport infrastructure on risk. Environment and Planning 34:2193-2210
Silva E Nele M Melo F Konozcy L (2016). Underground parallel pipelines domino effect. Journal of Loss Prevention in the Process Industries 43:315-331
Salzano E Cozzani V (2005). The analysis of domino accidents triggered by vapour cloud explosions. Reliability Engineering and System Safety 90:271-284
Salzano E Cozzani V (2012). Introduction external hazard factors in QRA Revista de Ingeniería. Universidad de los Andes. Bogotá D.C. p. 50-56
Schmitz P Swuste P Reniers G Nunen K van (2019). Mechanical integrity of process installations: an assessment based on bow-ties. Chemical Engineering Transactions (submitted)

Spoelstra M Mahesh S Kooi E Heezen P (2015). Domino effects at LPG and propane storage sites in the Netherlands. Reliability Engineering and System Safety 143:85-90
Sun Y Qian Y Zhang Y (2010). Risk analysis for vulnerabilities near chemical sites. IEEE Conferences 1-6
Sun D Jing J Zhang M Wang Z Zhang Y Cai L (2016). Investigating multiple domino scenarios by fragments. Journal of Loss Prevention in the Process Industries 40:591-602
Swuste P Groeneweg J Gulijk C van Zwaard W Lemkowitz S (2018). Safety management systems from Tree Mile Island to Piper Alpha, a review in English and Dutch literature for the period 1979 to 1988. Safety Science 107:224-244
Swuste P Gulijk C van Zwaard W Lemkowitz S Oostendorp Y Groeneweg J (2016a). Developments in the safety science domain, in the fields of general and safety management between 1970 and 1979, the year of the near disaster on Three Mile Island, a literature review. Safety Science 86:10-26
Swuste P Nunen K van Schmitz P Reniers G (2019). Process safety indicators, how solid is the concept? Chemical Engineering Transactions (submitted)
Swuste P Theunissen J Schmitz P Reniers G Blokland P (2016b). Process safety indicators, a review of literature. Journal of Loss prevention in Process Industries 40:162-173
TNO (1983). LPG A Study. Comparative analysis of the risks inherent in the storage, transhipment, transport and use of LPG and motor spirit. General Report, TNO, Apeldoorn
Török Z Ajtai N nTurcu A Ozunu A (2011). Comparative consequence analysis of the BLEVE phenomena in the context on Land Use Planning; Case study: The Feyzin accident. Process Safety and Environmental Protection 89:1–7
Venart J (2004). Flixborough The explosion and its aftermath. Process safety and Environmental Protection 82(B2):105-127
Vörös M Honti G (1974). Explosions of a liquid CO_2 vessel in a carbon dioxide plant. In Buschmann C (ed.) (1974). Loss prevention and safety promotion in the process industry. Proceedings of the 1st International Loss Prevention Symposium, The Hague, May 28th-30st, p. 337-346
Yu Q Zhang Y Wang X Ma W Chen L (2009). Safety distance assessment of industrial toxic release based on frequency and consequences: a case study in Shanghai, China. Journal of Hazardous Materials 168:955-961
Wang J Hung C Hung C Chang G (2009). Polychlorinated dibenzo-p-dioxin and dibenzofuran emissions from an industrial park clustered with metallurgical industries. Journal of Hazardous Materials 161:800-807
Wang H Ma Y (2009). Safety risk assessment technology of chemical industrial park based on grid partition and information diffusion theories. Proceedings of the IEE International Conference on Grey Systems and Intelligent Services, November 10th-12th Nanjing, China p.1359-1364
Wang B Wu C Huang L Zhang LKang LGao K (2018). Prevention and control of major accidents (MAs) and particularly serious accidents (PSAs) in the industrial domain in China: Current status, recent efforts and future prospects. Process Safety and Environmental Protection 117:254-266
Yu Q Zhang Y Wang X Ma W Chen L (2009). Safety distance assessment of industrial toxic release based on frequency and consequences: a case study in Shanghai, China. Journal of Hazardous Materials 168:955-961
Zhang L Reniers G (2018). Applying a Bayesian Stackelberg game for securing a chemical plant. Journal of Loss Prevention in the Process Industries 51:72-83
Zhang L Reniers G Chen B Qiu X (2018). Integrating the API SRA methodology and game theory for improving chemical plant protection. Journal of Loss Prevention in the Process Industries 51:8-16
Zhou D (2013). Study on risk management of the chemical industry park. Proceedings 2011 International Conference on Business Management and Electronic Information, May 13th-15th May, Guangzhou, Vol 4 p. 92-95
Zhou D Zhang M (2017). The integrated safety assessment on chemical industry parks. Proceedings of the 9th International Conference on Intelligent Human-Machine Systems and Cybernetics p. 105-107
Zhou J Reniers G (2018a). A matrix-based modelling for fire induced domino effects. Process Safety and Environmental Protection 116:347-353
Zhou J Reniers G (2018b). Petri-net evaluation of emergency response domino triggered by fire. Journal of Loss Prevention in the Process Industries 51:94-101

AREA	CHEMICAL CLUSTER
Eemsdelta	Delfzijl
Geleen-Sittard	Chemelot
Zeeland/kanaalgebied Gent-Terneuzen	Zeeland
Rotterdam/Botlek	Rotterdam-Rijnmond Pernis Botlek Europoort Maasvlakte Dordrecht
Moerdijk	Moerdijk
Amsterdam	Amsterdam

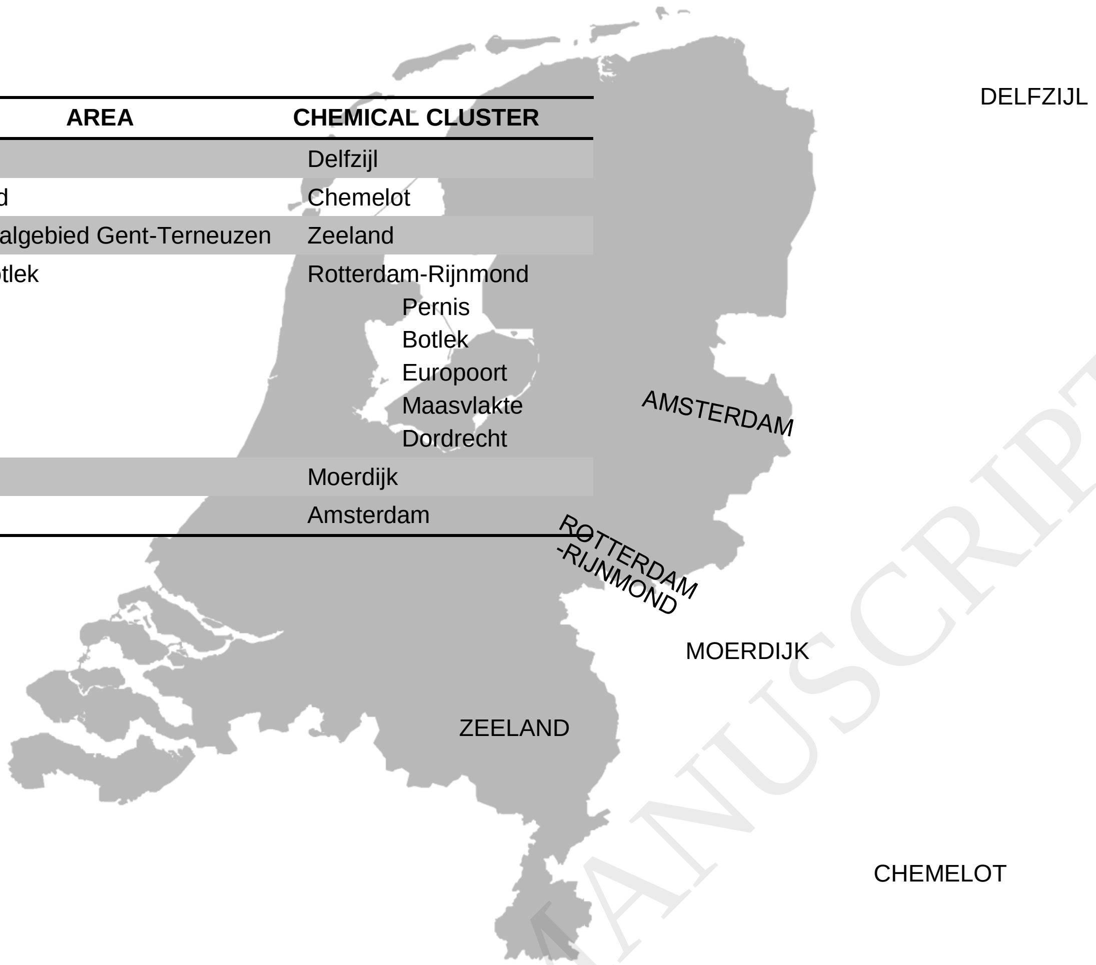


Figure 1 Chemical clusters in the Nederlands

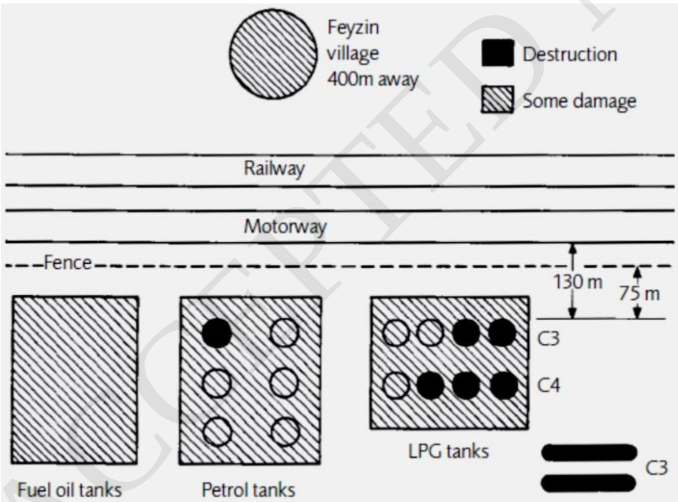


Figure 2 The tank park of the Feyzin refinery (IChemE, 1987)

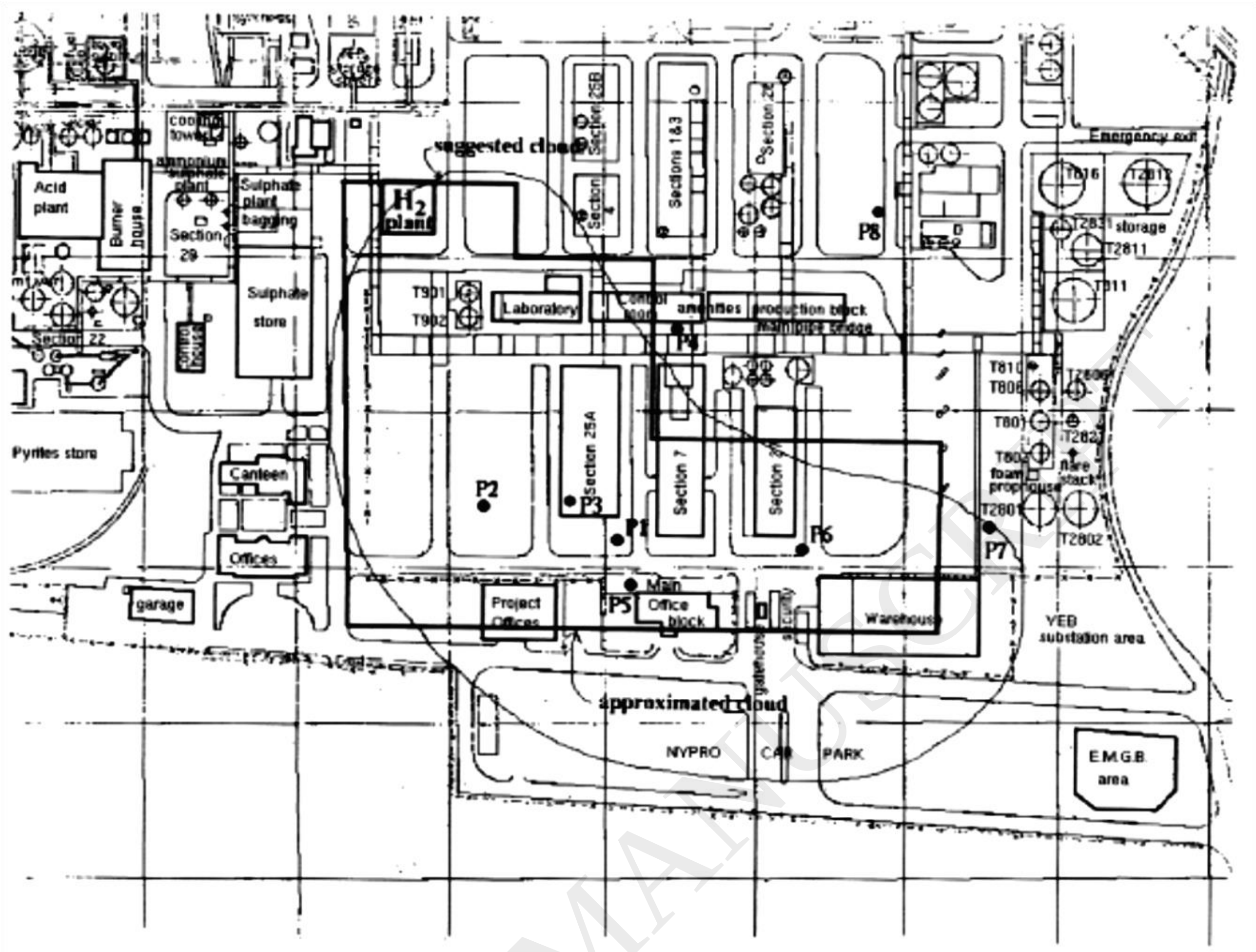


Figure 3 Nypro Ltd in Flixborough The 'banana line' represents the size of the gas cloud (Lees, 1980)

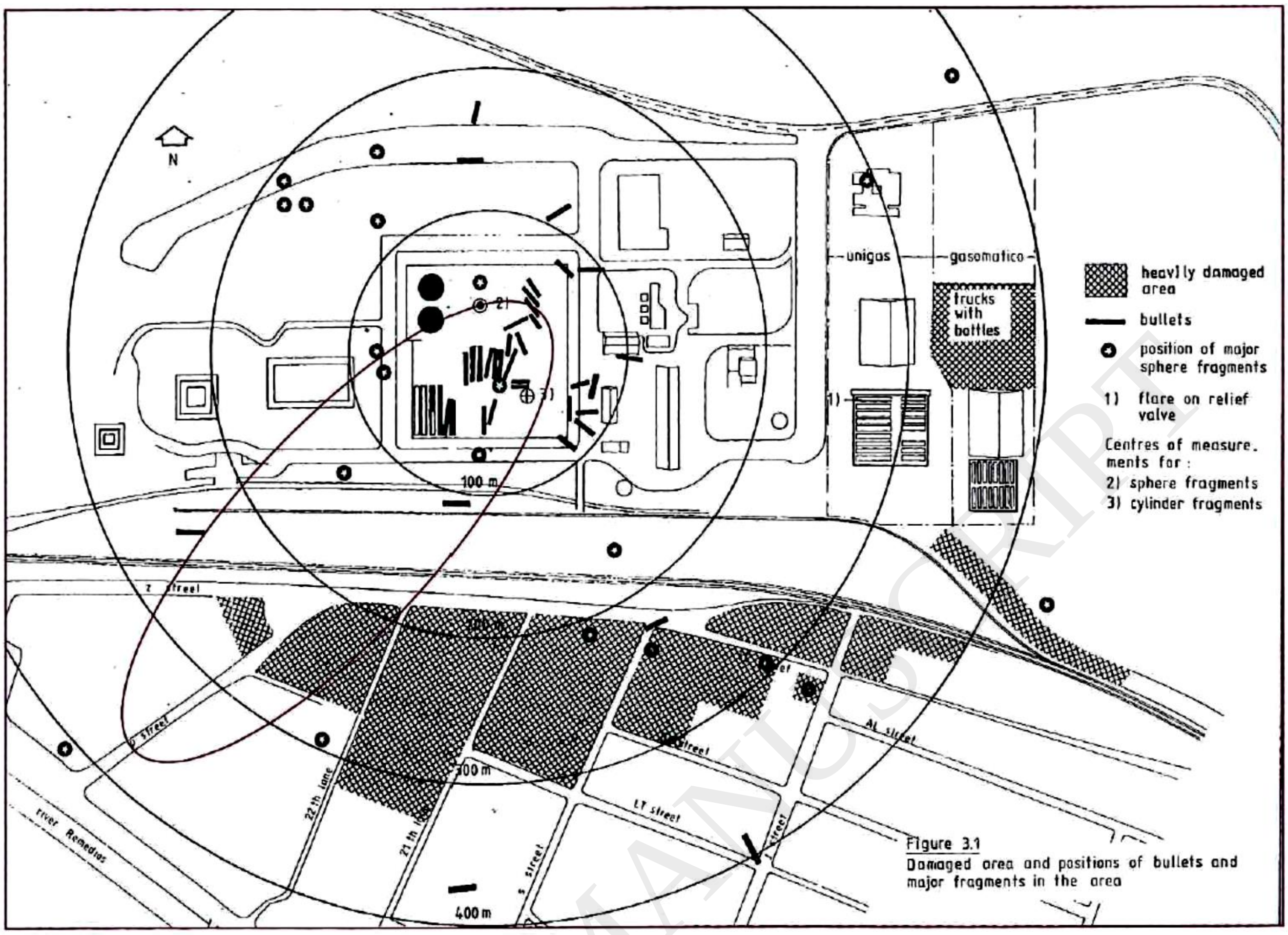


Figure 4 PEMEX location Mexico City, heavy damaged area (shaded) and the fragments. Globally, the initial gas cloud has been drawn (Pietersen, 2009)

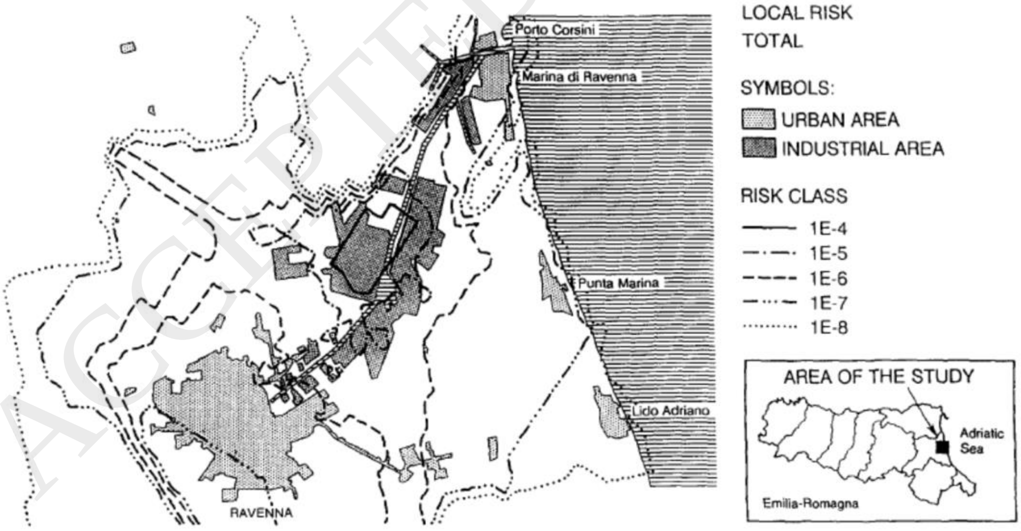


Figure 5 Overall risk contours ARIPAR project (Egidi et al., 1995)

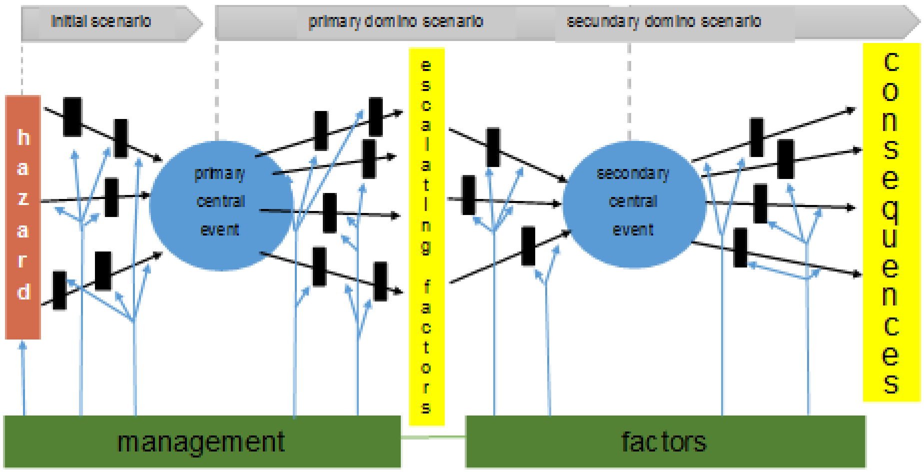


Figure 6 A domino effect bowtie consisting of two domino events

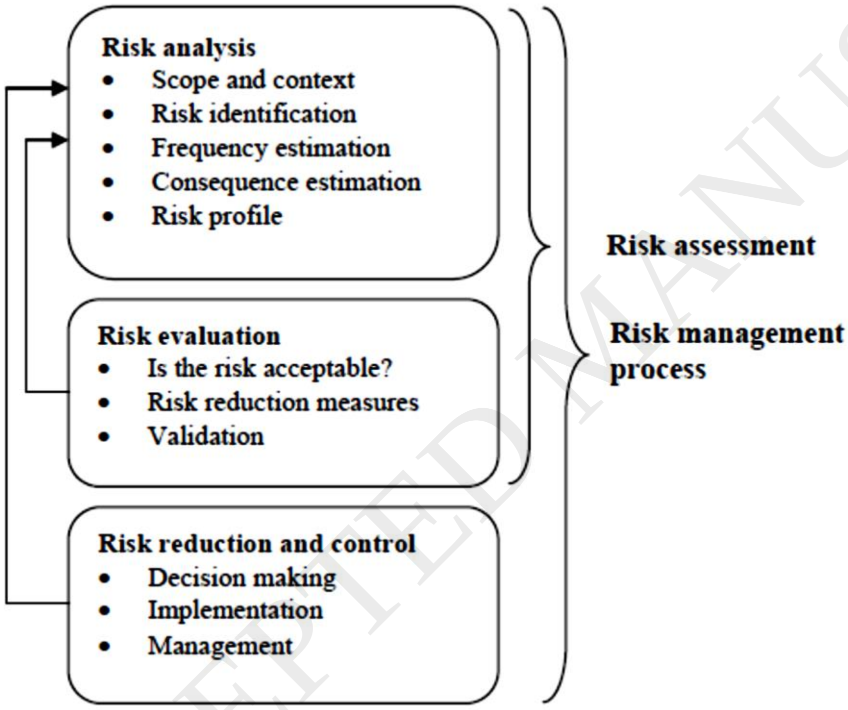


Figure 7 The risk management process (from Kardell and Lööf, 2014)

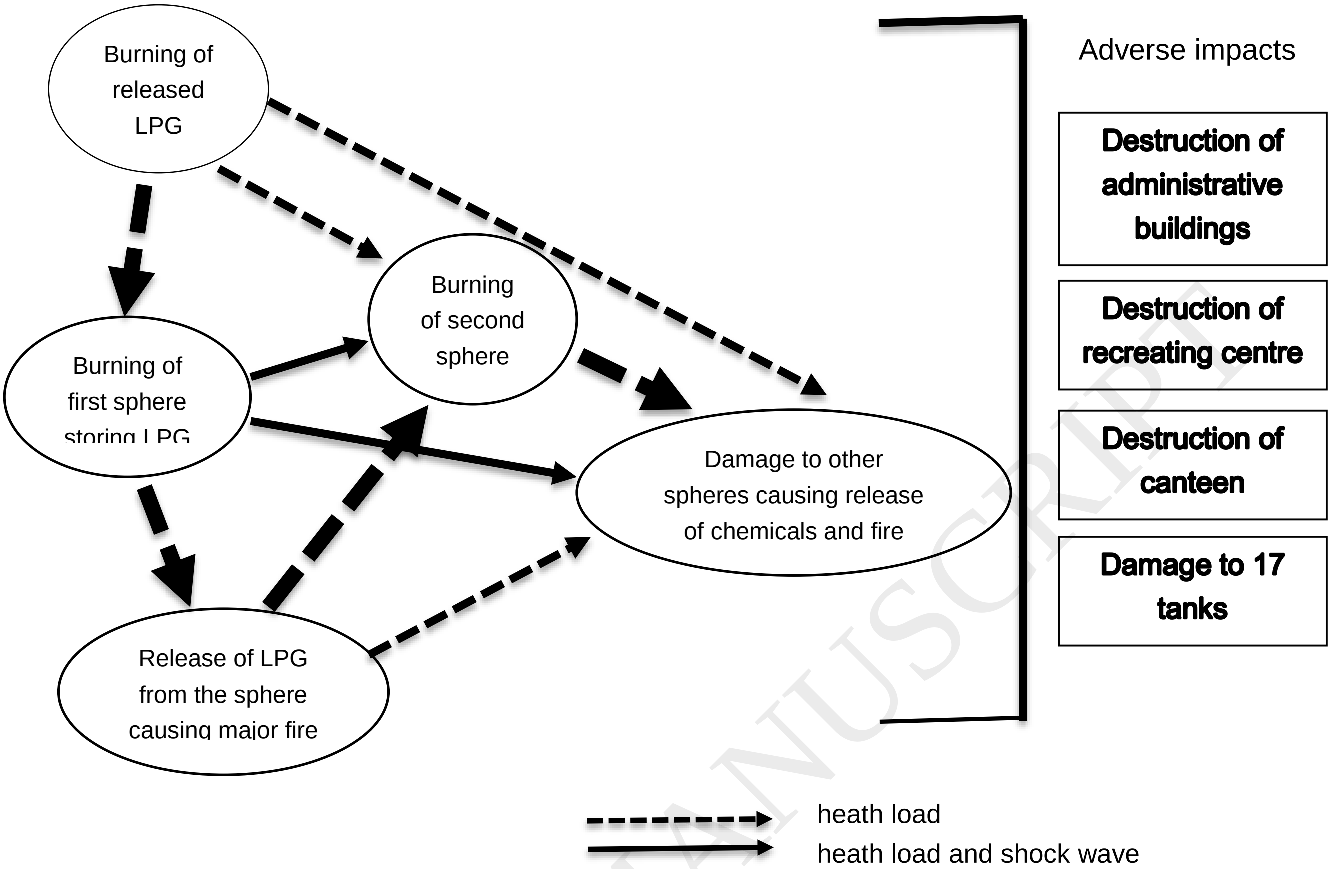


Figure 8 Most probable sequence of events leading to the HPCL's Vishakhapatnam disaster (after Khan and Abbasi, 1998a) The thickness of the lines represents the intensity of the heat load impact

Table 1 Escalating factors and expected secondary scenarios (Salzano and Cozzani, 2012)

(1) expected scenarios are also dependant on hazards of chemicals

(2) A primary failing reactor vessel can lead to other scenarios (e.g. pool fire, BLEVE, toxic emission)

Table 1 Escalating factors and expected secondary scenarios (Salzano and Cozzani, 2012)

Primary scenario	Escalation vector	Expected secondary scenarios[1]
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[2]	fragments, overpressure	any
Confined explosion[2]	overpressure	any
BLEVE	fragments, overpressure	any
VCE	overpressure, fragments	any
Toxic release	concentration	none

(1) expected scenarios are also dependant on hazards of chemicals

(2) A primary failing reactor vessel can lead to other scenarios (e.g. pool fire, BLEVE, toxic emission)