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Methods and models in process safety and risk management: Past, present and future

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ABSTRACT

The paper reviews past progress in the development of methods and models for process safety and risk management and highlights the present research trends; also it outlines the opinions of the authors regarding the future research direction in the field. Based on the open literature published in the leading journals in the field of safety, risk and reliability, the review covers the evolution of the methods and models developed for process safety and risk management. The methods and models are categorized as qualitative, semi-quantitative, quantitative and hybrid. The progress in the last few decades is discussed in the context of the past. Developments in the current decade formulate the basis of the present trends; future directions for research in these fields are also outlined. The aim of the article is to provide a historical development in this field with respect to the driving forces behind the development. It is expected that it will help researchers and industrial practitioners to gain a better understanding of the existing concepts. At the same time the aim is to provide direction to bridge the existing gaps through research and developments.

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1. Introduction

Continuing technological and social development of the world creates enormous demand for energy, chemicals, commodities, and food. This leads to an increase in the size and complexity of processing plants. This has inevitably created new hazards and increased risk that must not be compromised with mere economic benefits; instead they are required to be prevented and mitigated. Unfortunately this is not the case as accidents keep occurring with different levels of severity. Khan and Abbasi (1999a) conducted a comprehensive study on major process accidents that occurred during 1926–1977 and recommended the need for accident forecasting, consequence assessment, and development of emergency management plans. The report of Marsh Energy Practices listed 100 largest property damage losses that have occurred in hydrocarbon processing industries from 1970 to 2011 (Marsh, 2012). There are a number of databases maintaining the record of accidents which occurred in process industries and their respective consequences. Among them, the Major Hazard Incident Data Service (MHIDAS), Major Accident Reporting System (MARS), Process Safety Incident Database (PSIC), Failure and Accident Technical Information System (FACTS) and World Offshore Accident Database (WOAD) are the most recognized and widely used databases. Pondicherry University Process-industry Accident Database (PUPAD) is a comprehensive open-source database to assist past accident analysis (Tauseef et al., 2011). In the present work, authors performed a brief analysis of notable past process accidents that occurred during the last two decades using the accident information available in open literature including from the United States Chemical Safety Board (Marsh, 2012; Khan and Abbasi, 1999a). This will help to develop an overall view of accident trends and their consequences (property and production loss). Fig. 1 is the plot developed using the information available in the above mentioned resources. It is observed that the accident trend has not followed a uniform pattern. Both accident occurrences and their consequences show a non-uniform fluctuation. This non-uniform trend confirms the uncertain and unpredictable behavior of accidents and their consequence and reinforces the need of efficient and effective process safety and risk management to implement preventive and mitigating safety measures to reduce both the likelihood and severity of industrial accidents.

Process safety is the common global language used to communicate the strategies of hazard identification and analysis, risk assessment and evaluation, safety measures, and safe critical decision making. Process safety is identified as an integral part of process development and manufacturing rather than considering it as an "add-on" to the process (Gibson, 1999). Process safety differs from occupational safety as it solely focuses on preventing and mitigating major process accidents such as fires, explosions, and toxic releases, whereas occupational safety focuses on workplace hazards such as trips, slips, and falls. Process safety assessment/management includes several essential steps (Bahr, 1997). Though every step is equally important, hazard identification, risk assessment and management can be considered as the key steps of process safety management. Hazard identification, known as safety brainstorming for "what can go wrong", identifies as many process hazards as are possible. "Risk" can be considered as the measurement of process safety and defined as the combination of "how bad an accident would be?" and "how often could it happen?". It can be quantitatively expressed as a function of probability or frequency and their consequences (CCPS, 2000, 2007). During the risk analysis, understanding about the systems' risk is portrayed in terms of qualitative and quantitative elements. Risk/safety management combines efforts to manage risk through risk estimation, risk evaluation, and risk-based decision making and design improvement.

There are a number of review articles published focusing on different area of process safety and risk management such as hazard identification, risk assessment and management, accident modeling, and inherent safety. Khan and Abbasi (1998a) briefly discussed existing risk assessment techniques and methods and their advantages and disadvantages. A different perspective of risk was discussed by Aven and Kristensen (2005). They discussed risk analysis in terms of some prevailing perspectives such as engineering, economics, social science, anthropology, and unifying approaches. The existing risk assessment and analysis techniques published in scientific literature were discussed by Marhavilas et al. (2011). Their analysis was limited to a discussion of only the key risk assessment methods and also was focused only on articles published during 2000–2009. Accident modeling is used to formulate an accident scenario prior to risk analysis and generate an overall picture of system safety. Lehto and Salvendy (1991) performed a systematic evaluation of the strength and limitation of accident causation models developed before the

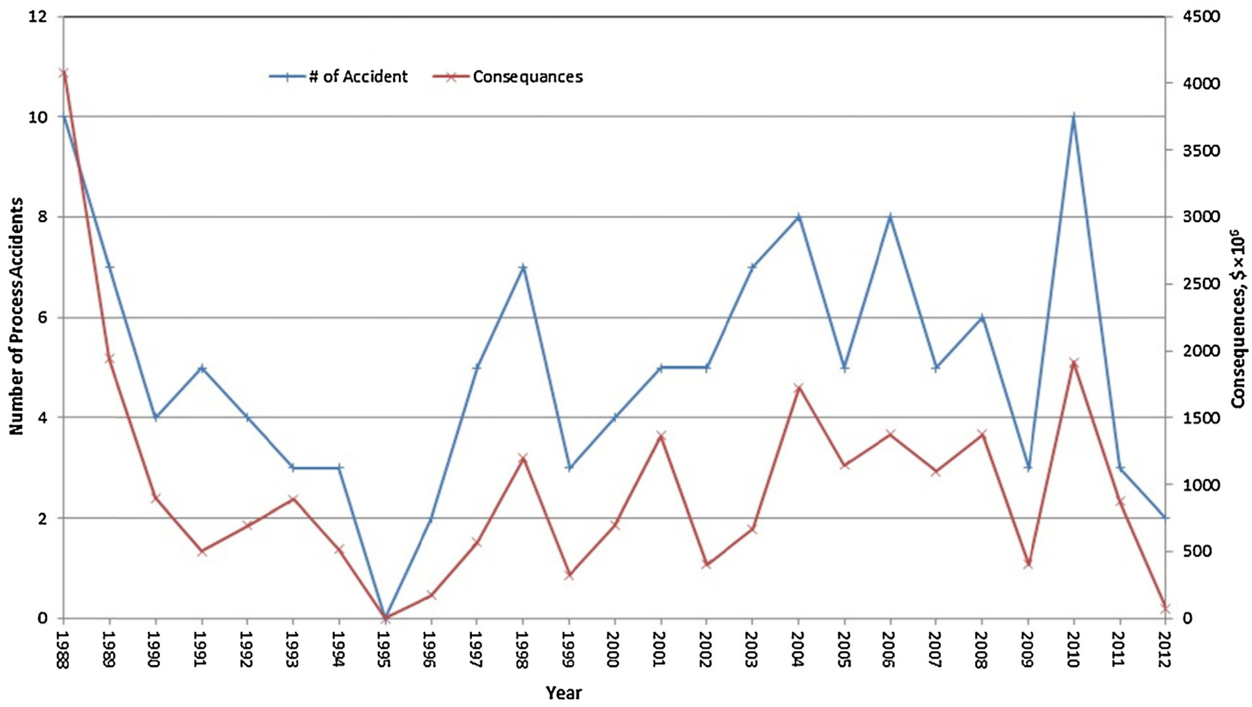

Fig. 1 – Accident trend analysis from 1988 to 2012.

1990s, and also discussed their application to different risk assessment techniques. Katsakiori et al. (2009) also performed a review of selected accident causation models and investigation methods in terms of five requirements: descriptive, revealing, consequential, validating, and practical. Evaluation of applicability of Inherently Safer Design (ISD) principles for different stages of a process life cycle was conducted by Hurme and Rahman (2005). Three inherent safety indices: Inherent Safety Index (ISI), Prototype Inherent Safety Index (PIIS) and i-safe were evaluated using a case study (Rahman et al., 2005). Hendershot (2006) discussed the different ISD strategies with examples to provide a better understanding of how the application of ISD strategies varies from industry to industry, plant to plant and stage to stage of the process design life cycle. Review of the progress of inherent safety and its development during the period of 2001–2011 and future opportunities were thoroughly discussed by Srinivasan and Natarajan (2012).

Though there are a number of review articles published and openly accessible, none of them was able to include all the aspects of process safety and risk management in one concise article. Also, no review article was found which discusses the recent development of process safety and risk management. The objective of this work is to provide a historical development of process safety and risk management and present research trends. Several classification criteria are used to develop a better understanding about existing concepts, methodologies and techniques related to process safety and risk assessment. The article has been structured so that first it introduces the origin of process safety and risk management where early developments and motivation for those developments are discussed. Then past progress will be discussed. In this section, developments of safety and risk management are discussed by categorizing three different types: qualitative, quantitative, and hybrid. These three main types are again categorized into three subcategories: hazard identification and analysis, risk assessment, and safety management. Then authors summarize the current research trends and future directions.

The scope of the review is restricted to topics directly related to process safety and risk assessment that published in journal papers. Conference papers are not considered due to limited availability in public domain and less technical content. Eight key journals are selected. The literature survey is performed based on key words such as process safety, process risk, risk assessment, risk management, safety assessment. Topics related to reliability, maintainability and availability engineering, fault identification and diagnosis, chemistry and environmental science, and other development which are not directly related to process safety but can be useful in process safety are not selected.

2. Origin of concept of process safety and driving forces for its development

The origin of the term “process safety” and its international evolution is associated with the major process accidents that occurred during the time period between 1960 and 1990 as a result of rapid industrialization and technological movement: Flixborough, United Kingdom (UK) (1974); Seveso, Italy (1976); Bhopal, India (1984); Piper Alpha, UK (1988) (Kletz, 1999; Macza, 2008; Planas et al., 2014). It is evident that the concept of process safety has been successfully used in process industries even before this time period. E.I. DuPont, founded in 1802 to manufacture gunpowder, has successfully utilized the concept of process safety to prevent serious injuries and incidents creating a good foundation for current process safety and risk management (Klein, 2009). More importantly, the contribution of Professor Trevor Kletz to the field of process safety and his involvement with the origin and evolution of process safety is worthy to discuss throughout this article. The evolution of process safety is closely connected with Professor Trevor Kletz’s professional and academic career, especially his professional career at Imperial Chemical Industries (ICI), England (Kletz, 2012). Scientific research on process safety and risk also started simultaneously and it is considered that the

1970s were the golden decade of research in this field (Kletz, 1999; Planas et al., 2014).

A number of research organizations and research programs have been established to advance process safety and to translate the findings to industrial applications. The major accident which occurred during that time was the main driving force to establish research organizations and programs. In 1985, immediate after the Bhopal accident, the American Institute of Chemical Engineers (AIChE) formed the Center of Chemical Process Safety (CCPS) to develop the guidelines, methodologies, standards and safe work practices for chemical process industries. CCPS published their first guideline book, "Guidelines for Hazard Evaluation Procedures" in 1990. After the Flixborough accident, the United Kingdom government introduced the "Health and Safety at Work etc. Act 1974" to protect and ensure the health and safety of people at work. Subsequently the Health and Safety Commission was established and then the Health and Safety Executive (HSE) was established. The HSE was established in 1975 mainly focusing on development of health and safety legislation that enforces the hazard identification process in the industrial workplace. The European Federation of Chemical Engineering (EFCE) formed the European Process Safety Center (EPSC) with the objective of promoting best process safety practices across Europe. The center for pollution control and energy technology in Pondicherry University, India was established in 1994 to work on process safety and risk management. This unit works closely with industry and academia to promote process safety application. The Mary Kay O'Connor Process Safety Center was established in 1995 associated with Texas A&M University, United States of America (USA) to provide expertise, education, research, and services in the areas of hazard analysis, risk management, emergency management, and safety training.

The main regulatory or legislative responses were also developed as a result of major process accidents that occurred during this time period. The Seveso Directive was established in 1982 by the European Commission as a response to the industrial catastrophic accident which occurred at a chemical plant in Seveso, Italy in 1976. In 1996, the Seveso Directive was replaced by the Seveso II Directive by adopting the Control of Major Accident Hazards (COMAH) regulation passed in 1984, UK (Macza, 2008). Major accidents such as nuclear meltdown (Three Mile Island, 1979), the Union Carbide plant toxic release accident (Institute, West Virginia, 1985), the Phillips 66 Polyethylene plant fire and explosion (Pasadena, 1989) and the ARCO chemical cooperation plant explosion (Channelview, 1990), that occurred during the period of 1970 to 1990 in the USA motivated the Occupational Health and Safety Administration (OSHA) to introduce the process safety management standard of 29 CFR 1910.119 in 1992. This standard was initially developed for the USA; however it later became a worldwide industrial best practice. Similar to the OSHA process safety management standard, the Environmental Protection Agency (EPA) issued Risk Management Program Regulation of 40 CFR Part 68 (Macza, 2008). The Canadian Chemical Producers Association (CCPA) issued guidance principles to responsibly manage hazardous material after the major train derailment accident when a rail car exploded causing the release of highly hazardous material such as styrene, toluene, propane, caustic soda, and chlorine (Belanger et al., 2009; Liverman and Wilson, 1981). After the Bhopal accident in 1984, the CCPA issued the "Responsible Care" initiative urging Canadian chemical industries to review existing safety practices to identify and report the potential weakness and relevant findings (Belanger et al., 2009). The American Petroleum Institute (API) issued recommended practice 750-1990 for Canadian industries which includes process safety management and hazard analysis methods (Elke, 2013).

In addition to guidelines, procedures and policies, methods and models were developed focusing on hazard identification and risk assessment. Since the major development of process safety and risk assessment is related to methods, models or a combination of both, this review paper only focuses on methods and models developed related to process safety and risk assessment. The past progress of methods and models published in international journals will be discussed in the next sections.

Table 1 – Main journals and their contribution to process safety and risk assessment and management.

Name of the journal	No. of articles related to topic	% contribution
Journal of Loss Prevention in the Process Industries (JLPPI)	178	13.14
Process Safety and Environmental Protection (PSEP)	53	7.21
Safety Science (SS)	43	2.96
Journal of Hazardous Materials (JHM)	80	0.84
Risk Analysis (RA)	39	1.97
Reliability Engineering and System Safety (RESS)	104	4.32
Process Safety Progress (PSP)	51	5.37
Journal of Risk and Reliability (JRR)	26	10.20

3. Past progress

The majority of research findings are available in the public domain such as journals, conferences, symposiums, and magazines. In this section, authors have made an effort to review, categorize, and summarize the technical articles published only in scientific journals. Since the scope of this study is process safety and risk assessment and management, eight key journals are selected which have similar aim and scope. The literature survey is performed based on key words: process safety, process risk, risk assessment, risk management, and safety assessment. The technical articles which have a direct relationship to the scope of study are chosen. Topics related to reliability, maintainability and availability engineering, fault identification and diagnosis, chemistry and environmental science, and theoretical development which are not directly related to process safety but which can be useful in process safety are not considered. Later, further filtration is carried out to select the articles that discuss and present the models and methods. A simple statistical analysis is done to show the contribution of each journal to process safety and risk management. The number of articles (approximate) published and percentage values are presented in Table 1.

The highest number of articles was published in the Journal of Loss Prevention in the Process Industries (JLPPI). JLPPI mainly focuses on the area of consequences modeling and prevention: explosion, fire and release characterizing, modeling and prevention. Process Safety Progress (PSP) is the official journal of the American Institute of Chemical Engineers (AIChE) which covers topics related to accident investigation, hazard identification and evaluation, consequence analysis, risks assessment and regulatory compliance, standards, training and education. It is observed that the PSP carries a large number of articles related to accident investigation and industrial applications. The Journal of Process Safety and Environmental Protection (PSEP) was started in 1996 and approximately 53 articles have been published. The Journal of Risk and Reliability (JRR) which was first published in 2006 as Part O of the proceedings of the Institution of Mechanical Engineers focuses on topics related to reliability and risk. Among the articles published in Reliability Engineering and System Safety (RESS), the majority focus on the process safety and risk assessment associated with the nuclear industry. Safety Science (SS) started in 1991 and covers a wide range of topics related to human safety. Though Risk Analysis (RA) primarily focuses on human health and safety risk, microbial risk and medical related risk, it also carries high quality technical articles related to process safety and risk management. The Journal of Hazardous Material (JHM) is the least contributor since its scope focuses on improving the understanding of the hazards and risk associated with materials to humans and the environment.

Method describes systematic procedures or guidelines for accomplishing or approaching a development related to process safety and risk management. Model covers mathematical, analytical, empirical, probabilistic, and computational models. Authors classified method and model into four different types: (1) qualitative, (2) semi-quantitative, (3) quantitative, and (4) hybrid. They are further categorized into three sub-categories: hazard identification and analysis, risk assessment, and safety management. These three sub categories are key elements of process safety management. The methods and models developed to identify and analyze the hazards and faults are discussed under the sub-category of hazard identification and analysis, whereas risk assessment covers estimation and assessment of probability of accident occurrence and consequences. Finally, risk evaluation, risk-based decision making, and application of safety measures in order to properly manage the safety of the system are discussed under safety management. The distribution of numbers of development related to these four types is shown in Fig. 2. It is noticed that research related to developing quantitative and hybrid techniques is increasing more than qualitative or semi-quantitative techniques. This implies that the quantitative representation or combination of both qualitative and quantitative (hybrid) representation are becoming more meaningful in process safety and risk management. Subsequent subsections will discuss the most significant and established techniques.

3.1. Qualitative analysis

Qualitative analysis refers to a non-numerical representation and explanation based on attributes of graphics, flow diagrams, graphs and sources of data. The most significant qualitative methods and models developed are listed in Table 2 and the following paragraphs discuss them in detail.

3.1.1. Hazard identification and analysis

The well established and widely used qualitative hazard identification method is the Hazard and Operability Analysis (HAZOP). The HAZOP is a well-established and accepted method which is used to identify and evaluate process hazards as well as to identify operability problems (CCPS, 2008; Crowl and Louvar, 2011). The HAZOP was developed and first utilized at Imperial Chemical Industries (ICI) in 1963 to identify the hazards and to recognize the equipment failures that lead to accidents (Kletz, 1999, 2012). It is worth mentioning that Professor Trevor Kletz was the leader in developing HAZOP within ICI and in advising and training relevant personnel to carry out the HAZOP process. The first publication about the HAZOP study appeared in 1974 (Lawley, 1974). Since HAZOP was first used in industry in 1963 and published in 1974, its research progress over the years was rapid and occurred mainly in the area of extending HAZOP's scope, applications of HAZOP and automating HAZOP. There are research efforts devoted to extending the scope of the HAZOP study modifying certain of its features to avoid the limitation of applicability to highly complex process systems. The subsequent chapters discuss the improvement and extensions of the standard HAZOP throughout the last two decades. The last paragraph of this sub-section summarizes the other noticeable hazard identification methods and models developed.

3.1.1.1. Batch HAZOP analysis. The initial development of HAZOP primarily focused on continuous manufacturing process/unit operations. Limitations of standard HAZOP analysis, when applying to batch process, were discussed by Mushtaq and Chung (2000) and a modified batch HAZOP approach was introduced to overcome those limitations. Since standard HAZOP analysis is manual, repetitive and time consuming, the automated tool named CHECKOP was developed to improve the efficiency and accuracy of hazard identification of the batch process (Palmer and Chung, 2008, 2009).

3.1.1.2. Modified HAZOP to study human, management and organizational factors. Standard HAZOP is further limited to assess hazards generated due to variation of process variables and is not able to take into consideration the interaction of human, management and organizational factors of a particular hazard. This results in a development of human HAZOP methodologies. The Safety Culture Hazard and Operability (SCHAZOP) approach was introduced by Kennedy and Kirwan (1998) to identify the specific safety management vulnerabilities that could fail in practice. Multilevel Hazop (HzM) was the integration of a modified HAZOP method with human HAZOP to analyze process deviations during the plant commissioning stage and to identify specific safety measures (Cagno et al., 2002). The HzM was performed in two dimensional ways: the vertical dimension envisaged the hierarchical breakdown of each procedure into an ordered sequence of steps whereas the horizontal dimension broke down each step into three logical levels. This way, it helped to record how deviations may occur at different levels and to establish safety measures (Cagno et al., 2002).

3.1.1.3. Modified HAZOP for programmable electronic systems. The standard HAZOP procedure was modified to perform hazard identification for programmable electronic systems, and the modified procedure was called Chazop (computer Hazop) (Schubach, 1997). Likewise, electronic systems, digital instrumentation and control systems are often used as safety measures. It is difficult to understand their failure, especially due to software failures. The dynamic flowgraph method (DFM) which is a digraph-based technique was used to validate the safety requirements of the digital instrumentation

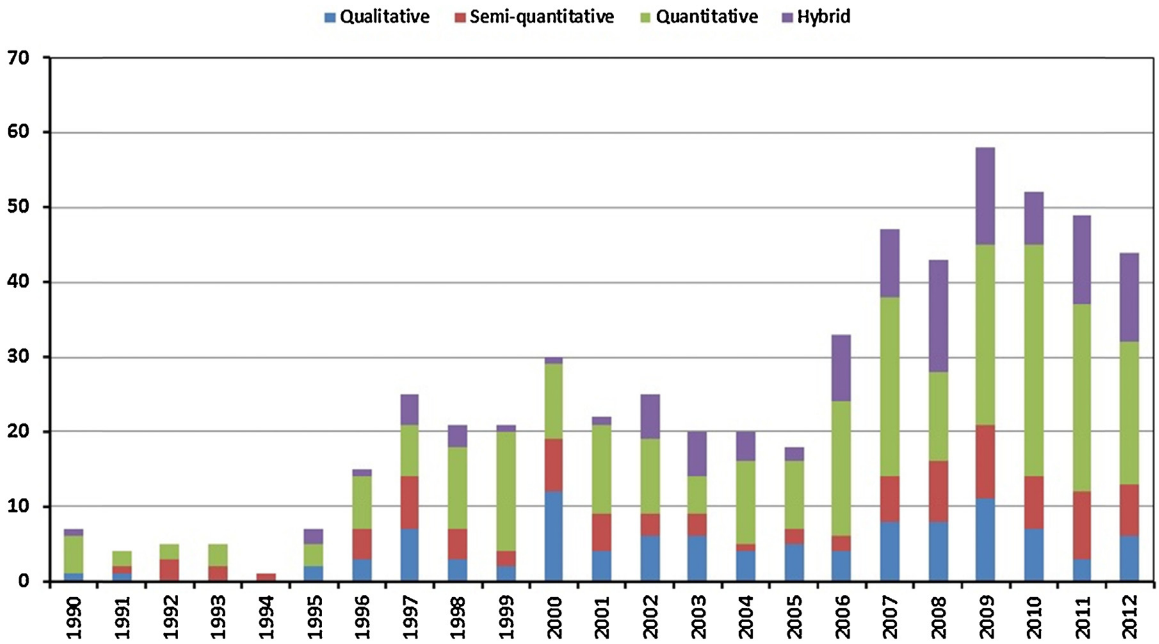

Fig. 2 – Distribution of analysis techniques over last two decades.

Table 2 – Research articles published related to qualitative analysis.

Author(s)	Journal	Method/model
Hazard Identification and analysis		
Vaidhyanathan and Venkatasubramanian (1995)	RESS	HAZOP Digraph (HDG) Model
Schubach (1997)	JLPPI	Chazop—the HAZOP analysis for programmable electronic systems
Khan and Abbasi (1997a)	JLPPI	optHAZOP—an optimal approach for HAZOP study
Khan and Abbasi (1997b)	JLPPI	TOPHAZOP—a knowledge based software tool for HAZOP study
Kennedy and Kirwan (1998)	SS	SCHAZOP—safety culture hazards and operability study
McCoy et al. (1999a,b,c, 2000a,b)	PSEP	HAZID—a computer aided hazard identification method
Mushtaq and Chung (2000)	JLPPI	Batch HAZOP methodology
Cagno et al. (2002)	RESS	HzM—multi level HAZOP analysis
Garrett and Apostolakis (2002)	RESS	Dynamic Flowgraph Method (DFM)
Baybutt (2003)	PSP	Major Hazards Analysis (MHA)
Triplett et al. (2004)	PSP	Chain of Event Analysis (CEA)
Zhao et al. (2005a,b)	PSEP	PHASuite—a software system for an automated hazard analysis
Labovský et al. (2007)	JLPPI	Model-based HAZOP study
Ramzan et al. (2007)	PSP	Extended Hazop
Laskova and Tabas (2008)	PSP	An integrated HAZOP and systematic hazard identification method
Cui et al. (2008)	PSP	LDGHAZOP—a layered digraph model for the HAZOP analysis
Palmer and Chung (2008, 2009)	JLPPI	CHECKOP—an automated tool for batch HAZOP analysis
Rahman et al. (2009)	JLPPI	ExpHAZOP$^+$—an automated HAZOP analysis methodology
Wang et al. (2009)	PSEP	Signed graph based HAZOP analysis
Wang and Gao (2012)	JLPPI	Database of expert knowledge
Risk assessment		
Baybutt (2007)	PSP	Improved Risk Graph
Baybutt (2012)	JLPPI	Use of risk tolerance criteria to determine the SIL
Safety management		
Svenson (1991)	RA	Accident Evolution and Barrier (AEB) Model
Hale et al. (1997)	SS	Structural Analysis and Design Technique (SADT)
Rasmussen and Grtinberg (1997)	JLPPI	Uncontrolled Flow of Energy (UFOE) Model
Youngblood (1998)	RA	Top Event Prevention Analysis (TEPA)
Duarte and Pires (2001)	PSP	Logic diagram based approach to improve the safety systems
Svedung and Rasmussen (2002)	SS	An accident mapping method
Kim et al. (2003)	JLPPI	yAGAS—an experience based approach to develop accident scenario
Gupta and Edwards (2003)	JHM	A graphical method to measure ISD
Leveson (2004)	SS	System Theoretic Accident Model Process (STAMP)
Licu et al. (2007)	RESS	Safety Occurrence Analysis Methodology (SOAM)
Santos-Reyes and Beard (2008, 2009)	JLPPI	Systematic Safety Management System (SSMS) Model
Reniers (2009)	JLPPI	Hazard/risk Analysis Review Planning (HARP)
Mohaghegh and Mosleh (2009)	SS	A safety framework to analyze human factors (SoTeRiA)
Kujath et al. (2010)	JLPPI	A conceptual accident model
Rusli and Shariff (2010)	JLPPI	Qualitative Assessment for Inherent Safety Design (QAISD)
Øien et al. (2011a,b)	SS	Development of risk indicators

and control system (Garrett and Apostolakis, 2002). Ramzan et al. (2007) developed the Extended HAZOP which was supported by dynamic simulation. Extended HAZOP adopted the concept of risk and included the following additional features which standard HAZOP cannot produce. These were: dynamic simulation, consequences classification, frequency classification, risk-based result documentation, and risk-based hazard ranking.

3.1.1.4. *Integrated HAZOP*. Integration of HAZOP with other process hazard analysis methods is another extension of traditional HAZOP analysis to improve its hazard identification capabilities. To perform the risk assessment in the semiconductor industry, an integrated HAZOP/FMEA (Failure Mode and Effects Analysis) methodology was developed (Tramell and Davis, 2001). For highly complex dynamic systems, the methodology by integration of the mathematical model and HAZOP was presented by Labovský et al. (2007). This methodology helps to decrease the possibility of overlooking hazards and to increase the efficiency of the hazard identification process. A systematic hazard identification method was introduced to perform along with HAZOP which enhanced the hazard identification process by providing an opportunity to identify the major sources of potentially critical accidents and their consequences beyond the boundaries of the premises (Laskova and Tabas, 2008). This method can also be used for scheduling and maintenance activities of plant operations. Information generated by the HAZOP study and other process hazard analysis (PHA) methods is required to be stored in a proper way for use in safety oriented design and decision making. The HAZOP analysis results were combined with the accident analysis results to develop a database of expert knowledge which supports the operators' understanding of operations and for making decisions (Wang and Gao, 2012).

3.1.1.5. *Automated HAZOP*. Since HAZOP is a labor intensive and time consuming study, research on automating the process has become a more focused area in the safety community. HAZOPEX, which is a rule based expert system developed in the early 1990s (Karvonen et al., 1990) can be considered as one of the major developments in this area. Using the concept of the HAZOP study, a new hazard identification method called Qualitative Hazard Identification (QHI) was developed by Catino and Ungar (1995). The QHI is capable of generating faults and a relevant fault model. Subsequently, hazard identification was carried out by simulating these fault models (Catino and Ungar, 1995). Khan and Abbasi (1997a) developed an optimal approach termed optHAZOP to perform the HAZOP study utilizing an already developed information base. This method increased the efficiency, effectiveness and reliability of the HAZOP study. As a further improvement of optHAZOP, Khan and Abbasi (1997b) subsequently proposed a knowledge based software tool, termed TOPHAZOP, to further reduce the requirement of expert man-hours and to speed up the work of the study team. Subsequently, Khan and Abbasi (2000a) combined their previous developments of TOPHAZOP and optHAZOP and developed EXPERTOP which is a complete expert system. PHASuite is a software system to perform HAZOP analysis that increases the efficiency of analysis and provides an opportunity to reuse the safety knowledge generated from the analysis (Zhao et al., 2005a). This system consists of four main functional elements: information sharing, representation, knowledge base, and reasoning engine. It uses colored Petri Nets to represent chemical processes as well as the methodology for HAZOP analysis. The PHASuite was applied to a typical batch process of a pharmaceutical manufacturing facility to test and validate the tool (Zhao et al., 2005a,b).

HAZOPExpert is one major development in the area of automating HAZOP by using a knowledge-based system. Venkatasubramanian and Vaidhyanathan (1994) developed HAZOPExpert and implemented it in an object-oriented architecture using the expert system shell G2. However, HAZOPExpert was not able to analyze simultaneous propagation of the effects of more than one process variable deviation. It was also not able to handle the cyclic loops during propagation using the HAZOPExpert. To overcome these limitations, the HAZOP Digraph Model (HDG) was developed (Vaidhyanathan and Venkatasubramanian, 1995). Wang et al. (2009) developed signed digraph (SDG)-based HAZOP analysis to identify the most likely operating mistakes that may cause a system to deviate from its normal state. Since SDG based models only have two signs: positive and negative, the study was limited to applying three guidewords: more, less or none. This limitation leads to an incomplete analysis. To avoid this limitation, a layered digraph (LDG) model, termed LDGHAZOP, extended from SDG, was introduced by Cui et al. (2008). Subsequently, the integration framework was proposed to integrate LDGHAZOP to a commercial process design package called Smart Plant P&ID (SPPID) to perform HAZOP analysis through the life cycle (Cui et al., 2010).

The tool called ExpHAZOP$^+$ developed by Rahman et al. (2009) included some new features which were not available before their developments. Those features were the fault propagation algorithm and knowledge updating. ExpHAZOP$^+$ was capable of defining the propagation of deviation of downstream equipment and allowing a user to update the knowledge while performing the HAZOP study. Wang et al. (2012) developed a new HAZOP analysis assistant program, termed HELPHAZOP. The function of HELPHAZOP was to overcome several issues such as the inheritance instrument of experience knowledge, the classification of accident reasons, the recurrence of analysis process and the verification of analysis results raised during the practical application of the HAZOP analysis.

3.1.1.6. *Other qualitative models and methods*. A new process hazard analysis methodology called Major Hazards Analysis (MHA) was proposed by Baybutt (2003) with the sole purpose of identifying major hazards such as fire, explosion and toxic release. This method provided an efficient and complete identification of major hazard scenarios using a categorization scheme and brainstorming of initiating events that can lead to major accidents. A computer aided hazard identification method, called HAZID was developed. HAZID's development and its application were described by a series of five journal papers (McCoy et al., 1999a,b,c, 2000a,b).

3.1.2. *Risk assessment*

The qualitative developments for risk assessment are few; in fact, the authors did not find any significant development in the literature studied except standard risk matrices. However, the authors noticed that risk matrices have been considered as a semi-quantitative method in most published literature and authors agreed on it. But, if only qualitative terms are assigned to represent the probability of occurrence and severity of consequences, the risk matrix can be considered as a qualitative method because it has no quantitative representation. The concept of the risk matrix was first introduced by the Electronic System Center, US Air Force in 1995 (Garvey and Lansdowne, 1998). Since then, it has been widely used in almost all industries for risk representation. A comprehensive introduction of the basic concepts and extension of the standard risk matrix approach were discussed by Ni et al. (2010).

3.1.3. Safety management

In this category, authors mainly focused on accident modeling and inherent safety. Development related to management, organizational and human factors is also studied. The other important topic is development of safety management frameworks. It is observed that there are several safety management frameworks developed by different organizations and researchers according to the needs of their particular application.

3.1.3.1. Accident models. Accident models play a vital role in process safety management as they provide better understanding of the accident scenario and characterize the relation between causes and consequences. Since the early 1930s, a number of accident models and various approaches for accident modeling and analysis have been developed. The sequential aspects of accident occurrence were first used by Heinrich (1941) introducing the "Domino theory". Later, the Domino theory was updated, proposing a new model called "Loss Causation Model" with more emphasis on management and organizational factors (Bird, 1974). The model oriented methodology for accident investigation was proposed by Professor Trevor Kletz in 1988. This methodology used the concept of an accident causation chain in which an accident was placed at the top and the sequence of leading events and causes were developed beneath it (Kletz, 1988). The Management Oversight and Risk Tree (MORT) model was developed by Johnson in 1973 to analyze the system and to identify the relationships among management and organizational factors and plant operations (Johnson, 1980). MORT gives an idealized safety system represented as a logic tree, which contains specific control and general management factors.

The Accident Evaluation and Barrier (AEB) model developed by Svenson (1991) modeled the accident as a series of interactions between human and technical systems. This model asserted that the application of a barrier function between two successive errors can be used to avoid or interrupt the accident sequence, and consequently to prevent the accident. The most significant development in accident modeling during the early 1990s is the Swiss cheese model (Reason, 1990). Reason (1990) proposed the "Swiss cheese" model to demonstrate how human and organizational failures influence the accident process taking multi causality of an accident into consideration. The Swiss cheese model is used in many industries, especially the aviation industry, to prevent accidents due to human errors. In the Swiss cheese model, four successive cheese slices are placed sequentially representing safety barriers relevant to particular hazards, and the holes represent the latent errors. When the holes are lined up all barriers failed; hence an accident will occur. To perform a successful safety occurrence investigation that is an investigation of events that deviate from the desired system state as a result of equipment or human failure, a method called Systematic Occurrence Analysis Methodology (SOAM) was developed using the principles of Reason's Swiss cheese model (Licu et al., 2007).

Rasmussen and Grtinberg (1997) viewed an accident in terms of energy flow. They stated that an uncontrolled flow or transfer of energy generated due to loss of containment leads to an accident. Based on this concept the Uncontrolled Flow of Energy (UFOE) model was developed. Svedung and Rasmussen (2002) discussed a set of graphical representation approaches termed the accident mapping method to depict the relationship of accidents and hazards with socio-technological factors. Further, this work discussed the need of accident mapping in hazard analysis and introduced a set of graphical formats to describe the different contributing factors. Leveson (2004) described the deviation of safety as a problem of control structure embedded in an adaptive socio-technical system. Utilizing system theory and control system theory a new accident model, called Systems-Theoretic Accident Model and Processes (STAMP) was developed. In this model, accident occurrence is defined as a result of external disturbances, component failures, or dysfunctional interaction among system components.

Sklet (2006) discussed the event scenarios that lead to release of hydrocarbon at an offshore oil and gas production platform. Subsequently, safety barriers and their functions in preventing a particular release scenario were outlined. Later, Kujath et al. (2010) developed a conceptual accident prevention model which highlights the vulnerabilities of an oil and gas operation and provides appropriate guidelines to minimize the hazards and to prevent accidents. The safety barriers were identified to prevent, control or mitigate the accident process due to hydrocarbon release. This model was flexible as it identified safety barriers that can be substituted with other appropriate barriers for a specific facility. The safety barriers in the model have been further branched to identify sub-safety barriers. The safety barriers required to maintain the safety of dynamic positioning of a mobile drilling unit have been discussed by Chen et al. (2008). The barriers introduced in this work address three main functions: prevention of loss of position, arresting vessel movement and prevention of loss of well integrity. Instead of accident modeling, an experience based approach to develop accident scenarios, a computer automated tool called yAGAS (Yonsei Automatic Generator of Accident Scenario) which automatically formulates the list of accident scenarios and associated hazardous conditions was developed (Kim et al., 2003).

3.1.3.2. Inherent safety. The concept of "inherent safety" started flourishing before the 1970s (Hassim and Hurme, 2010), but with the accident that occurred at Flixborough in 1974, the concept was formally introduced to the world. In 1977, Professor Trevor Kletz's speech at the annual Jubilee lecture to the Society of Chemical Industry in London, 'What you don't have, can't leak', was the first public discussion of the concept of inherent safety. Professor Kletz argued that process risk minimization or elimination can be achieved through changing the properties of materials, the process operation and operating conditions rather than controlling them with add-on safety measures. Further, Professor Kletz proposed four key inherent safety principles: minimization, substitution, moderation, and simplification (Kletz, 1985).

The application of ISD principles to design and design decision-making based on inherent safety of the system has been identified as a reliable and efficient technique to produce a safer, sustainable and economically viable process plant. However, there is a lack of any established tool that can be used to facilitate the application of ISD principles to a particular process system. Gupta and Edwards (2003) proposed a simple graphical method to choose the best process route based on the ISD principle. The index was derived by the matrix representation of which the horizontal axis represents the process routes and the vertical axis or axes represent the parameters that affect safety. Rusli and Shariff (2010) proposed a qualitative methodology which is known as Qualitative Assessment for Inherently Safer Design (QAISD) to identify inherent hazards and to implement ISD principles to prevent or control the hazard. The QAISD was developed to be utilized mainly during the preliminary design stage. But, Rusli and Shariff (2010) further explained that this method could be used at later stages of the process design life cycle with suitable modifications.

3.1.3.3. Human, organizational, and management factors. Similar to technical and mechanical factors, human, management, and organizational factors play a vital role in process safety and risk assessment. Stanton and Baber (1996) stated that human error was predictable if operators' tasks and characteristics of the technology used were known. By means of this knowledge, it is possible to predict the type of errors that may arise. Modeling of organizational factors in safety performance faces a number of technical challenges. Mohaghegh and Mosleh (2009) emphasized the need for development of a set of theoretical principles which could be used to assess the performance of organizational safety models. As a result of their study, a safety risk framework called socio-technical risk analysis (SoTeRiA) that integrates technical, social and safety practices aspects was developed.

3.1.3.4. Safety management framework. Hale et al. (1997) proposed a safety management framework called Structured Analysis and Design Technique (SADT). This framework used accident modeling techniques to better represent the accident process. The complete analysis of system inputs, resources and constraints required to produce the desired output was generated by SADT. With potentially preventive capabilities, a systematic approach to manage and maintain the risk within an acceptable range in the operation, a Systematic Safety Management System (SSMS) model was developed by Santos-Reyes and Beard (2008). Their subsequent work described the application of the SSMS model to oil and gas operations (Santos-Reyes and Beard, 2009).

Safety case preparation is an essential task of process safety management. Formulation of the safety case mainly includes accident scenario development, cause-consequence analysis, and suggestions of safety measures. Top Event Prevention Analysis (TEPA) was developed to select the component based on the concept of importance measures. The selected components were then used to formulate the safety case (Youngblood, 1998). A logic diagram based system was proposed by Duarte and Pires (2001) to implement the safety management programs taking into account the impact of organizational and business changes. A Hazard/risk Analysis Review Planning (HARP) framework was proposed to choose the optimum risk assessment and management techniques according to the nature and type of the hazardous conditions present in the system (Reniers, 2009). This method took legislative requirements and company guidelines into consideration for deciding optimum risk assessment and management technique. Early warning and risk indicators also play a vital role in risk management. A theoretical background of developing risk indicators and early warning to prevent a major accident were discussed by Øien et al. (2011a). Its application to hydrocarbon related industries to validate the method was discussed by Øien et al. (2011b).

3.2. Semi-quantitative analysis

Semi-quantitative analysis falls in between quantitative and qualitative analysis and it produces approximate results rather than exact/absolute results. This method is useful when the direct measurement of process safety and risk is not possible whereas inference is acceptable. Table 3 is the list of the development of semi-quantitative methods and models.

3.2.1. Hazard identification and analysis

3.2.1.1. HAZOP and its extension. HAZOP and its various modifications are mainly built to perform the qualitative analysis of process hazards. Even though HAZOP analysis was automated (HAZOPExpert), it was still limited to produce quantitative results. Using the quantitative knowledge available in design, operating specifications and material properties, a semi-quantitative reasoning methodology was developed to filter and to rank the consequences generated by the HAZOPExpert system (Vaidhyanathan and Venkatasubramanian, 1996).

3.2.1.2. LOPA and its extensions. The Layer of Protection Analysis (LOPA) is a well-established and widely used semi-quantitative hazard analysis methodology. LOPA is generally conducted along with other qualitative hazard analysis methods or conducted as post hazard analysis. The fundamentals and guidelines of performing LOPA were discussed elsewhere (CCPS, 1993; Summers, 2003). LOPA is typically applied to high risk scenarios that have been identified through suitable hazard identification methods, mainly from the HAZOP study.

As discussed in earlier sections, the generation of an accident scenario at the hazard identification stage is time consuming and requires extensive experience and expert knowledge. The concept called ExSys-LOPA was introduced to simplify this difficulty by combining an expert system for accident scenario identification with the subsequent application of LOPA (Markowski and Mannan, 2010). The automated generation of high risk scenarios using HAZOP analysis was well discussed by Dowell and Williams (2005). Each identified scenario was analyzed according to the accident sequence process: initiation, propagation, and termination. Subsequently, required Independent Protection Layers (IPLs) were chosen to prevent or minimize the hazards and their consequences to a reasonable acceptable level.

During the LOPA, human factors are often overlooked. Therefore, focusing on effects of human factors in a specific hazard scenario, the framework called LOPA-HF was proposed by Baybutt (2002). Procedure controls were suggested that can apply during the LOPA analysis to prevent human failures (Freeman, 2008). This methodology was semi-quantitative and estimated the frequency of human error.

Markowski (2007) discussed the application of LOPA for analysis of the explosive atmosphere and this method was called exLOPA. The procedure of exLOPA began with classification of hazardous areas to identify locations where a flammable atmosphere can exist. The result of exLOPA analysis was then used to determine the likelihood of an explosive atmosphere. Determination of an ignition source was based on expert opinion. Subsequently, required independent protection layers were allocated to prevent or mitigate explosion

Table 3 – Research articles published related to semi-quantitative analysis.

Author(s)	Journal	Method/model
Hazard identification and analysis		
Vaidhyanathan and Venkatasubramanian (1996)	RESS	A semi-quantitative reasoning methodology
Khan and Abbasi (1998b)	PSP	The Hazard Identification and Ranking (HIRA) methodology
Baybutt (2002)	PSP	LOPA-HF—an application of LOPA for human failure analysis
Dowell and Williams (2005)	PSP	An automated quantification of high risk scenarios
Gordon et al. (2005)	SS	The Human Factor Investigation Tool (HFIT)
Markowski (2007)	JHM	exLOPA—an application of LOPA to analyze explosion hazards
Wei et al. (2008)	JHM	Use of LOPA to analyze reactive chemical hazards
Kim et al. (2009)	JLPPI	The modified TRIZ method
Markowski and Mannan (2010)	JLPPI	ExSys-LOPA—a use of expert system in accident scenario identification
Risk assessment		
Brockhoff et al. (1992)	JHM	A model to assess consequence of Chlorine and Ammonia release
Alexeeff et al. (1994)	RA	The Reference Exposure Level (RFL)
Khan and Abbasi (1997c)	PSEP	The Accident Hazard Index (AHI)
Kao et al. (2002)	PSP	The Runway Risk Index (RRI)
Hauptmanns (2004)	JLPPI	SQUAFTA—the semi-quantitative fault tree analysis
Al-Sharrah et al. (2007)	PSEP	A safety risk index
Aven (2008)	RESS	A semi-quantitative risk assessment tool
Rushton and Carter (2008)	PSEP	The Total Risk of Death (TROD) method
Deacon et al. (2010)	SS	A human error risk analysis method
Davis et al. (2011)	JLPPI	The Shortcut Risk Analysis Method (SCRAM)
Yu et al. (2012)	RA	A context-specific, scenario-based risk scale
Safety management		
Rouhiainen (1992)	SS	QUASA—a method to assess the quality of safety assessment
Goossens and Cooke (1997)	SS	A formal expert judgment and system failure analysis techniques
Lee and Harrison (2000)	SS	A personnel safety surveys
Cox and Cheyne (2000)	SS	The safety climate assessment toolkit
Safety management		
Long and Fischhoff (2000)	RA	A model to capture issues associated with risk ranking
Quintana et al. (2001)	SA	Continues Hazard Tracking and Failure Prediction Methodology (CHTFPM)
Shah et al. (2003)	PSEP	Substances, Reliability, Equipment, Safety and Technology (SREST) layer assessment method
Maroño et al. (2006)	RESS	PROCESO—method to evaluate operational safety in process industry
Khan et al. (2010)	PSP	Safety Performance Indicator (SPI) system

hazards. Further, application of LOPA to the reactive chemical hazard analysis was discussed by Wei et al. (2008).

3.2.1.3. *Index based approaches*. Khan and Abbasi (1998b) proposed the index based approach for hazard identification and ranking. This index called Hazard Identification and Ranking (HIRA) consists of two sub-indices: the Fire and Explosion Damage Index (FEDI) and Toxic Damage Index (TDI). The FEDI was estimated using several energy factors. The chemical, physical, and thermodynamic properties of materials were used to estimate the energy factors and penalties which were assigned to account for the impact of various parameters on the total damage. TDI was estimated using transport phenomena and empirical models based on an inventory of chemical, physical and chemical properties of the materials, toxicity of materials, and site characteristics. The magnitudes of these indices represent the severity of a major accident in terms of the size of the impacted area.

3.2.2. *Risk assessment*

3.2.2.1. *Risk assessment approaches*. Instead of a detailed quantitative risk assessment (QRA), a simple risk index was proposed starting with a fundamental definition of the risk, which was the product of the probability of occurrence and the severity of the consequences, for an extended definition (Al-Sharrah et al., 2007). Unlike standard risk assessment, the proposed risk index was comprised of four elements: frequency/probability of accident, hazardous effects of the accident, inventory of the chemical released, and the size of the plant. The unit of the index is expressed as the number of people affected per year. Aven (2008) also discussed the advantages of using semi-quantitative risk assessment instead of quantitative risk assessment. He proposed a semi-quantitative risk assessment method by means of hazard and barrier analysis, risk influencing factors (RIFs), and safety improvement measures. Since this method relies on historical records of hazardous situations, historical records on barrier performance and investigation reports, the estimated results might include a certain level of uncertainty.

3.2.2.2. *Consequence analysis*. Rather than developing complex mathematical equations to assess consequences of chlorine and ammonia release, a simple and transparent model was developed based on the fatality index (Brockhoff et al., 1992). The fatality index was estimated using historical accident data and consequences were determined for three different population density classes: rural, semi-urban and urban. Exposure risk assessment is performed using methods such as dangerous dose (DD), LD_{10} and significant likelihood of death (SLOD). Based on a weighted multiple threshold approach, a method called total risk of death (TROD) was proposed by Rushton and Carter (2008). The TROD was capable of analyzing the diverse hazardous conditions considering more than one threshold consequence. Risk was then predicted for each threshold consequence. Subsequently, each individual risk value was combined to make one single value by weighting the contribution to risk according to the predicted consequences for each threshold.

The investigation of the tank car derailment accident in northern California in 1991 led to the development of reference exposure levels (RELs) for the release of methyl isothiocyanate (MITC) (Alexeeff et al., 1994). Different REL were determined, such as REL to prevent disability (40 ppb) and REL to prevent life threatening injury (150 ppb) in order to develop emergency planning.

Indices were developed for impact assessment and ranking. Khan and Abbasi (1997c) claimed that indices reported for ranking the severity of an accident did not take into account the surrounding factors such as population density, assets and the sensitive ecosystem, or were not able to forecast impacts of likely accidents on the surroundings. To avoid those drawbacks, they proposed the Accident Hazards Index (AHI) incorporating both direct and indirect impacts of an accident on the surrounding factors which lay within the vulnerable regime. This method was capable of not only ranking the severity of an accident but also of forecasting the impacts of most credible accident scenarios.

Runaway reactions create a highly hazardous situation and their consequences are significant. Therefore, it is required to assess the risk of an exothermic runaway reaction timely and adequately. A simple semi-quantitative index called Runaway Risk Index (RRI) was proposed using simplified mathematical equations and a tabular approach (Kao et al., 2002). The RRI incorporated both severity and likelihood elements. Parameters, such as reactivity, stability, and enthalpy were used to measure the severity through a proper weighting method. Similarly, parameters such as risk and safety factors associated with operating conditions were used to estimate the likelihood of an event. Subsequently, estimated risk was categorized into six levels: extremely high, high, moderate, mild, low and very low, using RRI values for risk-based decision making.

Similar to vapor cloud explosion (VCE) and boiling liquid expanding vapor explosion (BLEVE), the dust explosion can be considered as a most serious explosion hazard in the process industry. Therefore, it is required to perform a systematic risk assessment to better understand the severity and likelihood of occurrence of a dust explosion. A Short-Cut Risk Analysis Method (SCRAM) was proposed by Davis et al. (2011) to identify the hazardous operation, areas and risk of a dust explosion. In this method, the likelihood of dust explosion was estimated based on the ignition probability and the probability of a dust cloud reaching its flammable limit. During consequences analysis, the effect of secondary explosion was also taken into consideration. A simple risk matrix was then used to rank the risk. A comprehensive review of causes, consequences and prevention of dust explosion was produced by Abbasi and Abbasi (2007).

3.2.3. *Safety management*

3.2.3.1. Inherent safety. Tugnoli et al. (2012) developed Inherent Safety Key Performance Indicators (IS-KPIs) providing a procedure to identify the inherent hazards and a method for quantifying the safety performance by means of consequences.

Shah et al. (2003) divided a process system into four different hierarchical levels: (1) substance layer that lists the properties of substances involved, (2) reactivity layer that lists the possible interactions between the substances, (3) equipment layer that lists the possible scenarios resulting from the combination of substances and operating conditions of all equipment, and (4) safety technology layer that describes the safety measures required to run a process safely. Then, the process system was further analyzed to determine the causes that lead the process system to become idle with respect to each layer mentioned above. Further, each layer was analyzed separately on a hierarchical basis, and ISD measures applied to the system based on the index value estimated for each layer. The complete framework to perform this analysis, called the Substance, Reactivity, Equipment and Safety Technology (SREST) layer assessment was thoroughly described and validated using a polymerization case study (Shah et al., 2003, 2005).

3.2.3.2. Safety management systems. Safety management should fulfill certain requirements. The concept of quality can be used to express the applicability and effectiveness of certain safety assessments to a particular process safety and risk management. A method to assess the quality of safety analysis, a semi-quantitative tool, called QUASA (quality of safety analysis) was developed by Rouhiainen (1992). In the QUASA method, a check-list based approach was used to identify the deficiencies of a particular safety assessment. Two simple equations were developed to estimate the validity and reliability of a particular safety analysis method; subsequently those values were used for decision making. The method developed by Acikalin (2009) can be used to quantify the effectiveness of the safety management systems. These quantitative results can be used to depict how well the implementation of a safety management system performs in a particular organization. Further it can be used as an indicator for an operator to decide on the requirement of specific elements of the safety management system. This method further helped to integrate quantitative risk assessment into the safety management system.

In addition to safety and risk assessment methodologies such as FMEA, fault tree, event tree, Goossens and Cooke (1997) described two techniques: a formal expert judgment and a system failure analysis (or accident sequences precursor methodology) to perform subjective expert assessment on design and model parameters and to derive the system failure probability, respectively. Long and Fischhoff (2000) highlighted several issues associated with timing of conventional risk ranking, the uncertainties of the hazardous situation, the method of solving, and how resources need to be allocated. Long and Fischhoff (2000) further proposed a model to capture these elements of risk-ranking situations. Using the Subjective Probability Distributions (SPDs), the initial belief about the magnitude of the risk was assigned. This probability was later updated using the information of the system after allocating resources. This method simplifies the nature of the risk ranking tasks even with semi-quantitative analysis. The model called Continuous Hazards Tracking and Failure Prediction Methodology (CHTFPM) was developed by combining principles of work sampling, control charts, and multivariate analysis to predict the safety of a particular system (Quintana et al., 2001). Sampling was used to observe the condition of accident occurrence and the data observed was then used to develop the control charts which characterize the system's safety and protection required. Operational safety management requires a proper method to measure the level of the operational safety. In addition to risk assessment and process safety methods, a safety index, termed procedure for the evaluation of operational safety (PROCESO) was introduced to perform a comprehensive assessment of operational safety (Maroño et al., 2006). Principles of system theory were used to develop the PROCESO method.

Lagging and leading indicators are often used in process industries to measure the required process safety performance. In brief, leading indicators are used to measure the input to the process system, whereas lagging indicators are simply the outcome of the systems. A risk-based process safety performance indicator called SPI (safety performance indicator) was proposed by Khan et al. (2010); leading and lagging indicators were analyzed considering three design elements: operational, design, and mechanical integrity. Each leading and lagging indicator was then assigned with risk factors; subsequently, risk was estimated for each element separately. In their method, a traffic color system was used to characterize the performance of the safety based on the previously described risk calculation.

3.3. *Quantitative analysis*

Based on literature studied in this work, it is noted that the majority of the research articles focused on quantitative development. The main benefit of quantitative analysis is that it provides a realistic numerical estimate for better understanding and informed decision making. The quantitative methods and models are listed in Table 4.

3.3.1. *Hazard identification and analysis*

An index called safety weighted hazard index (SWeHI) was developed to assess the damage due to major hazards: fire, explosion and toxic release, and to rank the process units based on the degree of the hazard (Khan et al., 2001a). SWeHI represents the radius of the area under moderately hazardous conditions. It is mathematically calculated using two factors. The first factor estimates the damage that may be caused by the unit in terms of an area with less than 50% probability of damage. The second factor estimates the credit due to control measures and safety arrangements in terms of the graphical method. Through the results of SWeHI, users were able to gain a snap-shot of the hazard level of a particular process unit as well as safety measures that need to be placed to mitigate the hazard or prevent it from occurring.

3.3.2. *Risk assessment*

The concept of "Risk" in safety related decision making can be traced back to ancient times but by the invention of probability theory by Pascal in 1657, the concept of risk started to use quantitative values, presently known as "Quantitative Risk Assessment (QRA)". A comprehensive review of the history of the concept of risk and risk assessment and management prior to the 20th century has been conducted by Covello and Mumpower (1985). Probabilistic risk assessment, also known as quantitative risk assessment, is the quantitative analysis of the risk. The basis of probabilistic risk assessment originated in the aerospace industry in 1960 and later, and was extensively used by the nuclear industry for reactor safety study (Bedford and Cooke, 2001). The United States Nuclear Regulatory Commission conducted an extensive study of the risk from commercial nuclear power plants (NUREG-1150). Probabilistic risk assessment performed as a part of NUREG-1150 consists of four major elements: system analysis, accident progression analysis, source-term analysis, and consequences analysis. Iman et al. (1990) described the background of NUREG-1150 development and a procedure to define the interface between the source-term and the consequences analysis. Further, the uncertainty analysis associated with NUREG-1150 PRA was performed using Monte Carlo simulation based on Latin hypercube sampling (Imanl and Helton, 1991). The quantitative risk assessment model called FEPQPM (Fire Explosion-Poisoning Quantitative Probability Model) was proposed to quantify the risk of hazardous chemical leakage (Si et al., 2012). This method included probability analysis to analyze the evolving accident with hazardous chemical releases.

The consequences analysis comprises several tasks. At the beginning it is required to select the release incident. The next step is to develop the source model which represents the material release process. During this analysis, mathematical and/or empirical models are developed to evaluate the phase behavior of materials, release rate and release duration. If the release material is flammable, fire and explosion models are used to study the behavior of the fire and explosion and their consequences. If the release material is toxic material, toxic release and dispersion models are developed to estimate the effects of the release on the plant and environment. Using the model output preventive measures are suggested.

3.3.2.1. *Risk assessment framework.* A systematic framework for quantitative risk assessment called optimal risk analysis (ORA) was proposed by Khan and Abbasi (1998a). The ORA methodology involves four main steps: (1) hazard identification, (2) hazard assessment, (3) consequence analysis, and (4) risk estimation. Each step used unique techniques and tools which were previously developed by Khan and Abbasi for conducting the optimal risk analysis. The HIRA technique was used for hazard identification which produced the damage radius and the areas with high probability of lethal impacts. Qualitative hazard assessment was carried out using the opt-HAZOP and TOPHAZOP techniques (Khan and Abbasi, 1997a, 1997b). The consequences analysis was performed using three techniques: MOSEC (modeling and simulation of fire and explosion in chemical process industries) (Khan and Abbasi, 1997c) to assess the impact of the fire and explosion, HAZDIG (hazardous dispersion of gases) (Khan and Abbasi, 1999b) to assess the impact of toxic release and dispersion and DOMIFFECT (Khan and Abbasi, 1998c) to assess the impact of the domino accident. The computer aided tool called PROFAT (probabilistic fault tree analysis) (Khan and Abbasi, 1999c) was used to perform the probabilistic hazards assessment. Using the information derived from above mentioned techniques, the risk was estimated. The application of ORA to the sulfolane manufacturing industry was also discussed by Khan and Abbasi (2001). Khan and Abbasi (1999d) developed a novel computer-automated tool TORAP (tool for rapid risk assessment in the petroleum refinery and petrochemical industries) to perform quantitative risk assessment for the petroleum refinery. The application of TORAP to perform a risk assessment of a fertilizer plant was later discussed by Khan et al. (2001b). Khan et al. (2001b) further discussed the likelihood of secondary and higher order accidents, often called domino effects.

The non-parametric predictive inference (NPI) is used to perform the probabilistic risk assessment with scarce data or in a situation where data revealed no failures (Coolen, 2006). In this method, a failure rate is defined as a range using lower and upper probabilities, rather than point estimates. In the case of zero failure observed, the lower estimate of the failure rate is considered as zero. This lower and upper probability

Table 4 – Research articles published related to quantitative analysis.

Author(s)	Journal	Method/model
Hazard identification and analysis		
Khan and Abbasi (1997d)	JLPPI	The HAZOP study time estimation model
Liaw et al. (2000)	JLPPI	A thermal hazard model
Khan et al. (2001a)	PSEP	SWeHI—the safety weighted hazard index
Risk assessment		
Singh et al. (1991)	RE	The IIT heavy gas model I and II
Kukkonen and Nikmo (1992)	JHM	A dense gas dispersion model in sloping terrain
Price et al. (1992)	RA	The Point Source Exposure Model (PSEM)
Marseguerra et al. (1995)	RESS	Dynamic probabilistic safety assessment using Neural Network
Bagster and Schubach (1996)	JLPPI	A model to estimate the material-specific length of the jet fire
Theofanous (1996)	RESS	The Risk Oriented Accident Analysis Methodology (ROAAM)
Rew et al. (1997)	PSEP	POOLFIRE6—a semi empirical model to estimate the thermal radiation from a hydrocarbon pool fire
Vandroux-Koenig and Berthoud (1997)	JLPPI	A model to study the jet release
Baum (1998, 2001, 1999)	JLPPI	A model to estimate the missile damage
Pattison et al. (1998b)	PSEP	A model to predict the dispersion of two-phase release
Rai and Krewski (1998)	RA	An uncertainty analysis of the multiplicative risk models
Scobel et al. (1998)	RESS	An integrated ROAAM
Khan and Abbasi (1998c)	PSP	DOMIFFECT—a domino effects analysis model
Khan and Abbasi (1998a, 2001)	JLPPI	The Optimal Risk Analysis (ORA)
Roser et al. (1999)	JLPPI	A flame front propagation model for a two connected vessels
Khan and Abbasi (1999d)	JLPPI	The Tool for Rapid Risk Assessment (TORAP)
Khan and Abbasi (1999e)	JLPPI	The modified plume path theory to model the heavy gas dispersion
Hankin and Brittter (1999a, 1999b, 1999c)	JHM	TWODEE—a shallow layer model for heavy gas dispersion
Kourniotis et al. (2000)	JHM	The statistical analysis of domino accident
Verlicchi et al. (2000)	PSP	The slip model for model the two-phase multicomponent release
Andrijievskij et al. (2001)	JLPPI	LOCADIS—the local aerosol dispersion model
Yuhua et al. (2002)	JLPPI	The models of gas release through holes of pipelines
Risk assessment		
Venetsanos et al. (2003)	JHM	DISPLAY-2—a two dimensional shallow layer model
Jo and Ahn (2003)	JHM	A simple model to estimate the gas release rate from pipeline
Pula et al. (2006)	PSRP	Grid-based approach for consequences analysis
Khan et al. (2006)	SS	The Human Error Probability Index (HEPI)
Fay (2006)	JHM	A two zone entrainment model for pool fire
Vinnem et al. (2006)	RESS	The major hazard risk indicators
Coolen (2006)	JRR	The Non-parametric Predictive Inference (NPI)
Lewthwaite et al. (2006)	JRR	The risk model for fire and explosion
Marseguerra et al. (2007)	RA	A fuzzy cognitive reliability and error analysis method
Coolen (2007)	RA	The non-parametric prediction of unobserved failure modes
Ferradás et al. (2008)	PSEP	The explosion consequence analysis based on characteristic curves
Alonso et al. (2008a), Alonso et al. (2008b)	JHM	The VCE consequence analysis using characteristic curves
Shafaghi (2008)	JHM	Application of Bayes' theorem for failure rate updating
Kalantarnia et al. (2009)	JLPPI	The dynamic risk assessment method
Gubinelli and Cozzani (2009a, 2009b)	JHM	An evaluation of fragment number, pattern, and drag factor of fire
Jo and Crowl (2009)	PSP	A flame growth model
Dong et al. (2010)	JLPPI	An evaluation of natural gas jet release
Markowski et al. (2010)	JLPPI	The fuzzy risk assessment
Yang et al. (2010)	JLPPI	An uncertainty reduction using Bayes' theorem
Zhou (2010)	SS	The SPA-fuzzy method based real time risk assessment
Shariff and Zaini (2010)	JHM	TORCAT—the toxic release consequences analysis tool
Abdolhamidzadeh et al. (2010)	JHM	FREEDOM—the frequency estimation of domino accident
Scarrott and MacDonald (2010)	JRR	The Extreme-value-model-based risk assessment
Lavasani et al. (2011)	JLPPI	The fuzzy risk assessment of oil and gas offshore wells
Padova et al. (2011)	JHM	The risk-based determination of fireproofing zone
Gerrard and Tsanakas (2011)	RA	A study of failure probability under parameter uncertainty
Risk assessment		
Quigley and Revie (2011)	RA	The minimax inference based procedure to estimate failure probability
Curcurù et al. (2012)	JLPPI	The method to analyze the epistemic uncertainty in FTA
Liang and Zhang (2012)	JLPPI	A wave change analysis (WCA) method for pipeline leak detection
Si et al. (2012)	SS	FEPQPM—the fire explosion-poisoning quantitative probability model
Safety management		
Murphy and Paté-Cornell (1996)	RA	The System Action Management (SAM) framework
Gentile et al. (2003)	PSEP	A fuzzy logic based inherent safety index
Khan and Amyotte (2004, 2005)	PSP, JLPPI	I2SI—an integrated inherent safety index
Shariff et al. (2006)	JLPPI	iRET—an integrated tool to assess the inherent safety
Suardin et al. (2007)	JLPPI	An integration of Dow's F&EI into process design and optimization
Srinivasan and Nhan (2008)	PSEP	An Inherent Benign-ness Indicator (IBI)
Leong and Shariff (2008)	PSEP	An Inherent Safety Index Module (ISIM)
Leong and Shariff (2009)	JLPPI	The Process Route Index (PRI)
Shariff and Leong (2009)	PSEP	The Inherent Risk Assessment (IRA)
Jalali and Noroozi (2009)	SS	A mathematical model to determine optimal escape route

estimation approach allows cautious and conservative inferences providing a range of risk values. Subsequently, Coolen (2007) used the same approach with relevant modification for multinomial data to predict the occurrence of new failure modes. As a modification of Coolen's (2007) work, Quigley and Revie (2011) proposed a method based on the minimax inference procedure to estimate the failure probability even when no events take place.

In addition to PRA, the approach called ROAAM (Risk Oriented Accident Analysis Methodology) was developed in the nuclear industry to assess high risk accidents incorporating the uncertainty associated with them (Theofanous, 1996). The ROAAM is a quantitative approach which uses the concept of "defence of depth". Later, the integrated ROAAM approach was developed by including key features such as explicit a priori integration of probabilistic and deterministic elements, consistency among these components, and utilization of this duality as a central element of defence in depth (Scobel et al., 1998). The integrated ROAAM was applied for accident management in the AP600 advanced light water reactor.

3.3.2.2. Dynamic risk assessment. One of the main disadvantages of traditional quantitative risk assessment (QRA) is its static behavior or inability to update the risk with time for emerging conditions that exclude the use of QRA in a dynamic system. Utilization of artificial neural networks to apply QRA to a dynamic system was first discussed by Marseguerra et al. (1995). The dynamic risk assessment methodology was developed using accident precursor data and the Bayesian updating mechanism by Kalantarnia et al. (2009). In their method, an event tree was used to identify the potential accident scenario and then estimate the end-state probability based on the available failure data. Subsequently, using the accident precursor data available with changing conditions, the safety barrier failure probability was revised. This produced updated end-event probabilities. Based on the revised probability, the risk profile was generated. Yang et al. (2010) performed a similar analysis to reduce the uncertainty of fault tree calculation using Bayes' theorem. They used the plant testing data that was total testing time and a component failure number to formulate the likelihood function for each component leading to a top event of the fault tree.

3.3.2.3. Failure probability estimation. Estimation of the probability of accident occurrence is equally as important as consequence analysis in order to estimate the risk of the system, thus to make a risk-based decision. Several statistical, probabilistic and mathematical methods are utilized to estimate the failure probability of components and accident occurrence. Reliability models are often used to estimate the failure probability of components as a function of time. When failure probability is not a function of time, which is known as a static model, stress (load)–strength models are commonly used. In stress–strength models, failure of a component is considered due to instantaneous stress placed on a system, but not due to the result of any prior effects. Yang (1996) proposed a load–strength inference model for a single load application based on Fisher's fiducial analysis and for a multiple load application based on the numerical integration method. In both failure probability evaluation methods, it is assumed that both load and strength follow normal distribution if none of the distribution parameters is known. A point estimate of the failure rate during probability calculation leads to uncertainty; thus, the accuracy of results is reduced. Updating based on Bayes theorem was successfully used to minimize the uncertainty and to improve accuracy. The application of Bayes' theorem to update the equipment failure rate was discussed by Shafaghi (2008). The prior failure probability obtained from the generic equipment failure data represents the initial belief before the new information. Then, Bayes' theorem updates the prior failure rate using the likelihood probabilities which is derived from information from the plant data.

3.3.2.4. Uncertainty treatment. One of the main concerns regarding probabilistic risk assessment is the uncertainty caused by numerical estimations. The uncertainty and variability analysis of the multiplicative risk model, which is defined as a product of two or more independent risk factors, was performed by Rai and Krewski (1998). In this approach, uncertainty analysis was performed in two ways. First, overall uncertainty was assessed using the analytical equation, then the contribution of individual risk factors was assessed using Monte Carlo methods. Combining a traditional process analysis method with fuzzy logic systems (FLS), a fuzzy risk assessment was proposed (Markowski et al., 2010). In addition to frequency and consequences analysis of a particular accident scenario, an element called the risk correction factor was introduced to take into account uncertainty of the accident scenario. Lavasani et al. (2011) also proposed a fuzzy logic based risk assessment methodology to perform quantitative risk assessment for offshore oil and gas wells. Uncertainty reduction of QRA using fuzzy set and evidence theory was discussed by authors such as Ferdous et al. (2011) and Curcurù et al. (2012).

3.3.2.5. Release and dispersion modeling. Based on the Eulerian approach, a mathematical model was developed to study the jet release of liquefied gases taking into account factors such as evaporation rate, humidity of air and turbulence of air, by Vandroux-Koenig and Berthoud (1997). To evaluate the hazard associated with the jet release of natural gas from a high pressure pipeline, a computational method was suggested by Dong et al. (2010). This method can be used to study both steady and unsteady release scenarios. The method to study the release of a two-phase multicomponent critical flow from broken pipes was discussed by Verlicchi et al. (2000). The proposed model, named a slip model, provided acceptable results for flow behavior, pressure and temperature profiles. Two mathematical source models: the hole model and pipe model, were developed to analyze the accidental gas release in a long transmission pipeline (Yuhua et al., 2002). The hole model was developed to analyze the gas release through a small hole, whereas the pipe model was more suitable for release through a hole corresponding to the complete breaking of the pipe. Jo and Ahn (2003) presented a simplified model to estimate the release rate from a hole on the high pressure gas pipeline.

The dispersion of a gas cloud from collapsed cylindrical shape containment was analyzed by Matthias (1990) who proposed a semi-empirical model to analyze the concentration profile. Later, Matthias proposed another model to predict the height, radius, concentration, and downwind location of a drifting dense gas cloud (Matthias, 1992). Singh et al. (1991) developed IIT heavy gas models I and II to determine the concentration isopleths due to the dispersion of gas heavier than air (or dense gas). IIT heavy gas model I considered release as instantaneous and cloud geometry was considered to be cylindrical. IIT heavy gas model II was developed for a continuous release and rectangular cloud geometry was considered. The model output produces a result in terms of isotons which can be easily interpreted by a non-technical operator.

Considering instantaneous release and a cylindrical gas cloud, a mathematical model was developed to analyze the dispersion of dense gas in a sloping terrain when wind direction is directly uphill and downhill (Kukkonen and Nikmo, 1992). Heavy gas cloud dispersion on a slope but in a calm ambient condition was modeled by using shallow water equations with appropriate boundary conditions (Webber et al., 1993). Utilization of a modified plume path theory to model the dispersion of the heavy gas model was discussed by Khan and Abbasi (1999e).

Development, application and validation of the UK Health and Safety Laboratory's shallow layer model for heavy gas dispersion, known as TWODEE, were described in a series of three journal papers (Hankin and Brittter, 1999a, 1999b, 1999c). The first paper described the mathematical basis of the TWODEE. Part two of three described the numerical methods used to solve the TWODEE mathematical model and the final paper described the testing and validation of the model with the experimental results taken on Thorney Island. Venetsanos et al. (2003) also developed a two-dimensional shallow layer model, termed DISPLAY-2, which describes complex features such as two-phase release, obstacles and inclined ground. The DISPLAY-2 model was capable of predicting the time and space evolution of a cloud formed by a two-phase release. A methodology to predict the dispersion of the two-phase release was proposed and validated (Pattison et al., 1998a,b). More literature which describes different aspects of two-phase release and dispersion modeling includes Bricard and Friedel (1998) and Fthenakis et al. (2003).

The environmental consequences assessment due to dispersion of aerosol substances was presented using an integrated simulation model, called LOCADIS (local aerosol dispersion) (Andrijievskij et al., 2001). The model was used to simulate the release of contaminants, interaction of aerosols with other particles in the atmosphere, the atmospheric dispersion of released aerosols, and the deposition of contaminants on the ground and surrounding infrastructure. A computer aided tool called the toxic release consequences analysis tool (TORCAT) was developed for consequences analysis and design improvement using ISD principles (Shariff and Zaini, 2010). Exposure models are used to determine the extent and the degree of employee exposure to toxins and physical hazards and to determine effects of toxins on humans. A Monte Carlo exposure model, also known as the point source exposure model (PSEM), was developed to estimate the long-term residential exposure from a point source emission (Price et al., 1992). The model provided the numerical estimation of the dose, age, and gender of highly vulnerable individuals. It further provided better representation of the distribution of toxic materials in the environment to age-specific dose histories of exposed individuals.

3.3.2.6. *Fire modeling and protection*. Fires are categorized into four main types: pool fire, jet fire, flash fire, and fire ball. Damages due to fires are considered a direct consequence of the heat flux generated from a particular type of fire. Dimension of the fire is considered a major element when estimating the heat flux and subsequent consequences. Bagster and Schubach (1996) proposed a method to estimate the material-specific length of the jet fire scaling the data obtained from experiments. The semi-empirical model called POOLFIRE6 was developed to model the thermal radiation due to a hydrocarbon pool fire (Rew et al., 1997). Fay (2006) proposed a two-zone entrainment model to depict the fluid flow and flame properties of the pool fire.

In order to apply the proper fire protection measures, it is required to decide the fireproofing zones. Padova et al. (2011) proposed a risk-based approach to identify the zones where fireproofing barriers measured should be applied considering the impact of the pool fire and jet fire.

3.3.2.7. *Explosion modeling and protection*. Vapor cloud explosion and boiling liquid expanding vapor explosion are two common explosion scenarios occurring in chemical process industries. Overpressure is considered as one of the critical parameters for explosion modeling and prevention. A mathematical model was developed to predict the overpressure from BLEVE based on the assumption of an adiabatic and reversible expansion process (Planas-Cuchi et al., 2004). Pula et al. (2006) evaluated the existing consequences model to choose the most suitable for offshore conditions. Once the model was chosen, it was enhanced by incorporating a grid-based approach and by integrating an enhanced ignition model that enable better consequences modeling.

As a result of an explosion in a confined vessel or structure, the vessel or structure gets ruptured resulting in the projection of debris, also known as missiles, over a wide area. With the absence of a proper blast wall, these missiles could cause significant damage to property and also cause injuries or fatalities. Further, it could trigger a secondary explosion resulting in further damage to the system. Therefore, a comprehensive analysis of damage due to missile effects is required. Baum (1998) proposed a mathematical model to predict the velocity of the "rocket" missile generated by failure of the cylindrical pressure vessel. The model was applicable considering the explosion occurred at the lower end of the vertical cylindrical pressure vessel and it was assumed that the vessel contained gas and cold liquid. However, with modification in a way that can take into account the liquid flashing to vapor during depressurization, this model can be applied to vessels containing hot liquid and cover gas. A subsequent development of Baum (1998) described a model that can used to estimate the peak velocity of end-caps and "rocket" missiles (domino accidents) generated by the failure of the horizontal pressure vessel containing a high temperature liquid (Baum, 1999). Baum (2001) further developed a model to predict the velocity of large missiles from axial rupture of gas pressurized cylindrical vessels. In addition to these developments, authors such as Hauptmanns (2001) and Pula et al. (2007) discussed the consequences assessment due to missile effects and domino effects of an explosion.

The determination of the expected number of fragments created by the explosion of a typical cylindrical vessel and the drag factor was conducted using simple mathematical functions (Gubinelli and Cozzani, 2009a) and fragmentation patterns were defined based on the geometrical characteristics of the process vessel that were more vulnerable to fragmentation accidents (Gubinelli and Cozzani, 2009b). The utilization of characteristic curves for explosion consequence analysis was developed and reported in Alonso et al. (2008a), Alonso et al. (2008b), and Ferradás et al. (2008). The impact of the projectiles generated from the explosion and characteristics of different types of projectiles were detailed in Mébarki et al. (2009a,b), Sun et al. (2012), Zhang and Chen (2009).

It is important to estimate the time for flame front propagation along the connecting pipe when designing the protection measures for explosion in a pipe connected to a pressure vessel. The experimental setup was built to simulate the accident scenario, to collect the data, to develop the mode, and to estimate the time of flame front propagation (Roser et al., 1999). In their experimental set up, two primary process vessels (1 m^3 and 4.25 m^3) were connected via a pipe to a secondary vessel with a capacity of 9.4 m^3. The feeding process was carried out mechanically or pneumatically. It is also important to estimate the pressure–time history during explosion to understand the impact of the explosion, and to suggest protection measures. Flame growth models are used to accurately predict pressure–time histories. Jo and Crowl (2009) highlighted the limitation of application of existing flame growth models to study explosions with large pressure increases. A novel flame growth model was then developed to predict the propagation of the flame front and to estimate the pressure histories over a wide period of time and with large pressure increases.

3.3.2.8. *Domino effects and damage analysis.* Khan and Abbasi (1998d) discussed several models to analyze the domino effects. Four separate frameworks were introduced, which depended on the initiating events of the domino events. Khan and Abbasi (1998d) listed four main initiating events: fire, explosion, toxic release and a combination of both fire and explosion. The results of these models produced the likelihood of occurrences of domino events and sequences of domino effects by using a deterministic model combined with probabilistic analysis. A statistical approach to analyze the domino effect was discussed by Kourniotis et al. (2000). In this approach, past accidents were statistically analyzed to understand the pattern of domino accident occurrence, consequences, and substances involved with it. This methodology further used Bayesian inference to update the results based on new information about the accident. More specifically, the domino impact due to explosion overpressure was studied by Cozzani and Salzano (2004). The probit models were developed that can be used later for probabilistic risk assessment using the information obtained through the analysis of available data of the process equipment. It is worth mentioning that Professor Valerio Cozzani and his co-workers have published a number of journal articles related to domino accident analysis. A simulation based method was proposed by Abdolhamidzadeh et al. (2010). The methodology was called FREEDOM (frequency estimation of domino accidents) and was capable of evaluating highly complex and non-linear systems, but was unable to handle more than a few uncertain parameters.

3.3.3. *Safety management*

3.3.3.1. *Inherent safety.* Though the majority of the indices developed to assess a systems' inherent safety level are semi-quantitative, authors highlighted a few notable quantitative approaches. I2SI (Khan and Amyotte, 2004, 2005) is a structured guideword approach developed to measure the inherent safety level of a process unit. This approach is composed of two main sub-indices: the Hazard Index (HI) and Inherent Safety Potential Index (ISPI) which specify hazard potential, inherent safety potential, and add-on controls. I2SI is also capable of performing the inherent safety evaluation along with an economic evaluation, but I2SI addresses only hazard reduction rather than risk reduction.

The integration of process simulation software, HYSYS and spreadsheet into an inherent safety assessment at the design stage was discussed by Shariff et al. (2006) and their tool was called an integrated estimation tool (iRET). The extended development of iRET, known as the Inherent Safety Index Module (ISIM) was discussed by Leong and Shariff (2008). These authors further developed an inherent safety assessment method using process simulation data that can be used in the preliminary design stage named the Inherent Risk Assessment (ISA) method (Shariff and Leong, 2009). Incorporation of the DOW fire and explosion index into design optimization at the conceptual stage using ISD principles was discussed by Suardin et al. (2007). During the conceptual design stage, process chemistry is studied to evaluate available chemical synthesis routes. The chemical reactions involved, raw materials, intermediate and by-products, storage, transportation, and waste treatment associated with each synthesis route are further studied. Each chemical route will carry certain inherent hazards. To choose the best chemical route in terms of inherent safety, the indexing approach called Inherent Benignness Indicator (IBI) was developed by Srinivasan and Nhan (2008). Each process route was compared considering the material used, reaction involved, and the process parameters, using the principal component analysis (PCA) technique. Consequently, each route was ranked to select the most inherently safe chemical process.

The majority of indices developed for selecting chemical process routes were treated as chemicals in the process system seen as individual components rather than considering them as a mixture (Leong and Shariff, 2009). As a solution for this limitation a new index called the Process Route Index (PRI) was proposed based on the process parameters that influence the explosion of a chemical process such as flammability limits. Landucci et al. (2008) studied possible inherently safer alternative processes for hydrogen storage in terms of key performing indicators that were developed based on consequence assessment and credit factors. Further, their work discussed the application of ISD principles of "substitution" and "moderation", since process hydrogen can be stored as a less hazardous hydride. Application of ISD principles to plant layout design was presented in a series of two journal papers (Tugnoli et al., 2008a, 2008b). Their first paper described the application of the inherent safety guidelines and index method for layout design. The second paper described the index to evaluate the domino effects and demonstrated the proposed approach using a case study.

Similar to any other quantification, quantification associated with inherent safety assessment may also contain a certain extent of uncertainty. A fuzzy logic based method was developed to produce a more realistic estimation reducing the uncertainty associated with subjective analysis (Gentile et al., 2003).

3.3.3.2. *Human and organizational factors.* In high risk industries, precise quantification is required to prepare proper emergency management and planning. The mathematical model was developed to determine the shortest escape time from a given point to an alternative point and the shortest routes between all two possible points of an underground mine network (Jalali and Noroozi, 2009). The mathematical model was developed using the concept of Floyd–Warshall and π algorithms. To incorporate human and management factors into probabilistic risk assessment, Murphy and Paté-Cornell (1996) developed the System Action Management (SAM) framework. The SAM framework is comprised of four quantitative models of actions: a rational model, bounded rationality model, rule-based model, and execution model. These models characterized the relationship among the actions of individuals that affect physical systems and management factors such as training, supervision, procedures, and policies. The probabilistic approach of these models helped to predict human action while reducing the uncertainty of the risk estimation. Further, this approach can also evaluate management and organizational changes.

3.4. Hybrid analysis

Hybrid analysis is simply a combination of both qualitative and quantitative analysis. It differs from semi-quantitative because hybrid methods provide more precise and realistic quantitative results through its quantitative analysis. Further, it is noted that every semi-quantitative analysis may not include a qualitative part; instead, it could use only a simple quantification. Thus, hybrid analysis provides a comprehensive analysis of process safety and risk assessment. Table 5 lists selected hybrid methods and models developed during last two decades.

3.4.1. Hazard identification and analysis

There was a limited development of hybrid models and methods for hazard identification and analysis. Authors briefly discussed a few notable developments found only in the literature that have been investigated. Markowski and Mannan published a method called fuzzy Layer of Protection (fLOPA). The fLOPA was extended as suitable for particular piping failure and was called a piping fuzzy layer of protection (pfLOPA) (Markowski and Mannan, 2009). Application of fuzzy based LOPA to the natural gas industry was also discussed by Khalil et al. (2012). Another approach of uncertainty handling is application of the Bayesian Network. Yun et al. (2009) developed a methodology called Bayesian-LOPA. This methodology was focused on the LNG industry because failure data from LNG industry were sparse and unreliable.

3.4.2. Risk assessment

3.4.2.1. Fault tree analysis and its extensions. FTA graphically depicts failure propagation and the logical relationship between root causes and fault paths. Further, FTA is capable of providing a quantitative analysis using the reliability theory, Boolean algebra and probability theory. Though the procedure of FTA was described in numerous articles, the handbook of Fault Tree Analysis prepared by System and Reliability Research, United Sates Nuclear Regulatory Commission can be considered as more reliable and contains well documented information for FTA (Vesely et al., 1981). In 1961, the Bell Telephone Laboratories developed the FTA as a technique to perform the safety evaluation of the Minuteman Launch Control System (Duisault, 1983). The first technical article of fault tree construction and probability estimation was presented in 1965 at the System Safety Symposium organized by the University of Washington and the Boeing Company (Haasl, 1965). Subsequent development associated with FTA has shown a rapid growth. Aerospace and nuclear power industries were the main users of the FTA for their safety studies. The review of major developments related to FTA and its contribution before the 20th century can be found in Ericson (1999).

3.4.2.2. Qualitative aspects of fault tree analysis. The fault tree is to be constructed in a way so that it should capture all possible cause-consequence relationships and should depict them in a simple and understandable manner. The fault tree for a small system is relatively easy to construct, but for a complicated system, this task would be difficult and results in a large and complicated fault tree. The adaptation of properties of Binary Decision Diagrams (BDDs) to develop algorithms for fault tree construction and management was extensively discussed in literature. Rauzy (1993) utilized the BDD and its properties-Shannon's decomposition—to develop an algorithm to compute minimal cut sets and probabilities of root events. The proposed algorithm consists of two stage BDD computations: computing BDD encoding the fault tree and its minimal cut sets. The properties of BDD itself also can be used to estimate the minimal cut set by transforming the fault tree into a BDD (Sinnamon and Andrews, 1997). Way and Hsia (2000) discussed a simple component-connection method to build a BDD encoding fault tree. Reay and Andrews (2002) restructured the complex fault tree into smaller and simple sub-trees using a two-stage process. First, the Faunet reduction technique was used to reduce the fault tree to its minimal form eliminating any "noise" from the system by altering the underlying logic. Then, these sub-trees were further simplified using the linear-time algorithm. Finally, BDDs were developed for each sub-tree. Similar procedures for constructing a BDD for a large fault tree were discussed by Remenyte and Andrews (2006). To construct the BDD from large fault trees for coherent systems (coherent fault tree), Jung et al. (2004) developed a novel BDD algorithm. In this algorithm, a set of new formulas was introduced for "AND" and "OR" operations between if-then-else (ITE) connectives of a coherent system. As an alternative method to BDD, a Ternary Decision Diagram (TDD) was introduced to analyze the large non-coherent fault trees (Remenyte and Andrews, 2008). In BDD, every node has two branches: the 1-branch and 0-branch. In addition to these two branches, there was an additional branch called the consensus branch introduced into TDD to represent the relevance of the component to the system. Remenyte and Andrews (2008) presented the algorithm to convert non-coherent FT into TDD and a detailed quantification to estimate the probability of a top event.

Once a fault tree has been fully constructed, a number of computations can be performed. Most often, the first computation involves the Minimal Cut Set (MCS) analysis. MCS is defined as the combination of events that could lead to the top event. It is noted that some minimal cut sets will have a higher probability than others. There are different methods and algorithms available to estimate the minimal cut sets. There are two most common and simple methods: the top down and bottom up method. However, it is difficult to use these methods to evaluate large and complex trees. For complex trees, the computation of minimal cut sets is NP-hard. For a complex system an integrated method of both top down and bottom up was proposed by Contini (1995). This methodology was coded using "C" language and included a computer program called ISPRA-FTA. A computer algorithm of Critical Item Identification System (CIIS) was developed to determine the MCS for complex systems (Hwang et al., 1996). This approach utilized the top-down method and probability based truncation.

3.4.2.3. Quantitative aspects of fault tree analysis. The objective of the quantitative calculation of the fault tree is to obtain a precise and realistic top-event probability. It could be

Table 5 – Research articles published related to hybrid analysis.

Author(s)	Journal	Method/model
Hazard identification and analysis		
Liu and Chiou (1997)	RESS	The use of Petri Nets for failure analysis
Markowski and Mannan (2009)	JLPPI	The Piping Fuzzy Layer of Protection Analysis (pfLOPA)
Yun et al. (2009)	JLPPI	The Bayesian-LOPA
Markowski and Kotynia (2011)	PSEP	An application of BT to perform LOPA
Khalil et al. (2012)	JLPPI	The Fuzzy-LOPA method for Natural gas industry
Risk assessment		
Tulsiani et al. (1990)	RA	The Distribution Analyzer and Risk Evaluator (DARE) using fault tree
Vatn (1992)	RESS	An algorithm to find minimal cut sets
Rauzy (1993)	RESS	An algorithms for FT management using BDD
Contini (1995)	RESS	A hybrid method to minimal cut set analysis
Hwang et al. (1996)	RESS	The Critical Items Identification System (CIIS) algorithm
Rosenberg (1996)	RESS	An improved version of algorithm that developed by Vatn (1992)
Cho and Yum (1997)	RESS	An uncertainty importance measure in FTA
Sinnamon and Andrews (1997)	RESS	A method to transform fault tree into BDD
Lin and Wang (1998)	RESS	An uncertainty analysis sing fuzzy set theory
Rosness (1998)	RESS	The Risk Influencing Analysis (RIA)
Swaminathan and Smidts (1999a, 1999b)	RESS	The Dynamic Event Sequence Diagram (ESD)
Khan and Abbasi (1999c, 2000b)	PSP, JHM	PROFAT and PROFAT II—the computer aided tool for probabilistic fault tree analysis
Way and Hsia (2000)	RESS	A method to build a BDD encoding a FT
Bobbio et al. (2001)	RESS	A method to convert fault tree into Bayesian Network
Khan et al. (2001a,b,c)	JHM	SCAP—an integrated risk assessment method
Čepin and Mavko (2002)	RESS	Development of dynamic fault tree
Reay and Andrews (2002)	RESS	A conversion of fault tree into BDD using Modularization and Faunet reduction techniques
Khan and Abbasi (2002)	JLPPI	The Maximum Credible Accident Analysis (MCAA) method
Risk assessment		
Khan et al. (2002)	JLPPI	The modified SCAP
Demichela et al. (2003)	RESS	The use of the NOT and INH logic gates of FTA
Bouissou and Bon (2003)	RESS	The Boolean logic Driven Markov Processes (BDMP) method
Jung et al. (2004)	RESS	The BDD algorithm for large coherent fault trees analysis
Huang et al. (2004)	RESS	The posbist fault tree analysis
Cockshott (2005)	PSEP	The Probability Bow—Tie (PBT)
Remenyte and Andrews (2006)	JRR	A conversion process of the fault tree into the BDD
Ferdous et al. (2007)	PSEP	The revised PROFAT
Choi and Cho (2007)	RESS	An uncertainty handling of large coherent fault tree
Shalev and Tiran (2007)	RESS	The Condition-based Fault Tree Analysis (CBFTA)
Kohda and Cui (2007)	RESS	An application of DBN to model the failure of safety monitoring system
Yuge and Yanagi (2008)	RESS	The mathematical quantification of exact top event probability of fault tree with priority AND gate and repeated basic events
Remenyte and Andrews (2008)	JRR	The TDD algorithm for large coherent fault trees analysis
Limbourg et al. (2008)	JRR	An uncertainty reduction using Dempstar-shafer theory (DST)
Eleye-Datubo et al. (2008)	RA	The Fuzzy-Bayesian Network (FBN)
Marsh and Bearfield (2008)	JRR	The method to map event tree into BN
Markowski and Mannan (2008)	JHM	The Fuzzy Risk Matrix
Rao et al. (2009)	RESS	Dynamic FTA using Monte Carlo simulation
Ferdous et al. (2009a,b)	PSEP	An uncertainty handling of ETA using Fuzzy-based approach
Markowski et al. (2009)	JLPPI	An uncertainty handling of bow–tie model
Considine and Hall (2009)	PSEP	The Major Accident Risk (MAR) process
Røed et al. (2009)	RESS	The Hybrid Causal Logic (HCL) method
Brissaud et al. (2010)	JRR	The C-gate approach to handle uncertainties of FTA
Merle et al. (2011)	RESS	The dynamic fault tree analysis using algebraic determination
Codetta-Raiteri (2011)	RESS	The Generalized FT (GFT)
Risk assessment		
Vílchez et al. (2011)	JLPPI	The generic event tree models
You and Tonon (2012)	RA	The event tree analysis with imprecise probabilities
Khakzad et al. (2011)	RESS	The method to map fault tree into BN
Ferdous et al. (2012)	JLPPI	A method to handle and update an uncertain information of bow–tie
Khakzad et al. (2012)	RESS	An updating mechanism for bow–tie analysis
Peng-cheng et al. (2012)	SS	The Fuzzy-Bayesian Network (FBN)
Nývlt and Rausand (2012)	RESS	The use of Petri Nets to handle dependencies of event tree analysis
Safety management		
Aven et al. (2006)	JHM	BORA-Release: method description
Sklet et al. (2006)	JHM	BORA-Release: case study validation
Delvosalle et al. (2006), Dianous and Fiévez (2006), Salvi and Debray (2006)	JHM	ARAMIS Project
Duijm (2008, 2009)	JRR, RESS	The Safety Barrier Diagrams (SBD)
Vinnem et al. (2009)	JRR	The Generalized BORA-Release method
Rathnayaka et al. (2011a, 2011b)	PSEP	The System Hazard Identification, prediction and Prevention (SHIPP) method

achieved through using the fault tree diagram itself or using the minimal cut set. This is simple straightforward probabilistic calculation for small and simple fault trees. However, for large fault trees, manual calculation will be difficult. The other important fact is that it requires accurate usage of logical gates to obtain a valid and precise numerical estimation. Demichela et al. (2003) pointed out the use of an AND gate instead of an INH gate may lead to an overestimation probability of a top event of a fault tree. They further discussed a systematic mathematical background of the INH logic gate in order to use the fault tree analysis. Top event probability/frequency is obtained based on the failure probability/frequency of basic events and the logical connection of the FT diagram. Therefore, the probability assignment for the basic event is equally important.

Allocation of the probabilities of basic events of the fault tree is problematic with scarce information. Huang et al. (2004) pointed out this issue and developed posbist FTA to evaluate the failure probability of those systems. In this method, event failure behavior was characterized using the posbist reliability theory in the context of possibility measures rather than probability measures. A detailed mathematical background of quantification of the exact top event probability of a fault tree with priority AND gate and repeated basic events was presented by Yuge and Yanagi (2008).

During the quantitative analysis of a fault tree, the uncertainty associated with failure probabilities or failure rates of basic events can be propagated to the top event through the logical gates, which generate less accurate and more uncertain results. Therefore, methods and models need to be developed to handle the uncertainty. Identification of the basic events which significantly contribute uncertainty of the top event was discussed by Cho and Yum (1997). In their paper, the uncertainty importance measure to basic events or a group of basic events was estimated using the modified Taguchi tolerance design technique. Thus a quantitative value called a contribution ratio was estimated to evaluate the interaction effects of the uncertainties of the basic events to the top event probability. A method to quantify the percentage reduction of uncertainty of a top event with the uncertainty reduction of each basic event was also introduced.

To reduce the uncertainty associated with subjective and user defined probabilities, fuzzy set theory was combined with FTA (Lin and Wang, 1998). This method used standard fuzzy set based estimation. First, several linguistic expressions were transformed into fuzzy numbers and the experts' opinions were subsequently aggregated into a fuzzy number. Then, the estimated fuzzy numbers were converted into a fuzzy probability score (FPS). Finally, the FPS was transformed into the fuzzy failure rate. The application of fuzzy based FTA to the safety assessment of an oil and gas transmission pipeline was discussed by Yuhua and Datao (2005). Application of the Dempster–Shafer Theory (DST) of evidence to reduce the uncertainty associated with failure probabilities derived from expert judgment was discussed by Limbourg et al. (2008). Two main sources of uncertainties associated with MCS-based fault tree analysis were discussed by Choi and Cho (2007). They were: (1) truncation neglecting low-probability cut sets and (2) approximation in quantifying the MCSs that cause overestimation of a top event. To handle the first type of source of uncertainty, Choi and Cho (2007) proposed a delta-X Monte Carlo method where a combination of both the sums of disjoint products (SDP) approach and a correction factor approach (CFA) were used to handle the second source of uncertainty. Eventually, the results provided a better estimation of the top event probability and importance measures of large coherent fault trees. To handle the uncertainties associated with both basic event failure rates and their connection, an additional gate called "C-gate" or Continuous gate was proposed by Brissaud et al. (2010).

3.4.2.4. *Dynamic fault tree analysis*. In nature, the classical fault tree is a static tool which means that it is not capable of capturing the time dependency of the failure process. The dynamic fault tree may serve as a tool which is capable of incorporating the time dependency of the component failures. Čepin and Mavko (2002) discussed the development of the dynamic fault tree and its use of nuclear industry PSA. In this method, the classical fault tree was extended to a dynamic fault tree using a house event matrix and time dependent probabilistic models for basic events. The results of this method were used to prevent equipment's arrangement which results in higher unavailability. Another way to develop the dynamic fault tree is to add four additional dynamic gates: priority AND (PAND), sequence enforcing (SEQ), standby or Spare (SPARE), and functional dependency (FDEP). To solve these dynamic gates, methods such as Markov models, Bayesian Belief methods, and numerical methods were being used. Rao et al. (2009) discussed the limitation of these methods for solving dynamics gates and they proposed a Monte Carlo Simulation based dynamic fault tree approach as a solution to those limitations. Instead of a simulation approach, an algebraic framework was later proposed to algebraically model the dynamic gates and to determine the structure function of any dynamic fault tree (Merle et al., 2011).

Updating the basic event based on real time information may reduce uncertainty and the dynamic behavior of the system is captured. Shalev and Tiran (2007) developed a method called Condition-Based Fault Tree Analysis (CBFTA) to update the failure rate of the top event with time. This methodology started with known FTA and uses information from condition monitoring (CM) methods such as vibration analysis, oil analysis, and electric current analysis to estimate the new failure rate of the basic event. Using this revised basic event failure rate, the top event was re-calculated. This process continued whenever new CM information arrived.

Codetta-Raiteri (2011) discussed the modeling capabilities of several fault tree extensions such as Parametric Fault Trees (PFT), Dynamic Fault Trees (DFT), and Reparable Fault Trees (RFT). Each modeling primitive consists of different capabilities in different ways. For instance, PFT was proposed to provide the compact modeling of replicating parts whereas DFT was introduced to represent the functional dependency between events, to represent dependencies concerning the order of the events and to represent the dependency of spare components. Codetta-Raiteri (2011) proposed the Generalized Fault Tree (GFT) combining each primitive which allows the complete representation of the redundancies and symmetries of the system structure, to set different dependencies and to model the repair process using one modeling technique.

3.4.2.5. *Computer-aided fault tree analysis*. A computer aided software tool called the Distribution Analyzer and Risk Evaluator (DARE) was developed by Tulsiani et al. (1990) to automate fault tree construction and quantification. DARE incorporated the uncertainty analysis, conditional expected risk, and multiple objectives with fault tree analysis. Khan and Abbasi (1999c) developed an analytical simulation methodology and computer aided tool called PROFAT (Probabilistic fault tree analysis) to perform FT management which includes fault tree construction, minimum cut set analysis, probability analysis and importance measure estimation. The improved version of this tool named PROFAT II was later introduced and published in JHM in 2000 (Khan and Abbasi, 2000b). Later, Ferdous et al. (2007) developed the revised version of PROFAT. The improvement of the revised version of PROFAT included a new modularizing technique which was based on the KHIC algorithm for handling large complex systems, graphical interface for fault tree synthesis and probability analysis and a method to determine minimal cut sets. However, this approach was unable to reduce the uncertainty associated with subjective and user defined probabilities of basic events. Therefore Ferdous et al. (2009b) later further improved the developed method using a fuzzy based approach. In their method, the top-event probability was de-fuzzified with the weighted average method. Then the top-event probability was calculated by weighting each membership function in the output by its respective maximum membership value. Further, the revised PROFAT can produce cut sets importance measures and sensitivity analysis that can be effectively used for design modification.

3.4.2.6. *Event tree analysis and its extensions.* The event tree analysis (ETA) is used to perform consequence analysis by identifying and evaluating the accident sequence process. ETA is also a graphical approach which represents the logical relationship of an accident sequence from the initiating event to final consequences with the failure of safeguards applied to the system. It can be used to estimate the probability of the final outcome. ETA was initially utilized in business decisions making, where it was known as a decisions tree. The application of ETA to process safety analysis may have been introduced during the development of a reactor safety study in 1975 by the United States Nuclear Regulatory Commission (Ericson, 2005). The details of ETA were well captured in Ericson (2005). The major application of quantitative risk analysis including fault tree and event tree analyzes was to assess the safety of the nuclear reactor in 1975 (WASH-1400, 1975).

Vílchez et al. (2011) developed a set of generic fault tree models for the most common accident scenarios that involve different combinations of hazardous conditions and corresponding intermediate probabilities. In their study, loss of containment and release scenarios were considered the most frequent and common initiating events. Case specific event trees can be developed taking this generic event tree model as an initiating point.

Handling of an uncertainty associated with the event that leads to the end event was discussed by Ferdous et al. (2009a). They developed combined fuzzy and evidence theory based approaches which treat different types of uncertainties. In order to handle the imprecision and subjectivity, a fuzzy-based approach was used, and evidence theory was used for handling inconsistent, incomplete and conflicting data. Utilization of imprecise probabilities in ETA was mainly owing to insufficient information or when it is not practically or economically feasible to obtain additional information. The methodology and detailed mathematical background quantifying the event tree with imprecise probabilities were discussed by You and Tonon (2012).

3.4.2.7. *Bow–tie analysis.* To better represent the causal-consequence relationship of a particular accident scenario, the bow–tie (BT) model is used. It is named the bow–tie diagram as it resembles the shape of a bow–tie. The BT model is developed by connecting fault tree and event tree models to a critical event. The research related to bow–tie model development is an emerging area and it has already been in use in the majority of chemical process industries.

Cockshott (2005) combined rapid risk ranking (RRR) which was a simple qualitative method based on the risk matrix that is used to estimate the likelihood and consequences severity for an unwanted incident to assess the risk level with traditional BT diagrams, and the Probability Bow–Tie (PBT) was proposed. Cockshott (2005) further described a framework for constructing PBT and a mathematical background and computer aided program based on a spreadsheet to perform quantification.

As we previously discussed, fuzzy logic is extensively used to deal with uncertainty and imprecision associated with both FTA and ETA. It is obvious that the fuzzy set theory is certainly applicable for the bow–tie model as well. Application of fuzzy set theory to handle the uncertainties associated with bow–tie was discussed by Markowski et al. (2009). Later, Markowski and Kotynia (2011) discussed the application of the bow–tie method with respect to layer of protection analysis. Application of the fuzzy logic system (FLS) was also discussed. A further advanced methodology to characterize the uncertainty of the BT model, aggregate the knowledge and to update the prior knowledge was discussed by Ferdous et al. (2012). In this methodology, fuzzy set theory was used to deal with uncertainty due to vagueness, imprecision, and subjectivity in the expert knowledge, whereas evidence theory was used to handle the uncertainty due to ignorance, incompleteness and conflicting evidence. In order to aggregate the expert knowledge obtained from multiple experts, Dempster and Shafer (DS) and Yager combination rules were used, which provide a better approximation. Finally, their method described updating of the prior knowledge using a fuzzy-Bayesian approach. Khakzad et al. (2012) discussed the application of Bayes' theorem for probability updating. In their method, the two stages Bayesian updating was used: (1) basic event failure probability updating of the FTA and (2) safety barrier failure probability updating of the event tree. Subsequently, end event probabilities were re-calculated based on posterior or updated probabilities. The likelihood probability distributions used for both updating processes were connected to plant dynamics; thus the BT model produced dynamic results with the system variation.

3.4.2.8. *Bayesian network analysis.* The main disadvantage of FTA, ETA, and BT is that events are considered as statistically independent. In these methods, events are mainly considered as binary events and the relationship between events can be represented by Boolean gates. Further, these models lack updating and inference capabilities. As an alternative, the Bayesian Network (BN) is proposed. It is a widely used and powerful tool in the area of artificial intelligence to represent uncertain knowledge and dependency in probabilistic systems. Currently, BN is being used for applications related to safety and risk assessment. Many articles have been published, from definitions of BN to advanced development. It is not in the scope of this paper to discuss the fundamentals, properties, and theoretical background of BN. This paper focuses on topics of utilization of BN in the area of safety and risk assessment.

By mapping fault tree into BN, it is able to capture the dependency of the events. Bobbio et al. (2001) presented an algorithm to convert fault tree to the Bayesian network. In this method, the conditional probability tables for each node were developed considering the node as a binary component; i.e. for a given generic component C, C = 0 or C implied the component failure and C = 0 or $\bar{C}$ implied the component is working. Based on this information, the basic forward and backward inferences were performed. In addition, various modeling extensions such as FT with common cause failure, noisy gates, multi-state variables, and sequentially dependent failures were discussed. This mapping algorithm has certain limitations when incorporating the dependent failures, and functional uncertainty which is associated with deciding the logical gate, and expert opinion (Khakzad et al., 2011). As a result, a generic mapping algorithm was developed to address these limitations. Mapping an event tree into a Bayesian network was discussed by Marsh and Bearfield (2008). The purpose of their paper was to develop a single generalized model to replace a number of separate event trees developed to analyze the train derailment accident.

In order to handle the time dependent data or time series data, the Dynamic Bayesian Network (DBN) is more suitable than classical BN (Murphy, 2002). Application of the DBN to model the decision criteria of a safety monitoring system was presented by Kohda and Cui (2007). DBN modeled the entire behavior of the system including the safety monitoring system. The logic of DBN was dynamically modified based on the sensor output data that was monitored at regular intervals from the control system. This method helped to prevent or minimize the expected loss caused by failure of the safety monitoring system due to failed-dangerous or/and failed-safe events.

Even though BN itself is capable of minimizing the uncertainties, it is still required to integrate a suitable method to handle the events that involve insufficient and vague knowledge. A fuzzy-Bayesian network was proposed to handle such types of uncertainties and it was demonstrated in a maritime human performance case study (Eleye-Datubo et al., 2008). Most recently, Peng-cheng et al. (2012) used a fuzzy-Bayesian network approach to precisely quantify the impact of organizational factors for human reliability analysis. This method is a combination of the accident casual model that represents the causal relationship between organizational factors and human reliability. This model can perform both causal and diagnostic inference. Røed et al. (2009) also developed a methodology which combines BN and a method which represents the causal relationship of an accident, named HCL (Hybrid Causal Logic) and validated this with an offshore case study. An improved version of HCL mapping fuzzy fault tree (FFT) into a Bayesian Network (BN) was discussed by Wang et al. (2011).

3.4.2.9. Risk assessment framework. The hybrid method named Risk Influence Analysis (RIA) was discussed by Rosness (1998) to identify and assess risk reduction and prevention measures for large-scale distribution systems. This method included a procedure to identify a set of relatively stable conditions that influences the risk level, called risk-influencing factors. The qualitative part of this method was used to classify and describe the accident types and identify the risk-influencing factors using “conceptual trees”. The quantitative estimation included an estimation of the risk contribution of each accident type given a current state of risk-influencing factors. Further, it estimated the risk influence associated with each risk-influencing factor.

Khan et al. (2001a, 2001b, 2001c) developed an integrated methodology, namely SCAP, in which risk assessment steps are interactively linked with implementation of safety measures. The procedure started with a hazard identification process to identify and rank fire, explosion, and toxic hazards using the HIRA method. Qualitative hazard assessment and probabilistic hazard assessment were then performed simultaneously. During the qualitative hazard assessment, the Maximum Credible Accident Analysis (MCAA) technique was used to generate possible accident scenarios. The consequences of each scenario were then estimated using MAXCRED. The details of MCAA were discussed elsewhere (Khan and Abbasi, 2002). Probabilistic hazard assessment was performed using the fault tree technique and fault tree construction, and quantification was automated by PROFAT. The next step of SCAP was to estimate and evaluate risk. If estimated risk was acceptable, the design would continue without changing. However, if the estimated risk was unacceptable, suitable safety measures were applied and risk was re-calculated. This was an iterative process which is performed till safety reaches the desired level. Later, the SCAP methodology was again discussed adopting some modification to the hazard identification (Khan et al., 2002). In this methodology, SWeHI methodology was used instead of the HIRA, and the estimated index called Safety Performance Index (SPI).

Risk matrix is a common industrial best practice used for risk based decision making. Risk interpretation using a traditional 4×4 risk matrix may produce imprecise and vague results. As a solution for this limitation of the traditional risk matrix, the fuzzy risk matrix was introduced (Markowski and Mannan, 2008). In this method, all variables of the risk matrix were defined based on fuzzy set and appropriate membership function. The output also produced fuzzy based results which was more realistic.

The Baseline Risk Assessment Tool (BART) was a risk assessment methodology which combined simple QRA techniques with bow–tie to identify and assess hazard and risk that may be created from processing or activities carried out in an upstream onshore/offshore installation (Cherubin et al., 2011).

3.4.3. *Safety management*

3.4.3.1. Safety barriers analysis. The safety barrier diagram is another popular method in risk modeling and assessment. It is simple and helpful in communicating with non-experts as it depicts the accident process as a failure of safety measures. The definition, syntax and principles of constructing safety barrier diagrams were introduced by Duijm (2008). His paper further discussed a simple quantification method that evaluates the likelihood of the consequence for a given expected probability of an initiating event and the probability of failure on demand of the safety barriers. A subsequent article discussed this method in more detail and suggested this tool could be used as a safety management tool (Duijm, 2009). Focusing on risk analysis of platform specific hydrocarbon release accidents, a safety barrier based approach called (Barrier and Operational Risk Analysis) BORA-Release was developed and discussed in a series of two papers published in JHM.

In the first paper, the methodology of BORA-release was described (Aven et al., 2006). The methodology consists of eight steps: (1) development of a basic risk model including release scenarios, (2) modeling the performance of safety barriers, (3) assignment of industry average probabilities and risk quantification, (4) development of risk influence diagrams, (5) scoring of risk influencing factors, (6) weighting of risk influencing factors, (7) adjustment of industry average probabilities and (8) recalculation of the risk in order to determine the platform specific risk. The second paper discussed the application of the method to real time application and results were also discussed (Sklet et al., 2006). Later, a generalized methodology was developed rather than focusing only on hydrocarbon releases (Vinnem et al., 2009).

The European Commission's Joint Research Centre initiated ARAMIS (accidental risk assessment methodology for industries) project as a collaborative research project with number of organizations focusing on risk assessment and risk-based decision making. A number of papers have been published in different journals related to ARAMIS and its associated developments. Kirchsteiger (2002) discussed the background, motivation and objectives of development. The methodology and its developments were described in detail in Delvosalle et al. (2006), Dianous and Fiévez (2006), Salvi and Debray (2006).

Khan and co-workers developed an accident modeling approach to predict accidents in processing facilities. The methodology called System Hazard Identification, Prediction and Prevention (SHIPP) was a systematic safety management method based on a sequential accident model which incorporates the concept of the safety barrier to model the accident sequence (Rathnayaka et al., 2011a). The model used FTA and ETA to develop the cause-consequence relationship. The model relies on process history and accident precursor information. The updating mechanism used in this method was based on Bayes theorem and updated probability of abnormal events whenever new information arrived. Most importantly, the predictive model was capable of predicting the risk profile of the system dynamically. The methodology description and case study validation are available in Rathnayaka et al. (2011a,b). Application of SHIPP methodology to an LNG case study was later discussed (Rathnayaka et al., 2012).

4. Current research trends

Papers published during 2013 revealed that the future trend of process safety and risk management development inclined to the following areas:

- Hazard identification and analysis
  - Atypical hazard identification
  - Dynamic process monitoring for hazard/fault identification
- Risk assessment
  - Dynamic risk assessment and management
  - Advanced consequence modeling
- Safety management
  - Inherently safer design
  - Advanced accident modeling

In this section, authors discussed selected journal papers published focusing on the above mentioned areas.

4.1. *Hazard identification*

4.1.1. *Atypical hazard identification*

With the increment of the complexity of the process and plant, new hazards may be generated, and those hazards must be detected early. Paltrinieri et al. (2013) proposed a method to identify atypical hazards, named the Dynamic Procedure for Atypical Scenarios Identification (DyPASI). DyPASI supports identification and assessment of atypical potential accident scenarios related to substances, equipment and plants based on early warnings or risk notions. Wu et al. (2013b) proposed a novel model for the failure analysis model based on multilevel flow modeling (MFM) and HAZOP. Hazard analysis of sub systems is challenging due to their complexity and dynamic component interactions. To perform hazard analysis for such systems, a new hazard analysis technique called SimHAZAN that uses multi-agent modeling and simulation results was proposed (Alexander and Kelly, 2013). Research continues to address the limitation of HAZOP and to develop novel methods that can avoid HAZOP's limitations. Wu et al. (2013a) proposed a computer-aided hazard evaluation method based on domain ontology called the Scenario Object Model (SOM). This methodology can be used to represent the content and structures of the hazard identification process.

4.1.2. *Dynamic process monitoring for hazard/fault identification*

Real time monitoring of process operations and process upsets are of paramount importance to establish required safety measures. Effective and timely identification of process faults is vital to prevent or control major accidents. The Principal Component Analysis (PCA) method is widely used as a statistical fault detection technique. Harrou et al. (2013) proposed a PCA based fault detection algorithm along with a generalized likelihood ratio (GLR). The advantage of using GLR is that it is able to model the fault detection even in the absence of the process model. The framework to enhance maintenance decisions based on real time information obtained from process monitoring was developed by Elhdad et al. (2013). In this method, a combination of real time signals that were triggered during the plant safety shutdown process, ontology and business rules were used to facilitate stakeholders and management making the right maintenance decisions for a petroleum plant.

Ni et al. (2013) proposed a method to predict the location of pipeline leaks using the improved and integrated method of a support vector machine and particle swarm optimization theory (PSO-SVM). Small leaks in pipelines can be detected through traditional detection methods which use pressure or a vibration signal. Xu et al. (2013) claimed that these traditional methods produced less information from a leakage signal because the high frequency component of a leakage signal weakens rapidly. Therefore, they proposed a novel detection method based on acoustic waves.

A multivariate risk-based fault detection and diagnosis technique was proposed by Zadakbar et al. (2013). The proposed technique was capable of eliminating faults that are not significant and providing dynamic risk indication at each sampling stage. Their work shows that use of a Kalman filter combined with the risk assessment method provided robust analysis of false alarms.

4.2. Risk assessment

4.2.1. Dynamic risk assessment and management

Dynamic risk assessment has many advantages over traditional static risk assessment. The dynamic changes of the hazardous conditions of highly complex technical and social systems can be modeled using various methods. Further, quantification of uncertainty helps to improve precision of the risk calculations. The real time updating of risk provides better assessment of risk and thus better management of risk. Adopting dynamic risk assessment and a management model help to predict an abnormal situation and thus better inform decision makers for early actions. This way abnormal events can be prevented before they occur rather than relying on end of the pipe safety measures. This way dynamic risk management helps to enhance the inherent safety aspect of process operation.

4.2.1.1. Dynamic risk assessment methods. Application of Bayes theorem to update the failure probabilities taking into consideration the dynamic changes of the system has also been discussed to some extent prior to 2013. This section focuses on further development.

Integration of BN with many qualitative and quantitative risk and hazard assessment methodologies enhances accuracy, quantitative power, and reduces the uncertainty. Further, properties of BN such as updating, prediction and forward and backward inference provide significant information for decision makers to make accurate and timely safety critical decisions. The BN facilitates risk quantification even in the case of scarce information and for complex models. Pasman and Rogers (2013) discussed the application of BN along with LOPA and explained using a case study. A system with three protection layers was investigated using a discrete BN model and a mixed continuous-discrete BN model. Cai et al. (2013) used the Dynamic Bayesian Network (DBN) to quantitatively assess the impact of human errors on offshore blowout accidents. In this method, a causal relationship was modeled using a pseudo-fault tree and then was converted into BN taking repair of faults into consideration. The important observation of the results was that the human factor failure probability of a barrier that was applied to prevent human errors reached stability when the repair was considered, whereas it increased continuously when the repair action was not considered. State-of-the-art application of BN in FTA for systems for which the minimal link sets (MLSs) and minimal cut sets (MCSs) are known was presented by Bensi et al. (2013). Model and parameter uncertainty reduction using Bayesian analysis was discussed by Droguett and Mosleh (2013).

A mapping algorithm to convert traditional bow–tie to BN was proposed by Khakzad et al. (2013a). This proposed method differs from other mapping techniques as it demonstrates the fact that probability adapting is more effective than probability updating in dynamic safety analysis. The advantage of probability adapting is that the effects of the generic prior probability reduce since they are updated based on accident precursors or observations. Khakzad et al. (2013b) demonstrated the application of the BN to offshore drilling safety assessment. Khakzad et al. (2013c) furthered their research and used discrete-time BN to solve the dynamic fault tree without the remedy of Markov chains.

4.2.1.2. Uncertainty handling methods during dynamic risk assessment. During the last two decades fuzzy logic and Bayesian analysis were two common methods used in process safety and risk assessment in order to deal with uncertainties. Some of the methods and models developed are discussed in Section 3. Vast possibilities exist with these two methodologies to further extend new model development that would be able to overcome limitations of previously developed methods; hence, results will be closer to reality. Jamshidi et al. (2013) proposed a novel method that integrates relative risk score (RRS) methodology and fuzzy logic for pipeline risk assessment. RRS methodology has been identified as one of the most popular pipeline risk assessment techniques developed based on an indexing approach; thus, lack of information and uncertainty were not able to produce realistic information. Integrating fuzzy logic with the traditional RRS method produces more accurate and realistic results and reflects the real situation. This method was able to take into account the relative importance among the parameters influencing pipeline damages such as third-party damage, corrosion, design, incorrect operation, product hazard, leak volume, dispersion, and receptors.

A fuzzy and evidence based approach along with sensitivity analysis to tackle the uncertainties of input data and model adequacy of the bow–tie model was proposed by Ferdous et al. (2013). This methodology has certain improved features over other methods currently developed. This methodology can accommodate experts' knowledge to handle uncertainty due to lack of information. The combined approach of fuzzy and evidence based theory addressed the subjective uncertainty, uncertainty due to ignorance and inconsistency associated with experts' knowledge. The model uncertainty was handled through introduction of dependency coefficients. Further, sensitivity analysis was proposed to identify the most significant contributing events to the final end event.

Uncertainty due to common cause failure (CCF) and diagnostic coverage (DC), also known as epistemic and aleatory influencing factors, which arise during safety instrumented system (SIS) performance analysis, was handled using fuzzy multiphase Markov chains (Mechri et al., 2013). To incorporate the uncertainty of basic parameters of systems and their impact on SIS performance, fuzzy numbers are used for elementary probabilities in Markov chains. This method illustrated how the imprecision induces changes in the safety integrity level of a particular SIS. The utilization of approximation to estimate the uncertainty information associated with Layer of Protection Analysis (LOPA) without using a partial derivative was discussed by Freeman (2013).

The probability assessment for expert knowledge contains a certain level of uncertainty, known as epistemic uncertainty. There are several methods developed to reduce the epistemic uncertainty that arises during probability assigning. Among them, possibility representation has been identified as an adequate method, especially when informative hard data are not sufficient to perform statistical analysis (Flage et al., 2013). Therefore, Flage et al. proposed an integrated probabilistic and possibilistic framework method to analyze the epistemic uncertainty associated with basic events of FTA. The epistemic and objective dependences of basic events and their effects on the top event of the fault tree were analyzed using Frechet bounds and the distribution envelope determination (DEnv) method (Pedroni and Zio, 2013). Results of this study concluded that both types of dependencies significantly affected the top event; however, the epistemic dependencies may have a higher contribution than objective dependences.

4.2.2. *Advanced consequence modeling and assessment*

Advanced mathematical, analytical and simulated models are being used to model release, dispersion, fire, and explosion. CFD modeling has become an attractive and promising technique for consequence modeling. However, experimental based validation is still play key role of consequence assessment and modeling.

Hydrocarbon release, dispersion, fire and explosion, specifically LNG, was considered one of the main research areas during 2013. Giannissi et al. (2013) presented the application of CFD modeling to simulate LNG dispersion in an open obstructed environment based on Falcon Series experiments. The modeling considered a two phase release of LNG and selected weather conditions. They also discussed the effects of the wind direction which may cause the creation of a pool formation.

The results of release and dispersion modeling are used to design the proper mitigation measures and to perform area classification. Forced mitigation using a water curtain is a well-known and effective method of reducing LNG vapor concentration by enhancing the dispersion. However, Kim et al. (2013) claimed that no engineering criteria have been developed to design an effective water curtain system because of lack of understanding of the complex droplet–vapor interaction. In order to fill this knowledge gap, a detailed study of the forced mitigation of LNG vapors was performed by Kim et al. (2013). The physical interactions of the droplet–vapor system were studied using the Eulerian–Lagrangian approach, and factors such as droplet size, droplet temperature, air entrainment rates, and installation configuration were also studied. CFD modeling was applied to develop the design guidance for an effective forced mitigation system. Sun and Guo (2013) assessed two potential LNG hazards: flammable vapor dispersion and pool fire radiation using CFD modeling to perform the hazardous area classification, the results of area calcification, and mitigation methods such as application of water curtains and foam firefighting.

The study of secondary events, also known as the domino accident, has become an area of interest for scholars. The effects of domino accidents are more significant and may lead to a catastrophic accident. Kadri et al. (2013) proposed a combined method that used probabilistic models and physical equations to quantify the effects of domino accidents based on quantification of the escalation vectors such as heat load, overpressure, and fragments. Further, the risk to the human (individual and social risk) due to overpressure and heat radiation was estimated using a human vulnerability model. The other significant feature of this work was hazardous zone classification based on physical damage and the probability of domino accidents. A more detailed analysis of hazardous area classification where an explosive gas atmosphere may exist was discussed by Tommasini (2013). Utilization of BN to estimate the domino effects probability and propagation patterns was discussed by Khakzad et al. (2013). The method updates the probabilities of events using the new information and the most probable path of domino effects was determined based on the new information arrived.

4.3. *Safety management*

4.3.1. *Accident modeling*

A combination of different methods and models is a present trend of developing accident models, which could provide more reliable accident analysis. Wang et al. (2013) developed an accident analysis model by combining Human Factor Analysis and Classification System (HFACS) and BN. The causes and prevention measures were proposed using an integrated HFACS-BN model, and then the Best-Fit and Evidential Reasoning (ER) methods were used to rank the proposed safety measures in terms of their cost effectiveness. The blowout accident scenario was modeled using the accident barriers (Xue et al., 2013). The safety barriers were proposed based on primary and secondary well control barriers and extra well monitoring barriers. Another five barriers: ignition prevention, escalation prevention, emergency response, blowout control and spill control were proposed to mitigate and control the consequences due to a blowout event. Kasai et al. (2013) developed an accident occurrence model for the risk analysis of industrial facilities based on the chemical reaction. The model introduced a defensive barrier to prevent a chemical accident that initiates chemical reaction. The uncertainty associated with the barrier was quantified using gamma distribution. Rathnayaka et al. (2013) proposed an accident modeling and risk assessment framework based on accident precursors information. The framework was developed based on SHIPP methodology and applied to deep water drilling operations.

4.3.2. *Inherent safety*

Inherent safety/inherently safer design is an emerging concept which generated research and industrial attention during recent years although the concept was established many years ago. Authors described papers published during the last two decades related to inherent safety in Section 3. In this section, authors highlight further development of inherent safety. Process operations and equipment design considering ISD options at an early design stage could be a better option to achieve higher safety standards and cost benefits. Application of inherently safer design strategies of intensification, attenuation and limitation of effects to model and design the low pressure chemical vapor deposition (LPCVD) furnace machine (reactor) was discussed by Chen et al. (2013a) and Chen et al. (2013b). Application of ISD principles to a laboratory setting where experiments are performed in extremely hazardous conditions was discussed by Theis and Askonas (2013). It is required to know the risk level of the system to successfully apply ISD strategies during the preliminary design stage. Shariff and Zaini (2013) proposed a technique which is based on a 2-region risk matrix concept to estimate the risk level at the preliminary design stage. The risk was estimated using a traditional method which is the product of severity and probability, and information required to assess the severity was obtained through a process simulator called iCON. Based on risk level, the requirement of inherent safety was decided.

Most of the past developments of inherent safety evaluation indices are hazard-based developments. However, scholars are currently focusing on both hazard reduction and likelihood reduction through application of ISD principles. As a result risk based indices are proposed. Rusli et al. (2013) proposed a framework called Quantitative Index for Inherently Safer Design (QI2SD) that evaluates the inherent safety level of the system in terms of element of risk rather than only considering hazard reduction. In addition to quantitative evaluation, it is capable of evaluating the hazard conflicts and trade-off which may arise during the application of ISD strategies and it facilitates the ranking of ISD alternatives for decision making.

5. Future direction

The systematic explanation of the methods and models developed, starting from origin to current research, provides a natural guide to future direction of research. It is clear that the current research trend has been in the area of inherent safety, dynamic and operational risk assessment, incorporation of human and organizational factors into risk assessment and integration of a safety protection layer (safety instrumented system) into risk assessment.

Transition from traditional quantitative risk assessment (QRA) to dynamic quantitative risk assessment (DQRA) is a natural evolution. DQRA enables implementation of inherent safety principles, features most desired in hazardous processes.

6. Summary and conclusion

The main objective of this review is to provide historical development and present research trends of process safety and risk management related development. Based on the open literature published in eight leading journals, the review covers the evolution of the methods and models developed for process safety and risk management. The scope of the review is restricted to topics directly related to process safety and risk assessment that published in journal papers. Conference papers are not considered due to limited availability in public domain and less technical content.

Use of process safety concepts in industrial practice started with the occurrence of major accidents between 1960 and 1990. The research activities on process safety and risk also started simultaneously and the 1970s is considered as the golden decade of research. The popular process hazard and risk analysis methods: HAZOP, FMEA, FTA and ETA were also introduced and implemented before the 1990s. The models and methods developed were categorized into four categories: qualitative, semi-quantitative, quantitative, and hybrid. It is observed that there is a gradual increase of a number of quantitative and hybrid developments with time whereas there is steady progress of qualitative and semi-quantitative techniques.

The review paper summarizes the past trend of developments. It is noted that researchers tend to focus on dynamic risk assessment and management rather than static or traditional risk assessment, and also risk-based decision making rather than hazard based decision making. Integration of dynamic fault detection and diagnosis with risk assessment have significantly improved safety in process facilities. A number of mathematical and analytical techniques were developed to handle the uncertainty of probabilistic quantification. Use of a simulation method for modeling fire, explosion and release was also identified as a new trend of consequences analysis. One of the major emerging areas of process safety is the implementation of inherently safer design strategies into industrial application. Significant research was carried out focusing on developing inherent safety evolution matrices, application of ISD strategies and quantification of inherent safety. Current trends of process safety and risk related development show that research is mainly focusing on challenges such as data uncertainty, scarcity of information and complexity of process systems.

The current trend is development of novel methods and models for real time risk assessment and decision-making. This helps to enhance inherent safety features of the hazardous operations.

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