

DEVELOPMENT AND VALIDATION OF A FRAMEWORK FOR ASSESSMENT OF DOMINO RISKS IN PROCESS INDUSTRIES

A Thesis submitted to the

UPES

For the award of

Doctor of Philosophy

In

Health Safety & Environmental Engineering

By

Arun P A

December 2024

SUPERVISOR

Prof. Syed Mohammad Tauseef



School of Advanced Engineering

UPES

Dehradun- 248007, Uttarakhand, India

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DECLARATION

I declare that the thesis entitled “**Development and Validation of a Framework For Assessment of Domino Risks In Process Industries**” has been prepared by me under the guidance of Prof. S M Tauseef, Associate Dean Research & Professor of Sustainability Cluster, UPES, Dehradun. No part of this thesis has formed the basis for the award of any degree or fellowship previously.

A handwritten signature in dark ink, appearing to read 'Arun P A', with a horizontal line underneath the name.

Arun P A

SAP ID- 500033521

CERTIFICATE

I certify that Arun P A has prepared his thesis entitled “**Development and Validation of A Framework For Assessment of Domino Risks In Process Industries**”, for the award of Ph.D. degree from **UPES**, under my guidance. He has carried out the work at the Sustainability Cluster, **UPES**.

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ABSTRACT

Major accidents in chemical process industries often involve a phenomenon of cascading effects known as domino effects in chemical process industries. These events are known to cause massive losses to people, the environment, and property. To control the risks of domino effects, we must effectively assess the risks of domino accidents. Though active research in this field was initiated in the late 90s, since then many frameworks, models tools, and techniques have been developed to assess and manage the risk of domino effects in chemical process industries, however, most Quantitative Risk Assessment studies (QRA) do not address risks posed by domino effects. Most of the modern techniques and frameworks were developed with little input from industry professionals. This led to a lack of acceptability of these tools and techniques among professional practitioners.

To meet the enhanced energy requirement, especially in developing countries more industrial complexes are being created leading to proximate positioning of industrial plants, increased handling of dangerous goods, and transit networks. Past accident analysis also suggests that the occurrences of domino effects are increasing in developing countries like India and China. The lack of specific legal regimes to govern the domino risks adds to these countries' accident vulnerability. The overall aim of this work is to bridge the gaps between industry and academia domino risk assessment practices by developing an industry-friendly framework with advanced risk assessment capabilities. Quantitative risk assessment of domino accidents has been challenging owing to the complexities involved in the accident propagation and data scarcity due to low probabilities of occurrence of these incidents. Chapter 1 of this thesis discusses the problems in detail, the research gaps identified, and the objectives framed for this study. The literature review of past accidents in chemical process industries, existing tools and techniques for domino risk assessment, various guidelines for risk assessment, and country-specific legal requirements related to major accident prevention are presented in Chapter 2.

A four-phase methodology was developed to achieve the objectives set for this study, which is detailed in Chapter 3. Academically popular tools for domino risk

assessment were identified using a systematic review of domino effect research from the Web of Science database using keywords. The search yielded 177 publications, based on the analysis of these documents this work categorizes the domino risk research into two periods; publications before and after 2015. A sharp rise in the number of publications during the later period was observed. Detailed discussion on the research trends in domino effects and tools identified are presented in Chapter 5. To analyze past accidents, we often rely on accident databases. This chapter compares the functionality of the recently launched Indian chemical industry database (CAIRS) with other well-known accident databases and its efficacy by performing past accident analyses.

The study showed that domino risk assessment research is active using graphical methods. The most popular graphical tools identified were Bayesian Networks, Dynamic Bayesian, and Petri-nets. These advanced risk assessment techniques were applied in a common tank farm for domino risk assessment. Traditional techniques such as ETA, FTA, and FMEA are incapable of modeling intricate domino escalations. Bayesian Network-based analyses are not capable of modeling temporal evaluations of domino effects. Based on this study, it was identified that both DBN and Petri-net models are better equipped to model domino risks. Considering the more computational time requirement and resource scarcity of Petri-nets, Dynamic Bayesian Network-based modeling is best suited for the present-day studies of domino risk assessment. The efficacy analysis of these tools is presented in chapter 6.

The current industry practices in domino risk assessment, needs & expectations of the industry were identified using an online survey. 48 QRA professionals from different parts of the world, with diverse backgrounds and experience levels, participated in the survey. The survey results are presented in chapter 7. The survey brought into light the tools and guidelines used by the industry. It was acknowledged that 78% of QRA professionals do not assess risks posed by domino effects in their QRA studies. The needs & expectations of the industry from the perspective framework

were identified. The self-rating given by QRA professionals in advanced and recently emerged risk assessment techniques such as Bayesian analysis, Petri-nets, and Fuzzy logic were also collected during the survey.

By analyzing the industry inputs and efficacy analysis of domino risk assessment tools, a two-stage approach was devised for assessing the risk of domino effects in chemical process industries. As the comprehensive risk assessment of domino risks is time-consuming and expensive, the first stage of risk assessment involves domino risk screening. For this, an innovative fuzzy-based risk-screening tool was developed as detailed in chapter 8. The membership functions were framed by analyzing the past 30 years of accident data. The developed tool was applied in past accident case studies and was able to accurately predict the domino risk.

The second stage involved a comprehensive domino risk assessment, which comprised of two activities; domino frequency estimation and domino risk estimation. This work proposed a methodology for determining domino frequency using dynamic Bayesian analysis, by slightly modifying existing QRA procedures. By adding a few extra steps to the existing QRA one can easily determine domino frequency with the help of QRA software. The proposed methodology offers an industry-friendly framework for the assessment of domino risks. The results of the developed methodology are validated with a case study consisting of six tanks. The methodology development and validation are presented in chapter 9. The developed framework is in line with current QRA practices followed by the industry and it meets most of the industry requirements. Chapter 10 summarizes the conclusions of this research work.

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CHAPTER 1

INTRODUCTION

Title of thesis- Development, and validation of a framework for assessment of domino risks in process industries

1.1 Statement of the proposal

1.1.1 Problem statement-

Process safety has been a great concern since the commencement of industrialization. Catastrophic accidents viz. Flixborough, England (1974), Seveso, Italy (1976), and Bhopal, India (1984) brought about significant changes in safety regulations and gave new impetus to research on process safety (Klein, 2009). Globally enforcing and advisory bodies such as AIChE (American Institute of Chemical Engineers), CCPS (Center for Chemical Process Safety), HSE (Health and Safety Executive), EFCE (European Federation of Chemical Engineering) came up with new concepts or regulations to manage safety in process industries. Despite these advances, major accidents are still happening around the globe. BP Texas oil fire (2005), fire in Indian oil corporation, Jaipur (2009), Amuay refinery explosion, Venezuela (2012), Tianjin storage tank explosion (2015), NTPC Unchahar power plant explosion (2017), Intercontinental Terminal Company (ITC) Tank Fire in Texas (2019), Fertilizer plant explosion Jiangsu, China (2019), ONGC Navi Mumbai plant fire (2019), LG Polymers Vizag gas leak (2020), Beirut explosion (2020), are a few examples of it.

Past accident analysis has shown that a major accident seldom happens standalone (Khan and Abbasi, 1999b; Abdolhamidzadeh, Abbasi, D Rashtchian, *et al.*, 2011). An initiating fire can result in more fires and/or explosions, similarly, an explosion may lead to a chain of accidents leading to a major accident. “An accident in which a primary unwanted event propagates within an equipment, or/and to nearby equipment, sequentially or simultaneously, triggering one or more secondary unwanted

events, in turn possibly triggering further (higher-order) unwanted events, resulting in overall consequences more severe than those of the primary event” is known as Domino accident. (Reniers and Cozzani, 2013a). Table 1.1 summarizes some of the devastating process safety accidents that occurred in the last 100 years. As one can infer from this table the past accident analysis of chemical process industry accidents also revealed that the majority of catastrophic accidents in chemical and process industries involve domino effects (Khan and Abbasi, 1999b; Mannan *et al.*, 2016).

Table 1.1 Characteristics of some major process accidents

Year	Location	Chemical /Unit	Event Sequence	Fatality	Other effects
1917	Canada	Ammunition ship	F-E-F-ship Collision –F-E	1800	8000 injured
1947	Texas City, US	Ammonium Nitrate	F-E-E	552	3000 injured
1974	Flixborough, UK	Cyclohexane	VCE	28	76 injured
1984	Mexico City,	LPG storage tank	VCE- Multiple BLEVE	650	6400 injured, 31 M\$ damage
1984	Bhopal, India	MIC	Chemical leakage	3787	>500k people injured
2005	Texas City	BP Refinery	VCE – F	15	180 injured, 1 B\$ damage
2009	Jaipur, India	IOCL refinery	F-VCE- multiple pool fires and Explosions	13	>200 injured 500,000 evacuated 40 M\$ damage
2015	Tianjin, China	Explosive flammable storage &	F-E-E	165	798 injured, 9 B\$ loss
2021	Leverkusen, Germany	Liquid chemical waste	Mechanical explosion-VCE-chemical leak	7	31 injured, Environmental Emergency

Kiranoudis & Markatos (2000) analyzed 207 major chemical accidents up to 1998 and concluded that the probability of occurrence of domino accidents is 39%. As detailed in subsequent sections, domino accident analysis is challenging owing to the complex mechanism involved, the requirement of refined input data, and data scarcity due to the low probability of domino incidents. At present research in this field are focused on modeling and management of domino incidents, most of the risk assessment models so developed are with little input from industry personnel. This gap is leading to the non-acceptability of these models among the industry community. The proposed work aims to bridge this gap, development of a user-friendly framework for domino risks will enable us to assess and manage risks more effectively and control any undesired events.

1.1.2 Background

Due to the complex mechanics involved in domino accidents, there is no universally accepted definition for domino accidents, however, it involves a cascading effect, the leakage or failure in one unit affects adjacent units of the same or nearby facility (Reniers and Cozzani, 2015) where the damage radius of the domino accident is much larger than the primary accident standalone. Different domino accident definitions used by various researchers are summarized in Table 1.2.

Table 1.2 Definitions of Domino Accident

Author(s)	Domino Accident Definition
“Third Report of the HSC Advisory Committee on Major Hazards. HSE UK, 1984”	<i>“The effects of major accidents on other plants on the site or nearby sites.”</i>
Bagster and Pitblado (1991)	<i>“A loss of containment of a plant item, which results from a major incident on a nearby plant unit.”</i>
(Lees, 1996)	<i>“An event at one unit that causes a further event at another unit.”</i>
(Faisal I Khan and Abbasi, 1998)	<i>“A chain of accidents or situations when a fire/explosion/missile/toxic load generated by an accident in one unit in an industry causes secondary and higher order accidents in other units.”</i>
Delvosalle (1996)	<i>“A cascade of accidents (domino events) in which the consequences of a previous accident are increased by</i>

Author(s)	Domino Accident Definition
	<i>the following one(s), spatially as well as temporally, leading to a major accident.</i> ”
Purple book	<i>“The effect that loss of containment of one installation leads to loss of containment of other installations.”</i>
(Arendt and Lorenzo, 2000)	<i>“An accident which starts in one item and may affect nearby items by thermal, blast or fragment impact.”</i>
Vallee (2002)	<i>“An accidental phenomenon affecting one or more installations in an establishment which can cause an accidental phenomenon in an adjacent establishment, leading to a general increase in consequences.”</i>
(European Parliament and Council of the European Union, 2003)	<i>“A loss of containment in a Seveso installation which is the result (directly and indirectly) of a loss of containment at a nearby Seveso installation. The two events should happen simultaneously or in very fast subsequent order, and the domino hazards should be larger than those of the initial event.”</i>
(Mannan, 2004)	<i>“A factor to take account of the hazard that can occur if leakage of a hazardous material can lead to the escalation of the incident, e.g. a small leak which catches fire and damages by flame impingement a larger pipe or vessel with subsequent spillage of a large inventory of hazardous material.”</i>
(Cozzani, Gubinelli and Salzano, 2006)	<i>“Accidental sequences having at least three common features:</i> <i>(1) a primary accidental scenario, which initiates the domino accidental sequence;</i> <i>(2) the propagation of the primary event, due to an escalation vector generated by the physical effects of the primary scenario, that results in the damage of at least one secondary equipment item; and</i> <i>(3) one or more secondary events (i.e. fire, explosion and toxic dispersion), involving the damaged equipment items (the number of secondary events is usually the same as the damaged plant items).”</i>
(Bozzolan and Neto, 2007)	<i>“An accident in which a primary event occurring in primary equipment propagates to nearby equipment, triggering one or more secondary events with severe consequences for industrial plants.”</i>

Author(s)	Domino Accident Definition
(Gorrens <i>et al.</i> , 2009)	<i>“A major accident in a so-called secondary installation which is caused by failure of a so-called external hazards source”</i>
(Antonioni, Spadoni and Cozzani, 2009a)	<i>“The propagation of a primary accidental event to nearby units, causing their damage and further secondary accidental events, resulting in an overall scenario more severe than the primary event that triggered the escalation.”</i>
(Reniers and Cozzani, 2013a)	<i>“An accident in which a primary unwanted event propagates within an equipment (‘temporally’), or/and to nearby equipment (‘spatially’), sequentially or simultaneously, triggering one or more secondary unwanted events, in turn possibly triggering further (higher-order) unwanted events, resulting in overall consequences more severe than those of the primary event”</i>

Reniers and Cozzani, (2013b) categorize domino effects into the following

- **Internal:** *“Begin and end of the escalation vector characterizing the domino event are situated inside the boundaries of the same chemical plant”.*
- **External:** *“Begin and end of the escalation vector characterizing the domino event are not situated inside the boundaries of the same chemical plant”*
- **Direct:** *“The domino event happens as a direct consequence of the previous domino event”.*
- **Indirect:** *“The domino event happens as an indirect consequence of a preceding domino event, not being the previous one”*

Quantitative risk assessment of domino accidents has been challenging owing to the complexities involved in the accident propagation and data scarcity due to low probabilities of occurrence of these incidents. Though Bagster and Pitblado (1991) developed a QRA framework for domino effects risk assessment, breakthrough research in the field of quantitative risk assessment of domino effects had happened only in the last 20 years, starting with the works of Khan and Abbasi in the late 1990s and early 2000s. They developed a computer-aided tool called DOMIFFFECT for domino risk assessment, which was the first reported tool for domino risk assessment (Jun, Hui and Yuan, 2015). Since then numerous approaches, methodologies, tools, and

techniques were developed by various researchers to manage the risk of domino effects. Process safety has been an active area of research in the past and exponential growth in a number of publications was observed in the last 5 years. Bibliometric analysis of research on process safety by Md. Tinajin and Khan (2019) showed that 62% of analyzed documents were related to methodological development for risk assessment. Swuste *et al.* (2019) analyzed research publications on domino effects and depicted a historical overview of domino effects research by reviewing research on domino effects between 1966 and 2018. They classify trends in domino research into different timelines, coinciding with Seveso directives, which is comprehensive legislation in the EU dealing with the prevention of major accidents in the European Union and affiliated countries. Post-Seveso III directive in 2012, most research has been centered on creating methodologies for dynamic risk assessment. Current research mainly focuses on the formalization of advanced methodologies such as Bayesian techniques, Petri net, Monte Carlo Simulation, Game theory, etc.

1.1.3 Industrial Practices

QRA is a method for estimating the risks associated with the operation of an engineering process that is both formal and systematic. The findings quantify the risks to people, the environment, and the business. They aid in better decision-making by highlighting the accident scenarios that have the greatest impact on overall risk. QRA studies are performed to comply with legal and other requirements that the acceptability requirements have been met and that the residual hazards are as low as is reasonably practicable (ALARP) region (Smith and Simpson, 2020). Risk assessment professionals are using commercial software packages for performing quantitative risk assessment (QRA). Each software package comprises a series of default assumptions based on the developers' experimental and mathematical research. As a result, in some instances, the outcomes differ (Witlox *et al.*, 2018). At present, for most of the QRA studies, domino risk assessment is out of their scope, this is attributed to the fact that domino risk assessment is not a mandatory requirement as per current legislation in almost all countries except the European Union.

One of the leading QRA software developers is DNV, they illustrate a methodology (DNV, 2021) for domino risk assessment using PHAST software. However, it doesn't address how to handle the temporal effects of domino propagation, which is an important consideration when forecasting accident propagation, and modeling based on this methodology can be misleading sometimes.

A more detailed discussion of current industrial practices for domino risk assessment is presented in Chapter 7.

1.1.4 Research Gap

As stated earlier method development has been an active thrust area in domino risk research, through a detailed literature review we have identified two major gaps in existing research, are

1. Though several studies were conducted to develop new tools and techniques with advanced capabilities to assess domino effect risk, very limited work has been carried out to evaluate the relative performances of these tools.
2. Majority of modern tools and techniques were developed with little input from industry professionals. This led to a lack of acceptability of these tools and techniques among professional practitioners.

1.1.5 Motivation/need for research

The frequency of domino accidents in developing countries is increasing, whereas it is almost constant in developed countries, especially in Europe (Abdolhamidzadeh et al., 2011). This can be linked with the legal and technological advances they put in to improve safety in process industries. Post-Seveso III, the frequency of major accidents has reduced considerably in European Union countries. Article 9 of the Seveso Directive focuses on domino effects and requires the evaluation of potential domino effect scenarios in process facilities.

It is reported that proper risk assessment and management can effectively control the risks of domino effects. This work is a modest attempt to develop a framework for assessing risk related to domino accidents by addressing the gaps in research highlighted

in section 1.1.4. Analyzing the risks using advanced and industry-friendly methods can significantly help in managing risks posed by domino effects.

1.2 Objectives

- To identify various tools used in domino accident risk assessment by reviewing the literature.
- To analyze the efficacy of existing tools for domino accident risk assessment using case studies.
- To develop a framework for assessing domino risks in process industries by incorporating the requirements of the industry.
- To validate the developed framework with the help of case studies.

CHAPTER 2

REVIEW OF LITERATURE

Abstract

This chapter provides a concise summary of various literature reviewed during this work. Section 2.1 discusses the trends in process safety research, and challenges in domino risk assessment are detailed in section 2.2. Past accident analysis of chemical process industries is detailed in section 2.4. Section 2.5 details existing tools and techniques available for domino risk assessment, and various risk assessment standards are guidelines are briefed in section 2.6. Section 2.7 provides an overview of worldwide legislation for major accident prevention. Key takeaways from literature reviews are summarized in conclusions.

2.1 Trends in Process Safety Research

A comprehensive review of research articles on process safety was presented by (Amin, Khan and Amyotte, 2019). They reviewed 7164 documents published in Web of Science, Scopus, and Compendex. USA (684), China (590), Canada (409) Italy (324), and Germany (296) are the major contributing countries in the field of process safety. The leading contributors from developing nations are China and India with 590 and 230 documents. Other countries which have contributed to this field are Iran, Malaysia, Qatar, Portugal, and Saudi Arabia. The majority of the research is related to methodology development. They have also identified major sources of publication and individual contributors in the field of process safety. F. I Khan is the leading researcher in this field with 290 documents and 9848 citations followed by Mannan M S, Valero Cozzani, and Genserik Reniers.

Swuste, van Nunen, Reniers, & Khakzad, (2019) depicts a historical overview of domino effects research. They reviewed the research on domino effects between 1966 and 2018. They classify trends in domino research into different timelines, coinciding with Seveso directives. Post-Seveso III the majority of the research are focusing on the development of methodologies for dynamic risk assessment.

Li *et al.* (2017) presented a bibliometric analysis of publication in domino effects. They referred to publications indexed on Web of Science and identified countries, institutions, and authors who have significantly contributed to domino effect research. It has been reported that European countries have a larger share of publications, this can be attributed to the legislative requirements in the EU, where Seveso directives mandate to assess risk due to dominos. C. Chen, Reniers, & Khakzad, (2020) analyzed the past 30 years of accidents involving domino effects and proposed a new classification of approaches for modeling and managing domino accidents. This works also attempted to draw future directions in the field of domino accident research.

2.2 Challenges in Domino Risk Assessment

Domino risk assessment presents significant challenges due to the complexity and interconnectivity of potential accidents in industrial settings. These challenges can be attributed to various factors, as detailed below:

2.2.1 Complex Interactions and Escalation

Domino effects involve a sequence of events where an initial accident triggers subsequent incidents. This cascading nature complicates the prediction and modeling of such events, requiring comprehensive analysis of primary and secondary scenarios. The necessity to understand and predict these interactions accurately adds layers of complexity to risk assessment (Mandley et al., 2012; Cozzani et al., 2013).

2.2.2 Lack of Standardized Methodologies

Despite significant research, there is no universally accepted methodology for assessing domino scenarios. Different approaches, such as threshold methods, distance-based methods, and probabilistic models, each have their advantages and limitations. This lack of standardization can lead to inconsistencies in risk assessments (Mandley et al., 2012).

2.2.3 Data Requirements and Computational Resources

Effective domino risk assessment requires extensive data on plant layout, equipment, and operational conditions. This data must be integrated into sophisticated models that often demand significant computational resources. Advanced tools like Computational Fluid Dynamics (CFD) are useful but resource-intensive, which can be a barrier for some organizations (Cozzani et al., 2013).

2.2.4 Uncertainty and Variability

The inherent uncertainty in the occurrence and progression of accidents poses a major challenge. Factors such as weather conditions, equipment aging, and human factors introduce variability that must be accounted for in risk models. Bayesian methods and Monte Carlo simulations have been developed to address these uncertainties, but they require robust data and substantial computational power (Mandley et al., 2012).

2.2.5 Integration of Safety Systems

Assessing the effectiveness of preventive and mitigative safety systems is crucial but challenging. The interplay between different safety barriers and their collective impact on reducing risk needs to be thoroughly understood and quantified. Tools like ‘DOMIFFECT’ (Khan & Abbasi, 1998) and the domino-adapted version of ‘Aripar-GIS’ have been developed to help with this integration, but they are not without limitations (Mandley et al., 2012).

2.2.6 Regulatory and Practical Considerations

Regulatory frameworks such as the Seveso Directives highlight the importance of considering domino effects in risk assessments. However, aligning these regulatory requirements with practical industrial applications requires careful balancing of detailed risk analysis with manageable implementation strategies (Cozzani et al., 2013).

2.3 Escalation Vectors in Domino Effect Risk Assessment

The study of (Khan & Abbasi, 1998b) identifies two patterns for domino escalation and propagation, they are direct and indirect escalations. Direct escalations are caused by heat radiation, overpressure, or fragmentations. These escalation vectors when impacted with other installations cause direct damages leading to domino accidents. On the other hand, indirect escalation vectors refer to secondary mechanisms that, while not causing immediate physical damage, create conditions that facilitate further accidents, like, loss of process control due to the effect of a primary accident. Past accident analysis (Abdolhamidzadeh et al., 2011; Darbra et al., 2010; Khan & Abbasi, 1999) on domino accidents suggests that most of the domino effects are due to direct escalations and the scope of indirect domino escalations is limited to chemical industrial clusters where different companies operate.

Direct Escalation Vectors

The primary escalation vectors in domino effects are thermal radiation, blast waves, and fragment projection. These vectors are often interrelated and can have compounded effects on the surrounding environment and infrastructure.

Thermal Radiation

Thermal radiation from fires and explosions can cause secondary fires and structural failures in nearby equipment. For instance, a jet fire can emit significant heat, potentially igniting adjacent vessels or causing structural weakening of materials, which can lead to further leaks and explosions (Chen et al., 2017; Foroughi et al., 2021; Landucci et al., 2015). The intensity of thermal radiation is a critical factor in determining the extent of damage and the likelihood of secondary incidents (Cozzani et al., 2013).

Overpressure

Blast waves from explosions are powerful shockwaves that can cause substantial damage to nearby structures. The pressure from these waves can rupture vessels, displace equipment, and break containment systems, leading to additional releases

of hazardous materials. The assessment of blast wave impacts involves understanding the overpressure and impulse generated by the initial explosion (Mandley et al., 2012; Cozzani et al., 2013).

Fragment Projection

Explosions can project fragments of equipment and structural debris over considerable distances. These high-velocity fragments can puncture tanks, pipelines, and other containment systems, leading to further releases of hazardous substances. The size, speed, and trajectory of fragments depend on the nature of the initial explosion and the materials involved (Mandley et al., 2012)

Combined Effects and Interaction of Vectors

In real-world scenarios, these escalation vectors often interact, leading to more complex and severe outcomes. For example, an initial explosion (blast wave) may cause a fire (thermal radiation), which then heats adjacent vessels to the point of rupture, causing further explosions and fragment projection. Understanding these interactions is crucial for comprehensive risk assessments and the development of effective mitigation strategies (Cozzani et al., 2013).

In their study Alileche *et al.*, (2015a) discusses the lack of consensus and standardization in defining and assessing domino effects in industrial safety scenarios. Despite decades of awareness and some scientific progress, there remains a significant gap between academic understanding and practical implementation, with industries lacking clear guidance and authorities often focusing only on identifying potential impact areas. The author suggests that developing a shared definition of domino effects and agreed-upon threshold criteria for different equipment categories could significantly improve the assessment and prevention of severe cascading scenarios. Table 2.1 summarizes the escalation vectors & their threshold for domino escalation

Table 2.1 Escalation threshold (Alileche *et al.*, 2015a)

Scenario	Escalation Vector	Modality	Escalation Threshold
<i>Flash Fire</i>	Heat Radiation	Fire Impingement	Flame envelope
<i>Fireball</i>	Heat Radiation	Flame Engulfment	Atmospheric: $H > 100 \text{ kW/m}^2$
	Heat Radiation	Distant Radiation	Pressurized: Escalation Unlikely
<i>Jet Fire</i>	Heat Radiation	Fire Impingement	Flame envelope
	Heat Radiation	Stationary Radiation	Atmospheric: $H > 15 \text{ kW/m}^2$
	Heat Radiation	Stationary Radiation	Pressurized: $H > 45 \text{ kW/m}^2$
<i>Pool Fire</i>	Heat Radiation	Flame Engulfment	Flame envelope
	Heat Radiation	Stationary Radiation	Atmospheric: $H > 15 \text{ kW/m}^2$
	Heat Radiation	Stationary Radiation	Pressurized: $H > 45 \text{ kW/m}^2$
<i>VCE (Vapor Cloud Explosion)</i>	Overpressure	Blast Wave Interaction	Atmospheric: $P_s > 22 \text{ kPa}$
	Overpressure	Blast Wave Interaction	Pressurized: $P_s > 20 \text{ kPa}$
	Overpressure	Blast Wave Interaction	Elongated (Toxic): $P_s > 20 \text{ kPa}$
	Overpressure	Blast Wave Interaction	Elongated (Flammable): $P_s > 31 \text{ kPa}$
<i>Confined Explosion</i>	Overpressure	Blast Wave Interaction	Atmospheric: $P_s > 22 \text{ kPa}$
	Overpressure	Blast Wave Interaction	Pressurized: $P_s > 20 \text{ kPa}$
	Overpressure	Blast Wave Interaction	Elongated (Toxic): $P_s > 20 \text{ kPa}$
	Overpressure	Blast Wave Interaction	Elongated (Flammable): $P_s > 31 \text{ kPa}$
<i>Mechanical Explosion</i>	Overpressure	Blast Wave Interaction	Atmospheric: $P_s > 22 \text{ kPa}$
	Overpressure	Blast Wave Interaction	Pressurized: $P_s > 20 \text{ kPa}$
	Overpressure	Blast Wave Interaction	Elongated (Toxic): $P_s > 20 \text{ kPa}$
	Overpressure	Blast Wave Interaction	Elongated (Flammable): $P_s > 31 \text{ kPa}$
<i>BLEVE (Boiling Liquid Expanding Vapor Explosion)</i>	Missile Projection	Blast Wave Interaction	Fragment Impact
	Overpressure	Blast Wave Interaction	Atmospheric: $P_s > 22 \text{ kPa}$
	Overpressure	Blast Wave Interaction	Pressurized: $P_s > 20 \text{ kPa}$
	Overpressure	Blast Wave Interaction	Elongated (Toxic): $P_s > 20 \text{ kPa}$
	Overpressure	Blast Wave Interaction	Elongated (Flammable): $P_s > 31 \text{ kPa}$
<i>Point-source Explosion</i>	Missile Projection	Blast Wave Interaction	Fragment Impact
	Overpressure	Blast Wave Interaction	Atmospheric: $P_s > 22 \text{ kPa}$
	Overpressure	Blast Wave Interaction	Pressurized: $P_s > 20 \text{ kPa}$
	Overpressure	Blast Wave Interaction	Elongated (Toxic): $P_s > 20 \text{ kPa}$
	Overpressure	Blast Wave Interaction	Elongated (Flammable): $P_s > 31 \text{ kPa}$

2.4 Past Accident Analysis

Kiranoudis & Markatos (2000) performed statistical analysis of 207 major industrial accidents from 1969 to 1998 and based on the study the probability of occurrence of a domino accident was observed to be 39%. It was also concluded that the risk of causing a domino accident depends on the type of substance involved with it. The probability of a domino accident for vapor hydrocarbons and liquid fuels were 58% and 49 % respectively.

Khan and Abbasi (1999b) analyzed major process industry accidents that occurred between 1926- 1997. They reported that though the number of accidents per year declined after the 1980s, the loss estimated accidents is increasing trend. In process plants, 49% of accidents are due to fire and explosion and 38% are due to toxic releases. And fatalities per accident are 3.27 and 2.49 for fire & explosion and toxic release accidents respectively.

Abdolhamidzadeh, Abbasi, Rashtchian, Abbasi, & Mae (2011) analyzed 224 accidents involving domino effects from 1917 to 2019 and concluded that 80% of domino accidents are reported in fixed installations and 20% during transportation. Domino effects are often associated with flammable substances and the leading initiating causes of domino accidents are vapor cloud explosion/fire (VCE/VCF). The average number of fatalities per domino accident has increased from 1990-2000. Among developing countries, the maximum number of domino accidents was reported in India.

2.5 Tools for Domino Risk Assessment

The early works of domino risk assessments were based on simplified QRA. The works of (Bagster and Pitblado, 1991), (Latha, Gautam and Raghavan, 1992), (Gledhill and Lines, 1998), (Seeley, Pettitt and Schumacher, 1993) were based on limited data available at that period and provided a simplified model for domino risk assessment; though it can be used in preliminary risk assessments, the usage of these methods are now outdated. Advanced probit models were proposed by (Cozzani, Gubinelli and Salzano, 2006; Antonioni, Spadoni and Cozzani, 2009b; Alileche *et al.*,

2015a) specifying threshold values for different escalation vectors. Bayesian network-based modeling can be applied in a wide range of accident scenarios. Bayesian network-based models were developed by (Jun, Hui and Yuan, 2015; Chen *et al.*, 2017; Khakzad *et al.*, 2018). Monte Carlo-based models were developed by (Jun, Hui and Yuan, 2015; Sun *et al.*, 2016). Some software-based models were developed to determine the probability and risk estimates of accidents involving domino effects (Faisal I. Khan and Abbasi, 1998a, 1998b; Khan and Abbasi, 1999a; Reniers and Dullaert, 2007; Antonioni, Spadoni and Cozzani, 2009a) are a few of them.

2. 6 Risk Management /Assessment Standards

2.6.1 ISO: 31000:2018 Risk management – Guidelines:

This ISO standard provides customizable guidelines for risk assessment that can be applied in any organization irrespective of risk nature and size sector. ISO 31000 sets out principles, frameworks, and processes for risk management. The risk management process prescribed by this standard is illustrated in Figure 2.1

2.6.2 ISO: 31010:2019 Risk management — Risk assessment techniques

This document guides the selection and application of various risk assessment techniques. It also summaries the strengths & limitations of various risk assessment techniques so that users can take an informed decision about the right tool for their application. The document lists 31 techniques that can be used in risk assessment and discuss attributes of selection, input parameters required for study, the procedure to be followed, and expected outcomes. Some of the techniques listed in the document include FTA, HAZOP, FMEA, LOPA, Bayesian analysis, etc.

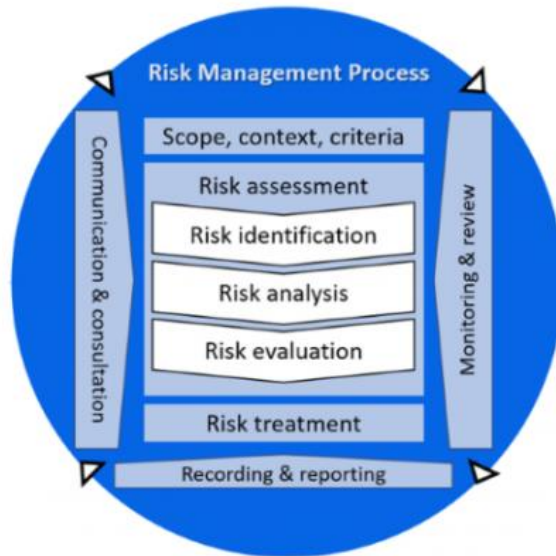


Figure 2.1 ISO Risk Management Process (International Standard Organization (ISO), 2018)

2.6.3 IEC/TR 61508 – Functional Safety

IEC 61508 is considered as the umbrella standard in functional safety. It specifies the standards for assuring that systems have been designed, implemented, operated, and maintained in order to deliver the required level of safety integrity (SIL). The risk associated with the system application is classified into four SILs, with SIL4 protecting against the most severe risks. This standard is having 8 parts.

2.6.4 IEC 61511- 'Functional Safety: Safety instrumented Systems for the Process Industry Sector

This is a performance-based standard that is specific to the process industry. It specifies the standards for specifying, designing, installing, operating, and maintaining a safety instrumented system (SIS).

2.6.5 ISO 26262- Road vehicles — Functional Safety

ISO 26262 standard was derived from IEC 61508. This is a twelve-part standard that is strictly for on-road vehicles, such as passenger vehicles, trucks, buses, and motorcycles, from conception to the manufacturing phase for electrical/electronic

systems. So it has limited application in domino risk assessment in chemical industries.

2.7 Worldwide legislation for major accident prevention

2.7.1 US – OSHA Process Safety Management Standard

The US Department of Labor's Occupational Safety and Health Administration created a regulation known as Process Safety Management in 1992. Process Safety Management of Highly Hazardous Chemicals, OSHA 1910.119, is the regulation's name (*Process Safety Management - Overview | Occupational Safety and Health Administration*, 2021) Its goal is to avoid or reduce the negative repercussions of release of hazardous substances, in the same establishment or nearby units. Industries that handle hazardous chemicals are expected to implement a PSM program that safeguards their employees, including contractors, and visitors. The OSHA PSM contains 14 elements

Standard 1910.119(e) addresses the Process Hazard Analysis (PHA), as per this requirement employers are qualitative assessment of the potential safety and health consequences of each of the identified hazards. This standard does not address domino risks in chemical process industries.

2.7.2 European Union – SEVESO Directives

The Seveso Directives are the primary legislation in the EU addressing the control of on-shore major accidents associated with dangerous substances. The latest of this directive ‘The Seveso III Directive’ came into effect on June 1, 2015. This is the only legislation in the entire world that mandates the domino risk assessment in Seveso establishments (“Directive 2012/18/EU” 2012). Article 9 of the Seveso Directive focuses on domino effects and requires the evaluation of potential domino effect scenarios in process facilities

2.7.3.1 China: State Administration of Work Safety (SAWS)

This Law is made to improve supervision as well as control over work safety in China, leading to the prevention of accidents that are caused due to absence of work

safety. As per the law, it is the responsibility of the local people's government at or above the county level to assign responsibilities and tasks regarding work safety and carry out periodic inspections in the production units located in their jurisdictional areas, where major accidents are liable to occur. When noticing hazards or any hidden hazards that may lead to accidents, the departments are required to deal with the matter immediately. When there are major hazards at the workplace that may pose threat to workers' safety and can cause major accidents, the supervisors have the right to suspend production and business operation until the hazard is eliminated and give orders to evacuate workers from the endangered zones. This law does not consider domino risks

2.7.3.2 China: PSM (AQ/3034-2010)

In China, the "Guidelines for chemical process safety management" standard (AQ/3034-2010) was made in line with OSHA PSM and it is having 12 elements. In August 2021 they have released a draft amendment of this standard and in that 8 new elements were added, one of the new elements added is safety management of major hazards. In the past, China has witnessed catastrophic chemical industry accidents the new standard aims to include more establishment categories under the ambit of the revised standard (*China releases industry standard "Guidelines for chemical process safety management" | Envilience ASIA*)

2.7.4 UK: COMAH- 2015

To implement the Seveso directive –III The Control of Major Accident Hazards Regulations (COMAH) 1999 was amended in 2015. The regulation applies to establishment operators and others such as local governments and emergency planners. In the revised law, emphasis has been given on domino risks. In terms of domino risks, the responsibility is broader, including a duty for domino group members to cooperate with neighboring sites to communicate relevant information (HSE UK,)

2.7.5 India: Manufacture, Storage and Import of Hazardous Chemical Rules (MSIHC)

This rule spells out the duties of the occupier which include the identification of major hazards in his facility, limiting their consequences, and providing training for employees. Employers shall prepare on-site emergency plans and coordinate with district authorities in preparing an off-site emergency plan. The rules do not address the domino effects related to major accidents (*The manufacture, storage and import of hazardous chemical rules*, 1989).

2.7.7 India: Chemical Accidents (Emergency Planning, Preparedness and Response) Rules

Hazardous chemicals have been classified based upon the criteria laid in part 1 Schedule 1. In Schedule 1 part ii, a list of hazardous chemicals. Threshold quantities of storage have to be considered, which is given in column 3 of schedules 2 and 3 respectively. It includes major accident installations like isolated storage and industry handling of hazardous chemicals on the site. Various crisis groups at different levels such as the central crisis group, state crisis group, district crisis group, and local crisis group formation have been mandated and their responsibilities are defined in this rule (MoEF, 1996)

2.8 Conclusions

Chapter 2 provides a comprehensive overview of the current state of research and practices in domino risk assessment within the process industries. The review highlights the significant contributions from various countries and leading researchers, illustrating the global interest and advancements in process safety. Key trends in research have been shaped by historical accidents and regulatory frameworks, notably the Seveso Directives, which have driven the development of dynamic risk assessment methodologies.

Despite advancements, the chapter identifies several challenges in domino risk assessment, including the complexity of interactions, the need for extensive data, and the lack of standardized methodologies. These challenges are compounded by the inherent uncertainties in accident progression, necessitating robust and flexible risk assessment tools.

The review of tools for domino risk assessment shows a progression from simplified QRA methods to more sophisticated models such as Bayesian networks and Monte Carlo simulations. These tools offer enhanced capabilities for modeling complex interactions and temporal evolutions in domino scenarios.

Risk management standards like ISO 31000 and IEC 61508 provide frameworks for general and functional safety, while specific standards for process industries ensure the reliability and safety of systems. However, only the Seveso Directives in the EU explicitly mandate domino risk assessment, highlighting a gap in global regulatory requirements.

The key takeaways from the literature review are,

- Past accident analysis suggests that, despite the advances we have made in terms of safety in process industries, major accidents are still happening around the globe, devastating consequences are observed when it involves a series of accident or cascading effect.
- Domino risk research is relatively new, with active research beginning in the late 90s. Consensus is being emerged among researchers on the usage of ‘**the domino effect**’ in accident scenarios involving cascading effects. The old literature in this field may not have used the term domino effects, hence it is important to use wider keywords to trace wider publications in this field.
- Literature review suggests research in this field is afforded by limited researchers, considering that the last bibliometric review on this field was

published based on data as of 2015, It would be interesting to know the recent research trends in this field.

- Though numerous methods and frameworks have been developed in the past when it comes to practice, the risk assessment studies in process industries do not address domino risks. The potential reasons for this lacuna are;
 1. Absence of legal requirements: No, countries or regions mandate domino risk assessment other than the European Union.
 2. The majority of modern tools and techniques were developed with little input from industry professionals. This led to a lack of acceptability of these tools and techniques among professional practitioners.
- Effective risk assessment and management strategies are crucial for mitigating the risks of domino effects. To facilitate this process, there is a pressing need for a comprehensive framework that can accurately model and quantify domino risks while remaining accessible and implementable within industrial contexts. Such a framework would bridge the gap between theoretical risk analysis and practical application, enabling stakeholders to make informed decisions and implement interventions to enhance system resilience.

CHAPTER 3

RESEARCH METHODOLOGY

Abstract

This chapter discusses the research methodology adopted for developing an industry-friendly framework for domino risk assessment. Section 3.1 provides an overview of the methodology. The subsequent section guides through the procedures and technical steps adopted in each phase.

3.1 Methodology Overview

This research used a four-phase approach for developing an industry-friendly framework for domino risk assessment in process industries. The different phases involved in the framework development are,

- Phase 1: Identification of tools for domino risk assessment
- Phase 2: Efficacy analysis of existing tools of domino risk assessment
- Phase 3: Identification of needs and expectations of the industry
- Phase 4: Development and validation of the framework

Phase 1: Identification of tools for domino risk assessment involved identifying tools being used by researchers for risk assessment for domino effects through systematic review and meta-analysis.

Phase 2: Efficacy analysis of identified tools involved a careful selection of domino risk assessment tools and evaluating the relative performance of these tools.

Phase 3: Identification of needs and expectations of the industry, involved collecting inputs from QRA professionals through interactions and surveys. Inputs and insights related to the current QRA practices, competencies on selected advanced risk assessment tools, and needs and expectations of the industry from the framework.

Phase 4: Development and validation of the framework involved preparation, validation, and refining of the framework based on inputs from phases 2 & 3.

The detailed methodology is illustrated in Figure 3.1

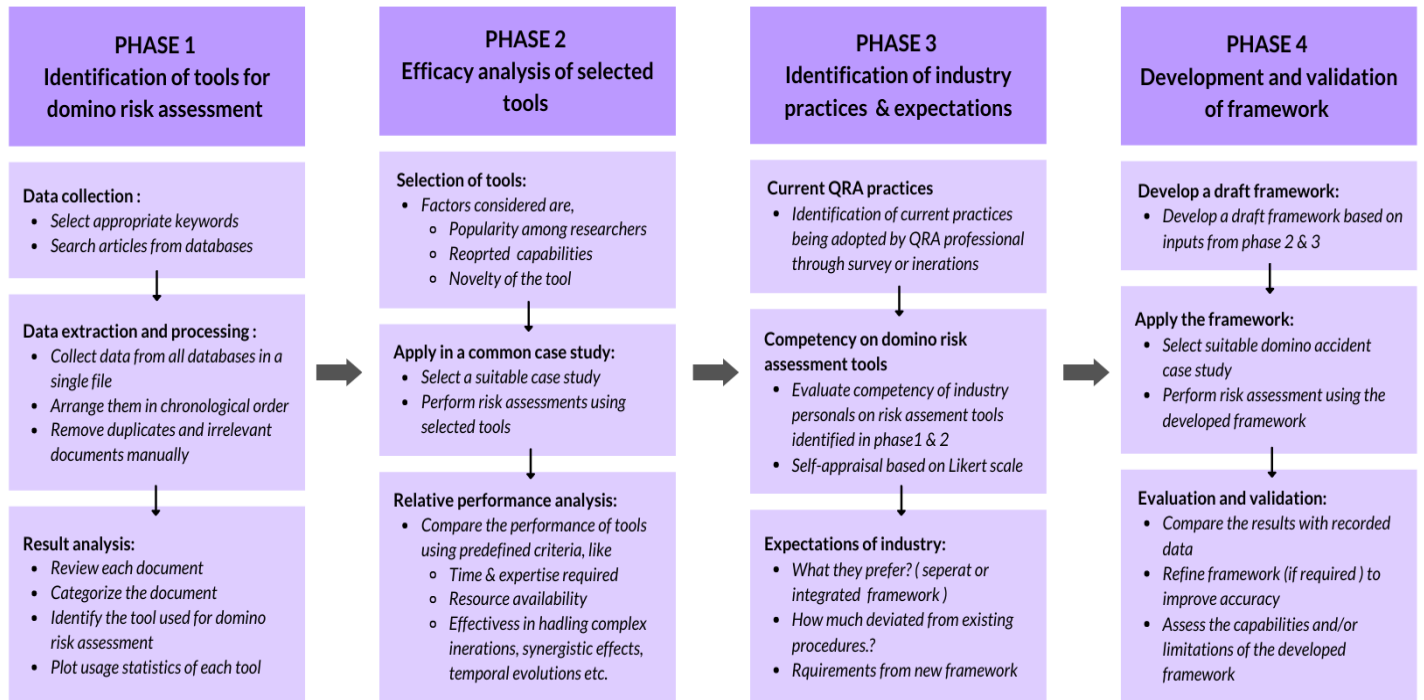


Figure 3.1: An overview of the research methodology

3.2 Methodology for identification of tools for domino risk assessment

To identify the tools for domino risk assessment and recent trends in domino risk assessment research a four-step approach based on a systematic review of the literature was framed as shown in Figure 3.2.

A systematic literature review can produce transparent and reproducible scientific results when compared to a traditional narrative study. It has been well-documented that studies based on these methods can result in reliable findings and reliable conclusions (Mengist, Soromessa and Legese, 2020; Zeng, Chen, Yang, Liu, *et al.*, 2020).

To conduct a detailed review of research trends in the domino effects and risk assessment tools, a four-step process for systemic review of literature. (Chen, Reniers and Khakzad, 2020; Zeng, Chen, Yang, Liu, *et al.*, 2020) was developed as shown in Figure 3.2.

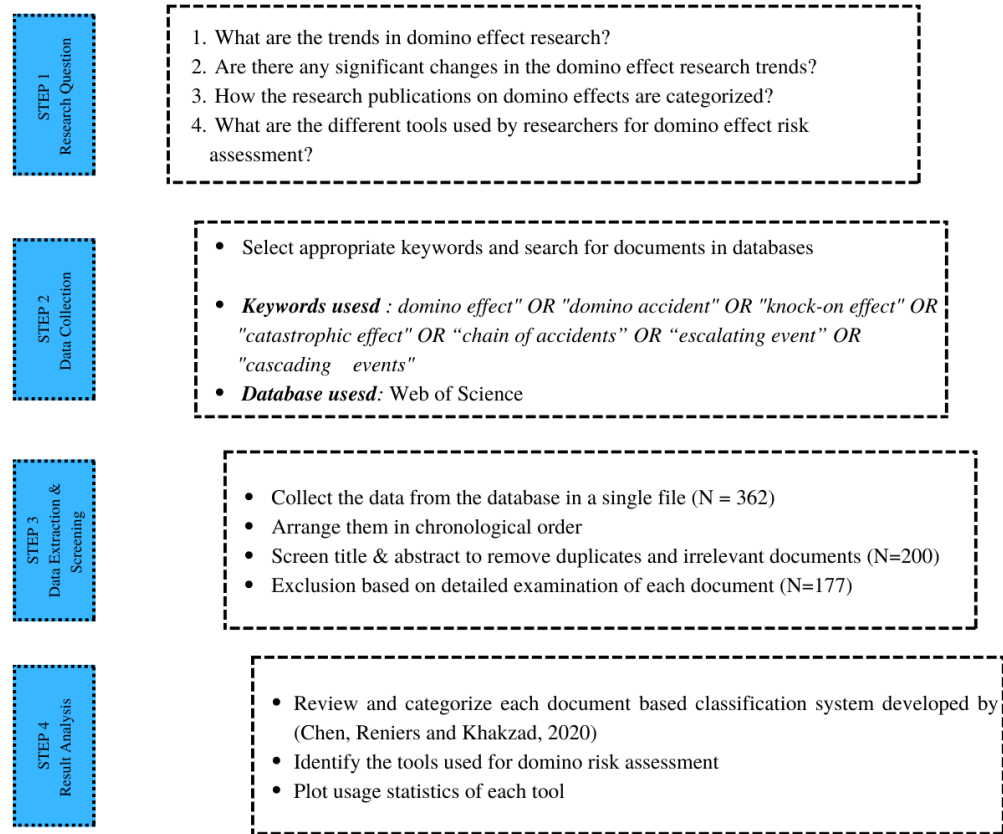


Figure 3.2 Methodology for the systematic review of literature

3.2.1 Research Questions

Based on the research objectives, the following research questions were framed.

1. What are the trends in domino effect research?
2. Are there any significant changes in the domino effect research trends?
3. How the research publications on domino effects are categorized?
4. What are the different tools used by researchers for domino effect risk assessment?

3.2.2 Data collection

Relevant articles were searched out from the Web of Science (WoS) database using keywords. This is an important step in data collection as the search results purely depend on the efficacy of the keywords used. In the past, researchers have used several keywords for searching documents in domino effects research (Li *et al.*, 2017; Swuste *et al.*, 2019; Chen, Reniers and Khakzad, 2020). In this study the following keywords were used; "**domino effect**" OR "**domino accident**" OR "**knock-on effect**" OR "**catastrophic effect**" OR "**chain of accidents**" OR "**escalating event**" OR "**cascading events**" on ECT index from 1998 to present. As indicated in the previous chapters the consensus is emerging in this field of research including the definition of '*domino effects*'; keywords other than "**domino effects**" are essential to identify early works in this field.

As the term domino effect is also popular in other disciplines such as computer science, certain categories of results such as computer science, medical science, etc. were excluded using the WoS category filter to refine the search results. This has been done to reduce labor during the manual screening stage of collected documents. The Web of Science database is known for including high-impact journals and reputable publications, ensuring that the literature included is of high quality and relevance. It was selected over other databases considering the credibility and reliability of the information available on the Web of Science, which is crucial for maintaining the standards of scholarly research on domino effects.

3.2.3 Data Extraction and Screening

The search using the above keywords yielded 362 articles, the details (full record feature) were exported to an Excel file. Then articles were arranged in chronological order. Initial scrutiny based on title, abstract screening, and removing duplicate entries, the number of articles was limited to 200, and from a further detailed examination of the collected articles, the relevant articles were found to be 177. A similar study by (Chen, Reniers and Khakzad, 2020) using different keywords and databases was able to capture 132 articles only.

3.2.4 Result Analysis

The collected articles were categorized based on a classification system proposed by (Chen, Reniers and Khakzad, 2020). To identify the research trends, bibliometric analysis was performed using co-citation network visualization methods using VOSviewer software.

3.3 Methodology for Efficacy analysis of tools for domino risk assessment

The efficacy analysis of Domino risk assessment tools involved three steps viz, tool selection, application in a common case study, and relative performance analysis as illustrated in Figure 3.1.

3.3.1 Tool Selection

The domino risk assessment tools are selected based on the following parameters

- Reported capabilities of the tool
- The popularity of the tool among the researchers.
- The novelty of the tool.

3.3.2 Case Study Selection & Application

The shortlisted tools will be applied in a common case study. A suitable case study, either a well-known domino accident case or a case study available in the literature will be selected. The selected case study should have all the information for performing the risk assessment before finalizing the case study it will be verified that all the information is readily available. The identified tools are then applied in that case study to perform the risk assessment.

3.3.3 Relative performance

Based on the identified capabilities and limitations of domino risk assessment tools a comparative study was performed. The following factors were considered while evaluating relative performance.

- Time & expertise required for the study
- Resource availability

- Input parameters required
- Effectiveness in handling complex interactions, synergistic effects, temporal evolutions, etc.

3.4 Methodology for Identification of Industry Practices and Expectations

In the absence of empirical data, expert judgment, and elicitation process are proven to provide valuable information about model parameter estimates to aid policy development and decision making; in the past, the expert elicitation methods have been used in many fields of research (Fischer *et al.*, 2014; Misuri, Landucci and Cozzani, 2020; Hadjigeorgiou *et al.*, 2022; Whiston *et al.*, 2022).

However, numerous techniques are available to conduct an expert elicitation process the most popular method is a survey-based method. In this work, a survey form was created with the help of Google Forms to collect the data. The data were analyzed to identify the current industry practices, and expectations of the industry. The survey questions were framed in consultation with three QRA experts having more than 10 years of professional QRA experience.

To identify the current industry practices in domino risk assessment and expectations of the industry, worldwide QRA professionals were invited to take part in an ad-hoc online survey. QRA professionals were individually approached for their willingness to participate in the survey. It is important to involve experts with diverse backgrounds to improve the accuracy of the results and draw meaningful conclusions (Hokstad, Øien and Reinertsen, 1998), experts from different industry roles (consultants, clients, EPC, contractors, etc.) and experience levels were approached for their input. The purpose and objectives of the survey were communicated to all participants through the introduction section of the survey.

The questions framed were categorized into three sections viz.

- Participants' demography
- Current domino risk assessment practices

- Competency & expectations of industry

3.4.1 Participants' Demography

This section was created to gather the demographic information of the participants. Questions were asked to collect information related to years of risk assessment experience, type of industry, designation, the organization they work for, and location of work.

Quantitative risk assessment, especially involving the domino effect requires in-depth knowledge about accident scenario selection, frequency estimation, etc. To negate the perceptions/misinformation of the novice QRA practitioners' responses from participants with less than 2 years of experience in risk assessment were not taken into account. Since the objective of this survey was to collect information about current QRA practices and needs & expectations of the industry, a linear weighting procedure, with the same weightage for each response was allocated. This simplified strategy was adopted to save computational time, while at the same time which meets the survey objectives.

3.4.2 Current QRA Practices

Responders were requested to select the tools that they use for QRA studies from the given list, and options included all major software (e.g. DNV PHAST, FLACS, ALOHA, Shepherd, and RISKCURVES). They were also provided with an option to mark '*others*' and enter the details if the tool they were using was not listed.

A similar question was asked to list the guidelines they refer to for QRA studies from a predefined list. Similar to the above question, responders can add a guideline if it was not listed.

Participants were asked to respond to some open and closed-ended questions related to current industrial QRA practices related to domino effects (e.g.

Do you consider domino accident scenarios while performing QRA? Describe how you select domino event sequences in QRA, Describe how you estimate the frequency & consequences of domino events in QRA. etc.)

Participants were given the option to leave the questions unanswered in some cases.

3.4.3 Needs, Expectations, and Competency of the Industry

In this section, questions were framed to identify the needs & expectations from the perspective framework and competency of the personnel in advanced risk assessment tools.

Questions were asked about their preferences (like whether they prefer a separate framework for domino risk assessment or a framework that is part of existing risk assessment studies), flexibility about deviations from the existing procedures on a Likert scale of 1-5, (1 - Not at all; 2- Slight; 3- Moderate; 4- Very; 5- Extremely). An open-ended question was asked to specify the top three requirements of the perspective framework.

Responders were asked to rate their competencies in advanced risk assessment techniques, which were selected from Phase 1 of the study. A Likert scale of 1-5 (1- Very Poor; 2- Below Average; 3- Average; 4- Above Average; 5- Excellent) was provided for rating. Participants' willingness to take part in the further framework development process was also collected.

The transcript of the survey is annexed at A4.

3.5 Methodology for Development & Validation of Framework

This section details the steps involved in the framework development and validation process.

3.5.1 Developing a Draft Framework

A draft framework for domino risk assessment was developed by analyzing the inputs from phases 2 & 3. In this work, a two-stage framework was developed. Stage 1 involved the developing framework for screening domino risk, and 2nd stage involved a comprehensive domino risk assessment framework.

3.5.2 Application of the Framework

A domino accident case study in literature with all relevant information was selected and a domino risk assessment was carried out using draft frameworks.

3.5.3 Evaluation & Validation

The results of risk assessment were compared with recorded data and based on the analogy of results the framework is refined to improve the accuracy or user-friendliness. Based on the study outcomes assess the capabilities and/or limitations of the developed framework.

CHAPTER 4

COMPARISON OF ACCIDENT DATABASES & PAST ACCIDENT ANALYSIS IN THE CHEMICAL PROCESS INDUSTRY

Abstract

This chapter compares the Indian chemical industry database, CAIRS with major global accident databases such as MHIDAS, eMARS, and FACTS. It compares the accident databases based on scope, accessibility, no of available accident records, information available, and process for updating the accident data. The past accident analysis for chemical process industries is also performed using eMARS and Indian databases. This study identifies recent major accident trends in Europe, the efficacy of the CAIRS database, and suggestions for improving its effectiveness.

4.1 Introduction

Though industrial accidents cause losses to human life, environment, and property, critical examination of these events can bring valuable information on accident morphology, and lessons learned from past accidents can prevent similar events in the future (Pike, 2017; Kletz and Amyotte, 2019). Accident investigation and follow-up of the results are vital in safety management systems, learnings from past incidents can help us to anticipate hazards and mitigate associated risks either by reducing the frequency and/or consequences of the event. With the help of accident investigation, the root cause of the accident can be identified and with corrective and preventive actions associated risks can be mitigated to make the workspace safer for everyone. To predict, identify, and mitigate industrial accidents, it is essential to gather and analyze past incident data. Research indicates that accident causes often get repeated (Khan and Abbasi, 1999b; Yilmaz *et al.*, 2020). By identifying frequently repeating patterns or causes, similar accidents can be

prevented in the future. The primary goal of past accident analysis (PAA) is to serve this purpose.

When processes are carried out at extreme temperatures and pressure, the probability of occurrence and severity of any undesired event would be extremely high. By properly analyzing the information obtained from past accidents, one can get to know the probable causes of failures and accidents in the chemical industry. Major accidents in the process industry are caused due to loss of containment due to process failures or due to natural events such as earthquakes, lightning, floods, etc., called Natech events. Unlike process equipment failure accidents Natech events can trigger accidents in the entire plant, most of the time the responses against these events are delayed due to lack of communication or non-availability of personnel leading to escalation of accidents. (Antonioni, Spadoni and Cozzani, 2009b; Krausmann *et al.*, 2011). Although we cannot completely safeguard against such natural disasters, we can find out the most vulnerable parts of the system and can add additional layers of protection for such installations. After identifying the vulnerable units/areas we can develop the system in such a way that it will have the least effect on such critical/vulnerable installations (Krausmann *et al.*, 2011).

The repeated disruption in a process industry can be an indication of a major fault that can lead to an accident. If these disruptions are more frequent, they raise questions about the risk controls in the organization. P.J.M. Sonnemans *et al.* analyzed industrial accidents from the FACTS database and concluded that repeated disruption can be considered a precursor to accidents, which indicates the failures in the control mechanism of the organization (Sonnemans and Körvers, 2006). By analyzing the past incident information it will become much easier to predict the common accident precursor in chemical process industries by looking at the factors like the chemical used, trends and chemical release mode, etc. (Koshy, Mallikarjunan and Raghavan, 1995).

Unlike other branches of science and technology, where experimental and analytical data are used; in accident analysis, performing experiments to forecast an

accident is a cumbersome task. The data we get from past accidents can be used to identify the root causes, which would help prevent similar accidents in the future. So it is important to analyze past accidents and learn from them so that the same situation is not repeated (Mannan, 2004; Abdolhamidzadeh, Abbasi, D. Rashtchian, *et al.*, 2011). Past accident analysis (PAA) is possibly the most powerful and frequently utilized activity for gaining insight into the reasons why accidents happen in the process industry. PAA gives important 'intelligence of knowing the past' with which techniques to forecast hazardous events or mitigate the effects of incidents can be planned (Khan and Abbasi, 1999b; Tasneem, M. and Abbasi S. A., 2010; Tauseef, Abbasi and Abbasi, 2011). Active research is being carried out in the field of accident analysis with the help of management tools and machine learning, incorporating data management tools such as Business Intelligence tools (BI Tools) in past accident analysis can provide valuable insights to develop business strategies and tactics (IAIANI *et al.*, 2021; Koklonis *et al.*, 2021; Nakhal A *et al.*, 2021; Nakhal *et al.*, 2021).

In the past India has been home to several chemical industrial accidents including the world's worst industrial disaster, the Bhopal gas tragedy. To collate the accident data systematically, the National Informatics Centre of the Ministry of Environment and Forest India, introduced a web-based accident reporting platform called Chemical Accident Information Reporting System (CAIRS). This chapter compares the functionality of this database with other well-known accident databases and its efficacy by performing past accident analyses.

4.2 Previous Works on Past Accident Analysis

Khan & Abbasi, in their work (Khan and Abbasi, 1999b) analyzed 3222 major accidents in chemical process industries reported between 1926-1997. Their study revealed that in process industries, 49% of accidents are caused by fire and explosions, and 38% by toxic releases. Their study concluded that, although the number of accidents per year decreased during the 1980s, the loss per accident is an

increasing trend. Fatalities per accident for fire/explosion and toxic release incidents are 3.27 and 2.49 respectively.

In the chemical industry, accidents involving cascading effects are known as domino effects, and often devastating destructions are caused by accidents involving domino effects. Predicting and forecasting a standalone accident is much easier than forecasting a domino effect by risk assessment which also requires past accident data. That is one of the reasons why very little work is being carried out on managing domino accidents in process industries, past accident analysis can provide valuable information to predict and manage domino effects in process industries (Abdolhamidzadeh, Abbasi, D. Rashtchian, *et al.*, 2011; Hemmatian *et al.*, 2014).

In their work (Kiranoudis and Markatos, 2000) conducted statistical research on 207 major industrial accidents from 1969 to 1998, and they identified that 39% of major accidents involve domino effects. The risk of domino accidents was determined to be dependent on the type of substance involved, and gaseous hydrocarbons pose (58%) more risk of causing domino accidents than liquid fuels (49%). Abdolhamidzadeh, *et al.* conducted another noteworthy study (Abdolhamidzadeh, Abbasi, D Rashtchian, *et al.*, 2011) on this topic by analyzing 224 accidents involving domino effects from 1917 to 2019 and concluded that 80 percent of domino accidents occur in fixed installations and 20% during transportation. Domino effects are frequently associated with flammable substances, and vapor cloud explosion/fire (VCE/VCF) is the most common initiating cause of domino accidents. Analysis of reporting trends indicated that domino accidents are more rigorously reported in developed countries. Among developing countries, India reports the highest number of domino accidents (34%) (Abdolhamidzadeh, Abbasi, D Rashtchian, *et al.*, 2011). Figures 1, 2, and 3 illustrate the domino accident reporting trends based on past accident analysis (Abdolhamidzadeh, Abbasi, D. Rashtchian, *et al.*, 2011).

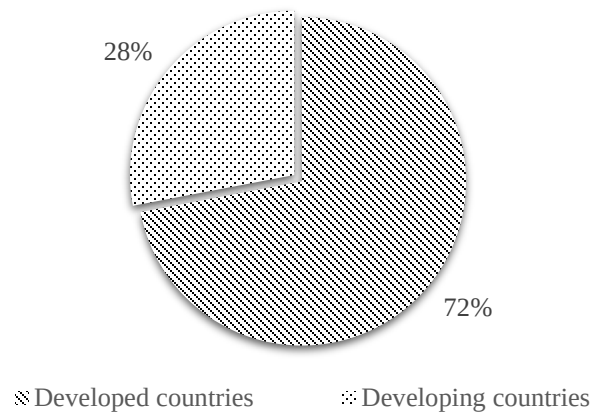


Figure. 4.1: Domino accident reporting

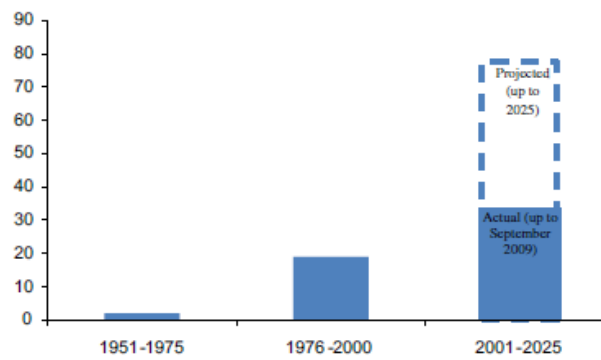


Figure 4.2: Domino accident reporting in developing countries

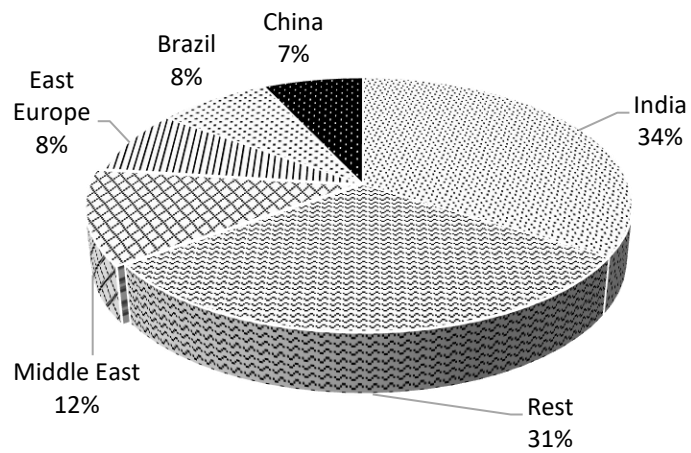


Figure 4.3: Pattern of domino accident reporting in developing countries

4.3 Chemical Process Industry Accident Databases

This section lists and discusses the major chemical industry accident databases, a comparison of databases is given towards the end of this section.

The main motive of accident investigation is to learn from the mistakes or lapses that led to the accident and identify remedial measures to prevent recurrences (Sivaraman, Arun and Tauseef, 2021). If multiple accident information are clubbed in a single source, the analysts will be able to gather pictures on a bigger canvas. Accident data clubbed under one unit is known as an accident database. By analyzing this information, we can identify the anatomy of accidents. Inferences from such analysis are being used for making or updating legal requirements, and issuing safe work guidelines for similar processes and industries.

As we know, even slight negligence can lead to a major problem in chemical industries, so it becomes important to identify the reasons for such accidents. After identification of the root causes, it should be mitigated. If the accident investigation reports of accidents are shared publicly, it can help all stakeholders who deal with similar hazards. Accident databases are a vast source of such information, so by reviewing them, both the industry and regulators can plan proactive measures to prevent the recurrence of accidents.

Generally, the accident databases are used for the following reasons: -

- To gain from past incidents: to perceive what has occurred? how has it occurred? and what the outcomes were, and why it occurred. By this, the designers can avoid the mistakes which have caused accidents in the past.
- Where adequate information is accessible, it might be feasible to create frequencies or probabilities of incidents, which can support risk assessment studies (Harding, 1997).

In the process industry, many databases maintain past accident data. Some of the well-known accident databases include FACTS, eMARS, MHIDAS, CAIRS, PUPAD, etc. All of these databases have their advantages and limitations, some of them are not free to use i.e. require some kind of subscription, and some of them are

not have accurate data (Tauseef, Abbasi and Abbasi, 2011). As there are very few databases available for past accident analysis (PAA) and those that are available are having issues with data accuracy. It becomes the need of time in the field of safety to have such a database; to provide a single platform to search about past accidents and work on learning from them to create a workplace as safe as possible.

The focus of this chapter is to review the existing literature related to past accident analysis and by analyzing the existing databases find out the problems and propose possible solutions to the identified problems so that professionals and researchers in the field of accident analysis can easily access the information and to make the workplace safer for others.

A brief description of the major chemical process industry accident database and merits and demerits are discussed below

4.3.1 Major Hazard Incident Data Service (MHIDAS)

This database was launched in 1986 by the Health and Safety Executive (UK), followed by the Canvey Island study, which highlighted the need for reliable data for quantitative risk assessment (Harding, 1997). This database contains information on global accidents involving hazardous materials (Harding, 1997). The study by Tauseef et al, (2011) identified data discrepancies in this database (Tauseef, Abbasi and Abbasi, 2011). MHIDAS provides information on the incident type, origin, causes, fatalities, injuries, and losses in the UK and abroad; but this database is no longer being updated.

Advantages

- Incidents can be analyzed based on activity, location, and people affected.
- Huge inventory of past accidents, since it is one of the oldest databases (More than 30 years)

Disadvantages

- To access a substantial fee is required.
- No longer being updated.

4.3.2 eMARS- The Major Accident Reporting System

The Major Accident Reporting System, later known as eMARS was launched by the European Commission in 1982, based on the recommendation of the Seveso directive ('Directive 2012/18/EU of the European Parliament and of the council of 4 July 2012 on the control of major-accident hazards involving dangerous substances', 2012). This database contains information from the Major Accident Hazards Bureau (MAHB) supplied by the EU and affiliated countries and the information includes both accidents and near misses. Reporting of events categorized as major accidents by SEVESO directive III is mandatory for EU countries and voluntary for affiliated countries. In terms of categories of information, this is the most comprehensive accident database; the available information includes year-wise accidents, industry type, involvements of domino effects, Natech events, transboundary impacts, etc. ("Directive 2012/18/EU", 2012).

Advantages

- EU member states have to report into eMARS compulsorily so most of the accidents get reported here
- Companies' names and locations are not provided in the database to avoid the blame game.
- Data is available in two forms i.e. "short report" and "full report" (Nivolianitou, Konstandinidou and Michalis, 2006).

Disadvantages

- As it takes almost two to three years to complete the report after proper investigation, so one has to wait for three years to access the full report.

4.3.3 Failure and Accidents Technical Information System (FACTS) Database

This is a global chemical process industry accident database launched by TNO Industrial and External Safety, nowadays it is being maintained by the unified Industrial & Harbour Fire Department in Rotterdam-Rozenburg. As of date, this is the largest repository of chemical industry accidents containing information on over 27500 industrial incidents. FACTS database gathers information from accident

reports of companies and governmental agencies (*Factsonline: chemical and industrial accident database*, 2022).

Advantages

- An abstract containing all important information about the accident is available for every accident. (3 levels of reports).
- FACTS contain information from professional sources (CSB, ARIA, MARS, ZEMA, NRC, NTSB, reports by companies and publications) so data are considered to be reliable.

Disadvantages

- Only ‘accident tables’ are freely accessible, fee required to access detailed information

4.3.4 Chemical Accident Information & Reporting System (CAIRS)

Chemical Accident Information & Reporting System (CAIRS) is an Indian chemical industry accident database developed by the Environment & Forest Informatics Division of the National Informatics Centre Govt. of India. Here accidents reported by companies are updated in the database by authorities specified under MSHIC Rule 1989 (Nair, 2010; *Welcome To CAIRS*, 2021). The flowchart for updating the data is illustrated in Figure 4.4

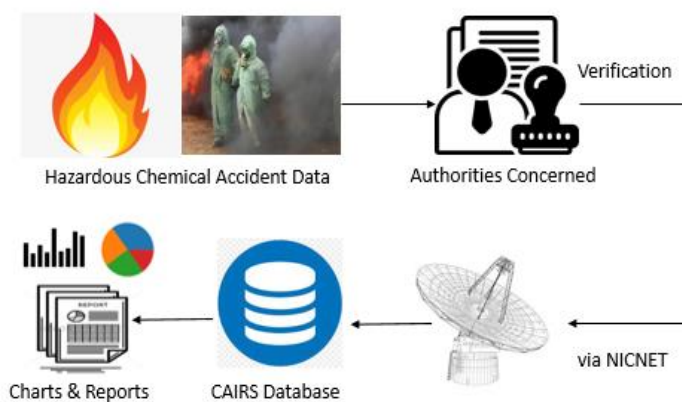


Figure 4.4 Data updating process in CAIRS

Advantages

- Includes both reports and charts that can be freely accessed
- Can choose from different authorities such as Chief Inspector of Factories, Chief Controller of Explosives, etc.
- Losses outside the premises are reported (Fatality, Injury, and Missing).

Disadvantages

- The root causes of most of the accidents are not mentioned.
- Not all accidents are reported in this database.
- Data duplicity and consistency issues.

Table 4.1 Comparison of accident databases

Database	Country	Scope	Accessibility	Process of Data Updation	No of Records	Available information
MHIDAS	UK	Global accidents involving hazardous materials from 1950 to 1990	Subscription required	• No longer being updated • AEA Technology was used to compile data from public domain sources like newspaper	8000+	• <i>Date & Location</i> • <i>Materials involved</i> • <i>No of the people affected</i> • <i>General & special causes</i> • <i>Economic loss</i>
eMARS	E U	Major accidents and near-miss information reported by EU and affiliate countries	Free	• Accident and near-miss information provided to MAHB by EU and affiliated countries under the Seveso directive	1165	Comprehensive information compared to other databases, includes • <i>Accident, site, and installation descriptions and classifications</i> • <i>Cause</i>

Database	Country	Scope	Accessibility	Process of Data Updation	No of Records	Available information
						<i>description and classifications</i> • <i>Consequences descriptions and classifications</i> • <i>Emergency response and legal actions.</i> • <i>Lessons learned</i>
FACTS	The Netherlands	Global accidents	Level 0 access: ‘Accident tables’ are freely accessible Levels 1 & 2: Subscription required for detailed reports	• Accident information from professional sources like company reports, government bodies, technical reports, and literature	27500+	The accident table contains basic information about the year, country, activity, and causes of accidents. The Coded abstract contains detailed information about • <i>Identification of location, operations, etc.</i> • <i>Detailed information about causes and consequences</i>
CAIRS	India	Incidents reported by authorities in India	Free	• Based on accident reports submitted to various governmental agencies	100+	• <i>Accident date and time</i> • <i>Company information</i> • <i>The Chemical involved & its type</i> • <i>Causes</i> • <i>Losses: Number of people killed/injured</i>

Database	Country	Scope	Accessibility	Process of Data Updation	No of Records	Available information
						<i>within and outside the premises</i>

The reported problems while performing past accident analyses using accident databases are (Tauseef, Abbasi and Abbasi, 2011),

- Improper accident reporting mechanism
- Record maintenance is not appropriate
- Hiding the actual cause of the accident
- The improper strategy of investigation.

Hence it is important to consider the strengths and weaknesses of the databases before performing past accident analysis

4.4 Past Accident Analysis

Comprehensive past accident analyses were performed by researchers; which include the works (Abdolhamidzadeh et al., 2011b; Bellamy, 1989; Darbra et al., 2010; Khan and Abbasi, 1999a; Kiranoudis and Markatos, 2000; Lees, 1996), etc. The last well-known PAA was performed by Abdolhamidzadeh, et al, in 2011, since significant PAA research was not performed for major accidents in the chemical process industry. We performed past accident analyses based on data available in eMARS and CAIRS databases. The period of analysis was selected from 2010 to 2021.

4.4.1 Past Accident Analysis from eMARS Database

During this period 495 accidents were recorded in the eMARS database; out of these detailed reports are available for 378 incidents. The event-wise yearly trends of reported events are illustrated in Figure 4.5, from the trends it can be

inferred that the total number of reported events is more or less steady and the number of major accidents is decreasing marginally in Europe. This indicates that the trends identified by (Abdolhamidzadeh, Abbasi, D Rashtchian, *et al.*, 2011) are still prevailing in Europe.

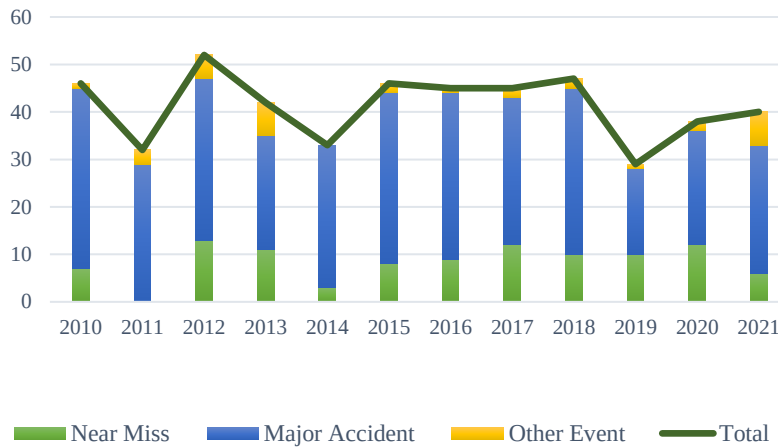


Figure 4.5 Year-wise accident reporting trends in eMARS

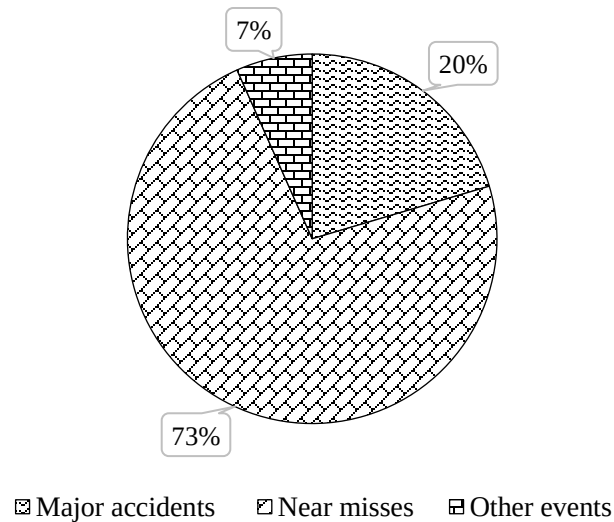


Figure 4.6 Types of accident reports in eMARS

As illustrated in Figure 4.6 out of these 495 accidents, 73% are major 20% are near-miss incidents and 7% are other events meeting the criteria defined in the Seveso directive annexure ('Directive 2012/18/EU of the European Parliament and

of the council of 4 July 2012 on the control of major-accident hazards involving dangerous substances', 2012).

Industry-wise recorded accident analysis can indicate the vulnerability of industries. The analysis, as shown in Figure 4.7 shows that 19 % of accidents were reported in petrochemical/oil refineries followed by the general chemical manufacturing industry (10%), and the power generation, supply, and distribution (6%) industries. Interestingly, there is a drastic reduction in the number of accidents reported in the general chemical industry during the analysis period compared to the previous decade (1998-2009) i.e., from 132 cases to 51; whereas the number of accidents in petrochemical/oil refineries increased from 84 to 93.

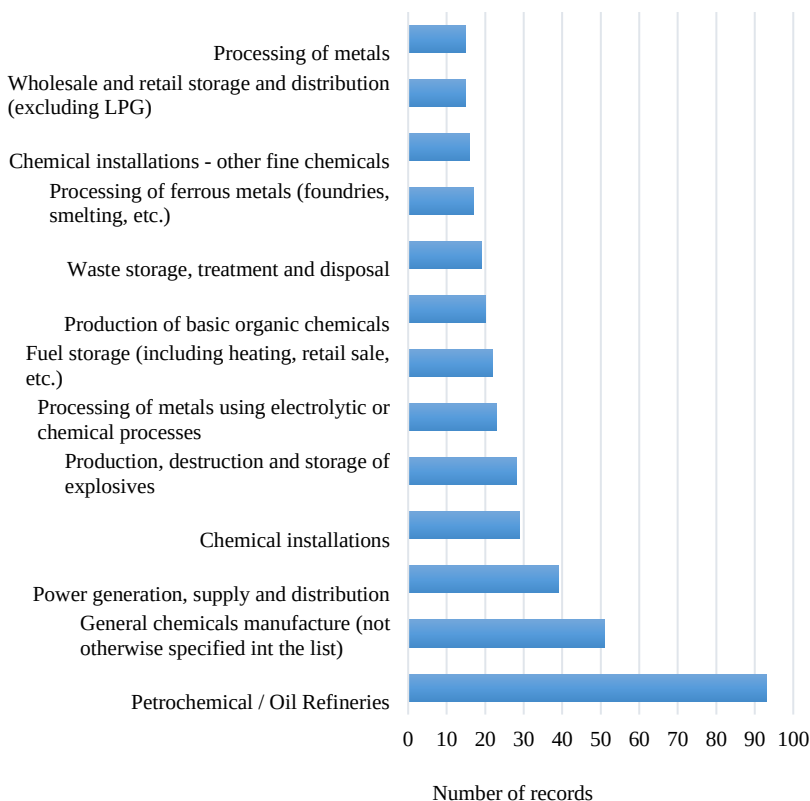


Figure 4.7 Industry-wise accidents reported in eMARS

eMARS also reports special circumstances involved with the recorded incidents such as the Natech event, domino, transboundary effects, and

involvement of contractors. Out of such 56 events, 54 % of cases involve contractors, and 21 % of cases involve domino effects as illustrated in Figure 4.8

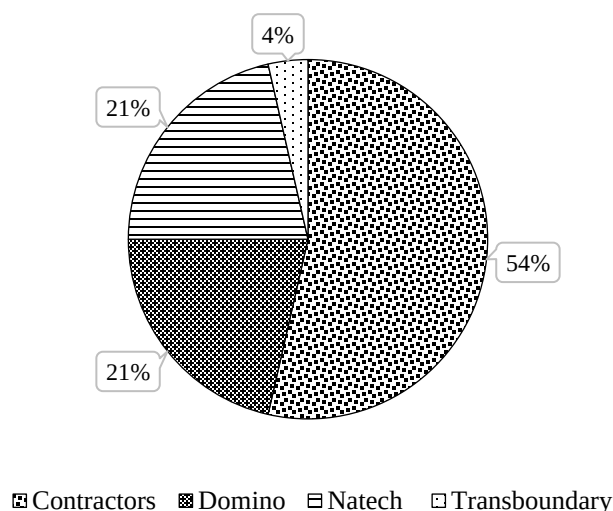


Figure 4.8 Accidents involving special circumstances (eMARS)

4.4.1 Indian Chemical Industry Accident Scenario

As illustrated in Figure 4.9, the analysis of chemical industry accidents reported to the various regulatory agencies in CAIRS, showed that out of twenty-nine states, only six states have reported the accidents so far. This data pointed out the poor accident reporting culture in the country. It was also found that there is a duplicity of data present in the CAIRS data. Some of the accidents are reported multiple times; e.g. the accident in Accura Lab Pvt. Ltd, Telangana on 25th September 2013 is reported twice; one with the accident cause details and another without this information. Similarly, if an accident involves multiple chemicals it is reported multiple times with different chemicals.

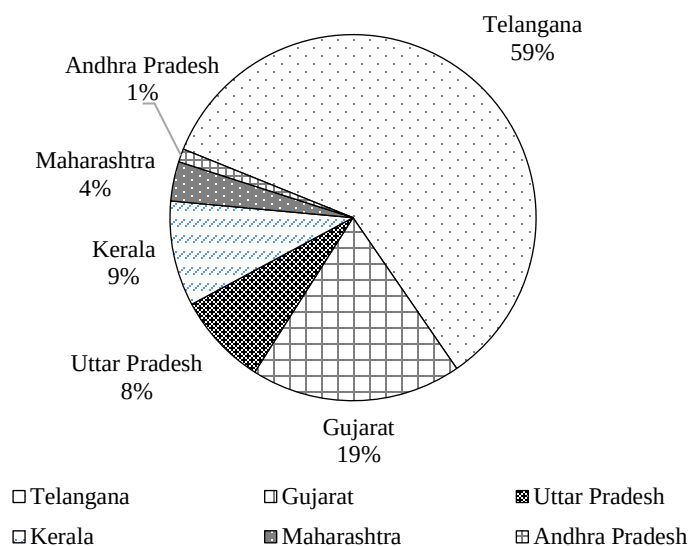


Figure 4.9 State-wise reporting of accidents (CAIRS)

The data collected from the CAIRS database were manually filtered to remove all duplicities and 68 records were obtained, which were submitted to the chief inspector of factories. The year-wise reporting trends are depicted in Figure 4.10. As shown there is no particular trend in the number of accidents reported in CAIRS. Maximum accidents were reported in the year 2016 while the minimum number was reported in the year 2014 and data is not available after 2018.

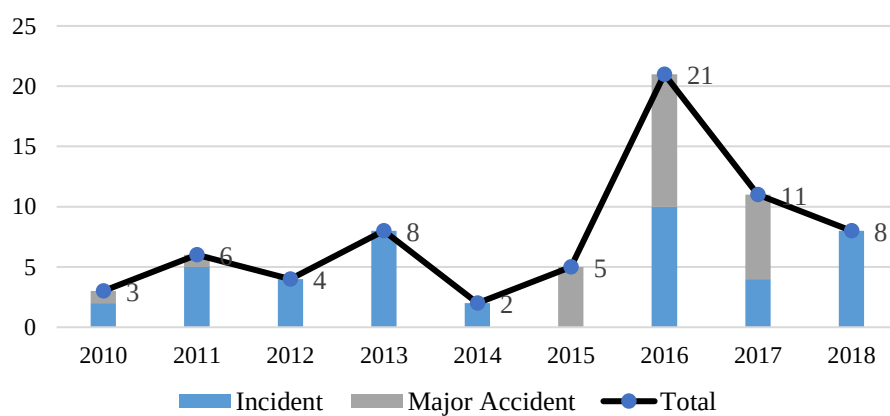


Figure 4.10 Year-wise accidents reported in CAIRS

One of the major drawbacks of the CAIRS is that the root cause of the accident is missing in most of the reports. Out of 68 accidents analyzed, only around

36 accidents have their root cause mentioned i.e. for around 58% of the accidents root cause is not mentioned. This shows that the investigative findings of the accident are not recorded for most accidents

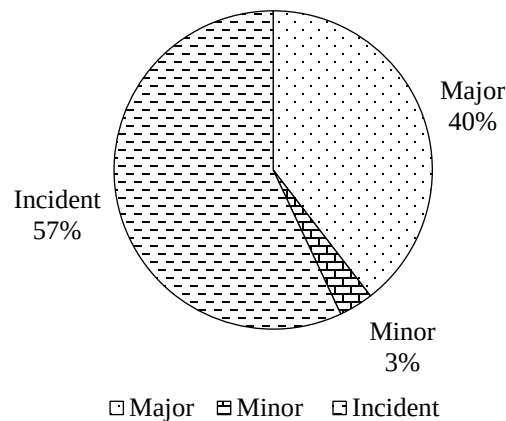


Figure 4.11 Accidents based on category (CAIRS)

Accidents are analyzed on types and the results are depicted in Figure 4.11. Based on the analysis, it was found that 57% of cases reported are incidents. In some cases, accidents with fatalities are considered minor accidents or incidents, while accidents with fewer casualties are considered major. So, there is no well-defined guideline or procedure to report an accident. This indicates a lack of monitoring of reported information in this database. At present, the information in this regard is not reliable and any conclusion based on this type of analysis can be misleading.

The analysis based on available information in these two databases can be concluded that the findings of accidents are better reported in eMARS, as the root cause, and event sequence of every accident is mentioned, which is missing in CAIRS. eMARS also provides more categories of information to assist in better PAA. The Indian database CAIRS needs urgent revisions to provide more reliable data.

4.5 Conclusions & Recommendations

This chapter reviewed past accidents in the chemical process industry. A comprehensive analysis of past accidents in the chemical process industry enables us to identify the recent trends in the chemical process industry. Accident databases aid the analysis of past accidents. The comparison of global databases for the chemical industry lists the merits and demerits of existing databases. The past accident analysis of accidents recorded in the European eMARS database and Indian CAIRS database has been performed. From the trends, it can be inferred that the total number of reported events is more or less steady and the number of major accidents is decreasing marginally in Europe. The past accident analysis based on eMARS results confirms the decrease in trends domino accident trends in Europe which was identified by researchers (Abdolhamidzadeh et al., 2011) still prevailing in Europe even after 10 years. The analysis of the Indian chemical industry based on accidents reported in the CAIRS database can lead to inaccurate conclusions as accidents are not reported promptly in this database and it requires an urgent revision to ensure data accuracy.

The suggestions to improve existing databases are,

- Accident databases available in the public domain would encourage researchers to undertake active studies in this field and would also enable risk professionals and policymakers to make data-driven decisions.
- Before publishing the details in accident databases, the data entering officials need to rigorously verify all the entries; including the root causes of incidents.
- Additional information needs to be incorporated into databases to meet the risk assessment requirements of the present world
- As most databases are country-specific, global collaborations are required to disseminate past accident information worldwide.

CHAPTER 5

RESEARCH TRENDS IN DOMINO EFFECT RESEARCH AND TOOLS FOR RISK ASSESSMENT

Abstract

This chapter portrays the results of recent research trends in domino effects analyzed using a systemic literature review with the help of VoSViewer. VOSviewer is a Java-based software for creating, visualizing, and analyzing maps based on network data. It also articulates the categorization of publications in the domino effect research and identifies domino tools being used by researchers for domino risk assessment.

5.1 Trends in Domino Effect Research

5.1.1 Domino Effect Research – An Overview

An extensive literature review was carried out using the Web of Science database. The keywords used for topic search were "***domino effect***" OR "***domino accident***" OR "***knock on effect***" OR "***catastrophic effect***" OR "***chain of accidents***" OR "***escalating event***" OR "***cascading events***", on the ECT index from 1998 till 6th July 2021. The search yielded 362 articles. Based on initial scrutiny of the title and abstract, the number of articles was limited to 200, and from a further detailed examination of the collected articles, the relevant articles were found to be 177. The details are annexed at A3.

The collected articles were categorized based on a classification system proposed by the researchers Chao Chen and the team (Chen, Reniers and Khakzad, 2020). In addition to the research topics ‘modeling’ and ‘managing’, an additional topic named ‘*Reviews*’ was introduced to accommodate a few relevant articles which address past accident analysis and significant review articles in the field of domino accident research. Characteristics of collected articles are summarized in Figure 5.1.

Out of 177 articles reviewed 103 articles focused on modeling, 54 on managing domino effects works, and 20 articles were review papers. 57 research studies were conducted on the risk assessment of domino effects in the chemical process industry. Among these 24 research works are based on graphical methods, 21 were based on analytical methods and 12 were based on simulation methods.

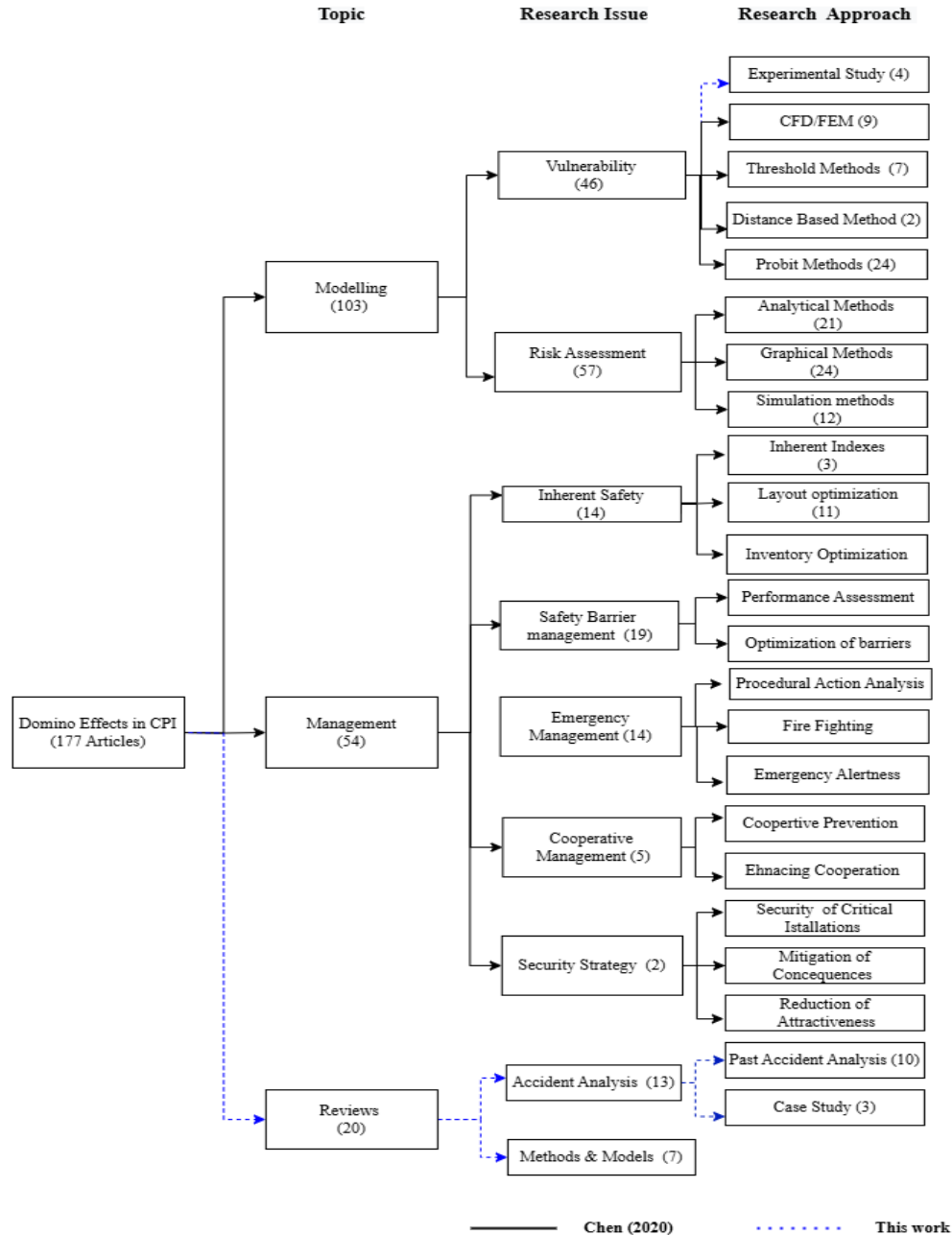


Figure 5.1 Characterization of publications in the domino effect research

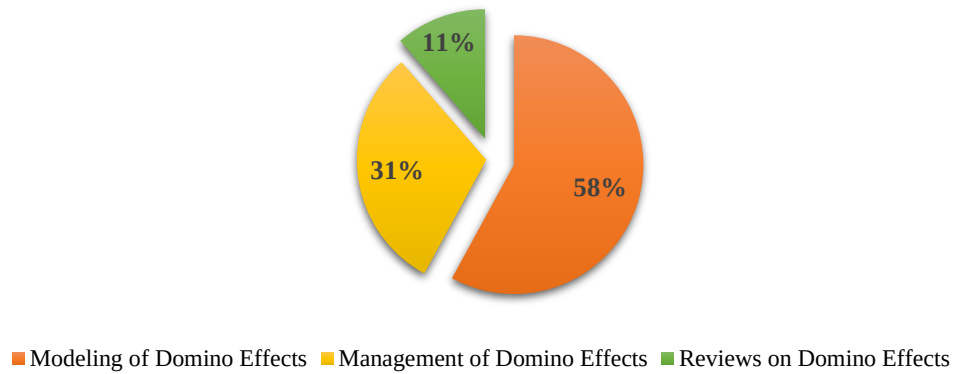


Figure 5.2 Topic-wise publications on domino effects

5.1.2 Temporal Distribution

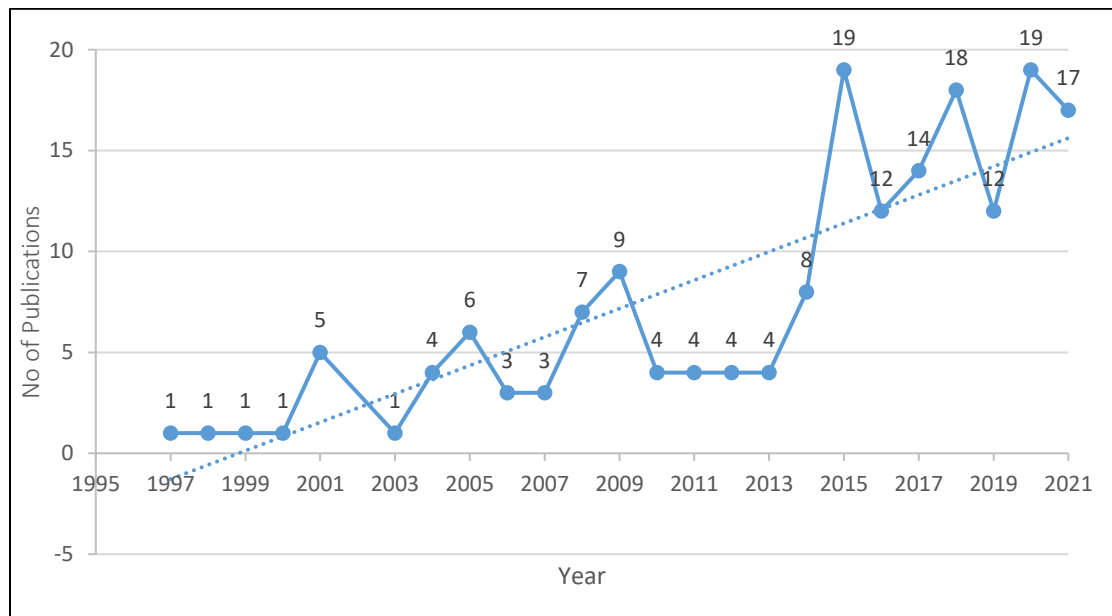


Figure 5.3 Year-wise publications on domino effects

Yearwise publications in the field of domino effects are illustrated in Figure 5.3. Active research in this field was initiated with the works of Khan & Abbasi in the late 1990s (Faisal I Khan and Abbasi, 1998; Faisal I. Khan and Abbasi, 1998a; Khan and Abbasi, 1999a). During the initial years, research on this topic was afforded by a limited number of researchers, and the average publication per year during this period was 3.88. Out of 177 publications, nearly 62% of the documents

were published during the past 7 years (2015-2021), amounting to 15.85 average publications per year. Before 2015 majority of the research publications were supported by EU countries, since 2015 visible changes in this pattern have been observed, as several articles with support from China emerged to appear after 2015. This research work analyzes the trends in domino effects research based on two time periods, publications before and on and after 2015. The sharp rise in the number of publications post-2015 can be attributed to the active contribution of Chinese researchers after the Tianjin domino accident in 2015.

5.1.3 Source Analysis

An earlier work of (Chen, Reniers and Khakzad, 2020) identified 132 articles from 32 journals. This work was able to identify 177 relevant publications through careful usage of keywords for literature search. The identified 177 articles were published in 28 journals and 90% (159) of the research articles were published in 10 Journals. The impact factor of these journals ranges from 1 to 12.2. It is interesting to note that more than 90% of the articles are published in 10 journals, Journal-wise publication distribution is illustrated in Figure 5.4.

Table 5.1 summarizes journal ranking-wise publications, 89% of the literatures are published in either Q1 or Q2 journals. As the art of domino research is afforded by limited and renowned researchers, they are expected to publish their work in renowned journals which get captured in WoS. Hence the impact of leaving non-WoS index journals on domino effect research is limited.

Table 5.1 Distribution of Publications Sources

Journal Ranking (2023)	No of publications	Percentage of publications
Q1	100	56%
Q2	59	33%
Q3	4	2%
Q4	12	7%
NA	2	1%
Total	177	100%

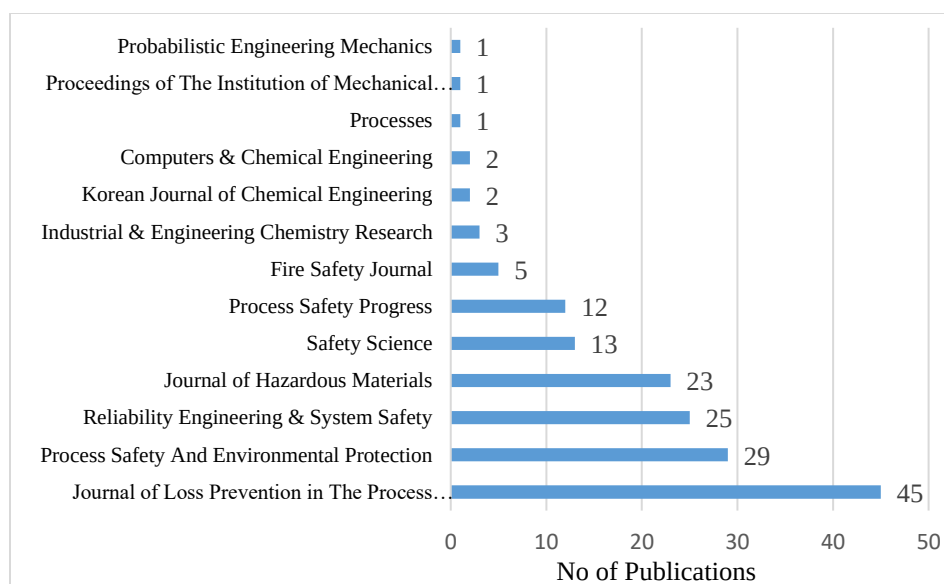


Figure 5.4. Journal-wise domino research publications

The top 10 research sources and their impact factor (2023) are listed in Table 5.2

Table 5.2 Major sources of publications

Sl. No	Journal	No of Publications	Impact Factor (2023)	Quartile Ranking
1	Journal Of Loss Prevention in The Process Industries	45	3.6	Q2
2	Process Safety and Environmental Protection	29	6.9	Q1
3	Reliability Engineering & System Safety	25	9.4	Q1
4	Journal Of Hazardous Materials	23	12.2	Q1
5	Safety Science	13	4.7	Q1
6	Process Safety Progress	12	1	Q4
7	Fire Safety Journal	5	3.4	Q2
8	Industrial & Engineering Chemistry Research	3	3.8	Q2
9	Computers & Chemical Engineering	2	3.9	Q2
10	Korean Journal of Chemical Engineering	2	2.9	Q2

The major sources of information included the Journal of Loss Prevention in The Process Industries, Process Safety And Environmental Protection, Reliability Engineering & System Safety, and Journal of Hazardous Materials.

5.1.3 Author and Co-Authorship Analysis

Bibliometric analysis of publications using network visualization can provide valuable information on active researchers and their research networks (van Eck and Waltman, 2014; Li *et al.*, 2017). The leading contributors during the 1997-2014 period were Valero Cozzani (17 documents), S A Abbasi (10 documents), Faisal Khan (7 documents), and Genserik Reniers (6 documents). The results of bibliometric network visualization are illustrated in Figures 5.5 a-d. From 1997 to 2014, 78 authors have contributed to domino effect research and 33 met the threshold of 2 or more co-authored documents and they form 10 research clusters. Whereas during the period 2015- 2021, 196 authors have contributed to this field and 52 researchers met the said threshold and they form 12 research clusters. The leading contributors during this period were Genserik Reniers (18 documents), Valero Cozzani (12 documents), Nima Khakzad (12 documents), Faisal Khan (11 documents), Gabriele Landucci (9 documents), Ji Jie (7 documents) and Guohua Chen (6 documents).

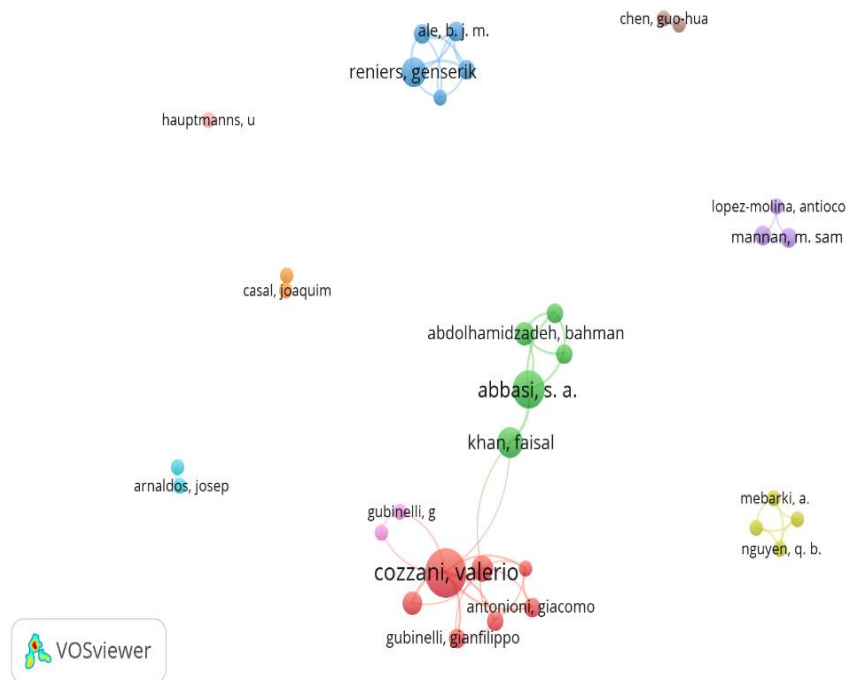


Figure 5.5 (a) Domino Research: Author Networks 1997-2014

As seen from Figure 5.5 (a) most of the publications during this period were done independently in each cluster without much collaboration with others. Only two clusters were performing collaborative research, Prof. F I served as the connecting link between Prof. V Cozzani and Prof. S A Abbasi cluster.

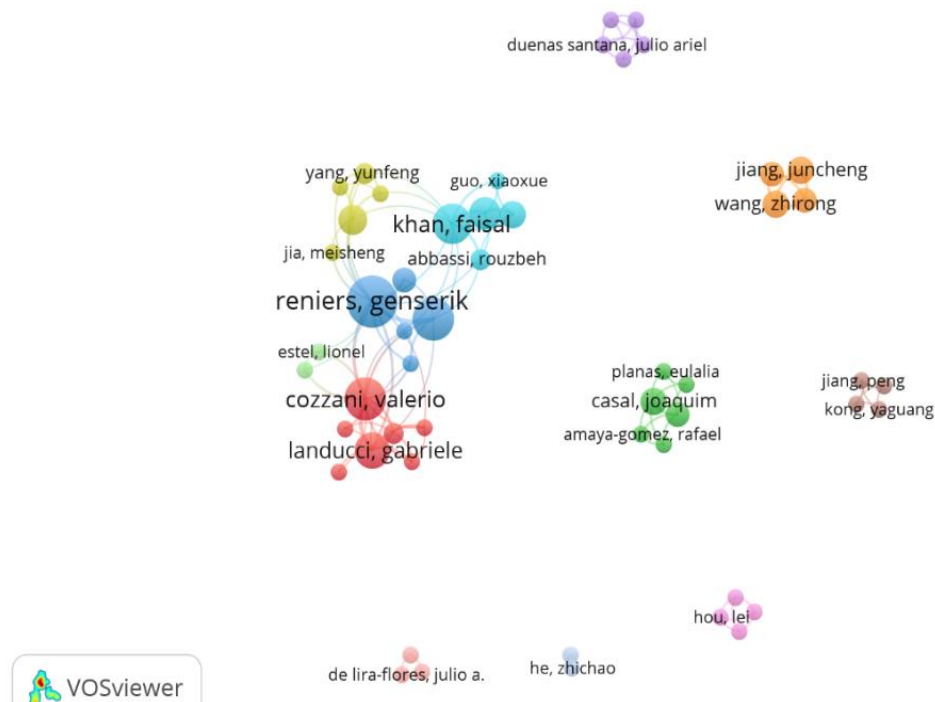


Figure 5.5 (b) Domino research: author networks 2015-2021

It is interesting to note that the domino effect research has gained a lot of attention among process safety researchers during the past six years. 60 out of 196 researchers who have contributed to domino research since were from Chinese institutions, it can be said that the active research in this field during 2nd phase was propelled by the active involvement of Chinese researchers, And the number of researchers with research interest in the field is increasing, especially among Chinese researchers.

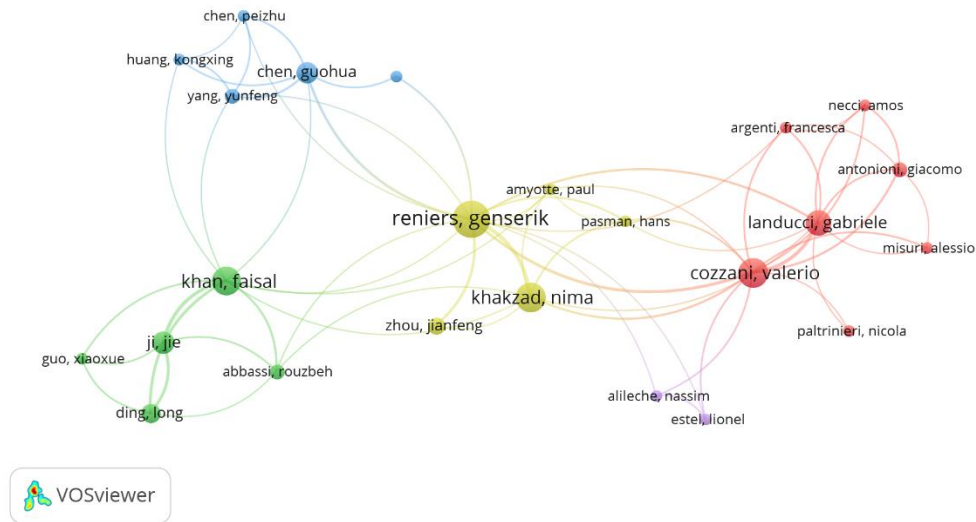


Figure 5.5 (c) Top 5 Domino Research Cluster Networks 2015-2021

As illustrated in Figure 5.5 (c) better collaboration between different research clusters was observed during this period. Reniers Genserik was observed to be not only the leading contributor but he was having research collaboration with all other leading research clusters.

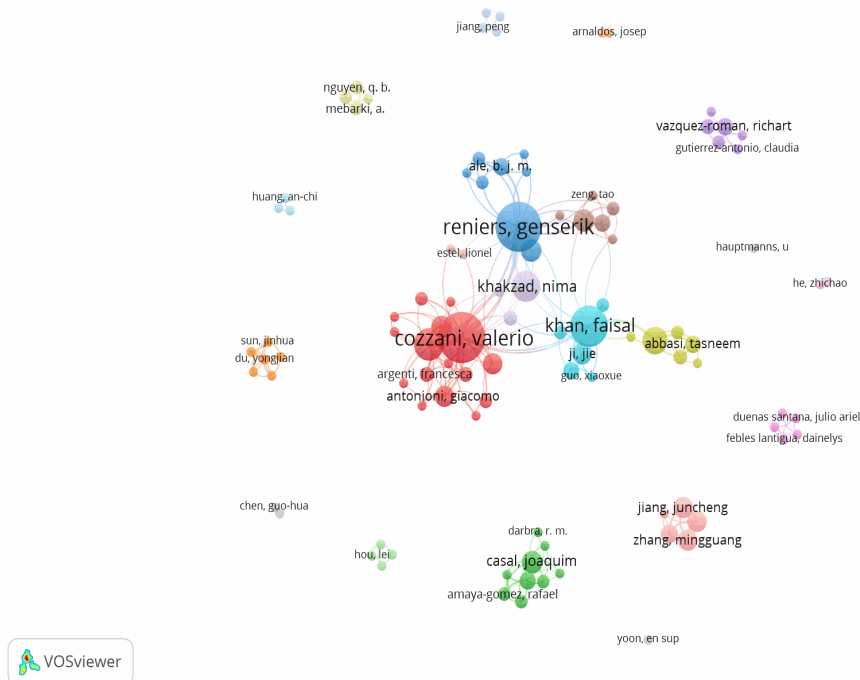


Figure 5.5 (d) Domino research: author network 1997-2021

Figure 5.5 (d) illustrates the network among researchers. The top contributing researchers during the period 1997-2021 are Valero Cozani, Genserik Renies, Faisal Khan, and Nima Kakzad.

5.1.4 Country Analysis

Country network and cluster analysis indicate the active countries in domino effect research and their network with other countries. As studied by many authors domino effect studies are mainly focused in Europe majorly because of the legal requirement for domino risk assessment and extensive sharing of information mandated by Seveso directives. This assumption is in line with the findings and is depicted in Figure 5.6 (a). The leading contributing countries during the 1997-2014 period were Italy (19 documents), India (9 documents), Belgium (6 documents), Netherlands (5 documents), Iran (5 documents), and Spain (5 documents). But when it comes to the later period ie 2015-2021 these premises don't hold. In the earlier studies, authors have pointed out the isolation of China in domino research through network analysis (Li *et al.*, 2017). In this study, the most active country in this research field was China, contributing to 34 publications and surpassing all European countries that had dominated in the past. Other leading contributing countries included the Netherlands (21 documents), Canada (13 documents), Italy (13 documents), and Belgium (12 documents). The results are illustrated in Figure 5.5 (b).



Figure 5.6 (a) Domino research: Country networks 1997-2014

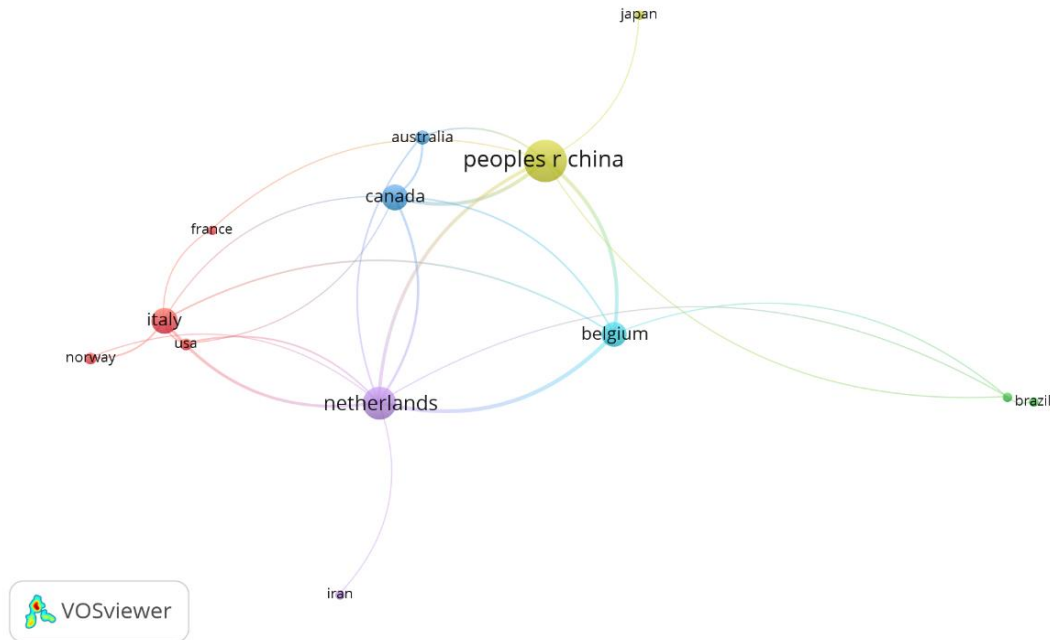


Figure 5.6 (b) Domino research: Country network 2015-2021

A significant change in country-wise participation in domino effect research was observed during 2015-2021. China not only emerged as the leading contributor but was also found to be collaborating with EU countries, Canada, and Japan in the domino effect research.

5.1.5 Institution Analysis

The purpose of institution network analysis is to identify the leading institutions in the field of domino research and their network with other institutions.

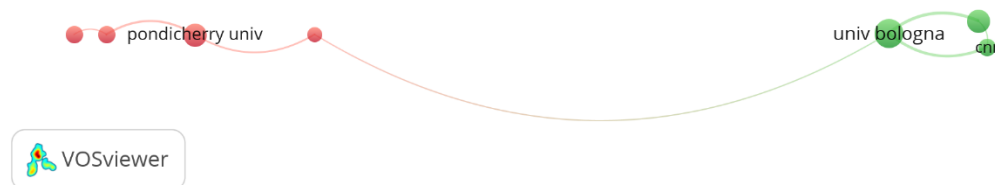


Figure 5.7 (a) Domino research: Institution network 1997-2014

During the period 1997- 2014, only 10 institutions met the criteria of 3 co-authorships with other institutions. The leading institutions were the University of Bologna, Italy, the University of Antwerp, Belgium, and Pondicherry University,

India, with limited cooperation between Memorial University, Canada, and the University of Bologna.

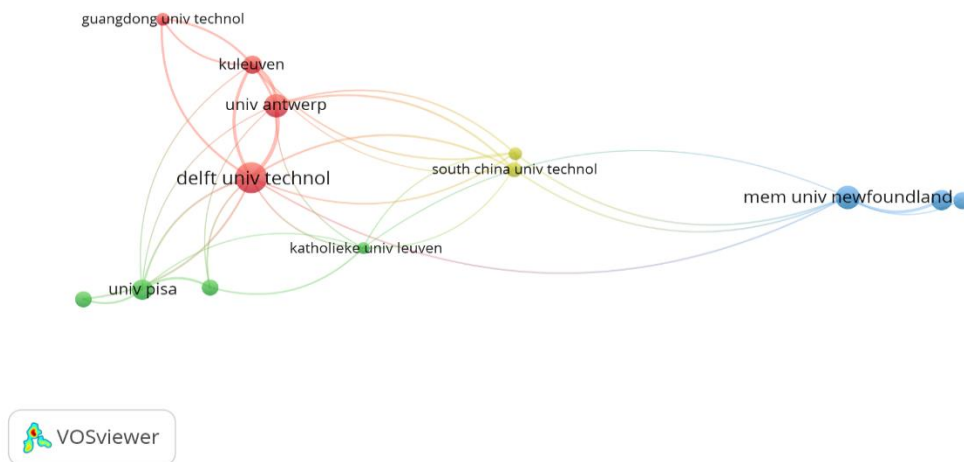


Figure 5.7 (b) Domino research: Institution network 2015-2021

During the later phase of domino research, the earlier picture was completely changed new institutions took over earlier institutions as leading contributors. This study shows that at present the leading institutions in domino research are Delft University, Netherlands, Memorial University of Newfoundland, Canada, University of Pisa, Italy, and the South China University of Technology, Guangzhou, China.

5.2. Tools for Domino Risk Assessment:

The systematic review of the literature using keywords yielded 177 documents, and out of these, 57 publications were focused on risk assessment aspects of domino effects. The research approach for risk assessment can be classified into Analytical methods, Graphical methods, or simulation methods(Chen, Reniers and Khakzad, 2020). It was identified that 24 research works were based on graphical methods, 21 were based on analytical methods and 12 were based on simulation methods.

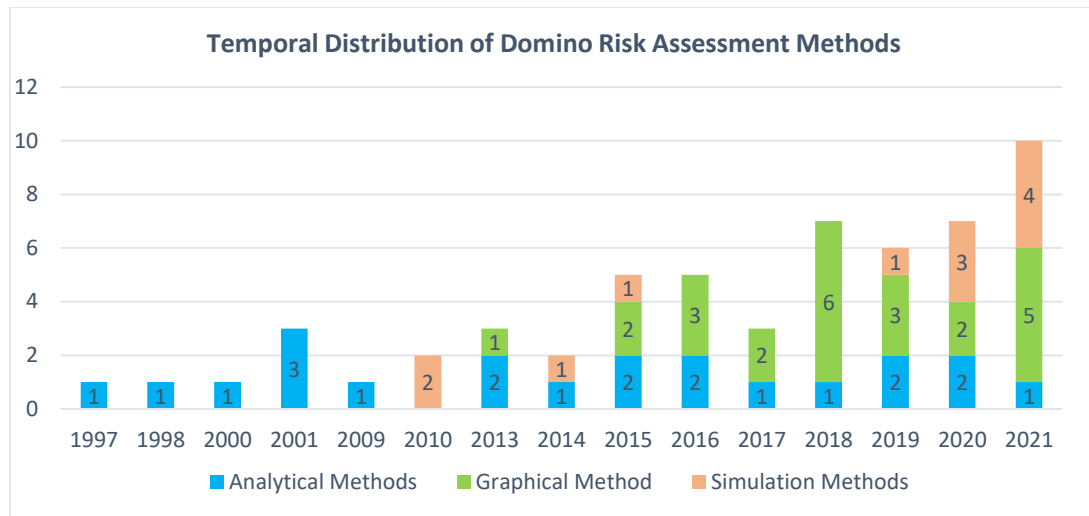


Figure 5.8 Temporal distribution of risk assessment methods

During the initial stages of domino risk research, few works were published focusing on risk assessment, and all of the risk assessment methods were based on analytical methods. The first simulation-based method for domino risk assessment was introduced by (Abdolhamidzadeh et al., 2011) and their work was based on Monte- Carlo-based simulation. The first ever graphical-based risk assessment method was conceptualized by Khakzad in 2013, he introduced the concept of a Bayesian-based risk assessment model. Through the graphical-based methods are relatively newer methods 42% of risk assessment publications are based on these methods. This shows that there is a huge consensus is emerging among researchers on the applicability and feasibility of these methods in risk assessment of domino effects. A brief description of the above methods is given below.

5.2.1 Analytical Methods

In analytical methods, the determination of escalation probabilities is based on an analytical relationship between escalation vectors and vulnerability probabilities (Khakzad, 2021). Some important works based on analytical methods include the publications of Bagster & Pitblado (1991), who used the distance-based approach to address higher-order domino effects, Khan & Abbasi developed software packages named MAXCRED & DOMIEFFECT to model domino effects (Faisal I. Khan and Abbasi, 1998b, 1998a). Cozzani et. al developed GIS based

software, Air-par GIS to perform QRA of domino effects (Cozzani, Antonioni and Spadoni, 2006; Antonioni, Spadoni and Cozzani, 2009b). A matrix-based approach was developed by (Zhou and Reniers, 2018) to model the propagation of fire-induced domino effects.

- **Limitations of analytical methods**

Though analytical methods are simple and computationally affordable compared to simulation techniques, they use oversimplified assumptions and most of the techniques framed based on analytical methods are incapable of modeling higher-order dominos. Hence risk assessment based on these techniques may underestimate the risk (Khakzad *et al.*, 2013; Chen, Reniers and Khakzad, 2020; Khakzad, 2021)

5.2.2 Simulation Methods

The majority of the risk assessments based on simulation methods are performed based Monte-Carlo method. The concept was introduced by Abdolhamidzadeh *et al.*, (2010). Monte- Carlo-based simulation can be used for risk assessment involving higher-order propagation another advantage of these methods is that they can accommodate synergetic effects during domino accidents. The computational time for risk assessment is substantial for Monte-Carlo simulation, another disadvantage is that simulations are based on random numbers often ignoring actual propagation paths.

5.2.3 Graphical Methods

Risk assessment based on graphical methods has received great attention in past years. Because of its structure, it can easily model domino propagation, installations are represented by nodes while escalation vectors are drawn as links connecting the nodes. Various graphical models being used to model domino evolution include.

Table 5.3 Usage of graphical techniques in domino risk assessment

Methods	No of Publications
Bayesian Network	7
Dynamic Bayesian	6
Petri-net	4
Hybrid Technique	4
Event Tree	1
Graph Theory	2

The relative usage of the above methods is summarized in Figure 5.7 Risk assessment based on hybrid techniques that combine the above methods is also gaining importance. Graphical methods can tackle complex domino escalations and higher-order propagations and compared to analytical methods these methods can provide better frameworks for domino risk assessment (Chen, Reniers and Khakzad, 2020).

Table 5.4 Temporal Distribution of Graphical Risk Assessment Tools

Year	Bayesian Network	Dynamic Bayesian	Petri-net	Bayesian-Petri Net	Damage map	Event Tree	Fuzzy-Bayesian	Graph Theory	Total
2013	1								1
2015		1						1	2
2016	1				1			1	3
2017			1			1			2
2018	3	2	1						6
2019	1	1	1						3
2020		2							2
2021	1		1	1			2		5
Total	7	6	4	1	1	1	2	2	24

Table 5.4 portrays the relative usage of various graphical-based risk assessment tools used in domino risk assessment over the years. The most popular graphical-

based tools are Beyeaisn, Dynamic Bayesian & Petrinet. There have been many attempts to use combinations of tools in risk assessment.

5.3 Conclusions

This chapter discussed in-depth the trends in domino effect risk research and tools for risk assessment. 177 research publications on domino effects were identified using a systematic literature review, this work proposes a modified classification of literature, the new category “Reviews” accommodates some important research on past accidents and reviews on methods & models for domino risk management. The identified 177 articles were thoroughly analyzed to identify the temporal distribution, publication source analysis, and bibliometric analysis of publications using network analysis with the help of VOSviewer. This study classifies and analyzes the trends in domino effects research based on two time periods, publications before and after 2015. During the initial years, research on this topic was afforded by a limited number of researchers, who are mainly from Europe and the average publication per year during this period was 3.88. A visible change was observed from 2015 onwards, nearly 62% of the documents were published during the past 7 years (2015-2021), amounting to 15.85 average publications per year. During 1998-2014, only 78 researchers contributed to this field, and in the later stage, the number of domino risk researchers increased to 196. 60 of these 196 researchers were from Chinese institutions, the active research in this field in 2nd was propelled by the active involvement of Chinese researchers & 2015 marks the transition in domino effect research. The study identifies research clusters in the field of domino research and during the first phase, most of the publications were done independently by each cluster without collaboration, enhanced research collaborations among research clusters were observed during 2nd phase. More collaborative researchers were observed during 2nd phase China had broken its isolation in domino research and emerged to be the top contributor to this field and also more collaborative than any countries during the later phase.

The study identified various tools used for domino risk assessment by researchers, during the initial phase the risk assessment tools were based on analytical and simulation methods. Risk assessment based on graphical methods has received great attention in past years. Through graphical-based methods are relatively newer methods 42% of risk assessment publications are based on these methods. This shows that there is a huge consensus is emerging among researchers on the applicability and feasibility of these methods in risk assessment of domino effects. Compared to other methods graphical methods can easily model domino propagation, and can easily tackle complex interactions and higher-order progressions compared to analytical tools. And these are more suitable for providing a better framework for domino risk assessments. This work identified the relative use of various graphical methods the most commonly used methods are Bayesian and Dynamic Bayesian analysis, Hybrid techniques, which are a combination of two or more graphical methods are also gaining importance among researchers.

CHAPTER 6

EFFICACY ANALYSIS OF SELECTED TOOLS FOR DOMINO EFFECTS RISK ASSESSMENT

Abstract

This chapter focuses on the efficacy analysis study performed on selected tools for domino risk assessment. Section 6.1 provides an overview of various techniques available for domino risk assessment and section 6.2 discusses the limitations of traditional risk assessment techniques. Selected risk assessment tools were applied in a common case study, their relative performance was evaluated on various parameters and a qualitative comparative matrix was developed and is detailed in subsequent sections.

6.1 An Overview of Domino Risk Assessment Tools

The research approach for risk assessment can be classified into analytical methods, graphical methods, or simulation methods (Chen, Reniers and Khakzad, 2020). As detailed in the previous chapter the risk assessment based on graphical methods has received great attention in recent years. Because of its structure, it can easily model domino propagation, installations are represented by nodes while escalation vectors are by links connecting the nodes. Various graphical models being used to model domino evolution include Bayesian Networks, Dynamic Bayesian Networks, Petri-net, Event Tree Analysis, Graph theory, etc. Graphical methods can tackle complex domino escalations and higher-order propagations, and compared to analytical methods these methods can provide better frameworks for domino risk assessment (Chen, Reniers and Khakzad, 2020).

6.2 Limitations of Traditional Risk Assessment Tools in Domino Studies

Risk assessment techniques such as Event Tree Analysis (ETA), Fault Tree Analysis (FTA), Failure Mode and Effect Analysis (FMCA) have been in mainstream risk assessment for years and are being widely used by researchers and

industry professionals for safety and allied risk assessment studies. Extensively used risk assessment approaches such as ETA, FTA, and FMEA are inherently based on oversimplified assumptions, hence they are incapable of accurately predicting the risk, especially in a complex environment such as domino effects (Kabir and Papadopoulos, 2019). The limitations of event tree analysis in modeling domino effects are discussed by Nima Khakzad (Khakzad, 2021). He considered 3 tank layout as shown in Figure 6.1 and performed risk assessment using Event Tree Analysis.

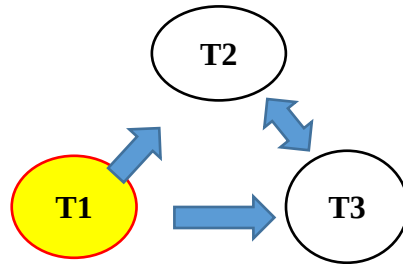


Figure 6.1: A three-storage tank layout

A fire initiated in Tank 1 can trigger a fire in Tank 2 and/or Tank 3. The possible domino escalation can be any of the following

- a) First-order domino: Fire in tank 1 triggers a simultaneous fire in tanks 2 and 3. Domino propagation can be denoted as $T1 \rightarrow T2 \& T3$
- b) Second-order domino: Fire in tank1 triggers fire in tank 2 their synergistic effect causes fire in tank 3, Escalation $T1 \rightarrow T2 \rightarrow T3$
- c) Second-order domino: Fire in tank1 triggers fire in tank 3 their synergistic effect causes fire in tank 2, Escalation $T1 \rightarrow T3 \rightarrow T2$

The Event Tree Analysis is the most preferred tool for the identification of consequences followed by a hazardous event. The ETA for the above domino scenarios are represented in Figures 6.2 (a) and 6 (b). The two ETAs were drawn as it was uncertain whether T2 or T3 would catch fire after a fire in tank 1.

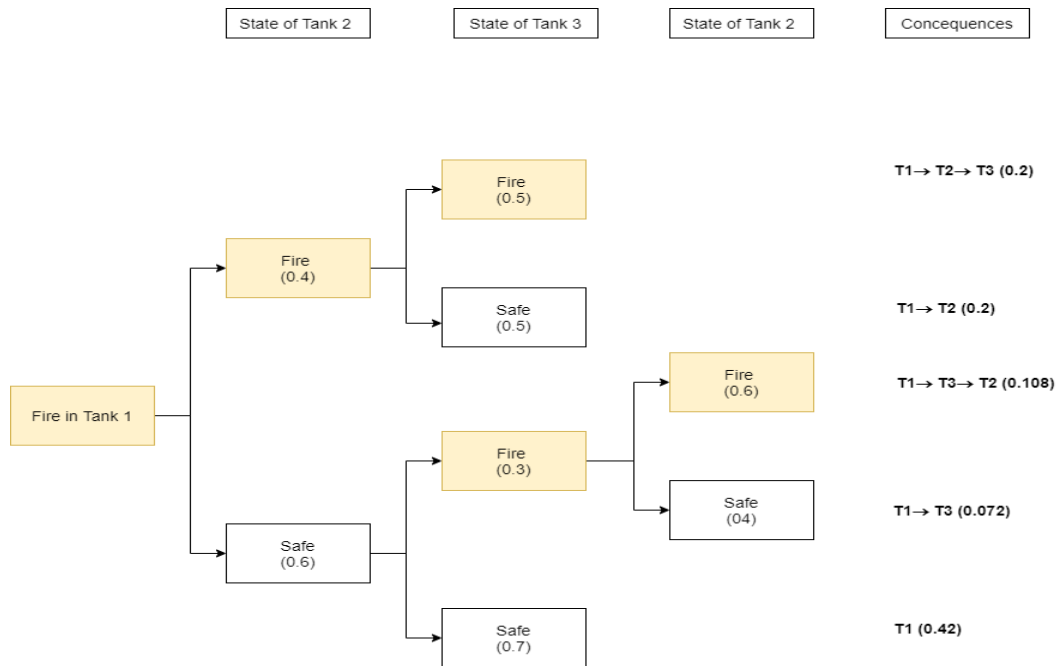


Figure 6.2 (a) Domino escalation assuming T2 catches fire before T3

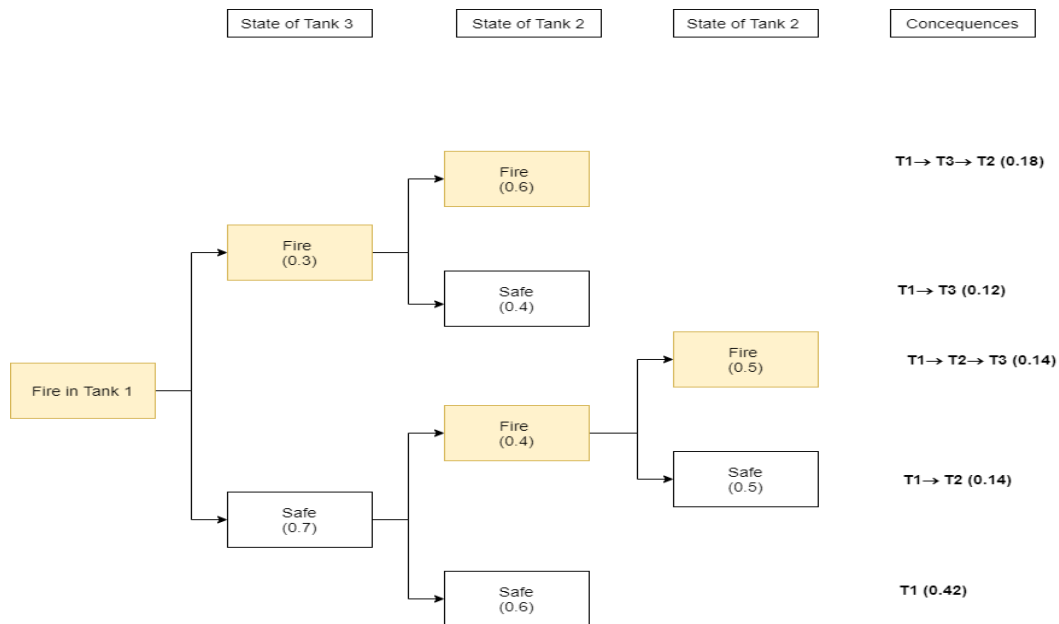


Figure 6.2 (b) Domino escalation assuming T3 catches fire before T2

Figure 6.2 (a) & (b) are logically similar, but they produce dissimilar probabilities for the same event. For the escalation $T1 \rightarrow T2 \rightarrow T3$, the analysis using

ETA can result in probabilities of 0.2 & 0.14 respectively, refer to Figures 6.2 (a) & (b). This is due to the inherent limitation of approaches such as ETA, FTA, and FMEA that they can't consider all failure scenarios at once. The situation can become worse in a complex layout with multiple escalation possibilities. During such analysis, the investigator will be forced to overlook some escalation possibilities, and analysis based on these techniques can result in inaccurate domino escalations.

Advanced risk assessment methodologies such as Bayesian Network (BN) and Petri-nets (PN) are developed to mitigate the limitations of conventional techniques. Both can take into account statistical, stochastic, and temporal dependencies of events and can consider multiple failure states of components during failure analysis.

6.3 Selection of Tools for Efficacy Analysis

The framework adopted for efficacy analysis is detailed in section 3.3 of the methodology chapter. The systematic review of the literature using keywords yielded 177 documents, and out of these 57 publications were based on risk assessment. As illustrated in Figure 6.3 out of these publications, 24 research works are based on graphical methods, 21 were based on analytical methods and 12 were based on simulation methods.

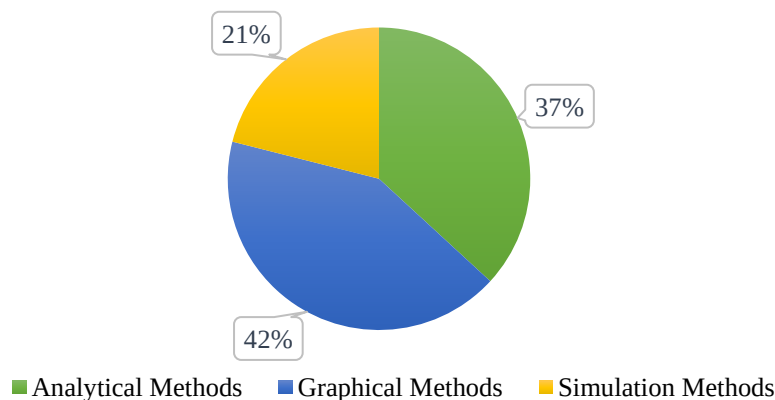


Figure 6.3: Distribution of domino risk assessment approaches

As discussed in the previous chapter, graphical methods are more advantageous than analytical and simulation-based methods, and risk assessment-based graphical methods are gaining popularity among researchers. Considering these facts only graphical-based tools were selected for efficacy analysis. The relative usage of various graphical methods in domino risk assessment is summarized in Table 6.1.

Table 6.1 Usage of graphical methods in risk assessment

Methods	No of Publications
Bayesian Network	7
Dynamic Bayesian	6
Petri-net	4
Hybrid Technique	4
Graph Theory	2
Event Tree	1

In this work, popularly used advanced risk assessment techniques such as Bayesian Network (BN), Dynamic Bayesian Network (DBN), and Petri-nets (PN) were selected for the efficacy analysis study in modeling domino risks. ETA was not considered owing to its inherent limitations in modeling complex scenarios as discussed in section 6.2. Though hybrid techniques are gaining the attention of risk researchers, these are based on the combination of two or more risk assessment techniques, and each such hybrid tool will have specific features entirely different from one another. And one needs to consider every such available combination for relative performance study. Due to this reason, hybrid techniques were not considered in this study.

6.4 Selection of Case Study

The efficacy analysis was aimed to evaluate the relative performance of Bayesian, Dynamic Bayesian, and Petri-net methods in modeling domino risks. For the sake of maintaining consistency and due to the scarcity of open-source software to model Petri nets, it was decided to use a published work on Petri-net as a reference and to model the same case with Bayesian and Dynamic Bayesian

methods. We could identify four publications using Petri-net; two were analyzing emergency response due to fires. Another one modeling a domino effect scenario triggered by a vapor cloud explosion. Kamil et al. (2019) have presented the use of a Petri-net model for a pool fire scenario. This case was chosen because the literature (Darbra et al., 2010) suggests that fire is the more prominent primary scenario for domino accidents. Their study used a hypothetical case to model the domino accident using Petri-net. For the efficacy analysis, the same case was simulated using Bayesian and Dynamic Bayesian networks, and the comparisons were drawn.

A layout of four identical, equispaced storage tanks of 10 T capacity containing gasoline as shown in Figure was considered as the case shown in Figure 6.4. Pool fire was considered as the primary accident scenario in tank 1, and the adjacent tanks damages due to heat radiation exposure. Each tank is covered with a dyke of 10 m diameter and the pool diameter was assumed to be 10 m.

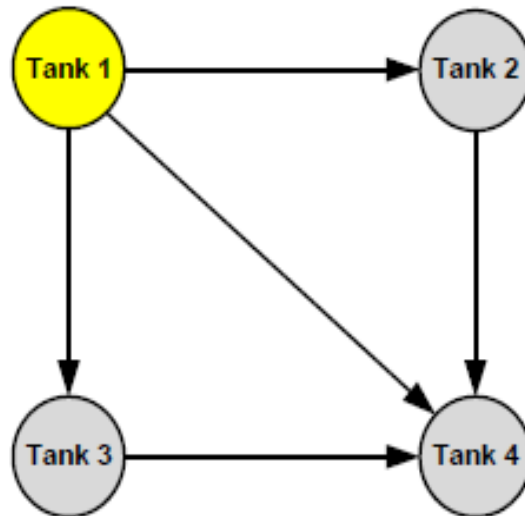


Figure 6.4 Tank Layout

Radiation received at different tanks due to the pool fire in tank 1 is indicated in Table 6.2.

Table 6.2 Radiation escalation vector

Ti→/Tj↓	T1	T2	T3	T4
T1	-	20	20	10
T2	20	-	10	20
T3	20	10	-	20
T4	10	10	20	-

6.5 Efficacy Analysis of Advanced Risk Assessment Techniques.

6.5.1 Application of Bayesian Networks

BN is a directed acyclic graph (DAG) for reasoning under uncertainty, the nodes represent variables and are connected by directed arcs. The arcs represent dependencies or the cause-effect relationships between variables. The strength of such dependencies is determined by the conditional probability assigned to the nodes (Weber, Simon and Iung, 2012; Khakzad *et al.*, 2013). BN uses the Bayes theorem to update the probability in the presence of evidence to yield posterior probability.

$$P(U) = P(X_1, X_2, \dots, X_n) = \prod_{i=1}^n P(X_i | pa(X_i)) \quad \dots\dots\dots(6.1)$$

The concept of Bayesian network-based risk assessment was introduced by Nima Kakhzad (Khakzad *et al.*, 2013). The probability of failure of tanks due to given radiation from tank 1 is calculated using the probit function proposed by Cozzani (Cozzani *et al.*, 2005a).

$$\ln(\text{tff}) = -1.13 \cdot \ln(Q) - 2.667 \cdot 10^{-5} \cdot V + 9.887 \quad \dots\dots\dots(6.2)$$

$$Y = 9.25 - 1.847 \cdot \ln(\text{tff}/60) \quad \dots\dots\dots(6.3)$$

Where ttf indicates time to failure, Y probit function, and Q & V indicates radiation exposure and volume of target tanks. Based on this, the conditional probability table (CPT) was formulated as shown in Table 6.3

Table 6.3 Conditional Probability Table

Tank 1	Tank 2	Tank 3	Tank 4 fire
Fire	Fire	Fire	5.49E-03
Fire	Fire	Safe	1.53 E-04
Fire	Safe	Fire	1.53E-04
Fire	Safe	Safe	0
Safe	Fire	Fire	0
Safe	Fire	Safe	0
Safe	Safe	Fire	0
Safe	Safe	Safe	0

The given scenario was simulated using GeNie software, with nodes representing tanks and arrows representing escalation. The marginal and conditional probabilities are fed into nodes as indicated in table 4. On firing the simulation the software (Figure 6.5 (b)) yields prior probabilities and setting T4 on fire as evidence yields posterior probabilities. The results are summarized in Table 6.4.

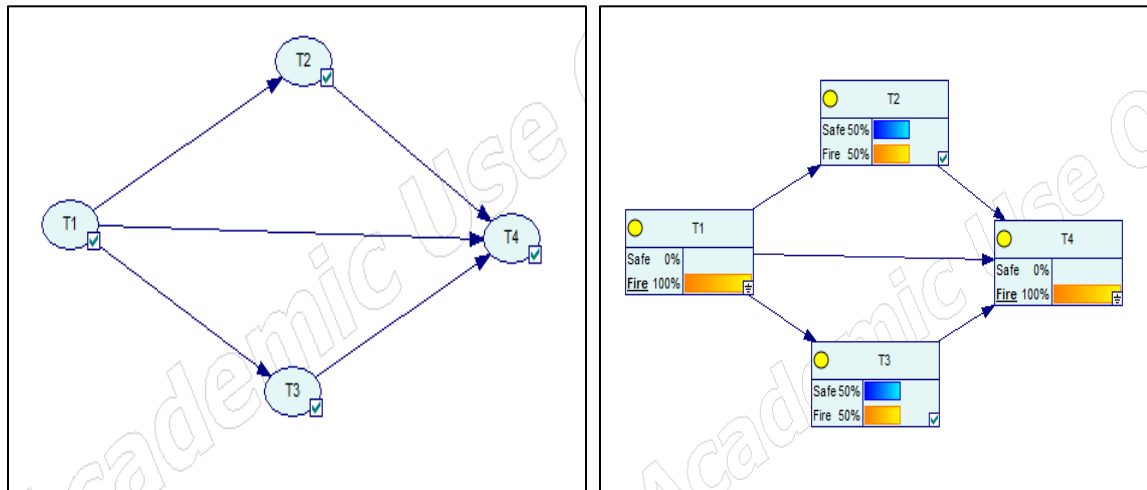


Figure 6.5: Bayesian Network developed: a) Prior b) Posterior conditions

Table 6.4 Probability Table

Tank	Prior Probability	Posterior Probability
T1	1 E-05	1
T2	5.42 E-11	0.5
T3	5.42 E-011	0.5
T4	1.65 E-14	Evidence

Based on the Bayesian simulation it can be inferred that after a fire in tank T1, there is an equal probability to propagate to T2 or T3, then T4.

6.5.2 Application of Dynamic Bayesian Networks

The Domino effect scenario was simulated by dynamic Bayesian analysis using GeNie software for the same layout. In addition to the conditional probability inputs, the time-to-failure (ttf) was also added to simulate the temporal changes.

The dynamic Bayesian network for the case is illustrated below. 6.6 (a) represents the prior condition and 6.6 (b) represents the condition after setting evidence, tank T1 on fire.

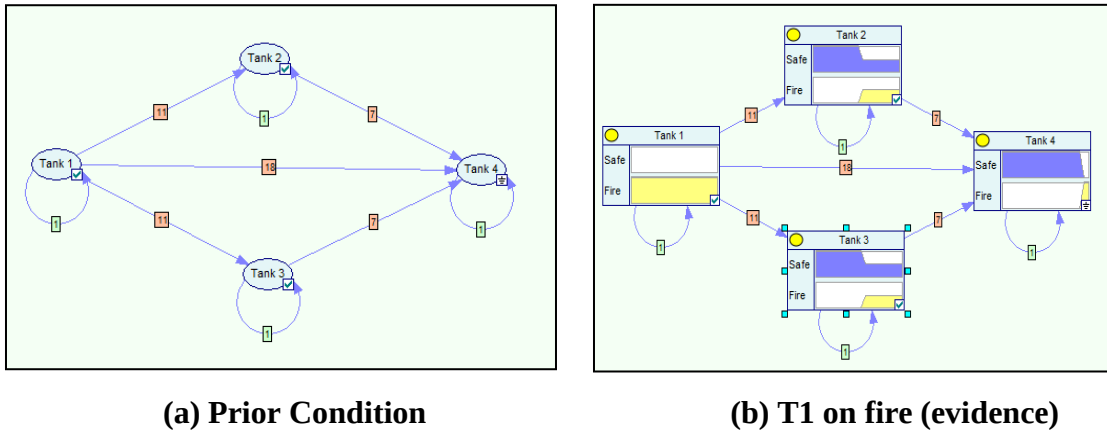


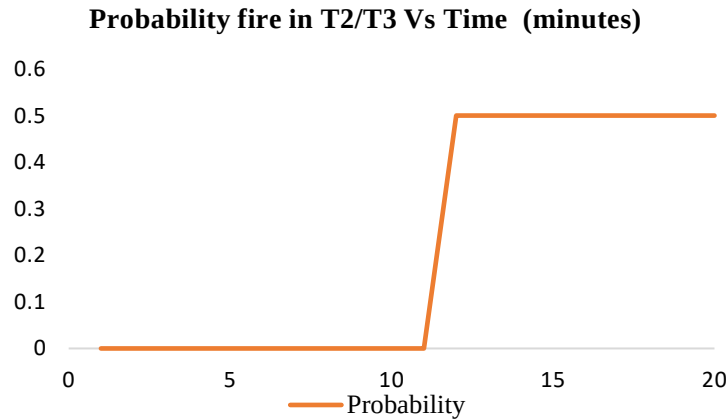
Figure 6.6: Dynamic Bayesian Network developed for the case study

The prior and posterior probabilities are tabulated in Table 6.5

Table 6.5 Probability table based on DBN analysis

Tank	Prior Probability	Posterior Probability, t= 11 m	Posterior Probability, t= 18 m
T1	1 E-05	1	1
T2	5.42 E-11	0.50051213	0.50053112
T3	5.42 E-011	0.49959056	0.49960955
T4	1.65 E-14	Evidence	Evidence

It can be inferred from dynamic Bayesian Analysis that the probability of fire in tank T2 or T3 increases after 11 minutes. This is an important feature of DBN, the time dependency domino effects can be predicted using dynamic Bayesian Analysis. Similarly, after 17 minutes probability of fire in tank T4 increases significantly. Temporal changes in the probability of fire in tank T2 or T3 are illustrated in Figure 6.7

**Figure 6.7 Temporal changes in the probability of tanks T2/ T3**

6.5.3 Application of Petri-nets

The Petri-net (PN) concept was first introduced by Carl Adam Petri in 1962. Petri-nets are still in the developing stage and only a limited number of software are available to model Petri nets. It has been reported that simulation using PN is time-consuming (Kabir and Papadopoulos, 2019; Kamil *et al.*, 2019).

For the comparison, this work used the results of M.Z. Kamil (Kamil *et al.*, 2019). They simulated the same case study using stochastic Petri nets.

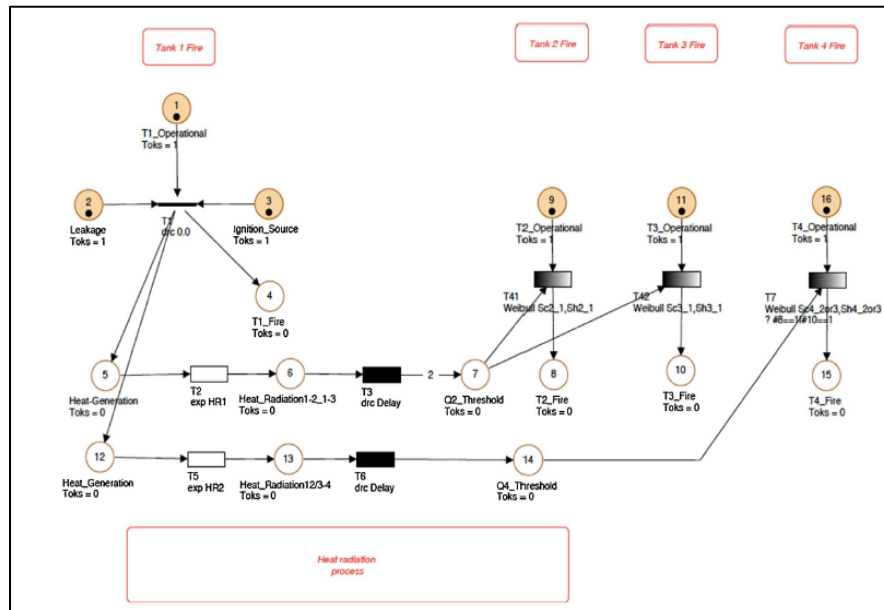


Figure 6.8 Petri nets developed by M.Z. Kamil et al. (2019)

The reported results of the Petri net simulation are comparable with dynamic Bayesian analysis and are illustrated in Figure 6.9.

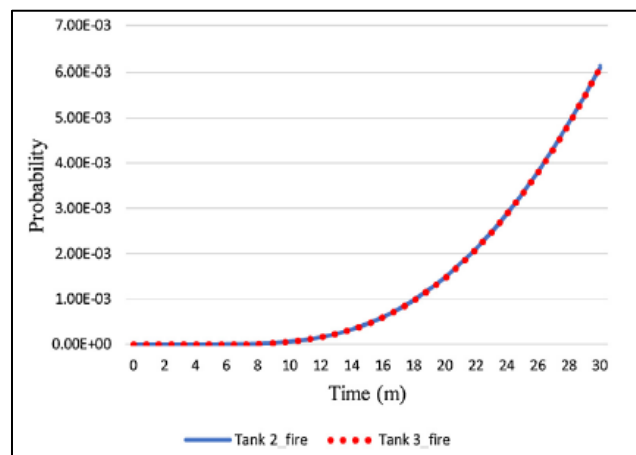


Figure 6.9 Results of Petri nets simulation (M.Z. Kamil et al. 2019)

6.5.4 Comparison of tools for domino risk assessment

Based on the identified capabilities and limitations of domino risk assessment, a comparative study was performed based on various factors such as

time and expertise required, ability to handle complex interactions, temporal, synergistic effects, and availability of resources. The results are summarized in Table 6.6.

Table 6.6: Comparative matrix for various graphical-based tools for domino risk assessment

Criteria	Techniques			
	ETA	BN	DBN	Petri-net
Complex interactions	No	Yes	Yes	Yes
Synergistic effects	No	Yes	Yes	Yes
Temporal evolution	No	No	Yes	Yes
Time required	Less	Average	More than BN	High
Availability of commercial software	Yes	Yes	Yes	No
Expertise required	Minimal	Moderate	Moderate	High

Based on the comparative study, it is obvious that the Event Tree Analysis cannot model domino effects as it cannot model intricate natures of domino accident escalations. These limitations also apply to traditional risk assessment techniques such as FTA and FMEA. Bayesian network-based analysis can model domino risks to a certain extent, but it is unable to model temporal evaluations of domino effects. Based on this study both dynamic Bayesian network and Petri-net models are better equipped to model domino risks. Petr-nets-based simulations are in the developing stage and only a limited number of software are available to model Petri nets, and a considerable amount of time is required for modeling compared to dynamic Bayesian modeling.

6.6 Conclusions

In this work, we identified the techniques that are being used for domino risk assessment by systematically reviewing publications in domino effect research. The analysis of 177 research publications in the Web of Science database showed that domino risk assessment research is active using graphical methods. The most popular tools identified are Bayesian Networks, Dynamic Bayesian, and Petri-nets. These advanced risk assessment techniques were applied in a common tank farm for domino risk assessment. Traditional techniques such as ETA, FTA, and FMEA are incapable of modeling intricate domino escalations. Bayesian Network-based analyses are not capable of modeling temporal evaluations of domino effects. Based on our study, it was identified that both DBN and Petri-net models are better equipped to model domino risks. Considering the more computational time requirement and resource scarcity of Petri-nets, Dynamic Bayesian Network-based modeling is best suited for the present-day studies of domino risk assessment.

CHAPTER 7

DOMINO RISK ASSESSMENT: CURRENT INDUSTRY PRACTICES, NEEDS & EXPECTATIONS OF THE INDUSTRY

Abstract

This chapter presents the findings from a comprehensive survey conducted to understand the current practices, competencies, and expectations related to domino risk assessment within the Quantitative Risk Assessment (QRA) community. The survey, which gathered responses from 45 experienced QRA professionals across various regions and industries, revealed several critical insights into the state of domino risk assessment and highlighted areas for future development.

7.1 Organization & Management of the Survey

The survey was conducted to identify current industry practices, needs, and expectations related to domino risk assessment within the Quantitative Risk Assessment (QRA) community. The methodology adopted for the survey is detailed in section 3.4 of the Methodology chapter. The survey was organized as follows:

1. **Participant Selection:** QRA professionals were identified and approached through the professional networking site LinkedIn. Efforts were made to ensure a diverse representation of professionals across different geographic locations, industries, and experience levels. This included professionals from North America, Europe, Australia, India, and the Middle East.
2. **Survey Instrument:** The survey included questions designed to gather insights on current QRA practices, tools, guidelines, and considerations of domino effects in QRA studies. Open-ended questions were included to capture detailed expectations and needs of the industry.

3. **Data Collection:** The survey was conducted online, allowing participants to respond at their convenience. A total of 48 QRA professionals participated, and after filtering out responses from those with less than two years of experience, 45 responses were considered for analysis.
4. **Data Analysis:** Responses were analyzed to identify common practices, tools, and guidelines used, as well as the extent to which domino effects are considered in QRA studies. The analysis also looked at the industry-wise and experience-wise distribution of participants.

To ensure that the number of responses did not adversely affect the overall results, the following steps were taken:

1. **Diverse Representation:** By including participants from different geographic regions, industries, and experience levels, the survey aimed to capture a comprehensive view of current practices and expectations. This diversity helps mitigate the impact of any single group's overrepresentation.
2. **Exclusion of Inexperienced Responses:** Responses from individuals with less than two years of experience in QRA were excluded to ensure the insights were based on adequate professional expertise. This helped in maintaining the quality and reliability of the data.

7.2 Demography of Participants

The survey was responded by 48 QRA professionals, the QRA experiences of the participants are shown in Figure 7.1. Most respondents had experienced 5-10 years (46%), followed by people with 10-20 years of QRA experience (30%). 3 respondents had less than two years of experience in QRA, to negate the perceptions/misinformation of the novice QRA practitioners' their responses were not taken into account during the analysis.

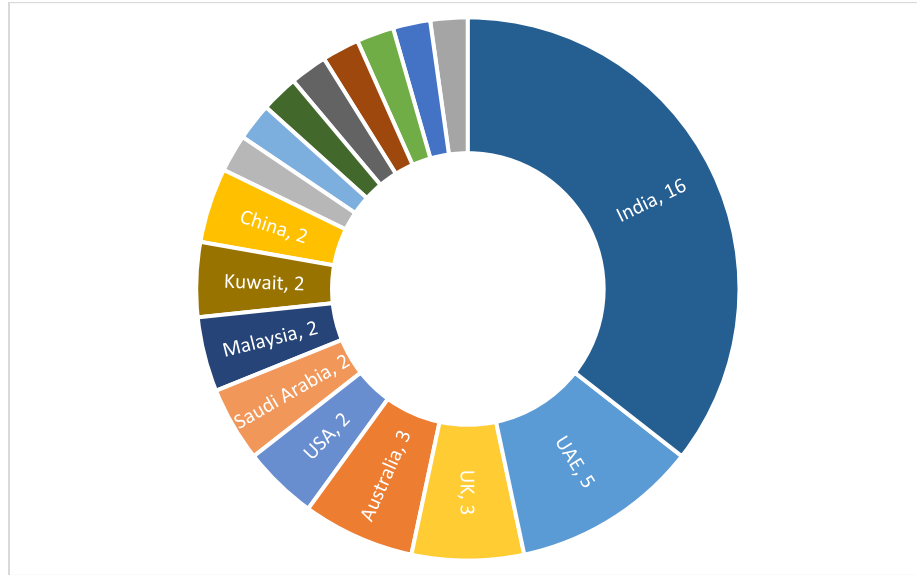


Figure 7.2 (b) Country-wise participation in the survey

The industry-wise participation in the survey is depicted in Figure 7.3. The quantitative risk assessment is a technically skilled job and often companies rely on competent consultants specialized in this profession, 37.8% of the respondents were clients, 35.6% of the participants were consultants, and 22.2% were working with EPC (Engineering, Procurement, and Construction) companies, as shown in Figure 7.2.

Industry Type

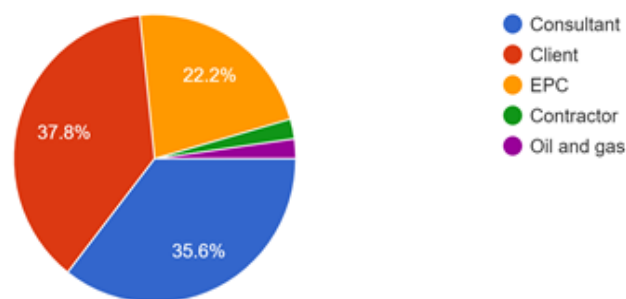


Figure 7.3 Industry-wise Survey Participation

QRA professionals from leading risk consulting firms and other reputed companies participated in the survey which included, DNV, Technip, Worley, Qatar Gas, Saudi Aramco, etc. People with a wide range of job positions such as directors, managers, lead safety, and senior safety engineers participated in the survey.

7.2 Current QRA Practices

Experts' responses to questions related to their QRA practices such as the tools and the guidelines they refer to in consideration of domino effects in QRA are summarized in this section.

The most popular software the professionals rely on for QRA was found to be PHAST software developed by Det Norske Veritas (DNV), Norway. More than 90% of the respondents use PHAST for QRA studies. Other popular software were FLACS & RISKCURVES by Gexcon, and ALOHA developed by the National Oceanic and Atmospheric Administration (NOAA) in collaboration with Environmental Protection Agency (EPA) US. Among these tools identified, only ALOHA is freeware and others are proprietary software.

Which tool/software do you use to perform QRA

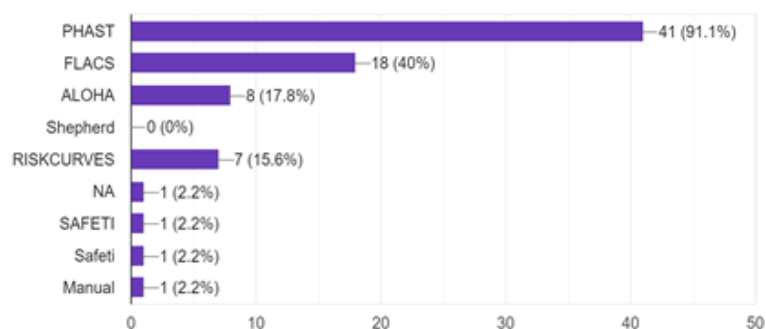


Figure 7. 4 Popular tool/software used for QRA

Often the quantitative risk assessments are governed by country-specific legislations. Nevertheless, most of the experts were found to rely on TNO-colored

books. The colored books developed by TNO serve as worldwide standard reference material for safety studies and as the foundation for software models.

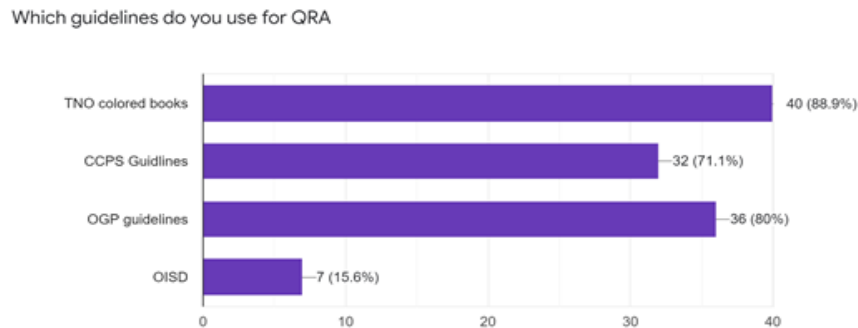


Figure 7.5 Popular guidelines for QRA

Other commonly used reference guides for QRA studies were, guidelines developed by the International Association of Oil & Gas Producers commonly known as OGP guidelines, and guidelines for QRA developed by CCPS (Center for Chemical Process Safety) US.

As depicted in Figure 7.6 only 26.7% of the experts expressed that they consider domino accident scenarios while performing QRA studies. On the other hand, 46.7% of the professionals do not consider a domino accident scenario during QRA.

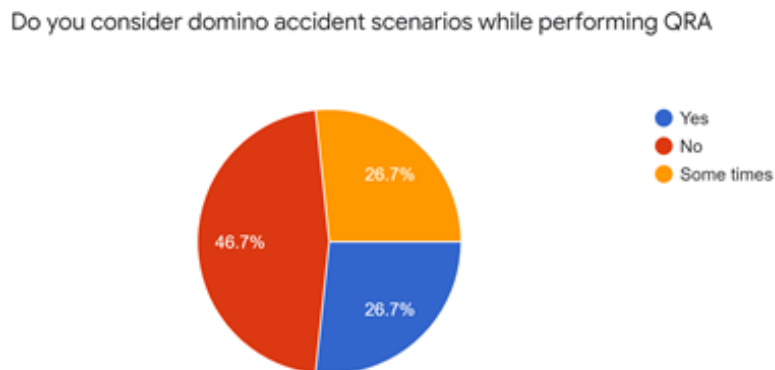


Figure 7.6 Consideration of domino scenarios during QRA

It was acknowledged by 77.8% of the QRA professionals that they do not assess risk caused by domino scenarios in QRA studies. The people who assessed domino risks in QRA studies were either from European Union or Canada.

Do you assess the risk caused by domino scenarios in QRA studies

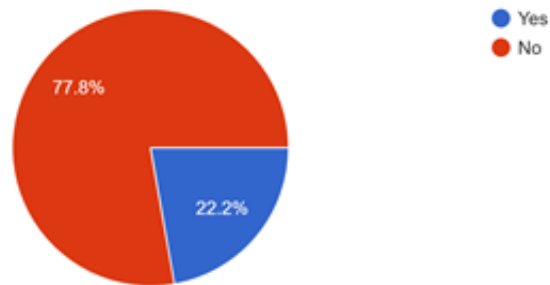


Figure 7.7 Domino risk assessment during QRA

7.3 Expectations & Competencies of the Industry

The outcomes of the survey related to QRA professionals' needs & expectations from the perspective framework and their competency in advanced risk assessment tools are summarized in this section.

7.3.1 Needs and Expectations of the Industry

As the domino risks were not being considered in existing QRA studies, it was an important choice to assess domino risks using a separate and dedicated risk assessment framework for domino effects or to assess domino risks along with existing QRA studies. In response to this question, 42% of the experts preferred assessing domino risk separately and 58% responded to assess domino risk along with existing risk assessment studies.

What do you prefer

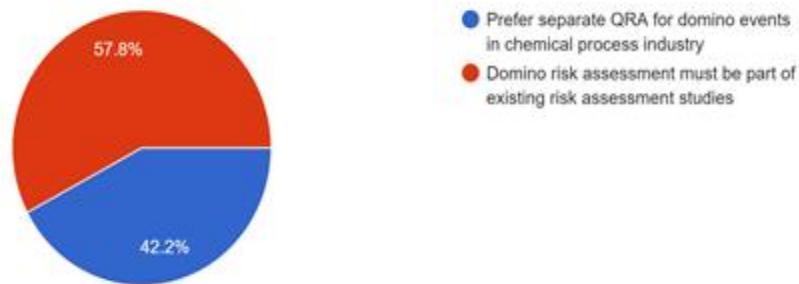


Figure 7.8 Preferences for risk assessment framework

Questions were raised to identify the expert's flexibility to deviate from existing procedures and protocols of QRA. The response received is shown in Figure 7.9, the majority of the professionals were ready to accommodate moderate deviations from existing procedures to assess the domino risks.

How much deviations would you allow from existing procedure (1 - Not at all; 2- Slight; 3- Moderate; 4- Very; 5- Extremely)

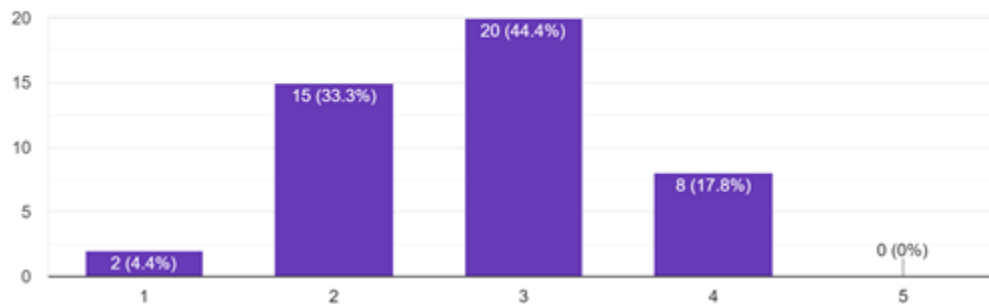


Figure 7.9 Extent of deviations from existing QRA procedures

An open-ended question was asked to specify the top three requirements of the perspective framework. Various expectations about the perspective framework were,

The framework must be able to generate,

- Frequency estimation
- Domino consequence
- The differential duration between the initial event & Domino Event
- The framework must be user-friendly, accurate, and customizable.

7.3.2 Competency

QRA experts were asked to rate their competencies in advanced risk assessment techniques, such as Bayesian, Petri-net, and Fuzzy logic analysis. The self-rating given by experts showed that the QRA professionals are having limited knowledge of advanced risk assessment techniques. The results are depicted in Figure 7.10 (a-c).

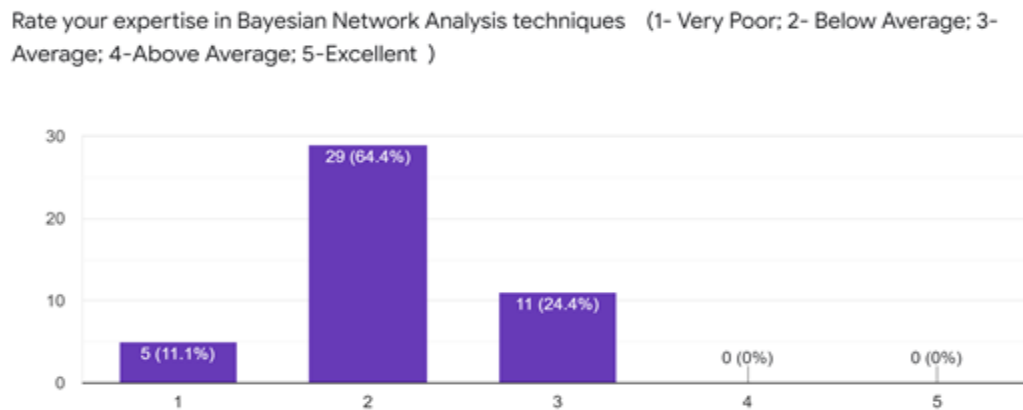


Figure 7.10 (a) Participant's competency in Bayesian network analysis

Rate your expertise in Petri net analysis (1- Very Poor; 2- Below Average; 3- Average; 4-Above Average; 5-Excellent)

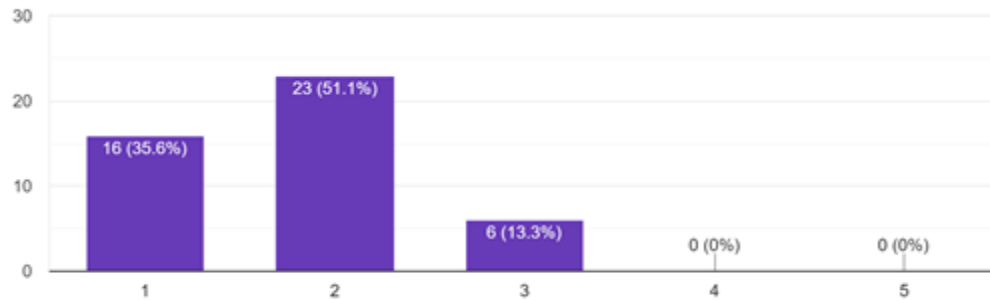


Figure 7.10 (b) Participant's competency in Petri-net analysis

Rate your expertise in Fuzzy logic analysis (1- Very Poor; 2- Below Average; 3- Average; 4-Above Average; 5-Excellent)

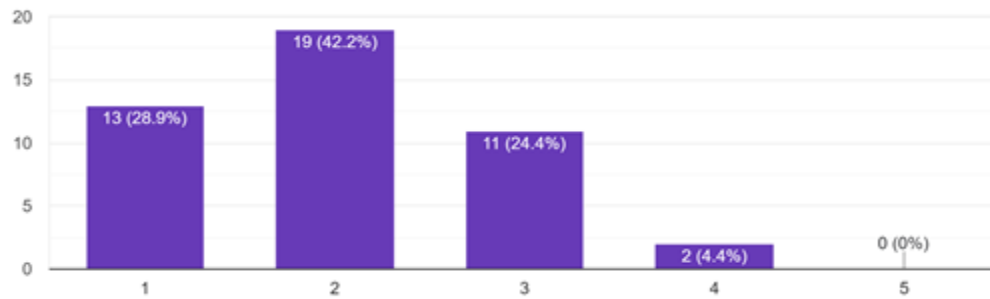


Figure 7.10 (c) Participant's competency in Fuzzy logic analysis

7.4 Review on the adequacy of sample size in this study

In qualitative research, the adequacy of sample size remains a subject of ongoing debate (Guest et al., 2020; Hennink & Kaiser, 2022). Research dealing with focused group interviews is often subjected to low sample sizes. Since there are no fixed rules for ascertaining the required number of sample sizes, saturation is an important aspect that needs to be addressed in qualitative research. Saturation refers to the point at which observing more data will not lead to additional information. There are studies, that support that in homogeneous groups, saturation is achieved using 12-15 participants (Guest et al., 2006), larger samples may offer enhanced

pattern identification capabilities. However, exceeding the necessary limit for qualitative samples can lead to ethical issues, such as wasting research funds, overburdening participants, and wasting time (Morse, 2015). On the other hand, inadequate sample sizes can compromise the credibility of research findings (Hennink & Kaiser, 2022). Hence researchers advocate for the selection of information-rich samples and the acquisition of diverse data through multiple or unstructured interviews (Marshall et al., 2013; Mwita, 2022). This approach aims to balance depth of insight with practical and ethical constraints in qualitative research.

In this work, the survey questionnaire was framed in consultation with three QRA experts having more than 10 years of professional QRA experience, this helped to include broad knowledge related to existing professional QRA practices in the survey questionnaire. By including participants from different geographic regions, industries, and experience levels, the survey aimed to capture a comprehensive view of current practices and expectations. This diversity helps mitigate the impact of any single group's overrepresentation.

Researchers suggest that with the help of saturation tables, one can document thematic saturation (Kerr et al., 2010; Guest et al., 2006). In the saturation table, themes, and sub-themes (codes) are represented in each row and columns represent sequential focus groups or individual interviews. The cells within the table indicate the initial identification of each theme. The saturation table provides visual and documentary evidence of saturation. As data collection progresses, the absence of new themes, concepts, or codes in the columns representing later interviews serves as a clear indication that saturation has been achieved. In this survey responses from 45 diverse professional QRA practitioners were collated, and the saturation table suggests that no new themes have emerged after the 22nd interview, demonstrating the thematic saturation.

Table 7.1 Saturation Table

Theme	Sub-theme	Responder No.																	
		1	2	3	4	5	6	7	8	9	10	11	12	..	22	..	45		
Tools for QRA	PHAIST	X																	
	FLACS		X																
	SAFETI						X												
	MANUAL									X									
	ALOHA												X						
	RISK CURVE															X			
Guidelines for QRA	TNO colored books	X																	
	OGP guidelines	X																	
	CCPS Guidelines			X															
	OISD			X															
Expectations from the new framework	Frequency estimation		X																
	Domino Consequence		X																
	Duration between initial event & Domino Event		X																
	Less time consuming											X							
	User friendly														X				
	Accuracy														X				
	Customization														X				

X indicates the response in which the sub-theme was first observed

7.5 Discussions

To identify the current industry practices in domino risk assessment and expectations of the industry a worldwide group of QRA professionals were invited to take part in an ad-hoc online survey. QRA professionals were identified through the professional networking site, LinkedIn and were individually approached for their willingness to participate in the survey. 48 QRA professionals participated in this survey out of which 45 responses were considered for analysis. As it is important to involve experts with diverse backgrounds for improving the accuracy of the results and drawing meaningful conclusions, experts from different industry roles (consultants, clients, EPC, and contractors) and experience levels were involved in this survey.

The survey brought to light the popular software and guidelines the QRA professionals rely on for QRA studies. Irrespective of the geographical differences

over 90% of the professionals were using PHAST software developed by DNV for QRA studies. The commonly used guidelines for quantitative risk assessment were TNO-colored books, OGP guidelines, and CCPS guidelines. It was evident from the survey results that most of the QRA studies do not consider domino risk. Though 53% of the participants consider domino accident scenarios in their QRA studies, it was acknowledged that 78% of QRA professionals do not assess risks posed by domino effects in their QRA studies. The persons who assessed domino risk in their QRA studies were majorly from the European Union, this showed that the domino risk assessment in QRA studies is governed by legislation.

The needs & expectations of the industry from the perspective framework were identified. To assess the domino risk using a new framework the experts were ready to accommodate moderate deviations from existing QRA practices and procedures. When it comes to the preference of assessing domino risks using a separate and dedicated framework or integrating domino risk assessment using existing QRA studies, 58% preferred that domino risk must be assessed in existing QRA studies, and the rest preferred a separate study for domino risk assessment. The competency of QRA professionals in advanced and recently emerged risk assessment techniques such as Bayesian analysis, Petri-nets, and Fuzzy logic is limited, with modestly better competency in fuzzy logic analysis.

7.6 Conclusion

This chapter presented the findings from a comprehensive survey conducted to understand the current practices, competencies, and expectations related to domino risk assessment within the Quantitative Risk Assessment (QRA) community. The survey, which gathered responses from 45 experienced QRA professionals across various regions and industries, revealed several critical insights into the state of domino risk assessment and highlighted areas for future development.

Major Findings:

1. Current QRA Practices:

- Dominant Tools: The survey identified PHAST, developed by Det Norske Veritas (DNV), as the most widely used software for QRA, with over 90% of respondents utilizing it. Other popular tools included FLACS, RISKCURVES, and ALOHA, although the latter is the only freeware among them.
- Guidelines: TNO-colored books emerged as the primary reference material for QRA studies, supplemented by guidelines from the International Association of Oil & Gas Producers (OGP) and the Center for Chemical Process Safety (CCPS).

2. Consideration of Domino Effects:

- Limited Inclusion: A significant finding was that only 26.7% of respondents consider domino accident scenarios in their QRA studies, and 77.8% do not assess the risks posed by domino scenarios. This indicates a gap in the integration of domino risk assessment within standard QRA practices.

3. Industry Expectations:

- Framework Preferences: The industry is divided on how to approach domino risk assessment. Only 42% of respondents prefer a dedicated risk assessment framework for domino effects, while 58% support integrating it with existing QRA studies.
- Flexibility and Requirements: Most professionals are willing to accommodate moderate deviations from current QRA procedures to incorporate domino risk assessment. Key requirements for a new framework include frequency estimation, domino consequence analysis, and the differential duration between initial and domino events.

4. Competency in Advanced Techniques:

- Limited Knowledge: The self-assessed competency of QRA professionals in advanced risk assessment techniques such as Bayesian networks, Petri-nets, and Fuzzy logic analysis is limited. This suggests a need for further training and development in these areas to enhance the effectiveness of QRA studies.

Novel Findings:

- Geographic Variation: The survey highlighted that professionals who do consider and assess domino risks predominantly come from the European Union or Canada. This supports that regional regulations and guidelines might influence the adoption of domino risk assessment practices, enforcing domino risk assessment through regulation can positively influence the industry to consider domino risk assessment in their QRA studies.
- Framework Customization: The need for a user-friendly, accurate, and customizable framework for domino risk assessment was a recurring theme. This underscores the industry's desire for tools that can be tailored to specific needs and contexts, enhancing their practical utility.

The survey results underscore a significant opportunity to improve QRA practices by integrating domino risk assessment more systematically. Addressing the identified gaps and aligning tools and frameworks with industry expectations can lead to more comprehensive and effective risk management strategies. These insights provide a valuable foundation for developing innovative approaches to enhance safety and risk assessment in the process industry.

CHAPTER 8

DEVELOPMENT OF A FUZZY-BASED SCREENING TOOL FOR DOMINO RISK

Abstract

This chapter details the development and validation of a fuzzy-based screening tool for domino risks. This chapter is arranged in the following manner, section 8.1 provides the rationale for choosing fuzzy modeling, and section 8.2 provides an overview of the fuzzy inference system (FIS). Section 8.3 proposes the methodology for developing the domino risk screening tool. The developed tool was applied in various case studies, as detailed in section 8.4, and it was found that the developed tool can predict the risk with reasonable accuracy.

8.1 Introduction

In chemical process industries, the accidents induced by domino effects are the ones that have the most disastrous outcomes. To meet the enhanced energy requirement, especially in developing countries more industrial complexes are being created leading to the proximate positioning of industrial plants, increased handling of dangerous goods, and transit networks (Necci *et al.*, 2015; Zeng, Chen, Yang, Liu, *et al.*, 2020). Past accident analysis also suggests that the occurrences of domino effects are increasing in developing countries like India and China. The lack of specific legal regimes to govern the domino risks adds to these countries' accident vulnerability (Abdolhamidzadeh, Abbasi, D Rashtchian, *et al.*, 2011; Hemmatian *et al.*, 2014).

It is well established that proper risk assessment and management can effectively control the risks of domino effects. The risk research of the domino effect was mainly focused in Europe majorly because of the legal requirement for domino risk assessment and extensive sharing of information mandated by Seveso directives (Li *et al.*, 2017). Though, active research in this field was initiated in the late 90s (Faisal I. Khan and Abbasi, 1998a), since then many frameworks, models tools, and techniques

have been developed to assess and manage the risk of domino effects in chemical process industries (Chen, Reniers and Khakzad, 2020).

Compared to standalone accident risk assessment, the domino risk analysis in chemical process industries is acknowledged as an extremely challenging task owing to the complexities and uncertainties in domino accident realization. The uncertainties in domino risk arise from various sources such as primary unit selection, escalation vectors to be considered, potential targets to determine the propagation of the domino effect, atmospheric conditions to determine the heat radiation and overpressure distribution, and distributions of personnel and property that affect the domino effect's consequences. This information is difficult to verify or uncertain. In a domino effect analysis, this unknown and uncertain knowledge is a significant problem that must be resolved for effective domino risk analysis (Cozzani, Gubinelli and Salzano, 2006; Ji *et al.*, 2018; Khakzad *et al.*, 2018). Fuzzy logic is a proven method for dealing with uncertain and imprecise data (Zadeh, 1965; Markowski, Mannan and Bigoszevska, 2009). The use of an expert knowledge system in fuzzy modeling can effectively tackle parameter and model uncertainties (Berihha *et al.*, 2012; Mahmood *et al.*, 2013; Pouyakian *et al.*, 2021). On the other hand, tools like Fault Tree Analysis, Event Tree Analysis, Bayesian Network, and Bowtie tools cannot deal with unknown failure data. The above-mentioned features of the fuzzy inference system make it an ideal tool for the domino risk assessment. Nevertheless, fuzzy systems are not devoid of restrictions and limitations as the reliability of fuzzy systems heavily depends on experts' subjective inputs. Comprehensive QRA of domino risks is both time-consuming and expensive, hence it is important to screen domino risks before any comprehensive studies. Considering the above features and limitations of fuzzy models, in domino risk assessment fuzzy-based models may be best suited as a risk-screening tool. Fuzzy models can offer cost-effective and rapid risk screening tools for domino risk assessment with equitable accuracy.

8.2 An Overview of Fuzzy Modelling

The different steps involved in fuzzy modeling are 1. fuzzification, 2. fuzzy inference, and defuzzification (Zadeh, 1965)

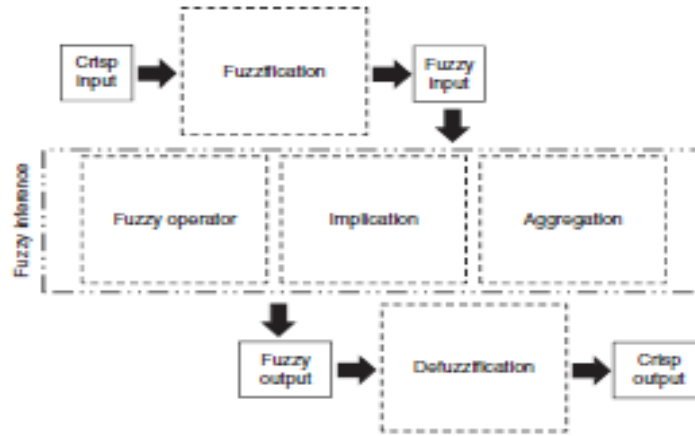


Figure 8.1 Methodology for fuzzy modeling

8.2.1 Fuzzification

Fuzzification is the process of translating crisp and real values into language functions and fuzzy sets by utilizing information from the knowledge base. Expert perspectives obtained through semi-structured interviews, literature reviews, or historical data can be used to collect information and formulate linguistic terms (Axelrod, 1976; Eden, 1988). Membership functions are created in this step to convert real values to fuzzy values. Typical types of membership functions include triangular, trapezoidal, and Gaussian types (Markowski and Mannan, 2008; Karimpour *et al.*, 2016). Experience, knowledge, problem, statements, and variable properties are used to select appropriate types of functions. The membership function is the curve that specifies how each point in the input space is converted into a membership value ranging from 0 to 1.

8.2.2 Fuzzy Inference

This is the most critical step in fuzzy modeling and is defined as the process of integrating fuzzy logic to create a mapping from a given input to an output. The major

fuzzy inference systems are the Mamdani model (Mamdani and Assilian, 1975), the Sugeno model (Sugeno, 1985), and the Tsukamoto model (Tsukamoto, 1993). The output of the model majorly depends on the type of FIS model. Among these, the most commonly used FIS model is the Mamdani model (Wang and Chen, 2014).

8.2.3 Defuzzification

The fuzzy inference system generates fuzzy outputs, defuzzification is the process of converting this into a crisp output. The different methods available for defuzzification are centroid, bisector, middle of maximum, smallest of maximum, and largest of maximum.

8.3 Methodology for developing a domino risk screening tool

The development of a screening tool for domino risk in the chemical process industry involved a four-step approach. They were,

1. Identification of risk factors
2. Fuzzification
3. Fuzzy Inference system
4. Defuzzification process

The overall methodology is illustrated in Figure 8.2

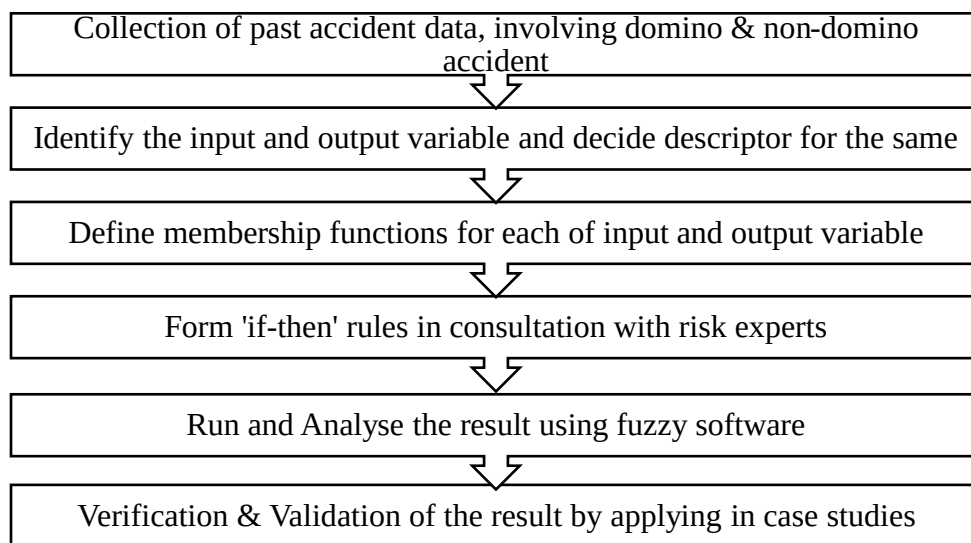


Figure 8.2 Overall methodology for developing domino risk screening tool

8.3.1 Identification of Risk Factors

A descriptive survey was carried out to identify and collect data on the last 30 years of accidents. Various reliable sources like accident databases and literature were referred to collect various parameters and specifications of primary and secondary units. The referred databases include eMARS and FACTS. Data from 50 accidents were collected, which included both domino and non-domino cases. The details are annexed at A3. The risk of domino depended on various parameters of causative and affected units and distance of separation. Since taking into account all such variables would be a cumbersome task, only the following critical parameters were identified as the risk factors (input variables) viz volume (Ton), pressure (bar), temperature (°C), type of installation (i.e. pipeline, process unit, or storage vessel) and distance between units.

8.3.2 Fuzzification Process

Fuzzification is the process of obtaining linguistic functions from real and crisp values. By analyzing collected past accident data, the frequency of the domino effect was determined for different ranges of input parameters. Based on the frequency of domino effect incidence, the input parameters were categorized into three linguistic categories, low, medium, and high. The dependency (frequency) of domino occurrence associated with each parameter and linguistic categorization is represented in Table 8.1

Table 8.1 Linguistic categorization of parameters

Sl. No (a)	Risk Factors (b)	Parameter Range (c)	Linguistic Term (d)	Total no of Events (e)	No. of domino events (f)	Frequency (f/50) (%)
1	Volume	0 T to 5 T	Low	9	7	14%
		5 T to 50 T	Medium	13	12	24%
		50 T to 50,000 & Above	High	19	17	34%
2	Pressure	0 bar to 10 bar	Low	6	6	12%
		10 bar to 50 bar	Medium	8	7	14%
		50 bar to 90 & Above)	High	8	8	16%
3	Temperature	(0 deg. C To 50 deg. C	Low	2	2	4%

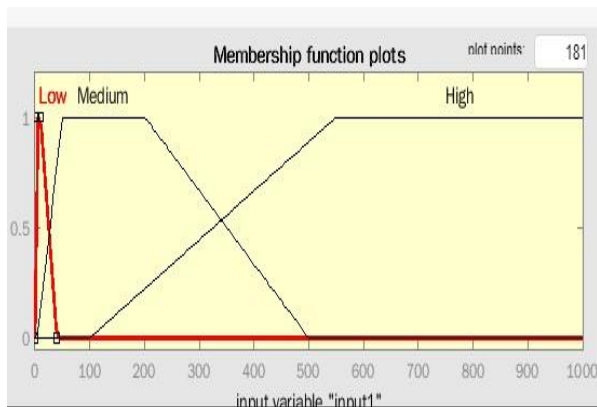
Sl. No (a)	Risk Factors (b)	Parameter Range (c)	Linguistic Term (d)	Total no of Events (e)	No. of domino events (f)	Frequency (f/50) (%)
4	Distance between units	50 deg. C to 150 deg. C	Medium	5	4	8%
		150 deg. C to 200 & above	High	7	7	14%
		0 m to 10 m	High	9	9	18%
		10 m to 50 m	Medium	6	6	12%
		50 m to 300 & above	Low	6	5	10%
5	Type of Installation	Pipe line and Truck tank (1)	Low	3	3	6%
		Storage Reactor and column (2)	Medium	4	4	8%
		Cylindrical Tank, Vessel, and Container (3)	High	36	31	62%

Trapezoidal type membership functions were used for fuzzification of inputs and output variables, based on experience (Markowski and Mannan, 2008) they can better represent failure data. The fuzzy sets developed for input and output variables are detailed in Table 8.2, and the corresponding membership functions created are illustrated in Figure 8.3

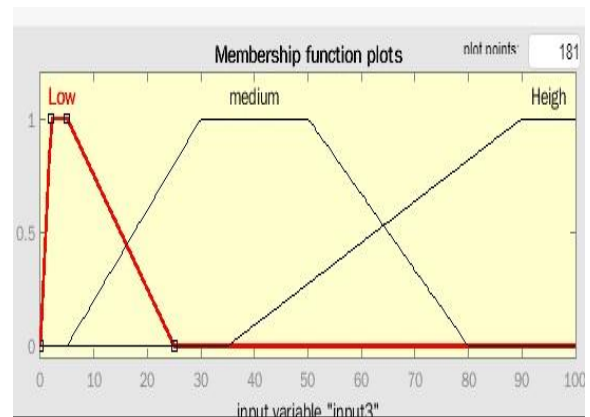
Table 8.2 Fuzzy Sets developed for input and output variables

Sr.no	Variable	Display range	Risk Range	Risk
1	Volume (Ton) (Input-1)	[0,50000]	[0,2,10,40]	Low
			[4,50,200,500]	Medium
			[100,550,40,000,50,000]	High
2	Temp in °C (Input-2)	[0,1000]	[0,20,40,60]	Low
			[40,65,135,165]	Medium
			[160,170,1000,1000]	High
3	Pressure in Bar (Input-3)	[0,100]	[0,2,5,25]	Low
			[5,30,50,80]	Medium
			[35,90,100,100]	High
4	Distance to adjutant tank (Input-4)	[0,500]	[0,2,5,25]	Low
			[5,35,165,275]	Medium
			[150,300,500,500]	High

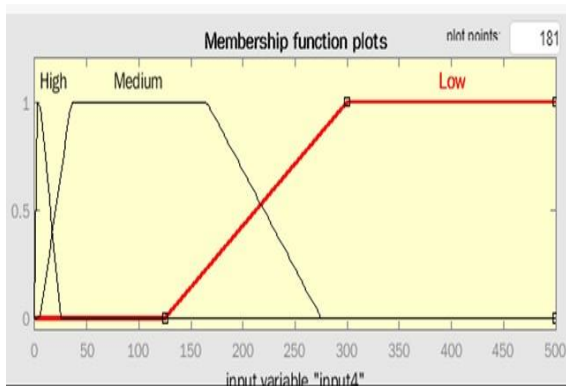
Sr.no	Variable	Display range	Risk Range	Risk
5	Type of installation / (Input-5)	[0,10]	[0,0.3,0.5,1.5]	Low
			[0.5,1.9,2,2.5]	Medium
			[2,3,10,10]	High
6	Domino Risk (Output)	[0,100]	[0,15,25,40]	Low
			[30,45,55,65]	Medium
			[50,80,100,100]	High



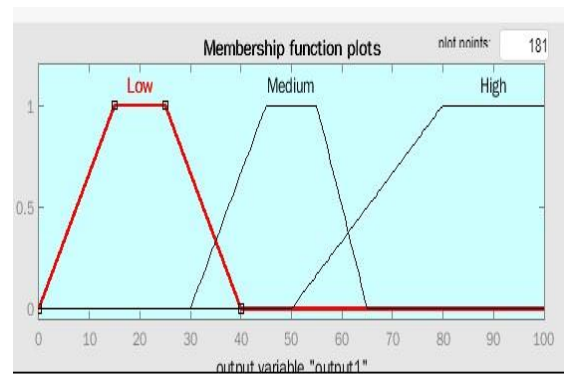
(a) Volume



(b) Pressure



(c) Distance between units



(d) Risk output

Figure 8.3 Trapezoidal membership functions created for different parameters

8.3.3 Fuzzy Inference System (FIS)

In this model, the Mamdani fuzzy inference system was used. The inference engine maps fuzzy input sets into fuzzy output sets with the help of ‘if-then’ rules with an AND connector. The rules were developed in consultation with five QRA experts having more than 15 years of experience in risk assessment in chemical process industries. We have developed 131 such rules, and these rules connect the inputs and outputs of FIS. An example of one of such rules developed was that, if the volume is high, the temp range is high, the pressure range is high, and the distance between two units is low, then the final risk is high.

8.3.4 Defuzzification Process

The defuzzification process involves converting fuzzy data to crisp ones. In this work, the centroid method was used for the defuzzification process using Matlab software.

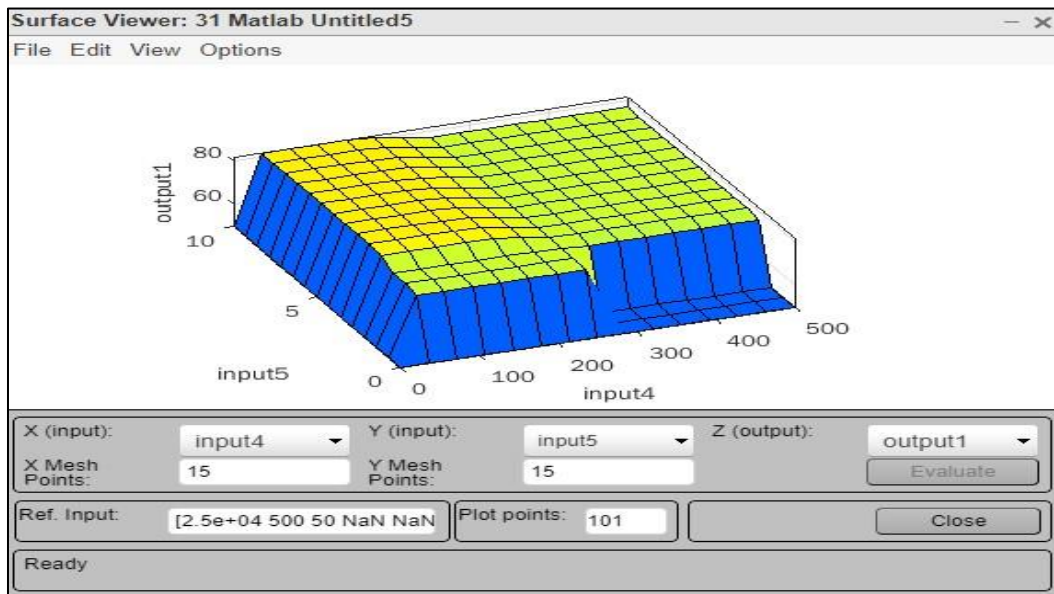


Figure 8.4 Distance between units and type of installation vs risk factor

The interdependency of the input variable on output can be represented using the surface plot. Figure 8.4 represents the interdependency of the distance between units and the type of installation with output risk.

8.4 Application in Case Studies

This section discusses the efficacy of developed tools for screening domino effect risks. The tool was applied to past accidents involving both domino effects and stand-alone accidents and its performance was evaluated.

8.4.1 Case study -1 (Involving domino effect)

On October 29, 2009, a severe explosion occurred in M/S Indian Oil Corporation's POL terminal, Jaipur, Rajasthan, killing 11 people and injuring 45 others. During the pipeline transfer operation, uncontrolled leakage from one of the valves resulted in a massive vapor cloud that engulfed the whole site. A blast happened when this vapor cloud found a source of ignition. The blast destroyed the terminal's equipment and buildings resulting in 9 of the 11 tanks catching fire in quick succession, spreading to the remaining two product tanks. The fire continued for the next 11 days. The incident resulted in extensive damage to buildings and properties of adjoining industries. The estimated cost of this accident was around 28 million ₹. (Oil Industry Safety Directorate, Ministry of Petroleum Natural Gas (MoPNG), 2011).

Table 8.3 Inputs and output parameters of case study 1

Case Study	Input -01 (Volume,T)	Input -02 (Temperature, Deg Celsius)	Input-03 (Pressure, Bar)	Input-04 Distance between units	Input-5 Type of Installation	Output (Risk)
Jaipur IOCL Fire Accident	38.976	1727	1	48	3	78.8

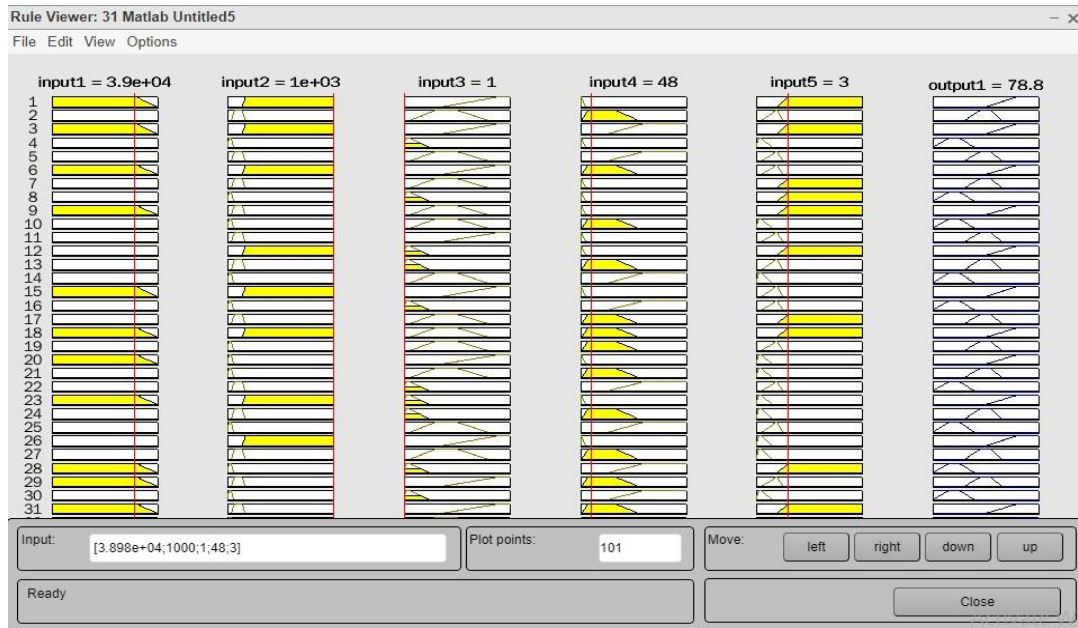


Figure 8.5 Graphical rules for case 1

The required input parameters were collected from the accident investigation report (Oil Industry Safety Directorate, Ministry of Petroleum Natural Gas (MoPNG), 2011) and fed into the fuzzy tool developed. IOCL Jaipur domino accident is considered to be one of the worst chemical accidents in India. The input parameters were fed into the developed fuzzy model using Matlab software and the final risk score of 78.8 was obtained as the output.

8.4.2 Case study -2 (Involving non-domino effect)

Secondly, the developed model was applied to a past accident involving a non-domino accident to identify the risk score, this an accident that happened in the EMPAK facilities, in Deer Park, Texas, in 1988 was considered. A tank contained approximately 13,000 kg of ethylene oxide, an explosion happened due to a chemical reaction, triggered by an accidental mixing of ethylene oxide with brine solution during unloading operations. The impacts were felt up to a distance of 240 m distance, but no domino effect was reported. The inputs and outputs from FIS are portrayed in Table 8.4 and Figure 8.6. For this case, the tool produced an output score of 20.

Table 8.4 Inputs and output parameters of case study 2

Case Study	Input -01 (Volume,T)	Input -02 (Temperature, Deg Celsius)	Input-03 (Pressure, Bar)	Input-04 Distance between units	Input-5 Type of Installation	Output (Risk)
Deer Park, Texas, 1988	14	27	0.6	240	3	20

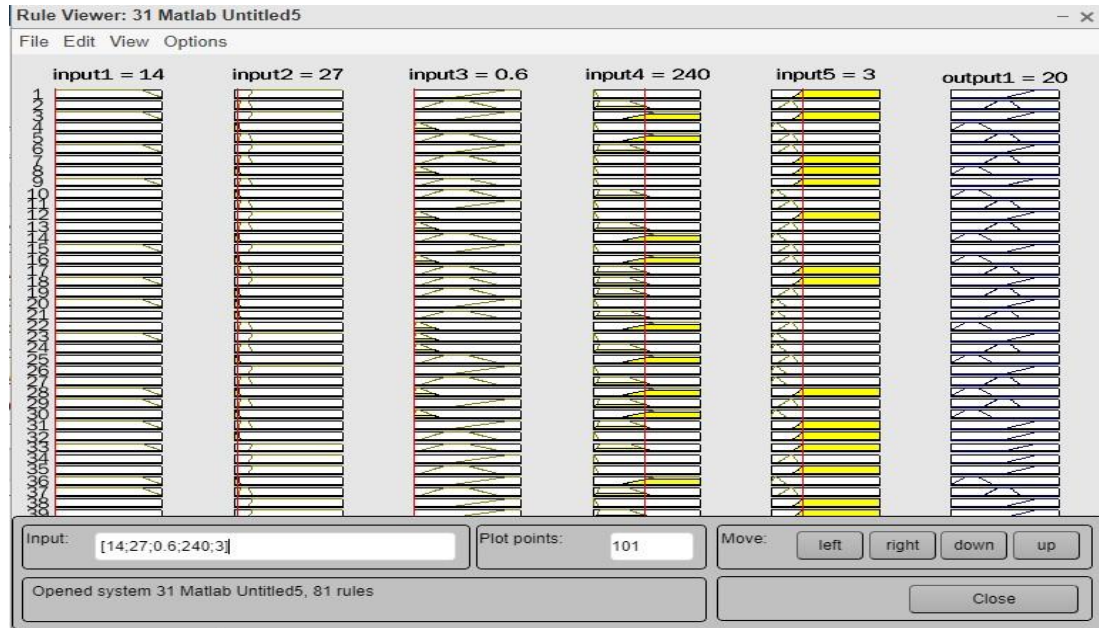


Figure 8.6 Graphical rules for case 2

Similarly, the developed fuzzy tool was applied in other accident cases, involving both domino and non-domino accidents. The results are summarized in Table 8.5.

Table 8.5 Risk score for various accident scenarios

Sr.no	Case Study	Input -01 (Volume)	Input -02 (Temp)	Input-03 (Pressure)	Input-04 (Distance to adjustment tank) m	Input-5 Installation	Output/ Risk Score
1	12/(Domino)	0.75	5	25	10	3	77.1
2	49/(Domino)	86.4	165	80	43	3	50
3	51/Domino	17657	120	90	31.7	3	81.1
4	52 /Non Domino	22.18	25.7	30	15	3	56.1
5	53/ND	4237	44	20	125	3	50
6	54/nD	2	700	150	100	1	50
7	55/nd	7	70	20	31	1	48.1

Sr.no	Case Study	Input -01 (Volume)	Input -02 (Temp)	Input-03 (Pressure)	Input-04 (Distance to adjustment tank) m	Input-5 Installation	Output/ Risk Score
8	57 /D	1649	60	0.6	97	3	77.5
9	58/d	90	120	51	200	3	48.3
10	59/nd	14	27	0.6	240	3	20
11	61/d	38976	1727	1	48	3	78.8
12	68/Nd	19	28	25	70	1	31

By analyzing the risk score generated for various accident cases, the following risk categorization was framed. It was evident from the application of this tool in different case studies, that the developed tool produced higher risk scores for accidents involving domino effects.

Table 8.6 Risk Categorization

Sr.no	Output Range	Risk category
1	0-40	Low
2	41-65	Medium
3	66-100	High

8.5 Conclusions

Domino effect risk assessment is a challenging exercise owing to its complex mechanisms and uncertainty. Literature review showed that while dealing with uncertain data, fuzzy models are more advantageous compared to other risk assessment methods. In this work, we have developed a domino risk screening tool based on a fuzzy inference system. The expert knowledge system is an ambivalent feature in FIS. To limit the bias of limited human knowledge about the dependency of various parameters on domino risk contribution, the past 30 years of accident data was analyzed and the frequency of the domino effect was determined for different ranges of input parameters. Based on the frequency, the input parameters were categorized into three linguistic categories, low, medium, and high. A trapezoidal membership function was assigned for input and output variables. The fuzzy inference system was created based on the Mamdani fuzzy inference system. 131 rules were developed to connect the input to output parameters. The developed system was applied in various case studies

involving domino and non-domino effects. For cases involving domino effects, the tool produced high output values, and a rating system for the output risk was developed. Though the developed system can be used in any stage of the chemical process plant project., the fact that it can predict the domino risk with minimum input parameters makes it a suitable tool for performing screening domino risks during the concept and feasibility study stage. In comparison to domino risk assessment with advanced risk assessment techniques the developed tool is user-friendly, less time-consuming, and comparatively lesser expertise is required to model domino risk. Though it has many advantages compared to other risk assessment tools since the rules framed are affected by expert knowledge and the limited historical data, which are inherent limitations of any fuzzy-based model, this can't be used as an alternative to existing comprehensive domino risk assessment models but can be used as an effective screening tool for domino risk assessment.

CHAPTER 9

DEVELOPMENT AND VALIDATION OF A COMPREHENSIVE FRAMEWORK FOR DOMINO RISK ASSESSMENT

Abstract

This chapter details the development and validation of a comprehensive framework for assessing domino risks in chemical process industries. The contents of this chapter are arranged in the following manner, section 9.1 details the inferences from efficacy analysis and expert survey, which provides the inputs for the framework development. Section 9.2 details the comprehensive framework developed for domino risk assessment. The developed framework was applied in a tank farm case study. The frequency estimations are performed using PHAST and ALOHA software with the help of dynamic Bayesian network analysis and are detailed in section 9.3. Section 9.4 discusses the validation of the framework developed, the results obtained are compared with values in the literature, and it was found that both the models were able to predict the domino propagation paths. The results of the PHAST modeling were found more consistent with the reference values.

9.1 Introduction

The overall aim of this work was to develop an industry-friendly framework for assessing domino effect accident risks in the chemical process industry. The studies undertaken in Chapters 6 & 7 serve as the inputs for the development of the framework. The efficacy analysis of existing risk assessment tools aided in identifying the most appropriate tools for domino effect frequency estimation. The current QRA practices, needs & expectations of the industry were identified using the expert survey as detailed in Chapter 7.

9.1.1 Inference from the Efficacy Analysis

The domino effect frequency estimation is a challenging task due to the complexities involved in accident mechanisms. In these situations, traditional frequency estimation techniques such as ETA, FTA, FMEA, and Bowtie techniques fail to model intricate domino escalations, as they cannot consider all failure scenarios at once. Domino escalation is a time-dependent activity hence temporal evolutions are of most importance. The efficacy analysis of academically popular advanced risk assessment techniques showed that both dynamic Bayesian network and Petri-net models are better equipped to model domino risks. As Petr-nets-based simulations are in the developing stage, only a limited number of software are available to model Petri-nets, and considering the greater modeling time involved; the dynamic Bayesian network technique was selected for the framework development.

The DBNs are capable of taking into account complex interactions, synergistic effects, and temporal evaluations of domino accidents. Several software packages are available to model dynamic Bayesian networks, and one can easily learn this technique with little effort.

9.1.2 Inference from industry expert survey

The current QRA practices, needs & expectations, and competency of the QRA professionals were identified using the survey. The popular tool for QRA was identified to be PHAST software and the commonly referred QRA guidelines were TNO colored books, OGP guidelines, and CCPS guidelines. As QRA professionals allow only moderate deviation from existing quantitative risk assessment practices. The new framework was developed in line with the current QRA practices. In this work, the domino risk assessment framework was developed by modifying the existing QRA methodology prescribed by the Purple book (Disasters Committee for the Prevention of, Disasters 1999) and CCPS guidelines (American Institute of Chemical Engineers. Center for Chemical Process Safety., 2000) for quantitative risk assessment

9.2 Development of a comprehensive framework

The developed framework is in line with the traditional QRA framework and it incorporates all the needs of interested parties. An overview of the domino risk assessment framework is shown in Figure 9.1.

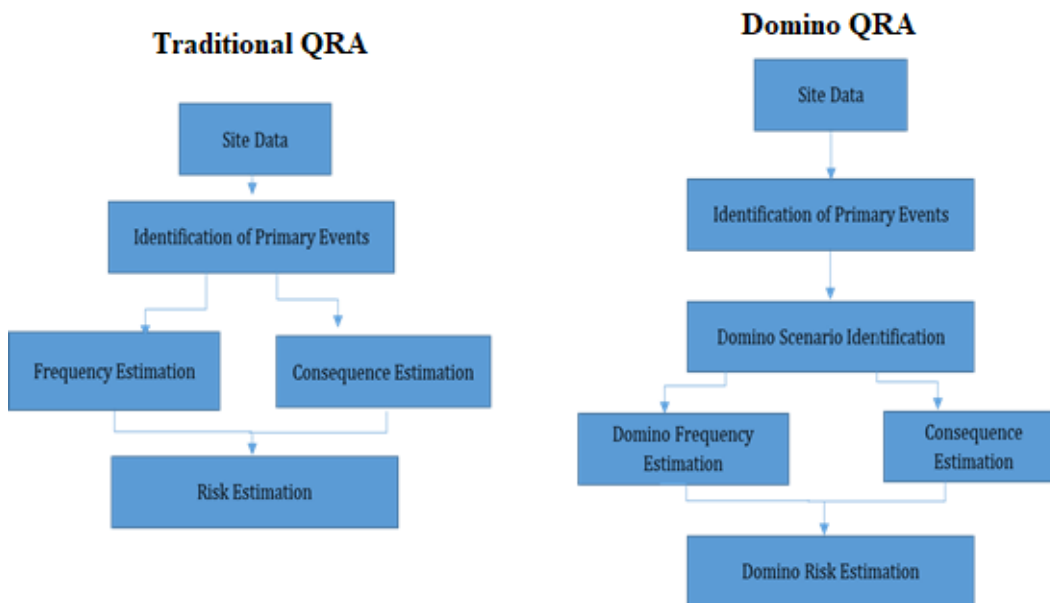


Figure 9.1 Domino QRA in line with traditional QRA

Primary accident scenarios are identified and selected by evaluating the site data. Scenario-specific risks are evaluated by assessing the probability and consequences of accidents in a traditional QRA. Similarly while assessing the domino risks in a chemical plant, primary accident units, and expected accident scenarios are evaluated to identify potential domino effects in nearby installations, by comparing the escalation vectors with the threshold values. Once a domino scenario has been established the domino effect frequency needs to be estimated using dynamic Bayesian analysis and consequences and risk can be estimated using PHAST or similar QRA software.

9.2.1 Methodology for Domino Frequency Estimation

The methodology for domino frequency estimation using consequence assessment software and DBN is illustrated in Figure 9.2. The key steps involved

and the detailed procedure for carrying out QRA based on the proposed methodology are discussed below.

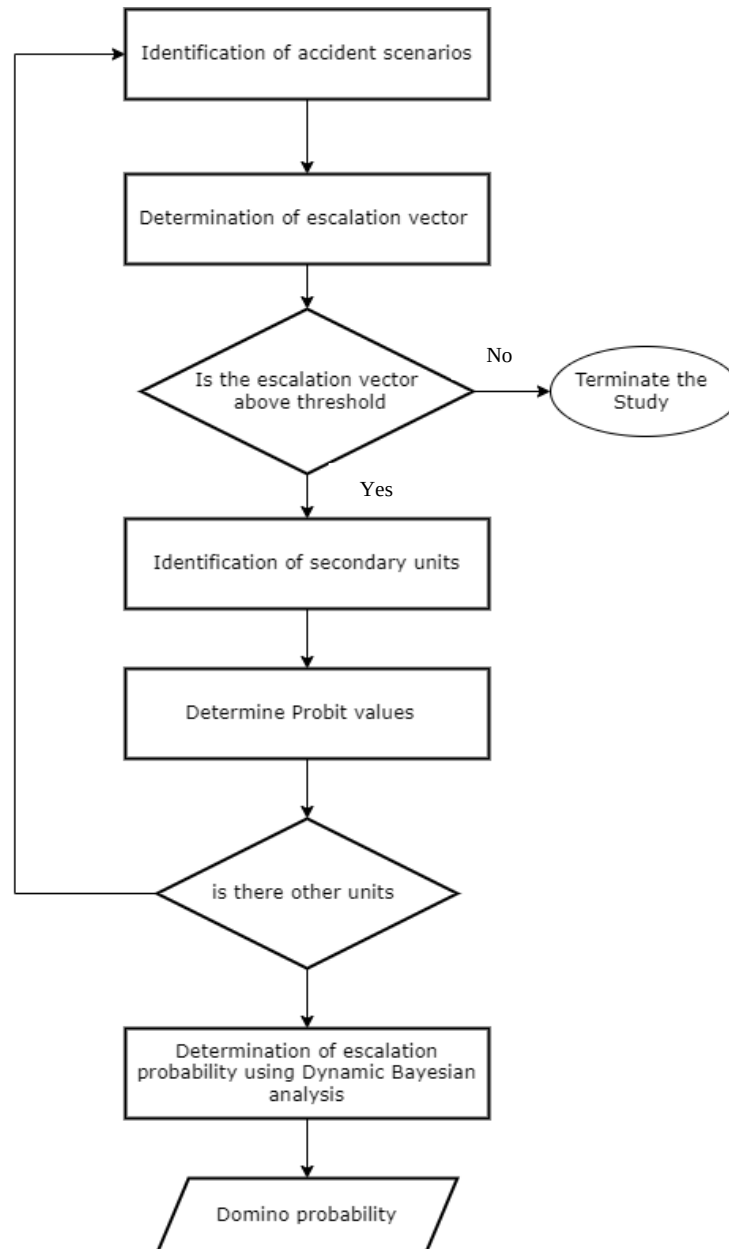


Figure 9.2 Methodology for Domino Probability Estimation

Step 1: Identification of accident scenarios

Referring to site layouts, process flow diagrams, and P&IDs can help the risk assessor in identifying the primary accident scenarios within the scope of the

study. For conciseness, the primary cause of accidents that can lead to a domino effect can be categorized into two (Cozzani *et al.*, 2005b).

1. *A Low Severity Initiating Event (LSIE)*: A relatively innocuous event such as jet fires from small-sized pipelines or pool fires from leaked seals can cause secondary accidents in the same installations. A critical examination of available HAZOP (Hazard and Operability Studies) reports can be extremely useful in this task. To facilitate this it is advised to initiate a comprehensive domino QRA of a chemical process plant once other safety study reports such as PHA (Process Hazard Analysis) and HAZOP are made available.
2. *A Major Accidental Event (MAE)*: A major initial accident in a unit can cause an accident in a secondary unit located in nearby installations or plants, with severe damage potential. Usually, such scenarios will be available in plant safety reports.

As QRA studies are being performed by external consultants, they tend to emphasize major accidental events often overlooking LSIE, which are site-specific. To identify all the primary accident scenarios in domino risk assessment it is essential that;

- 1) Comprehensive domino QRA is initiated after PHA or HAZOP studies, and
- 2) Facility personnel are consulted while deciding on primary accident scenarios.

Step 2: Determination of escalation vectors

For each primary accident scenario considered, the escalation vectors (the physical effects responsible for the secondary accident) need to be evaluated. The escalation vectors to be considered are heat radiation, overpressure, and fragments.

The escalation vectors that arise from primary accident scenarios can be determined using various consequences assessment software (PHAST, FLACS, or ALOHA).

Step 3: Comparison with escalation thresholds

In this step, the determined escalation vectors are compared with threshold escalation vector values available in the literature (Cozzani, Gubinelli and Salzano, 2006; Alileche *et al.*, 2017) for the domino effect causation. All the equipment falling inside the zones where physical effects exceed threshold values are considered as potential secondary units.

In software-aided consequence assessment, changing the default radiation intensity and overpressure contours values to threshold values will help the assessor to identify the impact zone of the primary accident and can locate potential secondary targets with ease; this is an added advantage of domino risk assessment using consequence-modeling software.

Step 4: Identification of potential secondary units

If the impact of the escalation vector on an affected unit is above the threshold value it is considered as a potential secondary unit in domino propagation. If none of the equipment falls inside the impact contours, it can be reasonably assumed that the primary accident cannot cause a domino accident and the study may be terminated after evaluating all the potential primary accident scenarios.

Step 5: Determine probit values

This step involves determining the vulnerability of identified target units due to accidents in primary units. Following Probit models (Cozzani *et al.*, 2005a; Landucci *et al.*, 2015) can be used to determine the affected unit's vulnerability due to the primary accident.

$$\text{tff (min)} = 0.0167 * \text{Exp}^{(cVd + e \ln(Q) + f)} \dots\dots\dots (9.1)$$

$$Y = 12.54 - 1.847 \ln (\text{tff (seconds)}) \dots\dots\dots (9.2)$$

Where tff refers to time to failure, Q is the radiation (kW/m²) indenting on the target unit of Volume V (m³), c, d, f are constants, and the values are tabulated in Table 9.1

Table 9.1 Values of constants for determining Probit values

Type of Unit	c	d	e	f
Atmospheric	-2.667x10 ⁻⁵	1	-1.13	9.877
Pressurized	8.845	0.032	-0.95	0

Step 6: Identification of higher-order units

Repeat steps 1-5 to identify all the possible tertiary and higher-order units. It is important to consider synergistic effects, i.e. escalation caused by the combined effect of lower-order units while exploring these units.

Step 7: Dynamic Bayesian simulation

Dynamic Bayesian Networks can be developed using commercially and publicly available software such as HIGUN and GeNie. The target units are represented as nodes in a DBN and arrows with time delay represent the temporal propagation path. Auxiliary nodes are created for posterior probability computation, the node with the highest probability is chosen as the vulnerable installation, and domino propagation paths are identified.

Step 8: Domino Probability Estimation

Once escalation paths are identified, the probability of domino accidents for different levels is determined using the following formula.

$$\text{Probability}_{\text{First order domino}} = \text{Primary event probability} * \text{Escalation probability}$$

9.2.2 Methodology for Domino Risk Estimation

Domino risk can be determined relatively easily using QRA software rather than by using manual calculations. Available software packages such as PHAST or RISKCURVES can be used for this purpose. After determining domino frequencies using the stated methodology in 9.2.1, populate population and ignition source details in QRA software as per the site conditions. To determine the first-order domino risks, select the identified vulnerable units and in the failure frequency data enter the accident frequency obtained from the dynamic Bayesian study. Similarly, the higher-order domino risks can be estimated using the same procedure. The methodology to be adopted is illustrated in Figure 9.3

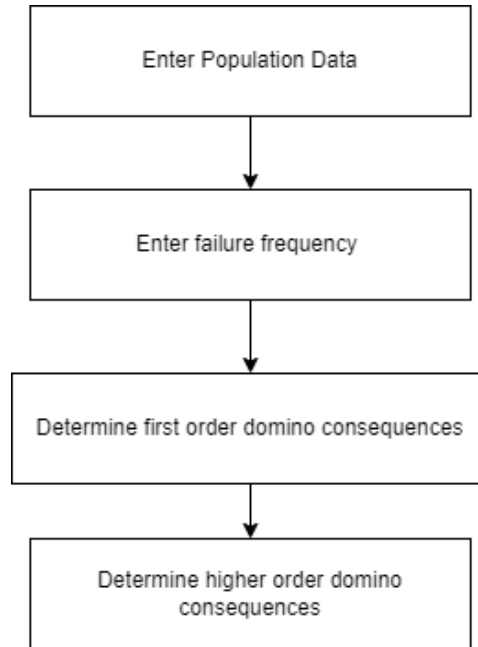


Figure 9.3 Methodology for Domino Risk Estimation

9.3 Application of framework in a case study

To verify the developed framework, the domino risk of a common tank farm was evaluated using the proposed methodology, and the results were compared with published results. For this purpose, a case study in literature was considered (Zeng,

Chen, Yang, Chen, *et al.*, 2020). The layout of the tanks is shown in Figure 9.4 and details are tabulated in Table 9.2

Table 9.2 Characteristics of Tanks Considered

Tank ID	Substance	Diameter (m)	Height (m)	Capacity (m ³)	Filling volume
T1	Toluene	15	13	2000	50%
T2	Toluene	15	13	2000	85%
T3	Methanol	15	13	2000	50%
T4	Methanol	15	13	2000	40%
T5	Methanol	15	13	2000	80%
T6	Methanol	15	13	2000	80%

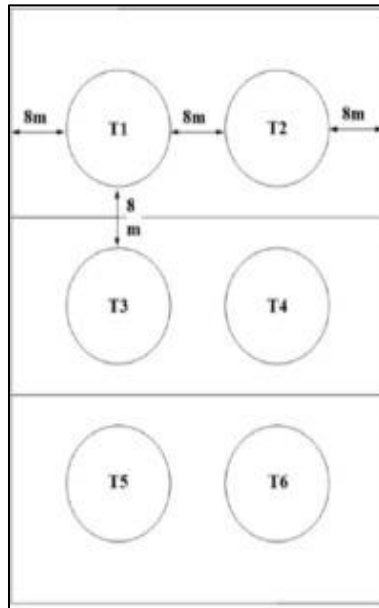


Figure 9.4 Layout of the tank considered for the study

Following atmospheric conditions are assumed,

- Wind speed - 2.7 m/s
- Atmospheric stability - Grade B
- The ambient temperature - 22.5 °C
- Relative humidity - 67%

Heat radiations due to pool fire accidents were determined using two leading consequence modeling software, PHAST and ALOHA. The results obtained and the procedure adopted are detailed in sections 9.3.1 and 9.3.2.

9.3.1 PHAST modeling

9.3.1.1 Domino Frequency Estimation

Step 1: Identification of the primary unit

As Tank 2 contains a high inventory of Toluene and the flash point of Toluene is less than methane the consequences of a loss of containment in Tank 2 would have a catastrophic effect compared to other tanks, so it is prudent to assume that the primary accident unit would be tank 2. As most of the tank farm fires are caused by pool fires, a pool fire scenario in tank T2 was considered as the primary accident scenario.

Step 2: Determine the escalation vectors

The intensity of radiation received by different tanks due to pool fire from tank 2 was simulated using PHAST consequence modeling software. In this work PHAST, 8.22 version was used for the analysis.

The PHAST simulation provides radiation intensity results at different distances from the source of the pool fire in tabular and graphical formats. Figure 9.5 illustrates the radiation intensity as a function of distance owing to the pool fire in Tank T2. Tank T1 is situated at a distance of 23.5 m from the center of tank T2, and the radiation intensity measured at a distance of 23.5 m is 22.4 kW/m², similarly, the heat radiation intensity observed at different tanks due to pool fire in T2 is determined.

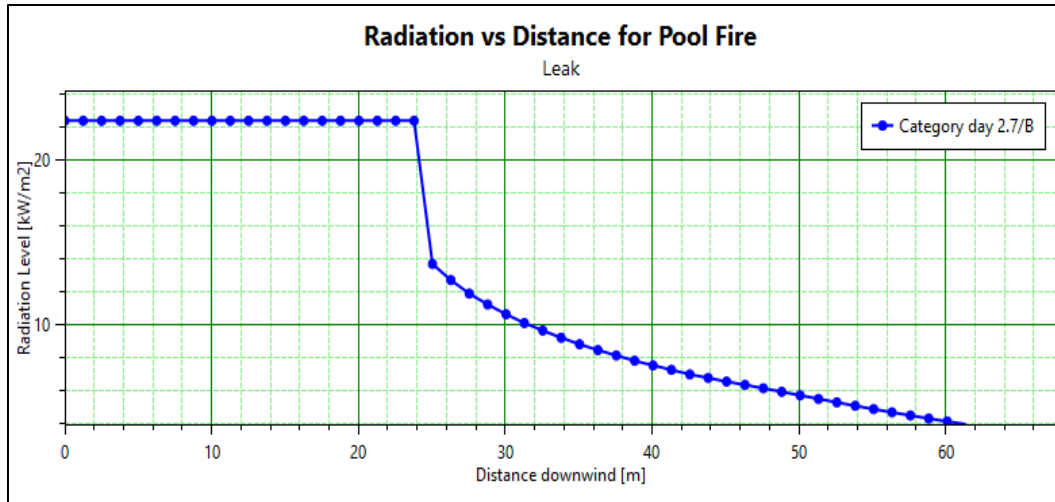


Figure 9.5 T2 Pool fire radiation vs distance obtained from PHAST

Similarly, pool fires were simulated in other tanks as well, and received by each tank due to pool fire in adjacent tanks was determined and shown in Table 9.3

Table 9.3 Heat radiation intensities of tank i to j (kW/m²)

$T_i \rightarrow T_j \downarrow$	$T1$	$T2$	$T3$	$T4$	$T5$	$T6$
$T1$	-	22.4	19.25	19	12.5	19.65
$T2$	23.8	-	19.25	19	19.65	12.5
$T3$	23.8	16	-	19		19.65
$T4$	12	22.4	19.25	-	19.65	19.65
$T5$	7	6	19.25	19	-	19.65
$T6$	6	8	19.25	19	19.65	-

Step 3-4: Identification of secondary units

The escalation threshold for heat radiation for an atmospheric tank is 15 kW/m² (Alileche *et al.*, 2015b), from Table 9.2 it can be identified that a fire in tank 2 would cause fires in T1, T3, and T4 and these tanks are considered as secondary units. In PHAST modeling, this step can be visually aided by plotting heat effect zones by replacing default values with escalation thresholds.

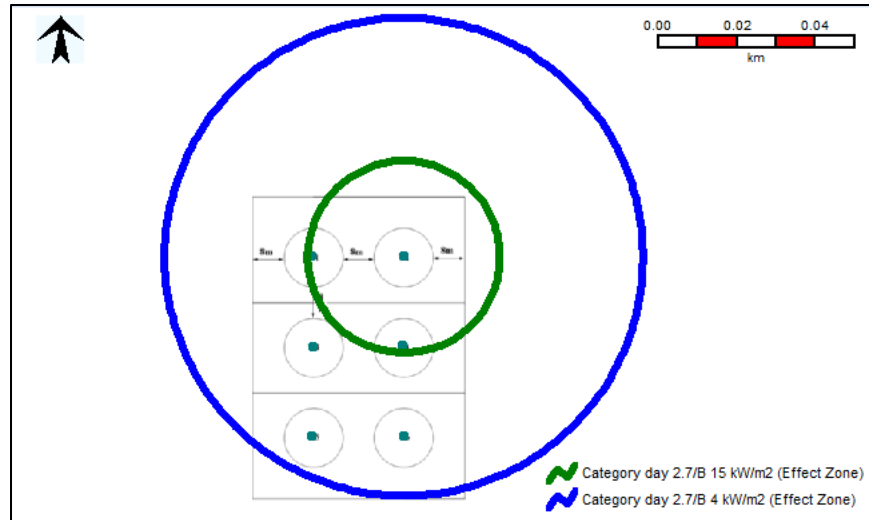


Figure 9.6 T2 Pool fire effect zone obtained from PHAST

The Incident radiative energy at tanks T5 and T6 are much lower than the threshold of escalation and they will not fail due to a pool fire in tank T2 alone.

Step 5: Determine the Probability of tank failure due to heat radiation

The failure probabilities of tanks are determined using equations 9.1 & 9.2. The calculated time to failure and probability of failure of different tanks are tabulated in Table 9.4

Table 9.4 Probability of failure of different tanks

Tank	Upper Tank	Heat Radiation (kW/m²)	t_{tf} (s)	t_{tf} (m)	Y	Failure Probability
T1	T2	22.4	566.3	9.4	0.8317	0.001534
T3	T2	16	828.2	13.8	0.1294	0.000056
T4	T2	22.4	566.3	9.4	0.8317	0.001534
T5	T1	7				No Failure
	T3	19.2	663.3	11.1	0.5395	0.000409
	T4	19	671.2	11.2	0.5177	0.000369
	T1+T4	26	470.9	7.8	1.1723	0.006468
	T1+T3	26.2	466.9	7.8	1.1883	0.006901
	T1+T3+T4	45.2	252.1	4.2	2.3265	0.375304

Tank	Upper Tank	Heat Radiation (kW/m ²)	t _{tf} (s)	t _{tf} (m)	Y	Failure Probability
	T3+T4	38.2	304.9	5.1	1.9753	0.124442
T6	T4	19	671.2	11.2	0.5177	0.000369
	T1	6				No Failure
	T3	19.2	663.3	11.1	0.5395	0.000409
	T1+T3	25.2	487.8	8.1	1.1071	0.004952
	T1+T4	25	492.3	8.2	1.0905	0.004623
	T3+T4	38.2	304.9	5.1	1.9753	0.124441
	T1+T3+T4	44.2	258.5	4.3	2.2798	0.326204

Step 6: Identification of higher-order units

Referring to Table 9.4, fire can only propagate to tanks T5 & T6 due to the synergistic effect of fire in secondary units.

Step 7: Dynamic Bayesian simulation

The dynamic Bayesian network was simulated using the GeNie software with a 30-minute time slice and the required conditional probability values are entered from Table 9.4. The developed network is shown in Figure 9.7.

Auxiliary nodes L1 & L2 were added to the dynamic Bayesian network to simulate first-order and second-order domino effects.

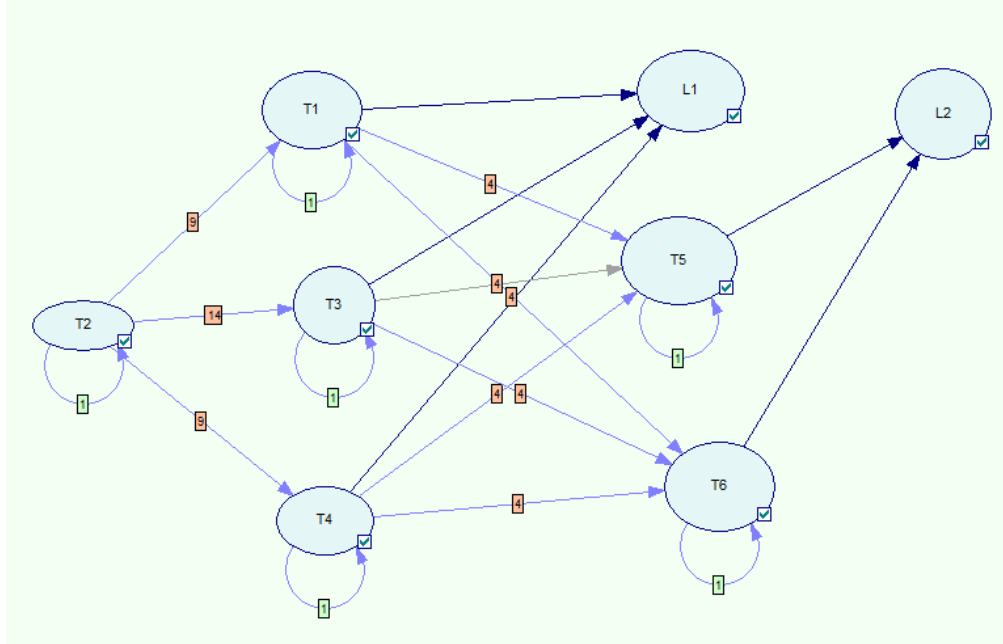


Figure 9.7 Dynamic Bayesian Network developed for the case study

Step 8: Domino Probability Estimation

To model the case dynamically, tank T2 was assumed to be subjected to pool fire at zero minutes. The prior probability of fire in each tank so determined is shown in Figure 9.8. As illustrated, the probability linearly increases with time. The probability of fire in tanks T1/T4 sharply raised after 9 minutes. The probability of fire in tanks T1 & T2 was observed to be 1.6×10^{-3} at 9 minutes. Similarly, the fire probability in tank T3 significantly increased after 13 minutes. First and second-order domino probabilities after 9 minutes were observed to be in the order of 10^{-3} and 10^{-7} respectively. The analysis showed that following a fire in tank T2 the probable escalation path was from T2-T1 or T2-T4.

DL1 and DL2 represent probabilities of first and second-order domino accidents.

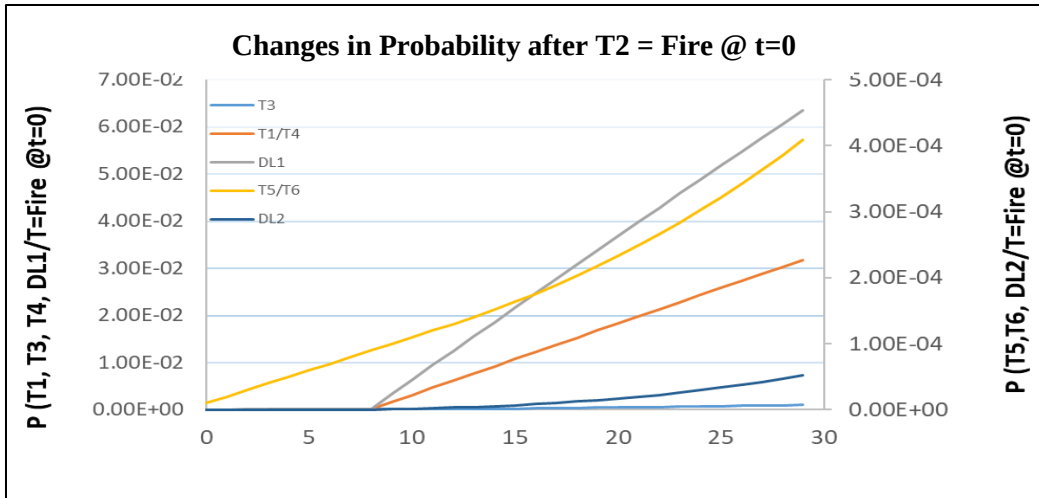


Figure 9.8 Prior probabilities of tanks (T2= fire @ t=0 minutes)

To model the first-order domino accident, a fire in tank T2 at t=0 minutes, and a fire in L1 at t=9 minutes were assumed. The outcomes of these scenarios modelled by DBN are depicted in Figure 9.9. The probabilities of fires in tanks T1& T4 were raised after 9 minutes. The probability of fire in T1/T4 was observed to be 48%. At this point, the fire probabilities in tanks T5 and T6 were 1.2×10^{-4} and 1.5×10^{-4} respectively.

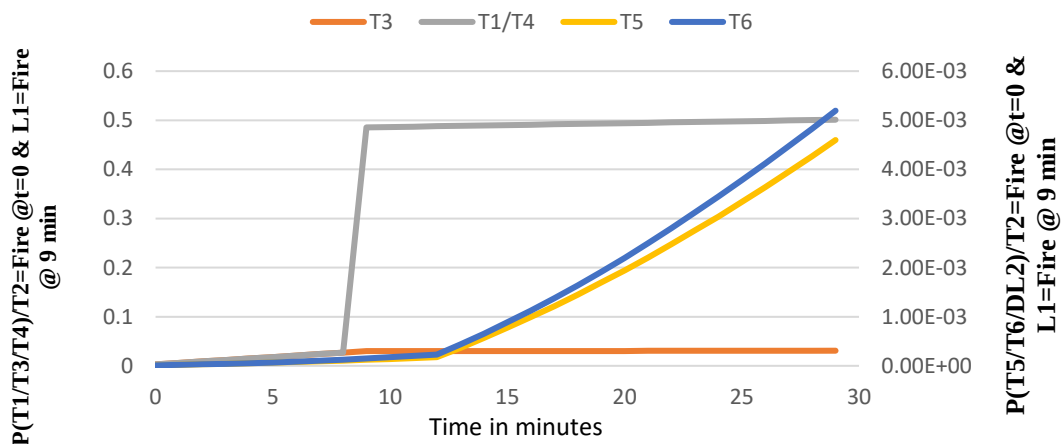


Figure 9.9 Posterior fire probabilities – in the event of first-order domino

The posterior probability also confirmed that in the case of first-order domino, the most vulnerable units were T1&T2 with 48% each.

To model a second-order domino scenario, L2 was assumed to be under fire at 13 minutes, after a fire in tank T2 (t=0) and L1 (t=9) minutes. For this scenario, the result of the dynamic Bayesian modeling is shown in Figure 9.10. Under this situation, all the probabilities increased first and then stabilized with time. For the second-order domino scenario, the fire probability in tank T4 (75%) was much higher compared to T1 & T3. Tank T6 (54%) showed a higher fire probability compared to T5 (46%). The analysis showed that the most vulnerable units in the case of second-order domino were tanks T6 and T4, which showed a higher probability of fires. From these results, it can be inferred that the probable path of second-order domino escalation would be T2-T4-T6. This scenario can be expected after 13 minutes.

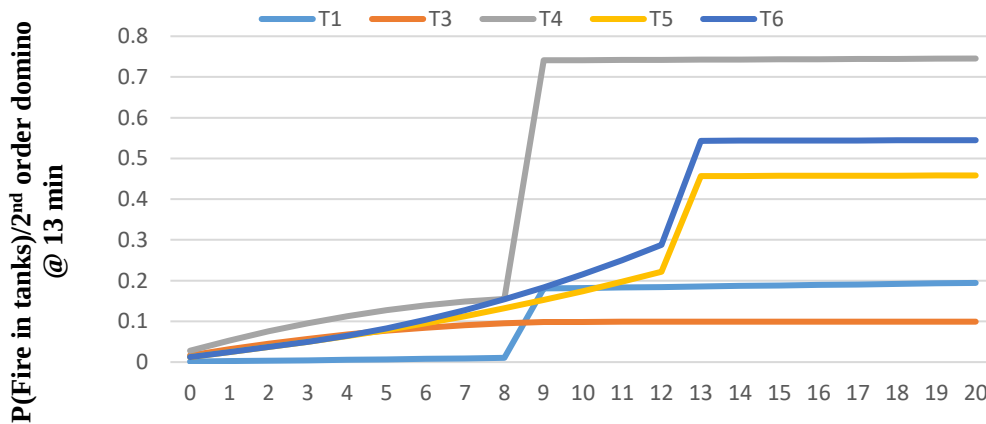


Figure 9.10 Posterior fire probabilities in tanks for second-order domino

Time depended domino probabilities are estimated using the following equations

$$\begin{aligned}
 \text{First-order domino probability (@ t=9 minutes)} &= P_{\text{Priamry}} * P_{\text{Escalation}} \\
 &= 1 \times 10^{-5} \times 0.48 \\
 &= 4.8 \times 10^{-6}
 \end{aligned}$$

$$\begin{aligned}
 \text{Second-order domino probability (@ 13 minutes)} &= P_{\text{Priamry}} * P_{\text{Escalation}} \\
 &= 1 \times 10^{-5} \times 0.75 \times 0.54 \\
 &= 4.05 \times 10^{-6}
 \end{aligned}$$

9.3.1.2 Domino Risk Estimation

Domino risks are estimated using the PHAST risk module known as, SAFATI. For consequence modeling, the population data, their distribution, and ignition source details are required. In this study, two types of ignition sources were considered i.e. DG set and vehicular parking with ignition probabilities of 0.8 & 0.4 respectively (Purple book,1999). Ten operators were considered positioned inside the tank farm and apart from this; an offsite population with a density of 0.42 people per square meter (average Indian population density) was assumed near the facility. The layout considered is illustrated in Figure 9.11

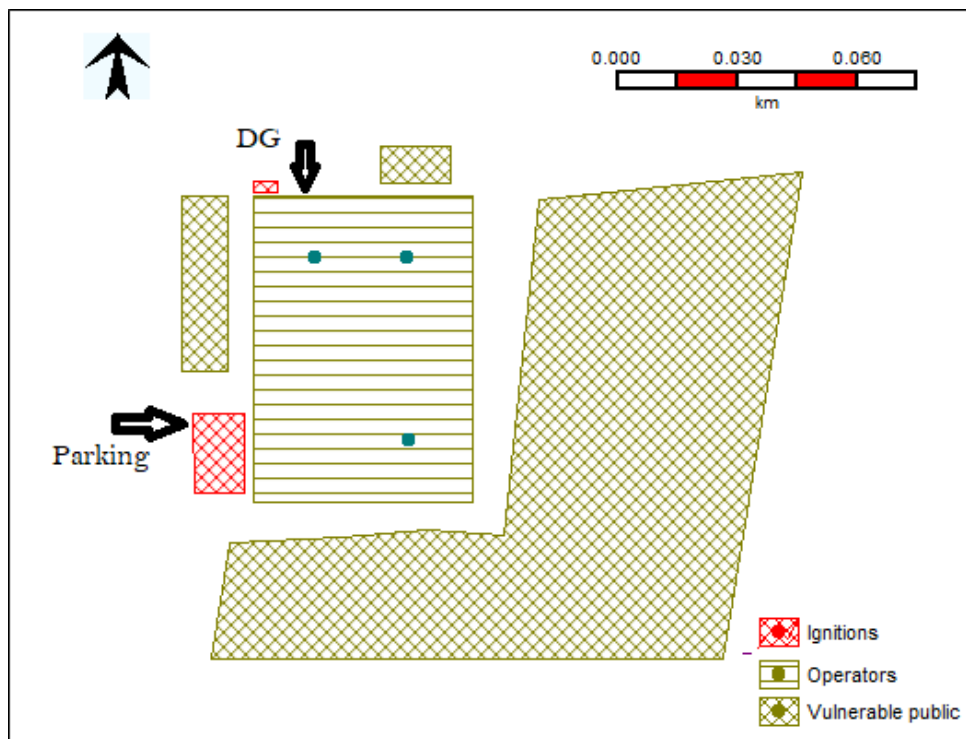
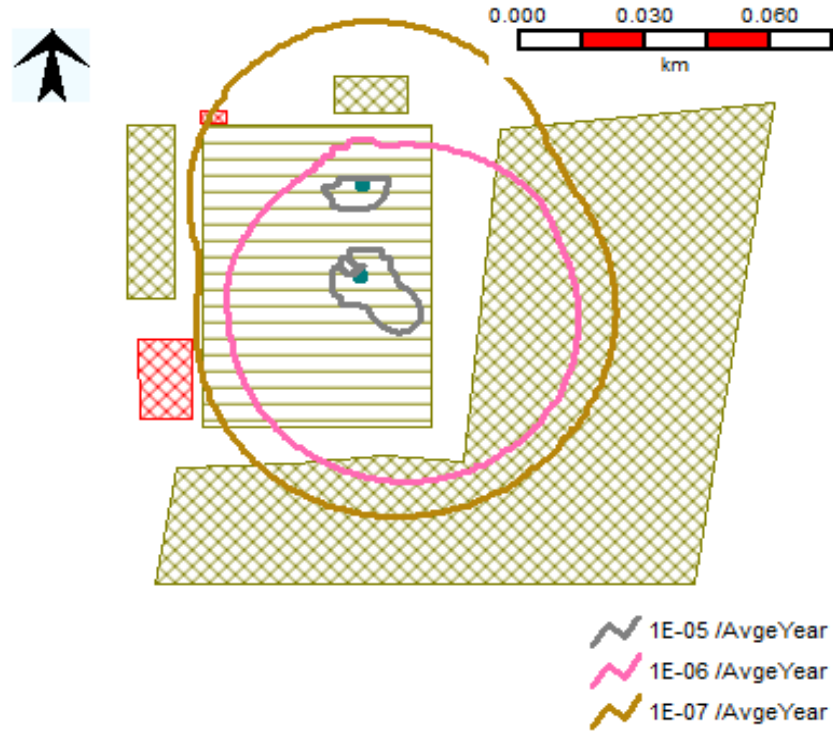


Figure 9.11 Layout with ignition sources and population distribution considered for consequences study

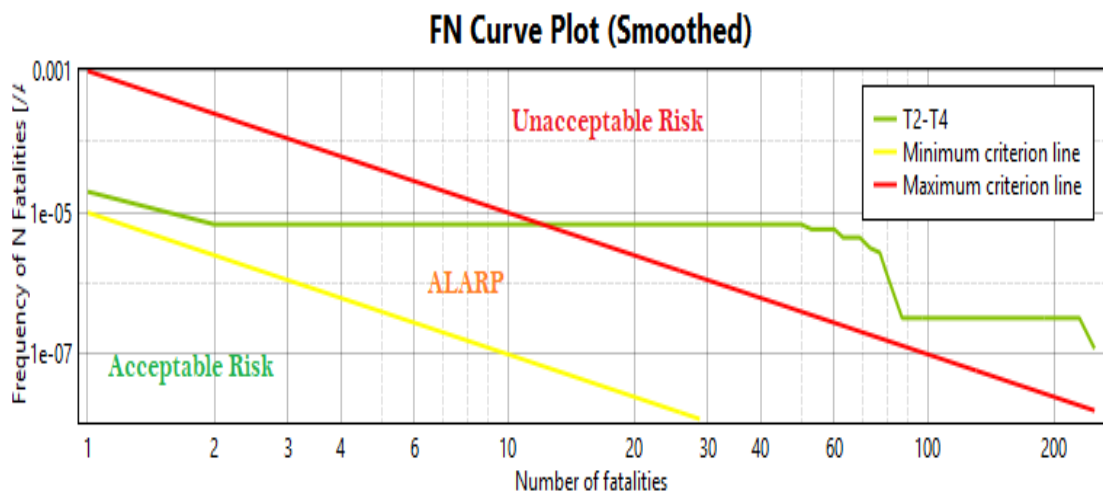
The above-determined frequencies are entered for tank failures and risk contours for the first and second-order domino scenarios.

1. First-order domino (T2-T4) at 9 minutes
2. Second-order domino (T2-T4-T6) at 13 minutes

Figures 9.12 – 9.13 illustrate the F-N curves and average fatality per year contour for the above scenarios.

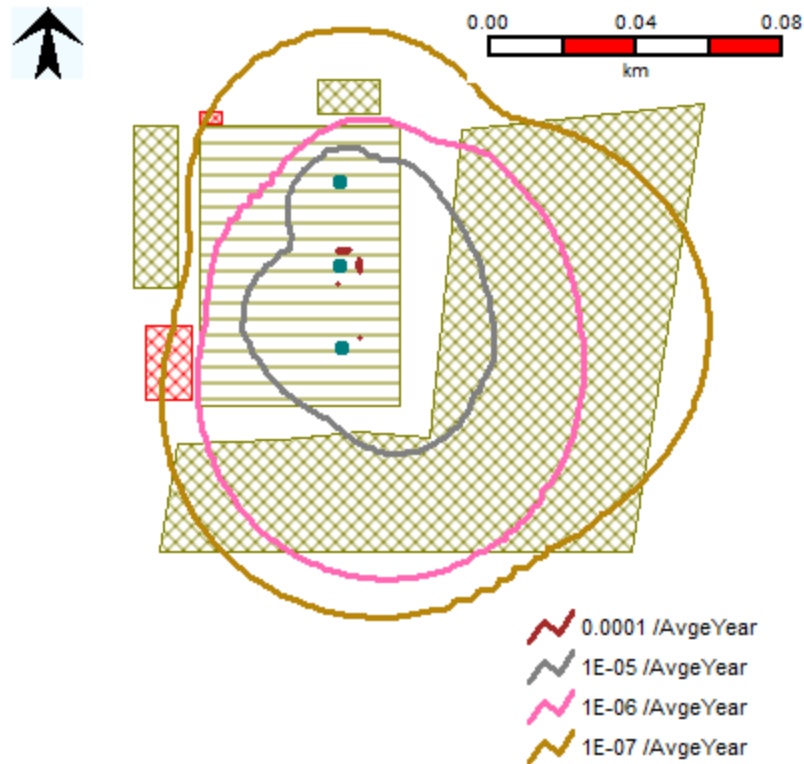


(a) Risk contour in case of first-order domino accident

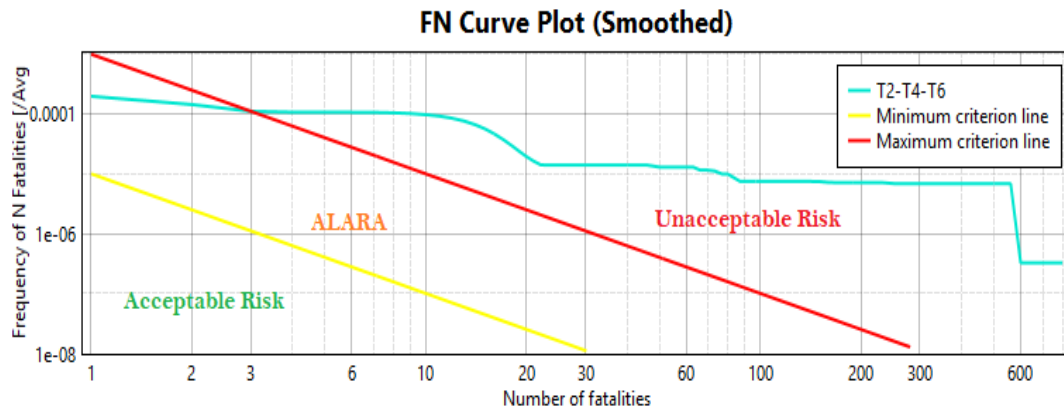


(b) F-N curve for first-order domino accident

Figure 9.12 Risks of first-order domino accident (T2-T4) from SAFETI modeling



(a) Risk contour in case of second-order domino accident



(b) F-N curve second-order domino accident

Figure 9.13 Risks of second-order domino accident (T2-T4-T6) from SAFETI modeling

As evident from figures 9.12-9.13 the risk of accidents considerably increased when accidents escalated to higher-order domino accidents, the effect zones due to various accident scenarios can be easily visualized using SAFETI

analysis. Software-aided domino risk analysis is relatively easy, less time-consuming compared to manual QRA, and provides a graphical representation of risk zones.

9.3.2 Domino Frequency Estimation using the ALOHA Modeling

The above case was simulated using ALOHA software and the heat radiation received by different tanks due to pool fires in adjacent tanks was determined and shown in Table 9.5.

Table 9.5 Heat radiation determined using ALOHA software

$T_i \rightarrow T_j \downarrow$	<i>T1</i>	<i>T2</i>	<i>T3</i>	<i>T4</i>	<i>T5</i>	<i>T6</i>
<i>T1</i>	-	32.8	7.47	3.12	1.12	1.06
<i>T2</i>	19	-	5.25	7.47	1.06	1.12
<i>T3</i>	19	20.6	-	7.47	7.47	5.25
<i>T4</i>	12.3	32.8	15.8	-	5.25	7.47
<i>T5</i>	3.82	7.4	15.8	15.8	-	7.47
<i>T6</i>	3.44	7.4	14	15.8	15.8	-

Based on the comparison of received heat radiation and threshold values tanks T1, T3 & T4 were considered as the primary targets due to a pool fire in tank T2. The ttf and failure probabilities were determined using equations 9.1 & 9.2 and tabulated in Table 9.6

Table 9.6 Probability of failure of different tanks (ALOHA)

Tank	Upper tank	Heat radiation (kW/m ²)	ttf (s)	ttf (m)	Y	Failure Probability
T1	T2	30.2	368.0	6.1	1.6277	0.01965
T3	T2	20.6	622.5	10.4	0.6569	0.00070
T4	T2	30.2	368.0	6.1	1.6277	0.01965
T5	T1	3.82				No Failure
	T3	15.8	826.8	13.8	0.1328	5.6581E-05
	T4	15.8	826.8	13.8	0.1328	5.6581E-05
	T1+T4	19.62	647.3	10.8	0.5847	0.00050
	T1+T3	19.62	647.3	10.8	0.5847	0.00050
	T1+T3+T4	35.42	332.1	5.5	1.8176	0.07303
T6	T3+T4	31.6	377.8	6.3	1.5794	0.03124
	T4	15.8	826.8	13.8	0.1328	5.6581E-05
	T1+T3	17.44	739.4	12.3	0.3388	0.00015
	T1+T4	19.24	661.8	11.0	0.5439	0.00041
	T3+T4	29.8	403.6	6.7	1.4570	0.01978
	T1+T3+T4	33	359.7	6.0	1.6699	0.043407

For this case, dynamic Bayesian networks were modeled using GeNie software as shown in Figure 9.14.

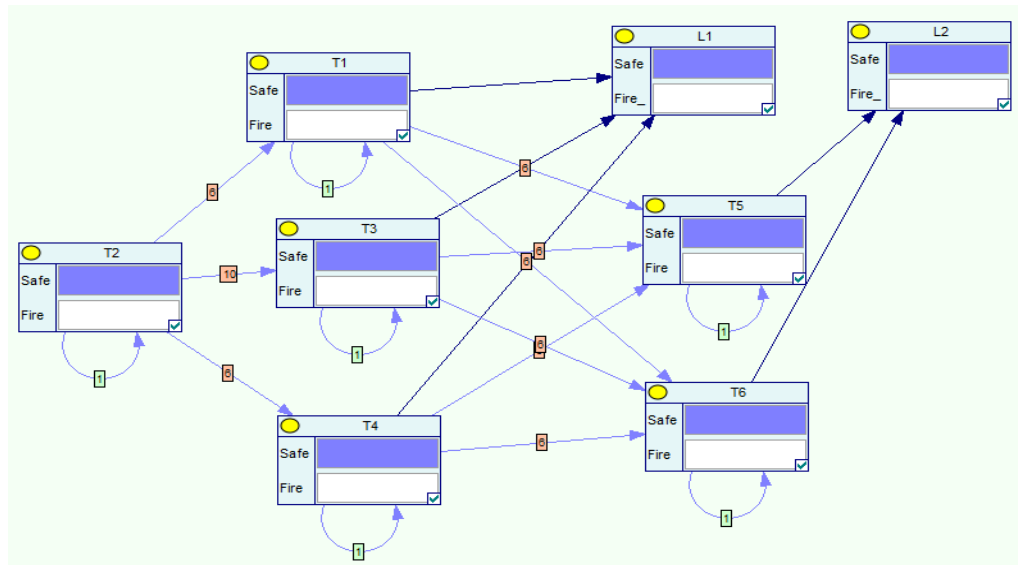


Figure 9.14 Dynamic Bayesian network developed for the case study

The dynamic Bayesian network (DBN) modeling based on heat radiation obtained from ALOHA showed that the fire probabilities in T1 & T4 raised significantly after 6 minutes of fire in tank T2, and for tank T3, this rise was observed after 10 minutes. After 10 minutes, the probabilities of first and second-order domino accidents were 0.3 and 7×10^{-5} respectively. After a fire in tank T2, the most probable path of escalation was either T2- T1 or T2-T4.

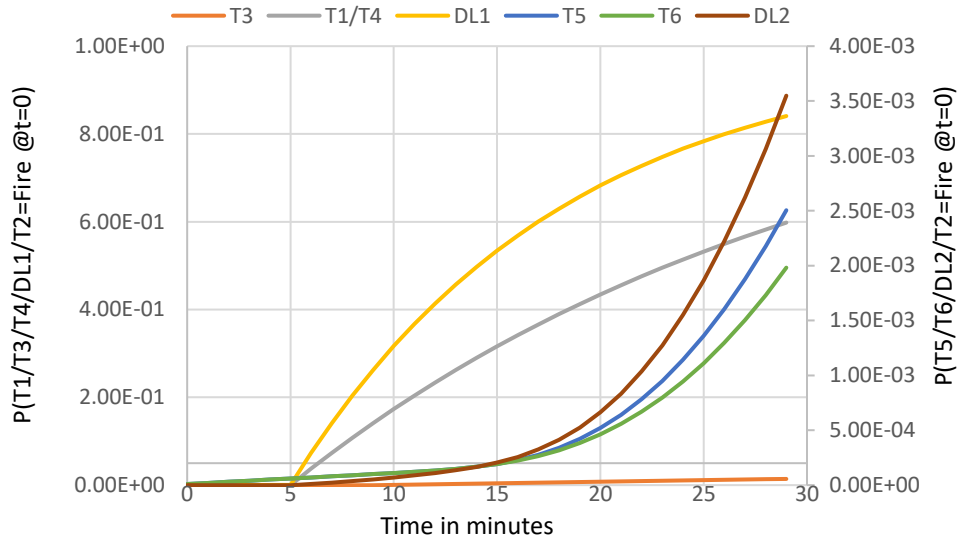


Figure 9.15 Prior probabilities from DBN (T2=Fire @t=0)

6 minutes after a fire in tank T2, L1 was assumed to be under fire for simulating a first-order domino scenario. The probabilities of failure of tanks for this condition are illustrated in Figure 9.16. The probabilities of failure of tanks T1 & T4 at 6 minutes were 51% each, indicating that in the case of a first-order domino both tanks T1 & T4 are equally vulnerable. After 12 minutes fire probabilities in tanks, T5 & T6 were 1.6×10^{-4} each and had equal chances of catching fire after first order domino.

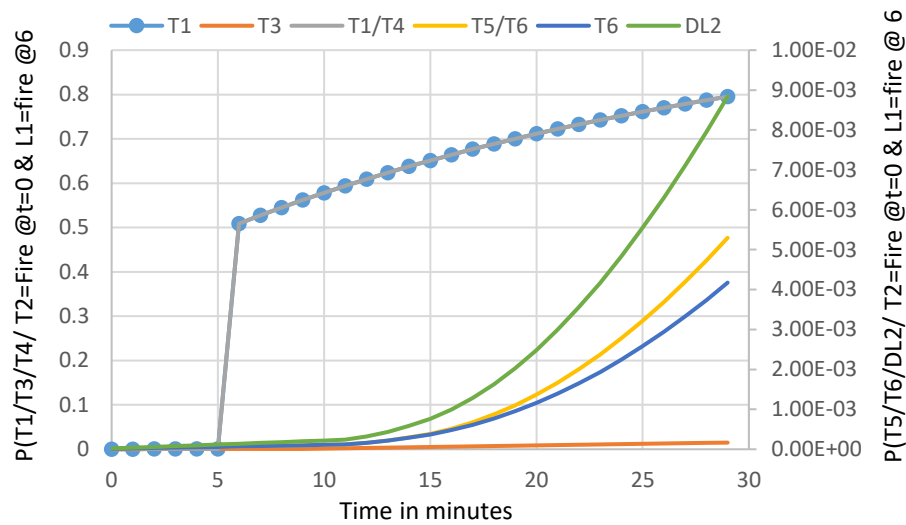


Figure 9.16 Posterior probabilities from DBN (T2=Fire @ 0 & L1=Fire @ 6)

For simulating the second-order domino scenario, fire in L2 was assumed at 12 minutes after a fire in L1 @ 6 minutes and T2 @ 0 minutes. In this situation, the fire probabilities in tanks T1, and T4 were 57 & 68% respectively. The fire probabilities in tanks T5 & T6 were 49% and 51 % indicating that the probable escalation path would be T2-T4-T6 or T2-T4-T5.

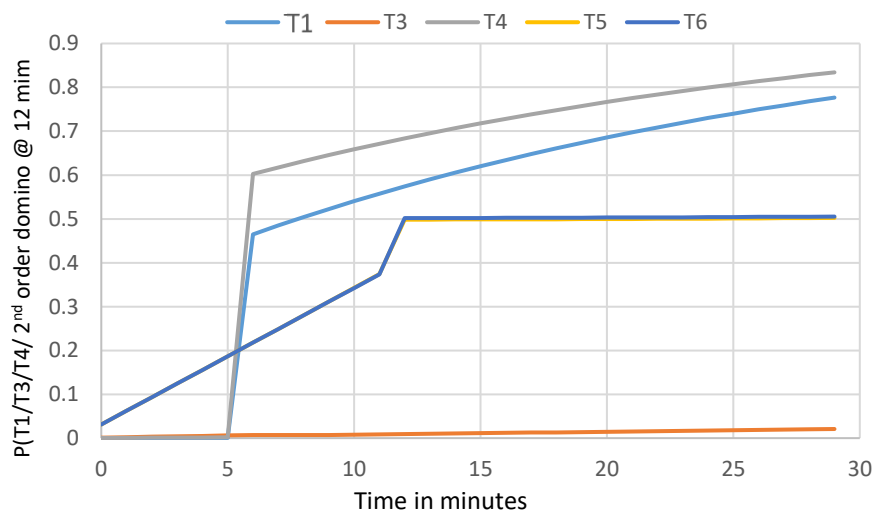


Figure 9.17 Posterior probabilities from DBN (T2=Fire @ 0 & L1=Fire @ 6 & L2 =Fire @ 12)

The application of ALOHA software was limited for domino probability estimation, as the overall risk in terms of the number of fatalities cannot be obtained using this software.

9.4 Validation of the framework

To verify the proposed framework for domino risk assessment the domino frequency results obtained for the case study through the proposed methodology were compared with the original work (Zeng, Chen, Yang, Chen, *et al.*, 2020). As the population and ignition sources were hypothetical data the comparison is limited to domino frequency estimates using PHAST and ALOHA software. The results of the comparison are tabulated in Table 9.7

Table 9.7 Result Comparison

Parameter	Using PHAST	Using ALOHA	Zeng et.al (2020)
First-order domino path	T2-T1 or T2-T4	T2-T1 or T2-T4	T2-T1 or T2-T4
Anticipated first-order domino time (minutes)	9	6	11*
T1 @ FDL	48%	51%	43%
T4 @FDL	48%	51%	43%
Second-order domino path	T2-T4-T6	T2-T4-T6 or T2-T4-T5	T2-T4-T6
Anticipated second-order domino time (minutes)	13	12	14
T1 @ SDL	19%	57%	31%
T4 @ SDL	74%	68%	63%
T5 @ SDL	46%	49%	25%
T6 @SDL	54%	51%	75%

* Though the authors have reported 1st and 2nd order domino timing as 6 & 7 minutes when we reproduced the same obtained timing as 11 & 14 minutes respectively. As seen in Table 9.7, both ALOHA & PHAST models can predict the domino propagation paths. In comparison to the ALOHA model, PHAST model

estimates were more reliable and were consistent with the reference reported values.

9.5 Conclusions

The development and validation of a comprehensive framework for assessing domino risks in the chemical process industry have been thoroughly detailed in this chapter. The study has provided a robust and industry-friendly approach to quantify and mitigate domino effects using advanced modeling techniques.

Key Highlights:

- The efficacy analysis and expert survey identified dynamic Bayesian networks (DBNs) as the most suitable method for modeling domino risks, given their ability to handle complex interactions and temporal evolutions.
- The framework aligns with traditional Quantitative Risk Assessment (QRA) practices, ensuring ease of integration and acceptance within the industry.
- The framework was validated using a case study involving a tank farm, with frequency estimations performed using both PHAST and ALOHA software. The results demonstrated the ability of the framework to predict domino propagation paths effectively.
- Comparative analysis indicated that PHAST modeling provided more consistent and reliable results in line with reference values.

Implications for the Industry:

- The validated framework offers a systematic approach to assess and manage domino risks, enhancing safety measures in chemical process industries.
- The use of widely recognized software tools (PHAST and ALOHA) ensures that the methodology is both practical and applicable in real-world scenarios.

CHAPTER 10

CONCLUSIONS

Abstract

The overall aim of this work is to bridge the gaps between industry and academia domino risk assessment practices by developing an industry-friendly framework with advanced risk assessment capabilities. A four-phase methodology was developed to achieve this aim. The different phases involved in the framework development were;

- Phase 1: Identification of tools for domino risk assessment
- Phase 2: Efficacy analysis of existing tools of domino risk assessment
- Phase 3: Identification of needs and expectations of the industry
- Phase 4: Development and validation of the framework

The conclusions drawn from each phase of the study are discussed below.

10.1 Past Accident Analysis

A qualitative comparison of the global database chemical industry accident database was performed. Past accident analysis showed that;

- The total number of reported events is more or less steady and the number of major accidents is decreasing marginally in Europe. This study confirms that the trends identified by researchers in 2011 are still prevailing in Europe.
- The analysis of the Indian chemical industry based on accidents reported in the CAIRS database can lead to inaccurate conclusions as accidents are not reported promptly in this database and it requires an urgent revision to ensure data accuracy.
- Suggestions are provided to improve existing databases.

10.2 Trends in Domino Effect Research

Based on a systematic review of 177 research publications in domino effect research, this work categorizes the domino risk research into two time periods; publications before and after 2015.

- This study identifies 177 publications on domino effects, serving as the largest inventory of domino literature to date. The research provides a refined classification of these domino publications.
- The research in this highly specialized field has gained a lot of attention among process safety researchers in the past seven years with new researchers joining hands with seasoned domino risk researchers.
- 62% of total documents were published on or after 2015.
- The sharp rise in the number of publications during the later period can be attributed to the active contributions of Chinese researchers after the Tianjin domino accident in 2015.
- Enhanced research collaborations between different research clusters, countries, and institutions were observed during the later period.

10.3 Tools for Domino Risk Assessment

- As traditional techniques such as ETA, FTA, and FMEA are incapable of modeling intricate domino escalations, the use of advanced risk assessment techniques is essential to model domino evolutions. The study showed that domino risk assessment research is active using graphical methods. The most popular graphical tools identified were Bayesian Networks, Dynamic Bayesian, and Petri-nets.
- Bayesian Network-based analyses are not capable of modeling temporal evaluations of domino effects.

- Based on this study, it was identified that both DBN and Petri-net models are better equipped to model domino risks.
- Considering the more computational time requirement and resource scarcity of Petri-nets, Dynamic Bayesian Network-based modeling is best suited for the present-day studies of domino risk assessment.

10.4 Industry Expert Survey

The current industry practices in domino risk assessments, needs & expectations of the industry were identified using an online survey. 48 QRA professionals from different parts of the world, with diverse backgrounds and experience levels, participated in the survey. The survey brought into light the tools and guidelines used by the industry.

- Irrespective of the geographical differences, over 90% of the professionals were using PHAST software developed by DNV for QRA studies.
- It was acknowledged that 78% of QRA professionals do not assess risks posed by domino effects in their QRA studies.
- To assess the domino risk using a new framework the experts were ready to accommodate moderate deviations from existing QRA practices and procedures.
- The self-rating given by QRA professionals in advanced and recently emerged risk assessment techniques such as Bayesian analysis, Petri-nets, and Fuzzy logic showed that they are having limited competency in these advanced risk assessment techniques.

10.5 Framework for Domino Risk Assessment

By analyzing the industry inputs and efficacy analysis of domino risk assessment tools, a two-stage approach was devised for domino risk assessment in

chemical process industries. As the comprehensive risk assessment of domino risks is time-consuming and expensive, the first stage of risk assessment involves domino risk screening.

- An innovative fuzzy-based risk screening tool was developed.
- The developed tool was able to accurately predict the domino risk.
- In comparison to domino risk assessment with advanced risk assessment techniques the developed tool is user-friendly, less time-consuming, and comparatively lesser expertise is required to model domino risk.
- Though the developed system can be used in any stage of the chemical process plant project, the fact that it can predict the domino risk with minimum input parameters makes it a suitable tool for performing screening domino risks during the concept and feasibility study stage.

The 2nd stage involved a comprehensive domino risk assessment, which comprised of two activities; domino frequency estimation and domino risk estimation. This work proposed a methodology for determining domino frequency using dynamic Bayesian analysis, by slightly modifying existing QRA procedures. By adding a few extra steps to the existing QRA one can easily determine domino frequency with the help of QRA software. The proposed methodology offers an industry-friendly framework for the assessment of domino risks. The results of the developed methodology are validated with a case study consisting of 6 tanks.

The key highlights of developed frameworks are;

- The proposed methodology can be easily integrated with the existing QRA procedures using PHAST or similar software.
- The developed framework is in line with current QRA practices followed by the industry.

- It meets most of the industry of the requirements such as;
 - It estimates domino frequency
 - It estimates domino consequences
 - The differential duration between the initial and domino events can be identified
 - It is customizable

10.6 Significance of Thesis Contributions to the Field

- The work identifies a significant increase in research since 2015 and analyses the research trends based on two time periods. The research in this field has been gaining significant attention among process safety researchers, especially Chinese researchers since 2015. And the research in this field is becoming more collaborative among researchers, institutions, and countries.
- The survey helps us to identify the QRA practices being adopted by the Industry, how domino effects are getting addressed in current QRA studies, the needs and expectations of the industry on domino risk assessment framework, and the competency of QRA professionals in advanced risk assessment techniques.
- This work presents an innovative framework for assessing domino risk in process industries, incorporating the needs and expectations of professional QRA practitioners. It bridges the gap between industry and academia by developing an industry-friendly framework with advanced risk assessment capabilities.
- The framework aligns with traditional Quantitative Risk Assessment (QRA) practices, ensuring ease of integration and acceptance within the industry.

10.7 Limitations of the Study

Limited Database Scope: The study is based on data from the Web of Science starting from 1998 onwards. Consequently, any significant works before this period might go unnoticed, potentially affecting the comprehensiveness of the research conclusions.

Expert Sampling Views: The perspectives shared by Quantitative Risk Assessment (QRA) experts might not be representative of the entire industry due to the limited sample size and possible biases in expert opinions.

Validation Limitations: The framework proposed in the study has not been tested in real-life QRA scenarios. This limitation raises concerns about its practical applicability and effectiveness when implemented in actual industrial settings.

Complexity of New Techniques: Advanced risk assessment techniques such as Bayesian networks, Petri-nets, and Fuzzy logic have shown limited competency among QRA professionals, indicating a steep learning curve and the need for additional training and resources for widespread adoption.

10.8 Challenges Ahead

As proper risk assessment can effectively control the risks of domino effects, risk assessment using the developed framework can help us to create safer chemical plants. The key three challenges that need to be addressed for effective domino risk management in the chemical process industries are;

1. **Absence of legal requirements:** At present, domino risk assessments are mandatory only in European countries. In the absence of any such legal requirements, industries will be reluctant to assess the domino risk of their facilities.
2. **Organization commitments:** Domino effects have the potential to cause massive disruptions to business. A responsible and committed organization shall go beyond the legal requirements to assess and manage domino risks posed by its operations to create sustainable industries.

3. Competency of QRA professionals: Another obstacle in effective domino risk assessment is the limited competency of QRA professionals in recently developed advanced risk assessment tools. The domino risk cannot be completely modeled with traditional risk assessment techniques. QRA professionals shall enhance their competency in advanced risk assessment techniques for effective risk assessment. Organizations especially universities shall create opportunities for their skill enhancement.

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ANNEXURE-1

List of Publications

1. **P. A. Arun**, S. M. Tauseef, and U. Uniyal (2022) “Comparison of Accident Databases and Analysis of Past Industrial Accidents in the Chemical Process Industry”, *Eng. Technol. Appl. Sci. Res.*, vol. 12, no. 4, pp. 8922–8927, <https://doi.org/10.48084/etasr.5079>
2. Srinivas Sivaraman, **P A Arun**, S M Tauseef (2021) Multi-Criterion-Based Qualitative Comparative Analysis of Root Cause Methods: Application to Deepwater Horizon Oil Spill, *Journal of Failure Analysis and Prevention*, Pages 1-21 <https://doi.org/10.1007/s11668-021-01212-9>
3. Vishwakama N., **Arun P.A**, Nandan A., Yadav B.P. (2020) Scenario Evaluation of Domino Effects in Process Industries: A Review. *Advances in Industrial Safety. Springer Transactions in Civil and Environmental Engineering. Springer, Singapore*. Page no. 85-99 https://doi.org/10.1007/978-981-15-6852-7_7.

ANNEXURE II

CHARACTERIZATION OF DOMINO RESEARCH PUBLICATIONS

Sl No	DOI	Year	Month	Topic	Research Issue	Research Approach	Tools Used	Other Keywords
1	https://doi.org/10.1016/j.jlp.2021.104449	2021	JUL	Modeling	Vulnerability modeling	Experimental study	Experimental study	Jetfire impingement
2	https://doi.org/10.1016/j.psep.2021.04.044	2021	JUN	Modeling	Risk Assessment	Analytical Methods	Matrix based	Framework, Matrix
3	https://doi.org/10.1016/j.ress.2021.107476	2021	MAY	Modeling	Risk Assessment	Simulation Methods	Agent Based (Monte Carlo)	Agent-based Model and Simulation ,
4	https://doi.org/10.1016/j.psep.2021.03.023	2021	MAY	Modeling	Risk Assessment	Simulation Methods	NS & NN	Combination of NS & NS, VCE case study
5	https://doi.org/10.1016/j.psep.2021.03.017	2021	MAY	Modeling	Risk Assessment	Graphical Method	Fuzzy-Bayesian	
6	https://doi.org/10.1016/j.jclepro.2021.126236	2021	APR	Modeling	Risk Assessment	Graphical Method	Bayesian-Petri Net	Case study, ALOHA
7	https://doi.org/10.1016/j.fuel.2020.120014	2021	APR	Modeling	Vulnerability modeling	Experiemental study	Experiemental study	Methane VCE
8	https://doi.org/10.1016/j.psep.2021.01.042	2021	APR	Modeling	Risk Assessment	Simulation Methods	Monte Carlo	Validation with DBN
9	https://doi.org/10.1016/j.psep.2021.02.025	2021	APR	Management	Emergency	Procedural Action Analysis		Dimensioning accident load
10	https://doi.org/10.1016/j.jlp.2020.104340	2021	MAR	Modeling	Risk Assessment	Graphical Method	Bayesian Network	PHAst
11	https://doi.org/10.1016/j.psep.2020.11.028	2021	MAR	Modeling	Vulnerability modeling	Experiemental study	Experiemental study	Jet flame

SI No	DOI	Year	Month	Topic	Research Issue	Research Approach	Tools Used	Other Keywords
12	https://doi.org/10.1016/j.psep.2020.12.042	2021	MAR	Modeling	Vulnerability modeling	CFD/FEM	PHAST, Ansys,	NaTech, Flood, Case study, QRA
13	https://doi.org/10.1016/j.psep.2020.11.050	2021	FEB	Management	Safety Barrier Management	Performance Assessment	FSEM	FMEA, Graph Theory, FSEM,
14	https://doi.org/10.1016/j.psep.2020.12.014	2021	FEB	Modeling	Risk Assessment	Simulation Methods	Monte Carlo	Projectiles,
15	https://doi.org/10.1016/j.psep.2020.12.004	2021	FEB	Modeling	Risk Assessment	Graphical Method	Petri-net	
16	https://doi.org/10.1016/j.engfailanal.2020.105106	2021	FEB	Modeling	Risk Assessment	Graphical Method	Fuzzy-Bayesian	
17	https://doi.org/10.1016/j.res.2020.107278	2021	JAN	Management	Safety Barrier Management	Performance Assessment	ETA	NaTech
18	https://doi.org/10.1016/j.psep.2020.07.014	2020	DEC	Modeling	Risk Assessment	Simulation Methods	Monte Carlo, Field Theory	Synergic effect, New method
19	https://doi.org/10.1109/TITS.2019.2946209	2020	NOV	Management	Emergency	Performance Assessment		
20	https://doi.org/10.1016/j.res.2020.107109	2020	NOV	Modeling	Risk Assessment	Analytical Methods	FSEM	FSEM, Case study new method
21	https://doi.org/10.1016/j.firesaf.2020.103192	2020	OCT	Modeling	Vulnerability modeling	CFD/FEM	FEM	
22	https://doi.org/10.1016/j.res.2020.106976	2020	OCT	Modeling	Vulnerability modeling	CFD/FEM	Ansys and empirical	
23	https://doi.org/10.1016/j.ssci.2020.104863	2020	OCT	Modeling	Vulnerability modeling	CFD/FEM	Ansys and experimental	FEM modeling of fragment
24	https://doi.org/10.1016/j.ssci.2020.104802	2020	SEP	Modeling	Risk Assessment	Graphical Method	Dynamic Bayesian	DBN, FSEM Framework

SI No	DOI	Year	Month	Topic	Research Issue	Research Approach	Tools Used	Other Keywords
25	https://doi.org/10.1016/j.ssci.2020.104744	2020	AUG	Modeling	Risk Assessment	Simulation Methods	Monte carlo	Synergic effect, NaTech
26	https://doi.org/10.1016/j.jlp.2020.104130	2020	JUL	Management	Emergency	Layout Optimization	LSCP	
27	https://doi.org/10.1177%2F1748006X19899235	2020	JUN	Management	Safety Barrier Management	Performance Assessment	Recursive aggregation method	Case Study
28	http://dx.doi.org/10.1016/j.jlp.2020.104148	2020	MAY	Management	Emergency	Resource Optimization	Heuristic algorithm.	MATLAB, Dynamic Allocation
29	https://doi.org/10.1016/j.jlp.2020.104155	2020	MAY	Management	Emergency	Procedural Action Analysis	PHAST	NaTech, Earthquake
30	https://doi.org/10.1016/j.ssci.2020.104618	2020	MAY	Review	Models and Methods			
31	https://doi.org/10.1016/j.jhazmat.2019.121813	2020	APR	Modeling	Risk Assessment	Simulation Methods	Monte Carlo	Multi-Hazard, Synergic Effect
32	https://doi.org/10.1016/j.compchemeng.2019.106705	2020	MAR	Management	Cooperative	Cooperative Prevention	Game Theory	Nash & Pareto equilibrium
33	https://doi.org/10.1016/j.jlp.2020.104095	2020	MAR	Modeling	Risk Assessment	Analytical Methods		NaTech, Lighting Framework,
34	http://dx.doi.org/10.1016/j.psep.2019.11.029	2020	FEB	Modeling	Risk Assessment	Graphical Method	Dynamic Bayesian	Synergic, Heat Radiation , Case study, Safety barrier
35	10.1016/j.res.2019.106646	2020	JAN	Review	Accident Analysis	Past Accident Analysis		C5 algorithm, PAA
36	https://doi.org/10.1016/j.ssci.2019.09.011	2020	JAN	Management	Safety Barrier Management	Performance Assessment	Bayesian Network	Offshore

SI No	DOI	Year	Month	Topic	Research Issue	Research Approach	Tools Used	Other Keywords
37	https://doi.org/10.1016/j.jlp.2019.103962	2019	NOV	Review	Accident Analysis	Past Accident Analysis		Statistical Analysis
38	https://doi.org/10.1016/j.jlp.2019.103975	2019	NOV	Modeling	Risk Assessment	Simulation Methods	Monte Carlo	Projectiles
39	https://doi.org/10.3390/pr7110849	2019	NOV	Modeling	Risk Assessment	Analytical Methods	AHP	
40	10.1016/j.res.2018.03.030	2019	NOV	Management	Security	Mitigation of consequences	DBN,	Intentional Attacks
41	https://dx.doi.org/10.1007/s10694-019-00830-y	2019	SEP	Management	Inherent Safety	Layout Optimization		
42	https://doi.org/10.1016/j.res.2019.04.006	2019	SEP	Modeling	Risk Assessment	Graphical Method	Dynamic Bayesian	NaTech , Forest Fire
43	https://doi.org/10.1016/j.res.2019.04.041	2019	SEP	Modeling	Risk Assessment	Analytical Methods	Numerical	FSEM
44	https://doi.org/10.1016/j.jlp.2019.04.016	2019	JUL	Modeling	Risk Assessment	Graphical Method	Bayesian Network	
45	https://doi.org/10.1016/j.psep.2019.01.021	2019	APR	Management	Safety Barrier Management	Optimization of Barriers		Safety Instrumented System, Plant layout
46	https://doi.org/10.1016/j.psep.2019.02.019	2019	APR	Modeling	Risk Assessment	Graphical Method	Petri-net	GSPN
47	https://doi.org/10.1016/j.jlp.2019.02.004	2019	MAR	Management	Emergency	Firefighting Analysis		Heat Radiation
48	https://doi.org/10.1016/j.jlp.2019.01.011	2019	MAR	Review	Accident Analysis	Past Accident Analysis		ETA, Parallel pipe line crater
49	http://dx.doi.org/10.1016/j.psep.2018.08.028	2018	NOV	Management	Inherent Safety	Layout Optimization		Heat Radiation, Over Pressure
50	https://doi.org/10.1016/j.jlp.2018.08.002	2018	NOV	Modeling	Vulnerability modeling	CFD/FEM	FLACS	Heat radiation, Experimental validation

SI No	DOI	Year	Month	Topic	Research Issue	Research Approach	Tools Used	Other Keywords
51	http://dx.doi.org/10.3390/en11113101	2018	NOV	Management	Emergency	Firefighting Analysis		Heat Radiation, Graph Theory
52	https://doi.org/10.1016/j.ijggc.2018.07.010	2018	OCT	Modeling	Risk Assessment	Graphical Method	Bayesian Network	Jet fire
53	https://doi.org/10.1016/j.ssci.2018.04.019	2018	OCT	Modeling	Risk Assessment	Graphical Method	Petri-net	Petri-nets
54	http://dx.doi.org/10.1016/j.jlp.2018.03.001	2018	JUL	Modeling	Risk Assessment	Graphical Method	Dynamic Bayesian	
55	https://doi.org/10.1016/j.oceaneng.2018.02.046	2018	JUN	Management	Safety Barrier Management	Performance Assessment		Heat Radiation
56	https://doi.org/10.1002/prs.11937	2018	JUN	Modeling	Vulnerability modeling	Threshold Method	Exceedence curve	
57	https://doi.org/10.1002/prs.11947	2018	JUN	Management	Emergency	Procedural Action Analysis		Heat Radiation
58	https://doi.org/10.1016/j.ingse.2018.03.011	2018	JUN	Modeling	Vulnerability modeling	Distance Based methods		Heat Radiation, Probabilistic methods
59	https://doi.org/10.1016/j.psep.2018.01.019	2018	MAY	Modeling	Risk Assessment	Graphical Method	Bayesian Network	
60	https://doi.org/10.1016/j.psep.2018.02.014	2018	MAY	Modeling	Risk Assessment	Analytical Methods	Matrix based	Heat Radiation
61	https://doi.org/10.1016/j.psep.2018.03.008	2018	MAY	Modeling	Risk Assessment	Graphical Method	Bayesian Network	Case study , NaTech
62	http://dx.doi.org/10.1016/j.jlp.2017.09.006	2018	MAY	Modeling	Vulnerability modeling	CFD/FEM	CFD	Heat radiation, CFD
63	https://doi.org/10.1021/acs.iecr.8b00103	2018	MAR	Modeling	Risk Assessment	Graphical Method	Dynamic Bayesian	
64	http://dx.doi.org/10.1016/j.jlp.2017.12.001	2018	JAN	Management	Emergency	Procedural Action Analysis	Perti-nets	Heat Radiation, Perti-nets

SI No	DOI	Year	Month	Topic	Research Issue	Research Approach	Tools Used	Other Keywords
65	https://doi.org/10.1016/j.jlp.2017.12.011	2018	JAN	Management	Emergency	Procedural Action Analysis		Heat radiation
66	https://doi.org/10.1016/j.ress.2017.09.007	2018	JAN	Management	Safety Barrier Management	Optimization of Barriers		Heat radiation
67	https://doi.org/10.1016/j.compchemeng.2017.05.022	2017	NOV	Management	Inherent Safety	Layout Optimization		Accidental Domino effect
68	http://dx.doi.org/10.1016/j.jlp.2016.10.012	2017	SEP	Modeling	Vulnerability modeling	Probabilistic Methods		fragments
69	http://dx.doi.org/10.1016/j.firesaf.2017.05.015	2017	SEP	Modeling	Vulnerability modeling	Probabilistic Methods		Heat radiation
70	http://dx.doi.org/10.1016/j.psep.2017.08.021	2017	AUG	Modeling	Risk Assessment	Analytical Methods		Pool Fire
71	https://doi.org/10.1016/j.psep.2017.06.019	2017	AUG	Management	Safety Barrier Management	Performance Assessment	Bayesian networks	Security risk
72	http://dx.doi.org/10.1016/j.ssci.2015.10.010	2017	AUG	Management	Safety Barrier Management	Optimization of Barriers		Heat Radiation, Land use planning
73	https://doi.org/10.1016/j.ssci.2015.12.028	2017	AUG	Modeling	Risk Assessment	Graphical Method	Event Tree	Event Tree
74	https://doi.org/10.1016/j.ssci.2016.04.017	2017	AUG	Management	Safety Barrier Management	Optimization of Barriers		Heat Radiation, Framework , Tank
75	http://dx.doi.org/10.1016/j.jlp.2017.04.017	2017	JUL	Modeling	Risk Assessment	Graphical Method	Petri-net	Petri-net
76	http://dx.doi.org/10.1016/j.jlp.2017.05.004	2017	JUL	Management	Safety Barrier Management	Performance Assessment	AHP	Probabilistics method
77	https://doi.org/10.1016/j.ssci.2016.12.019	2017	JUN	Management	Safety Barrier Management	Performance Assessment		Heat Radiation

SI No	DOI	Year	Month	Topic	Research Issue	Research Approach	Tools Used	Other Keywords
78	https://doi.org/10.1016/j.jlp.2017.03.011	2017	MAY	Management	Emergency	Procedural Action Analysis	reversed fuzzy Petri-net	Heat Radiation
79	http://dx.doi.org/10.1016/j.ress.2016.11.023	2017	APR	Management	Safety Barrier Management	Performance Assessment		Heat Radiation
80	https://doi.org/10.1016/j.psep.2017.01.004	2017	FEB	Modeling	Vulnerability modeling	Probabilistic Methods		Overpressure
81	https://doi.org/10.1016/j.jlp.2016.10.003	2016	NOV	Review	Accident Analysis	Past Accident Analysis		NaTech
82	http://dx.doi.org/10.1016/j.jlp.2016.06.004	2016	NOV	Modeling	Risk Assessment	Analytical Methods	PHAST	NaTech, Fukushima
83	https://doi.org/10.1016/j.jlp.2016.03.006	2016	NOV	Management	Safety Barrier Management	Performance Assessment		Heat Radiation
84	http://dx.doi.org/10.1016/j.ress.2016.06.004	2016	OCT	Modeling	Risk Assessment	Graphical Method	Graph Matrices, Graph Theory	
85	https://doi.org/10.1002/prs.11794	2016	SEP	Modeling	Vulnerability modeling	Probabilistic Methods		Human response
86	http://dx.doi.org/10.1016/j.jlp.2016.05.031	2016	SEP	Modeling	Risk Assessment	Analytical Methods		Overpressure, Pipeline
87	http://dx.doi.org/10.1016/j.ssci.2016.03.026	2016	AUG	Modeling	Risk Assessment	Graphical Method	Damage map	Synegetic effect, difference in escalation
88	https://doi.org/10.1016/j.ress.2016.02.005	2016	JUN	Management	Emergency	Procedural Action Analysis	event sequence diagram	Heat Radiation, event sequence diagram
89	http://dx.doi.org/10.1016/j.jlp.2015.11.020	2016	MAR	Management	Safety Barrier Management	Performance Assessment		Projectiles, Experiments
90	https://doi.org/10.1016/j.jlp.2016.01.023	2016	MAR	Modeling	Vulnerability modeling	Probabilistic Methods		fragments

SI No	DOI	Year	Month	Topic	Research Issue	Research Approach	Tools Used	Other Keywords
91	https://doi.org/10.1016/j.psep.2016.01.005	2016	MAR	Modeling	Risk Assessment	Graphical Method	Bayesian Network	Bayesian networks
92	https://doi.org/10.1016/j.ijhydene.2015.11.039	2016	JAN	Modeling	Vulnerability modeling	CFD/FEM	TRACE, ANSYS	
93	https://doi.org/10.1016/j.ijhazmat.2015.06.020	2015	DEC	Management	Inherent Safety	Layout Optimization		Heat Radiation
94	https://doi.org/10.1016/j.ijhazmat.2015.05.033	2015	NOV	Modeling	Risk Assessment	Analytical Methods		Heat Radiation, Pipeline
95	https://doi.org/10.1016/j.psep.2015.07.005	2015	NOV	Review	Models and Methods			
96	https://doi.org/10.1016/j.res.2015.05.017	2015	NOV	Review	Models and Methods			
97	https://doi.org/10.1016/j.res.2015.02.010	2015	NOV	Modeling	Vulnerability modeling	Probabilistic Methods		Over Pressure
98	https://doi.org/10.1016/j.res.2015.03.023	2015	NOV	Management	Safety Barrier Management	Performance Assessment		Heat Radiation
99	https://doi.org/10.1016/j.res.2015.05.022	2015	NOV	Management	Safety Barrier Management	Performance Assessment		Heat Radiation
100	https://doi.org/10.1016/j.res.2015.03.004	2015	NOV	Modeling	Vulnerability modeling	Probabilistic Methods		Heat Radiation
101	https://doi.org/10.1016/j.res.2015.04.015	2015	NOV	Modeling	Risk Assessment	Graphical Method	Graph Theory	
102	https://doi.org/10.1016/j.res.2015.04.007	2015	NOV	Modeling	Vulnerability modeling	Threshold Method		Heat Radiation , Over Pressure

SI No	DOI	Year	Month	Topic	Research Issue	Research Approach	Tools Used	Other Keywords
103	http://dx.doi.org/10.1016/j.res.2015.06.018	2015	NOV	Review	Models and Methods			Rationale for Safety distance for LPG storage in Netherland
104	https://doi.org/10.1016/j.res.2015.05.020	2015	OCT	Modeling	Risk Assessment	Analytical Methods		NaTech
105	http://dx.doi.org/10.1021/acs.iecr.5b02064	2015	SEP	Modeling	Vulnerability modeling	Experiemental study		
106	https://doi.org/10.1002/prs.11687	2015	SEP	Review	Models and Methods		PHA	
107	https://doi.org/10.1016/j.res.2015.03.021	2015	JUL	Review	Accident Analysis	Past Accident Analysis	PAA	BLEVE
108	https://doi.org/10.1002/prs.11701	2015	JUN	Review	Accident Analysis	Case Study		Case study
109	https://doi.org/10.1016/j.res.2015.02.007	2015	JUN	Modeling	Risk Assessment	Graphical Method	Dynamic Bayesian	
110	https://doi.org/10.1016/j.jlp.2015.05.005	2015	MAY	Modeling	Risk Assessment	Simulation Methods	Monte Carlo	Fragments
111	https://doi.org/10.1016/j.psep.2014.05.003	2015	JAN	Modeling	Vulnerability modeling	Probabilistic Methods		Fragments
112	https://doi.org/10.1016/j.psep.2013.06.002	2014	NOV	Management	Inherent Safety	Layout Optimization		Heat Radiation , Over Pressure
113	https://doi.org/10.1016/j.psep.2013.12.002	2014	NOV	Modeling	Risk Assessment	Simulation Methods	Monte Carlo	FREEDOM II
114	https://doi.org/10.1016/j.firesaf.2014.08.010	2014	OCT	Modeling	Vulnerability modeling	CFD/FEM	Abaqus	Numerical modeling Minimum safe distances between tanks
115	http://dx.doi.org/10.1016/j.jhazmat.2014.07.034	2014	AUG	Modeling	Vulnerability modeling	Probabilistic Methods		fragments

SI No	DOI	Year	Month	Topic	Research Issue	Research Approach	Tools Used	Other Keywords
116	https://doi.org/10.1016/j.jlp.2013.07.007	2014	JUL	Management	Inherent Safety	Layout Optimization	MILNP	
117	https://doi.org/10.1016/j.jlp.2014.01.003	2014	MAY	Review	Accident Analysis	Past Accident Analysis	PAA	
118	https://doi.org/10.1016/j.jlp.2013.07.009	2014	APR	Modeling	Risk Assessment	Analytical Methods		NaTech
119	http://dx.doi.org/10.1016/j.jlp.2013.08.015	2014	APR	Modeling	Vulnerability modeling	Probabilistic Methods		fragments
120	http://dx.doi.org/10.1016/j.psep.2012.09.004	2013	NOV	Modeling	Risk Assessment	Analytical Methods	Matlab Program	
121	https://doi.org/10.1016/j.psep.2012.10.010	2013	NOV	Modeling	Risk Assessment	Analytical Methods		Heat Radiation , Over Pressure
122	https://doi.org/10.1016/j.jlp.2012.11.001	2013	SEP	Management	Inherent Safety	Layout Optimization		Over Pressure
123	https://doi.org/10.1016/j.psep.2012.04.003	2012	SEP	Review	Accident Analysis	Case Study	Fishbone	Case study
124	https://doi.org/10.1016/j.res.2011.11.002	2012	SEP	Management	Safety Barrier Management	Case Study		Heat Radiation
125	https://doi.org/10.1080/00986445.2011.626094	2012		Management	Safety Barrier Management	Case Study	AHP	
126	http://dx.doi.org/10.1016/j.jlp.2011.06.029	2012	JAN	Modeling	Vulnerability modeling	Probabilistic Methods		fragments
127	http://dx.doi.org/10.1016/j.jlp.2010.06.013	2011	SEP	Review	Accident Analysis	Past Accident Analysis	PAA	
128	http://dx.doi.org/10.1021/ie101367g	2011	APR	Management	Inherent Safety	Layout Optimization		Heat Radiation, Over Pressure
129	10.1016/j.ssci.2010.11.002	2011	MAR	Modeling	Vulnerability modeling	Distance Based methods	Optimization	Discrete island analysis algorithm

SI No	DOI	Year	Month	Topic	Research Issue	Research Approach	Tools Used	Other Keywords
130	https://doi.org/10.1007/S11814-010-0445-7	2011	MAR	Management	Inherent Safety	Layout Optimization		Heat Radiation, Over Pressure
131	https://doi.org/10.1016/j.jhazmat.2010.06.049	2010	DEC	Modeling	Risk Assessment	Simulation Methods	Monte Carlo	
132	https://doi.org/10.1016/j.jhazmat.2010.07.061	2010	NOV	Review	Accident Analysis	Past Accident Analysis	PAA	
133	https://doi.org/10.1016/j.jhazmat.2010.06.049	2010	OCT	Modeling	Risk Assessment	Simulation Methods	Monte Carlo	
134	https://doi.org/10.1016/j.jhazmat.2009.12.013	2010	MAY	Management	Cooperative	Enhancing Cooperation		Game theory
135	https://doi.org/10.1016/j.jhazmat.2009.07.029	2009	DEC	Modeling	Vulnerability modeling	CFD/FEM		Heat radiation
136	https://doi.org/10.1016/j.advengsoft.2009.01.002	2009	SEP	Modeling	Vulnerability modeling	Probabilistic Methods		Projectiles , Framework
137	http://dx.doi.org/10.1016/j.jlp.2009.02.012	2009	SEP	Modeling	Risk Assessment	Analytical Methods		Heat Radiation ,Over pressure
138	http://dx.doi.org/10.1016/j.jhazmat.2008.12.113	2009	AUG	Management	Cooperative	Cooperative Prevention	Game theory	Game theory, Nash Equilibrium
139	https://doi.org/10.1016/j.ssci.2008.11.005	2009	AUG	Modeling	Vulnerability modeling	Probabilistic Methods		fragments
140	http://dx.doi.org/10.1016/j.jlp.2009.02.006	2009	JUL	Modeling	Vulnerability modeling	Probabilistic Methods		fragments
141	https://doi.org/10.1016/j.jlp.2009.02.005	2009	JUL	Modeling	Vulnerability modeling	Probabilistic Methods		fragments

SI No	DOI	Year	Month	Topic	Research Issue	Research Approach	Tools Used	Other Keywords
142	https://doi.org/10.1016/j.jhazmat.2008.07.056	2009	APR	Modeling	Vulnerability modeling	Probabilistic Methods		Fragments
143	https://doi.org/10.1016/j.jhazmat.2008.03.116	2009	JAN	Modeling	Vulnerability modeling	Probabilistic Methods		Fragments
144	http://dx.doi.org/10.1016/j.jhazmat.2008.02.089	2008	DEC	Management	Inherent Safety	Inherent Safety Indexes		Heat Radiation ,Over pressure
145	https://doi.org/10.1016/j.jhazmat.2008.02.091	2008	DEC	Management	Inherent Safety	Inherent Safety Indexes		Heat Radiation ,Over pressure
146	https://doi.org/10.1016/j.firesaf.2008.01.002	2008	NOV	Review	Accident Analysis	Past Accident Analysis	PAA	Jet Fire
147	http://dx.doi.org/10.1016/j.jhazmat.2008.01.076	2008	OCT	Modeling	Vulnerability modeling	Probabilistic Methods		Overpressure
148	http://dx.doi.org/10.1016/j.jlp.2007.06.007	2008	MAY	Management	Security	Security of Critical Installations		Intentional Attacks
149	https://doi.org/10.1016/j.firesaf.2007.06.008	2008	APR	Review	Accident Analysis	Case Study	Accident Case Study	Dust explosion
150	https://doi.org/10.1016/j.jhazmat.2007.07.040	2008	APR	Management	Emergency	Case Study		
151	https://doi.org/10.1016/j.jhazmat.2007.01.036	2007	AUG	Management	Emergency	Case Study		Evacuation decision making
152	https://doi.org/10.1002/prs.10178	2007	JUN	Modeling	Vulnerability modeling	Probabilistic Methods		Fragments
153	https://doi.org/10.1016/j.jhazmat.2006.06.041	2007	JAN	Management	Inherent Safety	Inherent Safety Indexes		Heat Radiation ,Over pressure

SI No	DOI	Year	Month	Topic	Research Issue	Research Approach	Tools Used	Other Keywords
154	https://doi.org/10.1016/j.jlp.2005.11.007	2006	SEP	Modeling	Vulnerability modeling	Threshold Method		Heat Radiation ,Over pressure, GIS
155	https://doi.org/10.1252/jcej.39.731	2006	JUL	Management	Inherent Safety	Layout Optimization		Accidental Domino accidents
156	https://doi.org/10.1016/j.jhazmat.2005.08.012	2006	FEB	Modeling	Vulnerability modeling	Threshold Method		Heat Radiation, Overpressure
157	https://doi.org/10.1016/j.jhazmat.2005.07.003	2005	DEC	Modeling	Vulnerability modeling	Threshold Method		Heat Radiation ,Over pressure
158	http://dx.doi.org/10.1016/j.res.2004.11.012	2005	NOV-DEC	Modeling	Vulnerability modeling	Probabilistic Methods		Overpressure
159	10.1007/BF02705777	2005	SEP	Management	Inherent Safety	Layout Optimization		Accidental Domino accidents
160	https://doi.org/10.1016/j.jlp.2005.03.001	2005	MAY	Management	Cooperative	Cooperative Prevention		Standardized Method
161	https://doi.org/10.1016/j.jlp.2005.03.002	2005	MAY	Management	Cooperative	Cooperative Prevention		Traditional Risk Analysis tools
162	https://doi.org/10.1007/1-4020-3721-X_2	2005		Review	Models and Methods			QRA
163	https://doi.org/10.1016/j.jhazmat.2004.09.002	2004	DEC	Modeling	Vulnerability modeling	Probabilistic Methods		Fragments
164	https://doi.org/10.1016/j.jlp.2004.08.003	2004	NOV	Modeling	Vulnerability modeling	Probabilistic Methods		Fragments
165	https://doi.org/10.1016/j.jhazmat.2003.09.013	2004	MAR	Modeling	Vulnerability modeling	Threshold Method		Overpressure

SI No	DOI	Year	Month	Topic	Research Issue	Research Approach	Tools Used	Other Keywords
166	https://doi.org/10.1016/j.jhazmat.2003.09.014	2004	MAR	Modeling	Vulnerability modeling	Threshold Method		Overpressure
167	https://doi.org/10.1002/prs.680220303	2003	SEP	Review	Models and Methods			
168	https://doi.org/10.1016/S0266-8920(01)00023-6	2001	OCT	Modeling	Vulnerability modeling	Probabilistic Methods		Fragments
169	http://dx.doi.org/10.1016/S0950-4230(01)00011-0	2001	SEP	Modeling	Vulnerability modeling	Probabilistic Methods		Fragments
170	https://doi.org/10.1016/S0950-4230(00)00055-3	2001	SEP	Modeling	Risk Assessment	Analytical Methods		Accidental domino effects
171	https://doi.org/10.1016/S0950-4230(00)00048-6	2001	JUL	Modeling	Risk Assessment	Analytical Methods		Accidental domino effects
172	http://dx.doi.org/10.1002/prs.680200207	2001	JUN	Modeling	Risk Assessment	Analytical Methods		Accidental domino effects
173	(Khan <i>et al.</i> , 2000)	2000	NOV	Modeling	Risk Assessment	Analytical Methods		Accidental domino effects
174	http://dx.doi.org/10.1002/prs.680190110	2000	SPR	Modeling	Risk Assessment	Analytical Methods		Accidental domino effects
175	https://doi.org/10.1002/prs.680180304	1999	FAL	Review	Accident Analysis	Past Accident Analysis	PAA	
176	https://doi.org/10.1002/prs.680170207	1998	SUM	Modeling	Risk Assessment	Analytical Methods		Accidental domino effects
177	http://dx.doi.org/10.1002/prs.680160312	1997	FAL	Modeling	Risk Assessment	Analytical Methods		MAXCRED-II

ANNEXURE III

TRANSCRIPT OF EXPERT SURVEY

Domino Risk Assessment- Industry Practices

- You are invited to participate in a web-based online survey on industry practices in Quantitative Risk Assessment (QRA) focusing on domino risks.
- The purpose of this survey is to identify the risk assessment practices and requirements of the industry related to domino effect risk assessments in chemical process industry
- This is a research project being conducted by Mr. Arun P A, research scholar, University of Petroleum and Energy Studies, Dehradun, India.
- It should take approximately 4-5 minutes to complete

* Indicates required question

Basic Information

1. Your Name *

2. Mail Id

3. Industry Type *

Mark only one oval.

☐ Consultant

☐ Client

☐ EPC

☐ Contractor

☐ Other:

4. Risk Assessment Experience in years *

Mark only one oval.

- ☐ 0 -2 years
- ☐ 3- 5 years
- ☐ 6-10 years
- ☐ 10-20 years
- ☐ 20+ years

5. Designation *

6. Company Name

7. Location

QRA Practices

8. Which tool/software do you use to perform QRA *

Check all that apply.

- ☐ PHAST
- ☐ FLACS
- ☐ ALOHA
- ☐ Shepherd
- ☐ RISKCURVES
- ☐ Other:

9. Which guidelines do you use for QRA *

Check all that apply.

- ☐ TNO colored books
- ☐ CCPS Guidelines
- ☐ OGP guidelines
- ☐ OISD
- ☐ Other: _____

10. Do you consider domino accident scenarios while performing QRA *

Mark only one oval.

- ☐ Yes *Skip to question 12*
- ☐ No
- ☐ Some times

11. Do you assess the risk caused by domino scenarios in QRA studies *

Mark only one oval.

- ☐ Yes *Skip to question 12*
- ☐ No *Skip to question 14*

QRA Domino risk assessment practices

12. Please describe how do you select domino event sequences in QRA

13. Please describe how do you estimate the frequency & consequences of domino events in QRA

Framework for domino risk assessment

14. What do you prefer *

Mark only one oval.

- ☐ Prefer separate QRA for domino events in chemical process industry
- ☐ Domino risk assessment must be part of existing risk assessment studies

15. How much deviations would you allow from existing procedure (1 - Not at all; 2- * Slight; 3- Moderate; 4- Very; 5- Extremely

Mark only one oval.

	1	2	3	4	5	
Not	☐	☐	☐	☐	☐	Extremely

16. Please list the top three requirements from the new framework

17. Rate your expertise in Bayesian Network Analysis techniques (1- Very Poor; 2- Below Average; 3- Average; 4-Above Average; 5-Excellent) *

Mark only one oval.

	1	2	3	4	5	
Very	☐	☐	☐	☐	☐	Excellent

18. Rate your expertise in Petri net analysis (1- Very Poor; 2- Below Average; 3- Average; 4-Above Average; 5-Excellent) *

Mark only one oval.

	1	2	3	4	5	
Very	☐	☐	☐	☐	☐	Excellent

19. Rate your expertise in Fuzzy logic analysis (1- Very Poor; 2- Below Average; 3- Average; 4-Above Average; 5-Excellent) *

Mark only one oval.

	1	2	3	4	5	
Very	☐	☐	☐	☐	☐	Excellent

20. Would like to take part in a project to develop industry friendly framework for domino risk assessment *

Mark only one oval.

☐ Yes

☐ No

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Proceed to submit your responses

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ANNEXURE-IV

PLAGIARISM REPORT



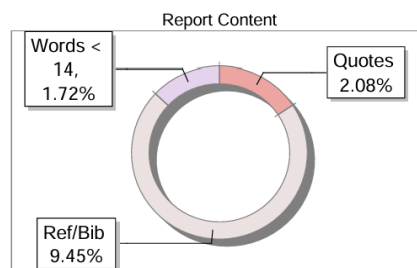
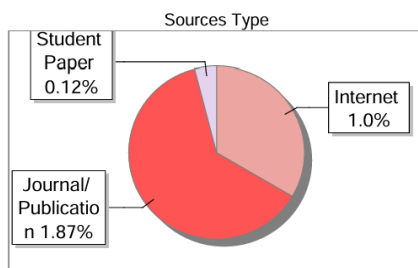
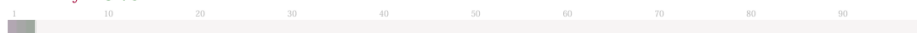
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Title	DEVELOPMENT AND VALIDATION OF A FRAMEWORK FOR ASSESSMENT OF DOMINO RISKS IN PROCESS INDUSTRIES
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Submission Date	2025-02-20 18:39:52
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