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Dynamic Risk Assessment and Management of Domino Effects and Cascading Events in the Process Industry

CHAPTER TWO

Domino effects in chemical factories and clusters, risk in the eye of the beholder: an historical perspective and discussion

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Contents

2.1 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).

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This chapter 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 focuses on these transitions in our knowledge, and determinants of complicated accident processes, leading to domino effects.

The Netherlands has a favorable business climate for the chemical sector. There are direct lines between the most important chemical centers in the Netherlands, Belgium, Germany, and northern France. Six of those chemical clusters are active (Fig. 2.1). 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 cluster is integrated via pipelines, roads, and water and railways (EPCA, 2007a). A chemical cluster is a geographically defined area within which various chemical devices are located, whether or not surrounded by nonchemical devices. The cooperation between these institutions can be absent, lightly, or intensively organized. 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

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

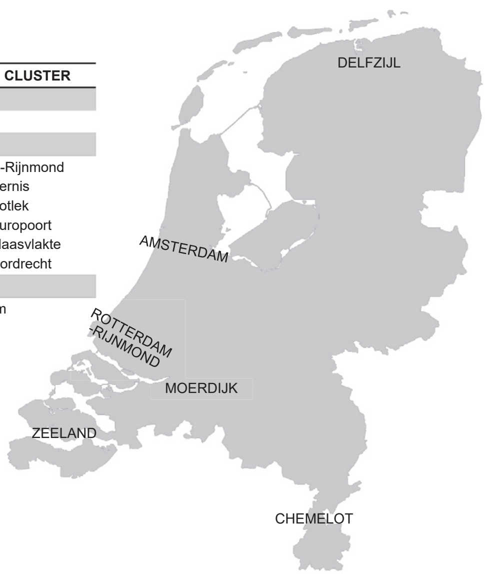

Figure 2.1 Chemical clusters in the Netherlands.

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 escalation 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 coauthors 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 coauthors 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 vector 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 compared to major accidents its probability of occurrence is very low.

2.2 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 Loss 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 gray literature is reviewed: research reports and available government documents. The search has resulted in more than 100 articles and documents.

After the World War II a massive upscaling of the chemical industry takes place in Western countries. The production capacity, storage, and transport of hazardous materials increase 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 ,coauthors 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 1990s. 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 modeling and risk assessment of domino effects (e.g., via Bayesian network and Petri nets), modeling 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."

2.3 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 not a trigger for research into domino effects (Khan and Abbasi, 1998a).

2.3.1 First period, 1966–95

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.

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 (Fig. 2.2).

The resulting fire starts a domino effect in spherical storage tanks. This leads one and a half hour later to a fireball, a BLEVE, a boiling liquid expanding vapor explosion, and flying fragments cause several BLEVEs. The fire weakens the legs of spherical storage tanks and tilts them, but these tanks do not explode. A number of petroleum and crude oil tanks catch fire. The water spray system is activated, but does not function adequately (Lees, 1980; IChemE, 1987; HSE 2010; Török et al., 2011).

The second major accident happens 1 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 Lincolnshire, 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 (Fig. 2.3). This major accident too is an internal domino effect (Parker, 1975; Lees, 1980; Høiset et al., 2000; Venart, 2004).

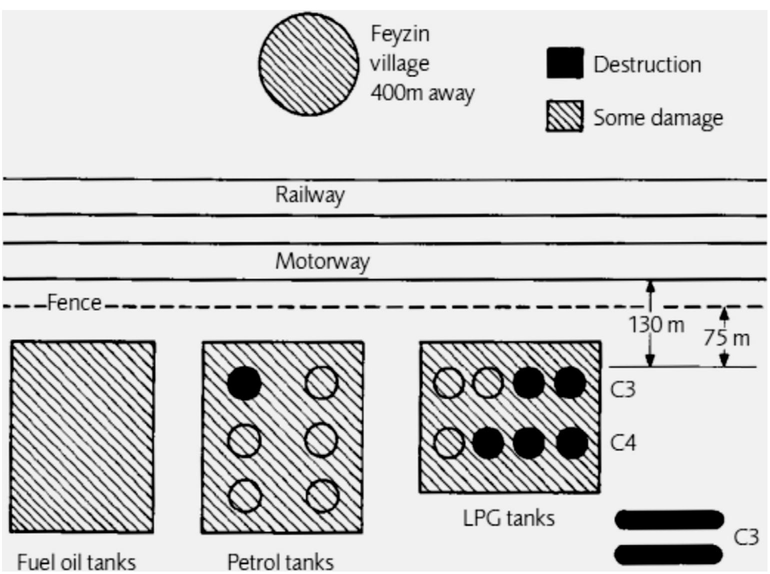

Figure 2.2 The tank park of the Feyzin refinery (IChemE, 1987).

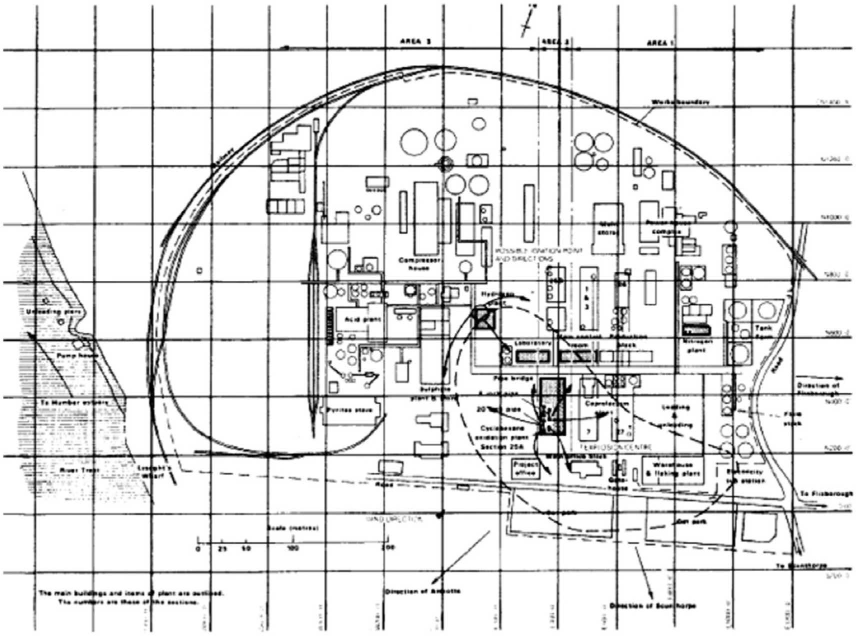

Figure 2.3 Nypro Ltd. in Flixborough. The "banana line" represents the size of the gas cloud (Lees, 1980).

In the early 1970s, the concept of risk makes its appearance in safety science, also initiated by the Flixborough disaster. In the Netherlands the so-called colored 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 (PRA) methods 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 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 hydrodesulfurizer of Shell. Domino effects are not included in this study.

A third major disaster of an internal domino effect takes place 10 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 thorns 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 (Fig. 2.4) (Pietersen, 1988; Lees, 1996). This is the worst ever recorded domino effect; some 650 people lost their lives.

Another disaster, 4 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., 2018). In the late 1990s the "safety integrity levels (SILs)" are added (Chaarlwood and Turner, 2004).

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 transshipment, 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.

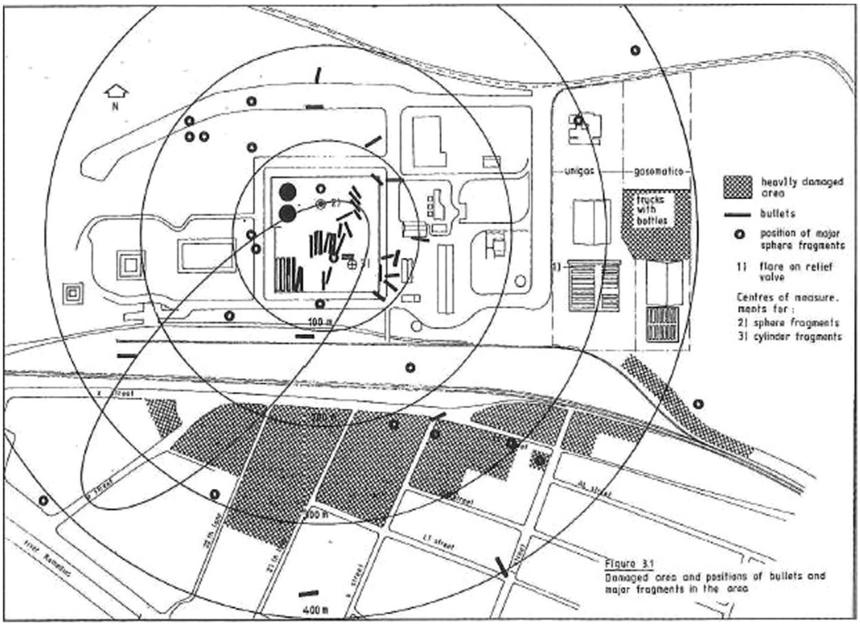

Figure 2.4 PEMEX location Mexico City, heavy damaged area (shaded), and the fragments. Globally, the initial gas cloud has been drawn (Pietersen, 2009).

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 have made a significant contribution to the risk contours (Fig. 2.5). The risk contribution is limited to locations where the road is close to inhabited areas (Egidi et al., 1995).

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 visualize these accident processes is a so-called double bowtie (Fig. 2.6). 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 (light gray in printed version) rectangle in the middle of the figure.

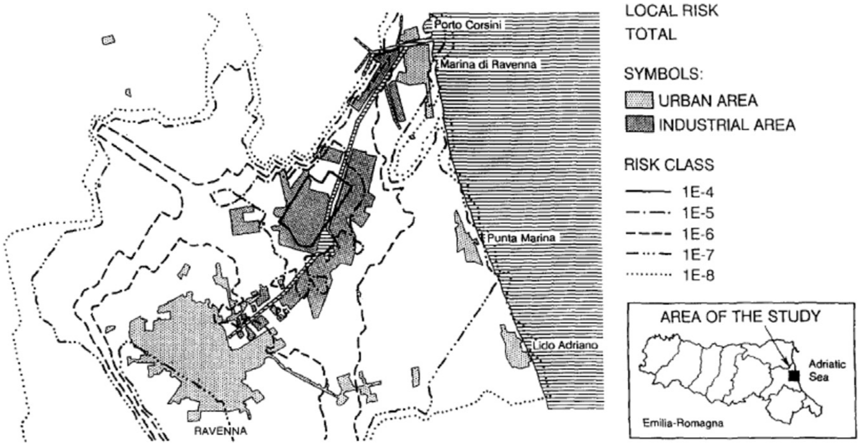

Figure 2.5 Overall risk contours ARIPAR project (Egidi et al., 1995).

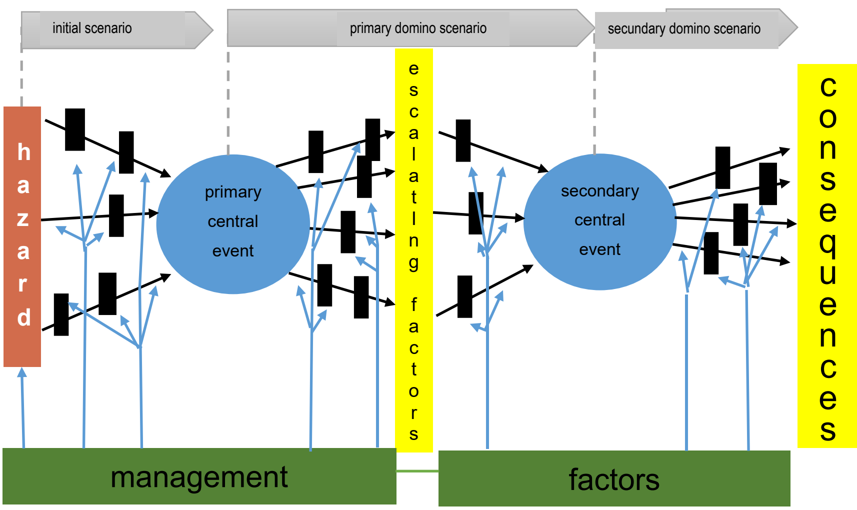

Figure 2.6 A domino effect bowtie consisting of two domino events.

According to the above definition of Cozzani and co-authors (2006, 2007), the propagation of dominos starts with these escalating factors, physical effects, that 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 (light gray in printed version) 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 (dark gray in printed version) rectangles at the bottom of the figure, influencing the quality of barriers, scenarios, and hazards through the blue (gray in printed version) vertical arrows. The blue (gray in printed version) lines represent nonphysical or organizational and human aspects. To manage domino effects adequately, both primary and secondary domino scenarios should be controlled.

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 modeling 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, or release of 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 counterproductive (Macgill and Snowball, 1983; Quarantelli, 1984; Swuste et al., 2016a).

2.3.2 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.

The first study provides an overview of 207 chemical major accidents between 1960 and 1998. 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 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 a "loss of containment" (LOC), leading to an explosion, or a fire with or without an explosion. These fires are not very frequent in maneuver 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). The third study 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 nonflammables, like CO_2, Cl_2, and overheated water, have created explosions and subsequent domino effects.

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-Melilli-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).

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 colored 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 to 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 5 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).

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, nonconfidential 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 keywords: 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 Fig. 2.6 inherent safe design represents the blue (gray in printed version) 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 m, while 300 m 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 focusing 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 is a major topic in literature.

2.3.3 Third period around Seveso III, 2012–18

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 modeling 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.

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 to 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 2.1) (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 a heat source might ignite (Necci et al., 2015).

Table 2.1 Escalating factors and expected secondary scenarios (Salzano and Cozzani, 2012).

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	Any
Confined explosion[b]	Overpressure	Any
BLEVE[b]	Fragments, overpressure	Any
VCE	Overpressure, fire impingement	Any
Toxic release	Concentration	None

[a]Expected scenarios are also dependent on hazards of chemicals.
[b]A primary failing reactor vessel can lead to other scenarios (e.g., pool fire, BLEVE, toxic emission).

Another point is 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 m between parallel pipelines appears to be sufficient (Ramirez et al., 2015; Silva et al., 2016).

As in the second period, modeling 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 belief 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 modeling 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).

In this third period, more attention is paid to barriers that can influence or control primary and secondary domino scenarios and to risk management (Fig. 2.7).

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

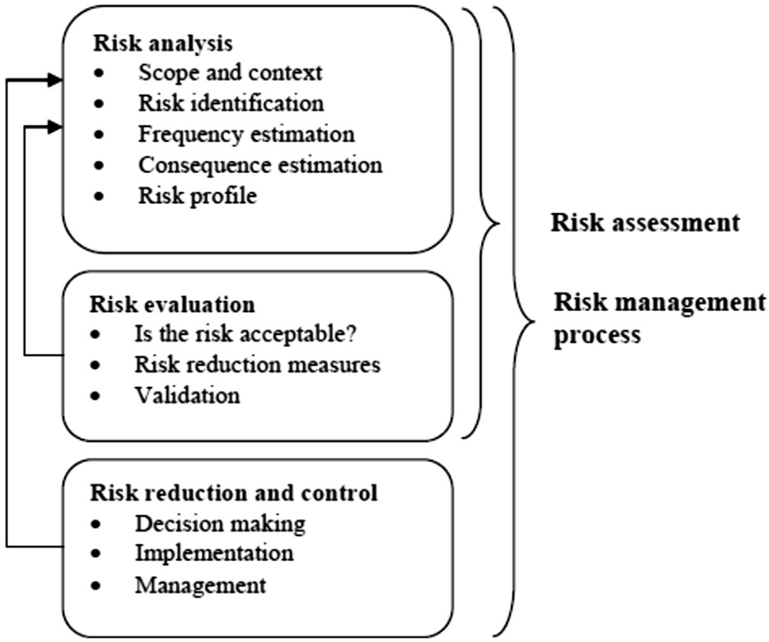

Figure 2.7 The risk management process. *From Kardell, L., Lööf, M., 2014. QRA with Respect to Domino Effects and Property Damage Report 5461. Lund University, Sweden.*

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. Modeling these responses and efficiencies in fire-induced domino effects are tested using Timed Colored Hybrid Petri nets (TCHPNs) (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 bowtie model in Fig. 2.6.

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., 2015a,b, 2016, 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).

Advances in Bayesian network approaches (dynamic Bayesian network) and development of a variety of software tools for modeling and analyzing Bayesian networks have enabled dynamic risk assessment of domino effects. Dynamic modeling of domino effects, specifically, has revealed the limitation of conventional (static) modeling of domino effects in considering spatial-temporal dependencies and thus not resulting in the most probable sequence of events during a domino effect (Khakzad et al., 2018b).

To make the discussion more concrete, consider a hypothetical fuel storage plant consisting of three storage tank of gasoline, where tank fire at T1 as a primary event can lead to a domino effect (Fig. 2.8). Moreover, assume that the conditional escalation probabilities have been calculated as: $P(T2 = \text{fire} \mid T1 = \text{fire},\ T3 = \text{safe}) = 0.4$; $P(T2 = \text{fire} \mid T1 = \text{fire},\ T3 = \text{fire}) = 0.6$; $P(T3 = \text{fire} \mid T1 = \text{fire},\ T2 = \text{safe}) = 0.3$; and $P(T3 = \text{fire} \mid T1 = \text{fire},\ T2 = \text{fire}) = 0.5$.

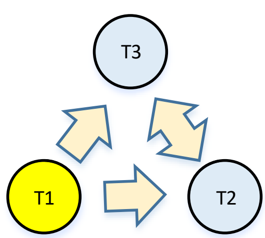

Figure 2.8 A gasoline storage plant consistent of three atmospheric storage tanks.

Considering event tree as one of the most popular QRA technique for determining the outcome of an undesired event (initiating event), one may develop the event tree in Fig. 2.9A to identify both the sequence of events and their probability given the tank fire at T1 whereas another one may come up with the event tree in Fig. 2.9B.

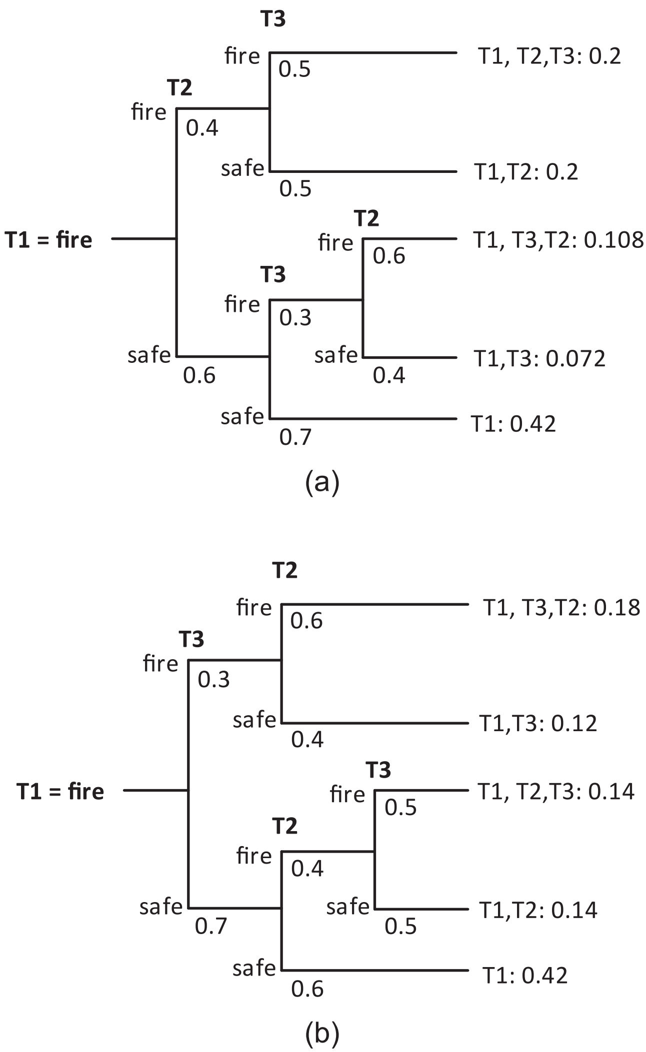

Figure 2.9 Event tree analysis for identifying the sequence of events given a primary tank fire at T1. Both the event trees are equivalent but resulting in different probabilities for the same sequence of events.

As can be seen, despite the fact that both event trees are logically equivalent, they result in different probabilities for the same sequence of events. For instance, the probability of P(T1 = fire, T2 = fire) has been calculated as 0.2 using Fig. 2.9A but 0.14 using Fig. 2.9B. Further, in Fig. 2.9A, the most probable path of fire spread is identified as T1 → T2 → T3 with a probability of 0.2 while in Fig. 2.9B the most probable path of fire spread is T1 → T3 → T2 with a probability of 0.18. As pointed out in Khakzad et al. (2018b), such discrepancy in the outcomes of conventional (static) QRA techniques arises mainly due to the limitation of such techniques in modeling mutual dependencies which does not allow for considering all possible sequences of events during domino effects.

Dynamic Bayesian network is a flexible and robust technique for effectively alleviating the foregoing drawback of conventional techniques. Fig. 2.10 depicts a dynamic Bayesian network (the left panel) developed for modeling the domino effect in the fuel storage plant in which the mutual interaction of T2 and T3 has been modeled using two time intervals. (Application of Bayesian network and dynamic Bayesian network to domino effect assessment is discussed in more detail in Chapter 3).

Given the same conditional escalation probabilities and taking advantage of probability updating aspect of Bayesian networks, the probability of different sequences of events can be calculated as P(T1, T2, T3) = 0.14, which is consistent with the one in Fig. 2.9B, P(T1, T3, T2) = 0.108, which is consistent with the one in Fig. 2.9A, P(T1, T2) = 0.28, P(T1, T3) = 0.18. The probability of simultaneous fire escalation to T2 and T3 is also calculated as P(T1, T2-T3) = 0.12. For instance, by instantiating the states of T1 = fire, T2 = fire, T3 = safe, T2_1 = fire, and T3_1 = fire as the evidence in the dynamic Bayesian network (left panel), the probability of evidence, which is P(e) = P(T1 = fire, T2 = fire, T3 = fire) = 0.14, has been calculated as shown on the right panel.

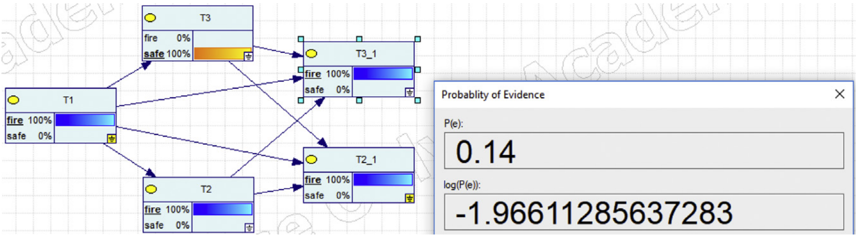

Figure 2.10 Application of dynamic Bayesian network to domino effect modeling in the fuel storage plant.

Aside from the modeling and risk assessment of accidental domino effects, a rather recent trend is research to security issues in relation to intentional domino effects (e.g., those triggered by terrorists) in the process industry (Argenti et al., 2018; Casson et al., 2018; Hossainnia et al., 2018; Landucci et al., 2015a,b; Reniers et al., 2015; Reniers, 2014; Zhang and Reniers, 2018; Zhang et al., 2018).

2.3.4 Central and Southeast 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 1970s. In India a major accident at a refinery near Vishakhapatnam in the late 1990s plays a similar role in Central and Southeast Asia. The neighboring country China has 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 centers. Despite major accidents in these sectors, these accidents did not seem to play a similar role as the domino accident in Vishakhapatnam, 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 Andhra 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 min later an adjacent storage tank explodes, followed by several tanks (Fig. 2.11).

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 m from the tank farm and the reporting of the initial leak 1 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

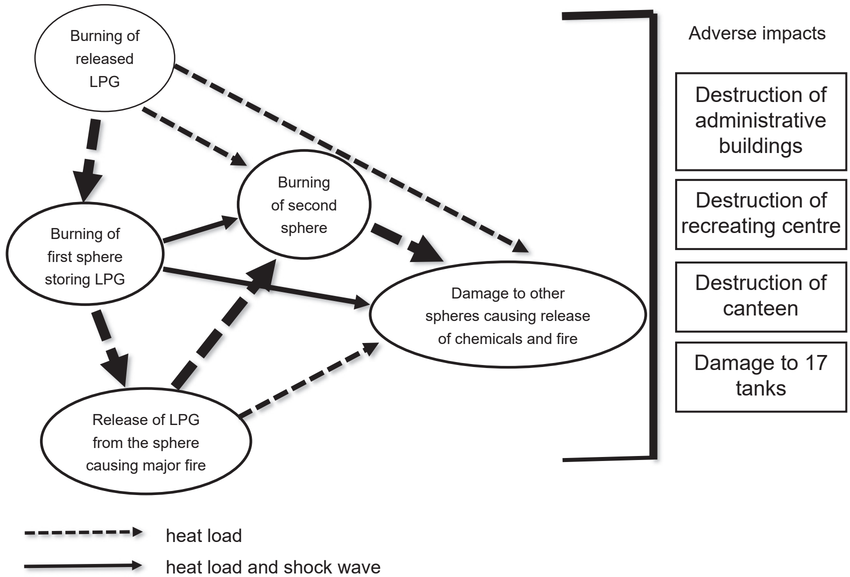

Figure 2.11 Most probable sequence of events leading to the HPCL's Vishakhapatnam disaster (after Khan and Abbasi, 1998a). The thickness of the lines represents the intensity of the heat load impact.

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).

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). 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).

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 is published 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 nonfailure 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 behavior of the system (Abdolhamidzadeh et al., 2010).

2.4 Discussion and conclusions

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 influences 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).

As we demonstrated in the previous section via a numerical example, even for a very simple case study the application of Bayesian network and conventional QRA techniques (event tree in this case) can result in totally different escalation probabilities and thus different sequences of most probable events. Such differences, however, do not come from the uncertainties in the input probabilities but rather from the perspectives of the modeler (the beholder) in interpreting the domino effect and his preferences in choosing among the available models. Nevertheless, as was shown in the example, the application of Bayesian network seems to result in more consistent results as compared with contradictory results of event tree analysis.

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 QRAs. Among 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 shown in 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 creates 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 30 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 seem to have played a role. There is a fairly constant production of articles about dominos from this country.

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