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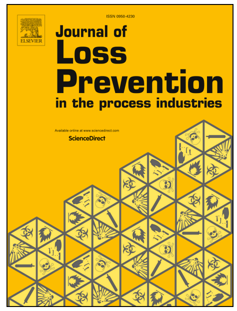

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Application of Risk Analysis in the Liquefied Natural Gas (LNG) Sector: An Overview

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Abstract

In recent years, the global demand for liquefied natural gas (LNG) as an energy source is increasing at a very fast rate. In order to meet this demand, a large number of facilities such as platforms, FPSO (floating production, storage and offloading), FSRU (floating storage and regasification unit) and LNG ships and terminals are required for the storage, processing and transportation of LNG. Failure of any of these facilities may expose the market, companies, personnel and the environment to hazards, hence making the application of risk analysis to the LNG sector a very topical issue throughout the world. To assess the risk of accidents associated with LNG facilities and carriers, various risk analysis approaches have been employed to identify the potential hazards, calculate the probability of accidents, as well as assessing the severity of consequences. Nonetheless, literature on classification of the risk analysis models applied to LNG facilities is very limited. Therefore, to reveal the holistic issues and future perspectives on risk analysis of LNG facilities, a systematic review of the current state-of-the-art research on LNG risk analysis is necessary. The aim of this paper is to review and categorize the published literature about the problems associated with risk analysis of LNG facilities, so as to improve the understanding of stakeholders (researchers, regulators, and practitioners). To achieve this aim, scholarly articles on LNG risk analysis are identified, reviewed, and then categorized according to risk assessment methods (qualitative, semi-qualitative or quantitative; deterministic or probabilistic; conventional or dynamic), tools (ETA, FTA, FMEA/FMECA, Bayesian network), output/strategy (RBI, RBM, RBIM, facility siting, etc.), data sources (OREDA handbook, published literature, UK HSE databases, regulatory agencies' reports, industry datasets, and experts' consultations), applications (LNG carriers and LNG fuelled ships, LNG terminals and stations, LNG offshore floating units, LNG plants), etc. Our study will not only be useful to researchers engaged in these areas but will also assist regulators, policy makers, and operators of LNG facilities to find the risk analysis models that fit their specific requirements.

Keywords: Liquefied natural gas (LNG), hazard identification, risk analysis, risk assessment, data sources.

1. Introduction

Loss of control of combustible products such as liquefied natural gas (LNG) can result in accidents with catastrophic consequences such as fire and explosion. In order to mitigate such consequences, safety measures are required to be designed by asset managers in accordance with regulatory requirements. For this purpose, risk analysis has emerged as a very useful tool to guide decisions on design, manufacturing, installation, operation and maintenance (O&M) and decommissioning of assets in safety critical industries.

According to Aven (2016), the study of risk analysis as a scientific field started about 30 to 40 years ago, hence making it a relatively young discipline. In spite of being a young discipline, risk analysis has been applied to a wide range of industries such as the medical sector, engineering infrastructure sector, transportation sector, security and defence sector, social and the legal sector to find appropriate technical, safety, economic and environmental solutions to their problems (Aven, 2016). Historically, risk analysis may trace its root to the nuclear industry (Pasman, 2015). Information from the United States Regulatory Commission (2016) also indicates that the first probabilistic risk assessment (PRA) technique was developed for a nuclear power plant in the 1970's, and since then, many new methods and tools have been developed. Villa *et al.* (2016) indicated that the risk analysis approaches are shifting from conventional approaches to more dynamic approaches, in order to enable decision makers continuously address operational, safety, economic and environmental challenges in safety critical industries.

In the past few decades, some authors have attempted to review risk assessment methodologies and applications in different industries. These studies are highlighted in the following:

Siu (1994) presented an overview of a number of alternative risk assessment methodologies for dynamic systems. Khan and Abbasi (1998) presented a state-of-the-art-review on techniques and methodologies for performing risk analysis in chemical process industries. Tixier *et al.* (2002) identified 62 papers published on risk analysis methodologies for industrial plants and then classified them into three different categories, including hazard identification, risk evaluation and risk hierarchisation. Marhavilas *et al.* (2011) identified, analysed and categorized risk assessment methods that appeared in the literature between 2000 and 2009. Pitblado and Woodward (2011) reviewed the historical progress, the lessons learned, prediction models, and unresolved technical issues with regards to LNG risk analysis. Necci *et al.* (2015) critically analysed the available tools and knowledge gaps concerning domino effect assessment in chemical process and energy industries. Villa *et al.* (2016) provided a comprehensive review on dynamic risk assessment methodologies and relevant applications in the chemical process industry.

Although the above-reviewed studies significantly contributed to the discipline of risk analysis, there still exist considerable gaps. Firstly, all articles focused on only one aspect of the risk analysis process, that is risk assessment methodology (Marhavilas *et al.*, 2011; Necci *et al.*, 2015; Tixier *et al.*, 2002; Villa *et al.*, 2016). Secondly, none of the articles focused on providing comprehensive review of risk analysis methodologies and application in the LNG sector. Thirdly, very few articles proposed a classification framework to categorize the published literature and report their findings. Despite the obvious progress made in the field of risk analysis, safety-related problems continue to be an issue in many safety critical industries (Knegtering and Pasman, 2009). Some examples of recent major incidents include the explosion in the Texas city refinery in March 2005; explosion of a natural gas condensate tank in Warffum, the Netherlands, in May 2005; fire at the Buncefield oil storage and transfer depot in December 2005; and the Deepwater Horizon oil spill in the Gulf of Mexico in 2010.

LNG is emerging as the preferred future fuel in many industries due to its higher efficiencies and less environmental concerns. This has led to significant growth in processing, storage and transportation of LNG in large volumes around the world. However, as LNG is a cryogenic fluid with vapour dispersion characteristics and thus highly flammable, the growth comes with additional health and safety challenges (Sun and Guo, 2013). Therefore, applying risk analysis in the LNG sector is crucial to securing the health, safety, security, and business success of companies.

Though the application of risk analysis in the LNG sector continues to receive considerable attention from practitioners and researchers, yet some regulators and the general public remain unconvinced about the safety of LNG facilities, thus delaying the expansion of existing facilities as well as preventing the construction of new facilities in some countries. To reveal the holistic issues and future perspectives on LNG safety, comprehensive and systematic literature review of current state-of-the-art research on application of risk analysis technologies in the LNG sector is increasingly becoming important. The aim of this paper is to review and categorize the literature published about the problems associated with risk analysis in the LNG sector, so as to improve the understanding of stakeholders (researchers, regulators, and practitioners). This also covers other aspects of risk management process, which may be missing in previous review studies. The reviewed literature will be classified according to risk assessment methods (qualitative, semi-qualitative or quantitative; deterministic or probabilistic; conventional or dynamic), tools (ETA, FTA, FMEA/FMECA, Bayesian network), output/strategy (RBI, RBM, RBIM, facility siting, etc.), data sources (OREDA handbook, published literature, UK HSE databases, regulatory agencies' reports, industry datasets, and experts' consultations), applications (LNG carriers and LNG fuelled ships, LNG terminals and stations, LNG offshore floating units, LNG plants), etc.

The remainder of this paper is organized as follows. Section 2 presents the review methodology as well as the framework used for classifying the published literature on application of risk analysis in the LNG sector. The details of the observations and findings of the classification framework are presented in Section 3, and the findings of the literature review will be discussed in Section 4. Finally, several gaps in current knowledge regarding the subject are mentioned and some recommendations for future research are provided in Section 5.

2. Classification process

2.1. Search and review methodology

The number of peer reviewed articles and conference papers which have employed risk analysis approaches in the LNG sector has seen an increase in the past two decades. The distribution of the number of papers is displayed in Figure 1.

Figure 1. Distribution of the number of papers over the past two decades.

The search and review process used in this paper is explained as follows: First, several academic databases were identified to search the literature. These databases included ScienceDirect, ISI Web of Science, EBSCOhost, Emerald, IEEE Xplore Digital Library, ProQuest, SpringerLink, Taylor and Francis, Wiley, Inderscience, Interscience, American Society of Mechanical Engineers (ASME) digital collection, Onepetro and Google scholar. These databases were selected because they hold the largest coverage of scientific peer-reviewed literature in relation to the LNG sector. Second, two keywords of "LNG" and "risk" were used in combination with other terms such as "analysis", "assessment", "methodology", "approach", "tool", "technique", "management", "mitigation" and "strategy" to identify the literature relevant to the topic. To achieve the highest level of relevance, only peer reviewed papers written in English and published in top-tier international journals and conference proceedings were considered. This means that Master's and doctoral dissertations, textbooks, book chapters, technical reports, working papers and lecture notes were excluded from this review. Third, some exclusion and inclusion criteria were used by authors to screen and select the relevant papers for this review. In this regard, the authors first screened the titles and abstracts of the identified papers and then excluded those studies which did not cover any of the themes captured in the classification framework (see Figure 2) were excluded. The keywords search resulted in a total of 125 documents, among which 66 documents were found relevant after applying the exclusion and inclusion criteria.

After critically scrutinizing the identified literature, our analysis resulted in 47 journal articles (Shindo *et al.*, 2000; Kim *et al.*, 2005; Ochiai *et al.*, 2005; Ronza *et al.*, 2006; Han *et al.*, 2008; Vanem *et al.*, 2008; Raj and Lemoff, 2009; Yun *et al.*, 2009; Nwaoha *et al.*, 2010; Vinnem, 2010; Nwaoha *et al.*, 2011; Parihar *et al.*, 2011; Tanabe and Miyake, 2011; Keshavarz *et al.*, 2012; Khalil *et al.*, 2012; Li and Huang, 2012; Rathnayaka *et al.*, 2012; Berle *et al.*, 2013; Chu *et al.*, 2013; Nwaoha *et al.*, 2013; Sun *et al.*, 2013; Aneziris *et al.*, 2014; Dan *et al.*, 2014; Elsayed *et al.*, 2014; Martins *et al.*, 2014; Mcinerney *et al.*, 2014; Noh *et al.*, 2014; Vianello and Maschio, 2014a; Vianello and Maschio, 2014b; Ahmed *et al.*, 2015; Giardina and Morale, 2015; Lee *et al.*, 2015; Martinez and Lambert, 2015; Fu *et al.*, 2016; Martins *et al.*, 2016; Yeo *et al.*, 2016; Ahn *et al.*, 2017; Jeong *et al.*, 2017; Renjith *et al.*, 2018; Baalisampang *et al.*, 2019; Badida *et al.*, 2019; George *et al.*, 2019; Kong *et al.*, 2019; Li and Tang, 2019; Sultana *et al.*, 2019; Yoon *et al.*, 2019; Leoni *et al.*, 2019) and 19 conference papers (Dogliani, 2002; Bozzolsco, 2005; Ballesio *et al.*, 2009; Spitzenberger, 2009; Kolodziej *et al.*, 2009; Chin and Saetren, 2010; Montewka *et al.*, 2010; Skramstad *et al.*, 2010; Roldán *et al.*, 2012; Souza *et al.*, 2012; Benyessaad *et al.*, 2013; Chu *et al.*, 2014; Devkaran, 2014; Melani *et al.* (2014); Hamedifar *et al.*, 2015; Zhao *et al.*, 2015; Jewitt, 2016; Stavrou *et al.*, 2016; Hogelin *et al.*, 2018).

2.2 Classification framework

In order to classify and analyse the literature for risk analysis in the LNG sector, we propose a classification framework that is shown in Figure 2. While reviewing the literature, we found that the application of risk analysis in LNG facilities can be categorized into five different themes, as explained below.

- Risk analysis methods (qualitative, semi-qualitative or quantitative; deterministic or probabilistic; conventional or dynamic).
- Risk analysis tools (Checklist, HAZOP, LOPA, ETA, FTA, FMEA/FMECA, Petri Network (PN), MCDM, Bayesian Network (BN), fuzzy set theory, Markov chain, computational fluid dynamics (CFD), hybrid methods).
- Output/strategy (Risk assessment, safety analysis, RBI, RBM, RBIM, facility siting, etc.).
- Data sources (historical data, OREDA handbook, experimental data, UK HSE databases, published literature, software tools and expert judgment).
- Applications (LNG carriers and LNG fuelled ships, LNG terminals and stations, LNG offshore floating units, LNG plants).

Figure 2. Classification framework for risk analysis in the LNG sector.

The above five categories were arrived at by initially identifying, reviewing and analysing scholarly and industrial contributions reported in scientific journals and conference proceedings. The classification framework was subsequently validated by experts including academics with several publications and years of experience in the field of risk analysis.

3. Classification of studies, observations and findings

Based on the systematic literature review and content analysis of the selected publications, the result of each category of the classification framework is reported in below:

3.1 Risk analysis methods

Many risk analysis methodologies have been developed and applied by researchers as a decision support tool, by providing descriptions of risk, in many fields. The main principles of risk analysis methodologies include: establishment of context, identification of hazard, calculation of failure frequencies, evaluation of consequences, and calculation of risk. Tixier *et al*. (2002) classified the published literature into qualitative and quantitative risk analysis methodologies. Villa *et al.* (2016) reviewed papers published on quantitative risk analysis methodologies in the chemical process industry. In this paper, we have classified the risk analysis methodologies according to the following criteria:

- Qualitative, quantitative, or semi-qualitative (semi-qualitative methods may also be referred to as hybrid methods).
- Deterministic, probabilistic, or hybrid deterministic-probabilistic.
- Conventional or dynamic.

Qualitative risk assessment is the most commonly used methodology to estimate uncertainties in many safety critical industries (for example, assessing the condition of safety barriers). According to Nwaoha *et al.* (2013), qualitative risk analysis methodology is a deductive method relying on the subjective judgements of experts as input information. It is perceived to be the quickest and simplest method amongst the risk analysis methodologies, since it requires little or no use of mathematical and computational skills. The results of the qualitative risk analysis methodologies are often represented by colour indicators. For instance, 'red' colour represents 'high risk' or unacceptable risk, meaning it is absolutely necessary to take steps to eliminate or reduce failure risk. 'Yellow' (or 'amber') colour represents 'medium risk', meaning that already existing risk reduction strategies can be used to manage the risks. 'Green' colour represents 'low risk', meaning it is almost unnecessary to take any action.

On the other hand, quantitative risk analysis is a systematic approach for identifying and quantifying potential accident probabilities and consequences using mathematical and computational models. According to Marhavilas *et al*. (2011), the application of quantitative risk analysis methods ensure that risk is estimated in quantity by utilizing simulation or experimental approaches or applying real life information as input information. Unlike the qualitative risk analysis, the results of a quantitative risk assessment are benchmarked against established quantitative risk acceptance criteria such as fatal accident rate (FAR) and/or individual risk (IR). Most international regulations require the use of quantitative risk assessment methodologies to support decision-making process for siting of industrial facilities with catastrophic failure consequences (Center for Chemical Process Safety (CCPS), 1999; National Fire Protection Association (NFPA) 59A, 2013). Simulation and operational research (OR) methods are widely used in quantitative risk analysis projects. For more on the requirements for performing quantitative risk analysis, the readers can refer to NORSOK Standard Z-013 (2010) set by the Norwegian Petroleum Directorate (https://www.npd.no/en/), as well as ISO 31000 (2009).

The semi-qualitative risk analysis is a hybrid of the qualitative and quantitative risk analysis methodologies. This is because both qualitative and quantitative risk analysis techniques have limitations, therefore in order to compensate for the limitations of each method, subjective inputs from experts are combined with quantitative risk analysis. This method is suitable when objective failure data are unavailable or insufficient. Berle *et al.* (2013) suggested that semi-qualitative methods employ quantitative techniques, however they do not utilize exact numbers for probability calculation or consequence assessment. When using semi qualitative methods, a Likert scale of 1-5 is often assigned to the probability of a risk occurring. Preliminary Hazard Analysis (PHA), failure mode, effect and criticality analysis (FMECA), hazard and operability (HAZOP) and Bayesian networks (BNs) are typical examples of semi qualitative risk analysis methods.

Risk analysis methods can also be classified as deterministic, probabilistic or a combination of deterministic and probabilistic (Tixier *et al.* 2002). Deterministic risk analysis approaches are used to evaluate the impact of a single hazardous event by determining the damage consequences, whereas probabilistic risk analysis methods are used to either evaluate the probability of an undesirable event or evaluate simultaneously its probability and consequences.

In addition to the above-mentioned categories of risk analysis methods, this review further classifies the methods into conventional risk analysis (CRA) and dynamic risk analysis (DRA) methods. Over the past two decades, CRAs have widely been applied to evaluate the risk of safety critical systems. Nonetheless, CRA procedures do have some major drawbacks (Khan and Abbasi, 1998). These include: unavailability of good quality data for the analysis, large set of uncertainties introduced to the decision-making process, rigid nature of the process, and the inability of decision-makers to update the overall risk assessments by taking into account new information due to dynamic nature of complex systems. In order to address these drawbacks, recent studies have geared toward the use of DRAs to support risk-based decision making (Villa *et al.* 2016). Also, the flexibility in the application of DRA methods for risk analysis makes them inherently superior to CRA methods, since decision makers will be able to continuously update the risk levels with new information. The use of DRA in safety critical industries such as the LNG sector can enhance safe operation and ensure well informed decision making in critical areas such as maintenance.

DRA methods have been applied to support the following activities in different safety critical industries:

- modelling dynamic situations and identification of missing accident scenarios (Swaminathan and Smidts, 1999a, 1999b);
- dynamic fault tree and event tree analyses (Cepin and Mavko, 2002; Bucci *et al.*, 2008);
- proposing dynamic risk assessment frameworks (Meel *et al.*, 2007; Meel and Seider, 2008);
- refinery accident modelling (Kalantarnia *et al.*, 2010);
- LNG tanker manoeuvring (Montewka *et al.*, 2010);
- LNG dispersion risk assessment strategies (Sun *et al.*, 2013);
- offshore oil and gas drilling (Abimbola *et al.*, 2014); and
- LNG carrier loading operation (Melani *et al.*, 2014).

Furthermore, DRA has been applied to several risk analysis case studies involving facilities such as Ethyl Benzene process plant (Meel and Seider, 2008), LNG importation terminals (Yun *et al.*, 2009), LNG Jetty (Chin and Saetren, 2010), process safety alarm systems (Pariyani *et al.*, 2012a, 2012b), LNG transportation systems (Berle *et al.*, 2013), regasification system (Martins *et al.*, 2014), LNG fuel storage tanks (Noh *et al*., 2014), LNG carrier anchoring system (Zhao *et al.*, 2015), loading arms for LNG (Stavrou *et al.*, 2016), FLNG platform (Yeo *et al.*, 2016), and natural gas regulating and metering station (Leoni *et al.*, 2019).

The distribution of the journal articles and conference papers about risk analysis methodologies in the LNG sector is shown in Table 1. As can be seen, there are five papers which employed qualitative risk analysis methods, 32 papers used quantitative risk analysis methods and 27 papers applied semi-qualitative risk analysis methods. It is evident from Table 1 that the number of papers utilizing quantitative risk analysis methods in the LNG sector has been increasing since 2000. This is then followed by the application of semi-qualitative and qualitative methods. This then emphasizes the point that quantitative risk analysis methods are recommended for risk and safety analysis in most safety critical industries.

Table 1. Distribution of the papers utilizing risk analysis methodologies.

It is evident from Table 1 that probabilistic risk analysis methods have been extensively used in the LNG sector. Among the papers reviewed under this category, 29 papers utilized probabilistic risk analysis methods, 27 papers used deterministic methods, and 6 papers used a combined deterministic-probabilistic approach.

The distribution of the papers utilizing conventional and dynamic risk analysis by year of publication is given in Table 2. The results indicate that the most popular type of risk assessment method in the LNG sector is CRA (48 papers), whereas DRA is gradually gaining popularity.

Table 2. Distribution of the papers utilizing conventional and dynamic risk analysis.

3.2 Risk analysis tools

Over the past two decades, several risk analysis tools have been developed to support risk-based decision making in various industries. In what follows, the most commonly used risk analysis tools are briefly described.

3.2.1 Checklist

This is one of the common approaches used in identifying hazards and risk exposure. Checklists are mainly developed based on accumulative knowledge and judgment of experts as well as information gained from previous projects. In risk analysis, checklist is known as the simplest and fastest way of identifying potential hazards. It involves asking series of questions and providing answers in a structured and systematic manner. The main characteristics of this tool include:

- it mostly produces qualitative outcomes;
- data collection process involves the use of interview, field visit and review of project documents;
- it requires well-trained individuals who understand checklist questions.

Though it is a simple tool, it has its own unique challenges such as: (i) team members have to spend a lot of time to review and trim down questions when they are no longer relevant to a project, (ii) since it relies on experience of individuals in developing questions, this introduces uncertainties into the final results, (iii) the results of checklist are mostly subjective or qualitative. In order to overcome these challenges, it is suggested to combine this tool with other risk analysis tools in the LNG sector.

3.2.2 Hazard and operability study (HAZOP)

This is a structured and systematic qualitative risk assessment tool for evaluating risk in industrial plants. It is a bottom-up approach used to identify potential hazards and deviation in operations that are likely to result in accidents and non-compliance. HAZOP is accomplished by brainstorming and using a set of special guide words (e.g. none, more of, less of, part of, more than, etc.) (Marhavilas *et al.*, 2011). One of the key uniqueness of this tool is that it brings out the imaginative abilities of team members when considering design intent, and operational and process deviations. The deviations are determined based on the experience of the project team, including a team leader, engineers, risk analysts, material specialists, operators, designers, and original equipment manufacturer (OEM), as well as historical information. HAZOP can be used to assess the risk of safety systems from different perspectives. Some of the advantages of this risk analysis tool are: (*i*) it is helpful when confronted with risks that are difficult to quantify, (*ii*) decision makers are not compelled to assign numerical values to probability of occurrence and severity of consequences, (*iii*) risks are not ranked, (*iv*) it has brainstorming built into its application, and (*v*) it is simple compared to other risk assessment tools. On the other hand, the main disadvantage of this risk analysis tool is its inability to assess risks in a multi component system where different components interact with each other.

3.2.3 Layer of protection analysis (LOPA)

This is a straightforward and simplified semi-quantitative tool applied in risk analysis to obtain quantitative results. As compared to other risk analysis tools, quantitative results are obtained with less effort and time (Yun *et al.*, 2009). In risk analysis, LOPA provides the basis for determining whether there are enough protective systems or safety features against hazardous events so as to reduce their risk. For LOPA procedure, the frequency of initiating event, consequences of failure, and likelihood of failure of protection layers are calculated to determine the level of risk for any given accident scenario. The main steps for performing LOPA are: (*i*) describe the accident scenario under investigation, (*ii*) identify initiating event and assign frequency to initiating event, (*iii*) identify consequence severity levels, (*iv*) decide on the requirements for risk reduction measures using risk matrix, (*v*) identify layers of protection, (*vi*) determine the probability of failure on demand for each layer of protection and mathematically combine them, (*vii*) determine the combined risk, (*vii*) compare the combined risk reduction effectiveness of the identified protection layers with the risk reduction requirement to determine whether additional risk reduction is needed. Depending on the severity of consequences of potential accidents, one or many protective layers will be required to prevent the accident from happening. For further details on procedures and application of LOPA, readers can refer to AIChE (2001) and Willey (2014).

3.2.4 Event tree analysis (ETA)

Event tree analysis (ETA) involves the use of logic models to determine all possible outcomes from accident scenarios (initiating events) that may lead to equipment failure or process disruption. ETA can be used to identify all potential accidental events and processes in a complex system. The main steps for performing ETA are: (*i*) identify all relevant initiating events that may result in an unacceptable risk, (*ii*) identify all safety measures needed to reduce the risk, (*iii*) construct event tree, (*iv*) describe the potential accidental sequences, (*v*) assign probabilities to each event sequence, (*v*i) calculate the probability of system’s success and failure by multiplying the probabilities of individual event sequences.

ETA has several advantages compared to other risk analysis tools. Rausand and Hoyland (2004) suggested that ETA produces a graphical representation of sequence of events after an accident. Also, ETA is suitable for evaluating multiple failures in complex and dynamic systems. On the other hand, the inability to analyse multiple initiating events or safety incidents at a time is a limitation of ETA.

3.2.5 Fault tree analysis (FTA)

This is one of the well-structured and widely used risk assessment tools for root cause analysis (RCA) of complex systems. It was first introduced by AT&T's Bell Laboratories in 1962 for a ballistic control system. FTA is a deductive failure analysis tool used by safety analyst to identify possible causes of system failure or process disruption before they occur (Kabir, 2017). In FTA, failure analysis of systems starts with a top event and works backwards toward determining the potential causes of top event. FTA produces graphical display by showing logical connection between failure and the path toward the failure of a system. The main steps for constructing a fault tree include: (*i*) definition of the system, (*ii*) definition of the top-level faults, (*iii*) identification of the potential causes for the top-level fault, (*iv*) identification of the next level event, (*v*) identification of root causes, (*vi*) assignment of probabilities to event, (*vii*) analysis of fault tree.

FTA can be used to analyse the faults in either a qualitative, quantitative or semi-qualitative way. The qualitative approach involves reducing the fault tree to a minimum set of events, whereas the quantitative approach requires calculating the probability of occurrence for the top event by means of statistical or analytical techniques. The probability of occurrence is estimated using quantitative information from each component. This information may include reliability and maintainability data such as failure probability, failure rate, and repair rate of a system.

One of the key advantages of FTA is that it helps decision makers identify the most critical components in a system so as to plan the most effective method of maintaining them (Kabir, 2017). Nonetheless, the conventional FTA is more suitable for safety and reliability analysis of those components experiencing single failure mode and exhibiting static failure behaviour throughout the life cycle. However, most of the modern complex industrial systems suffer from multiple failure modes and exhibit dynamic failure behaviour. Therefore, conventional FTA tool is unable to deal with dynamic failure behaviour of complex systems (Kabir, 2017). The inability of conventional FTA to deal with uncertainties in failure data is also another limitation. In order to overcome these limitation, some studies have extended the conventional FTA to dynamic fault tree (DFT) (Cepin and Mavko, 2002; Rao *et al.*, 2009; Boudali *et al.*, 2010), state/event fault tree (Kaiser *et al.*, 2007) and stochastic hybrid fault tree automaton (SHyFTA) (see Chiacchio *et al.*, 2016).

3.2.6 Failure mode and effects analysis (FMEA) / Failure mode, effects and criticality analysis (FMECA)

This is one of the most common inductive risk analysis tools used by safety analysts to investigate the potential failure modes, causes and effects of components failure in complex systems within different safety critical industries. The ability of decision makers to come up with possible ways of eliminating or minimizing potential failure modes of a system in order to enhance operational safety and reliability of the system is an added advantage for using FMEA. The procedure for using the tool starts with defining the system to be analysed, breaking it down into subsystems and components, identifying the potential failure modes and possible causes, determining the current controls (or solutions) to detect or prevent the causes, followed by evaluating the effect of failures on the system. For quantitative analysis, numerical values based on an agreed scale are assigned to probability of occurrence (O), severity of occurrence (S) and non-detectability (D). The Risk-Priority-Number (RPN) is then calculated by:

$$RPN = O \times S \times D. \qquad (1)$$

For further details on the procedures for conducting FMEA, the readers can refer to Shafiee *et al.* (2019). Despite the increase in FMEA application in safety critical industries, several of its limitations have been identified and reported in the literature over the years (e.g.

see Dinmohammadi and Shafiee, 2013; Shafiee and Dinmohammadi, 2014; Kabir and Papadopoulos, 2018). One of the most important limitations is the subjective nature of input data for *O*, *S* and *D*. These three factors are often determined based on experts' judgement, which usually reduces the degree of confidence in RPN results for decision making. Also, the issue of why different factors should be considered equally important has been reported in the literature.

FMEA was initially called 'failure mode, effects and criticality analysis (FMECA)'. The 'C' in FMECA indicates that the criticality of the various failure effects are considered and ranked. Therefore, FMECA is a kind of FMEA with criticality analysis. In FMEA, multiple failure analysis levels are possible, however, FMECA does not account for multiple failure interactions, meaning that each failure is considered individually. For this reason, industries are not very sincere to perform FMECA after performing FMEA.

3.2.7 Petri Network (PN)

This is a graphical and mathematical modelling tool that is applicable for risk analysis of dynamic complex systems. Murata (1989) indicated that PN is a promising tool for describing those systems characterised as concurrent, asynchronous, distributed, parallel, nondeterministic, and/or stochastic. PN offers the advantage of representing time sequence of events along with their durations (Lee and Lu, 2012). It uses two types of nodes, called places and transitions. The places interact with the transitions by connecting with directed arcs or vice versa (Kabir *et al.*, 2015). In PN, systems are graphically constructed as a set of conditions and events, where places represent conditions and transitions represent events. Circles are used to graphically represent the places which may contain tokens, whereas rectangles are used to represent transitions. The token in a place is also referred to as marking of the place. The token represents the set of initial conditions and this changes by the firing of transitions, which denote occurrence of event.

3.2.8 Multi criteria decision-making (MCDM)

Risk analysis of safety critical systems can be considered as a MCDM problem. This is because the risk analysis may involve multiple (both quantifiable and non-quantifiable) conflicting criteria, thus making it a complex decision-making problem. In tackling such complex decision-making problem, the application of MCDM is considered appropriate. In the literature, various MCDM tools such as Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), Elimination and Choice Expressing Reality (ELECTRE), Technique of Order Preference by Similarity to the Ideal Solution (TOPSIS), Preference Ranking Organization METHod for Enrichment of Evaluations (PROMETHEE), Vlsekriterijumska Optimizacija I KOmpromisno Resenje (VIKOR), etc. have been applied in different industries for different purposes. However, only one paper was found to have used fuzzy TOPSIS method for evaluating the risks related to LNG plant. A wide summary on MCDM methods can be found in Shafiee (2015) and Shafiee *et al*. (2019).

3.2.9 Bayesian network (BN)

This is a directed graphical model and a well-known structured interference tool which is very useful for dealing with uncertainty in risk and reliability decision-making process, combining information from different sources, and updating the results when new information becomes available (Langseth and Portinale, 2007). It is also useful for updating maintenance plans when operating conditions dramatically change. The main aim of BN is to model the posterior conditional probability distribution of the final outcome (often causal) of a system after obtaining new information. According to Rausand (2011), BN establishes a relationship between the causes and the final outcome of a system. A deeper insight into the application of BN is provided by Neapolitan (2004), Langseth and Portinale (2007) and Barber (2012). Many researchers consider BN as a suitable and promising tool to deal with uncertainties during risk analysis of dynamic complex systems such as LNG facilities.

3.2.10 Fuzzy set theory

One of the major limitations in risk analysis projects is the difficulty in obtaining good quality failure data for quantitative assessment due to paucity of statistical information about failure of subsystems and components. The insufficiency of good quality data is mostly addressed by the use of expert judgement or using data from similar systems or the use of generic data. However, the use of expert judgement and generic data can introduce higher degree of uncertainty, vagueness, and imprecision in the final risk assessment results. To deal with the uncertainty, vagueness and imprecision associated with the classical risk assessment tools, fuzzy set theory was developed. When applying fuzzy set theory, the uncertainty, imprecision and vagueness associated with human judgement are represented by linguistic scales (Shafiee, 2015; Animah, 2018).

The triangular fuzzy number (TFN) and the trapezoidal fuzzy number (TZFN) have been widely used for risk and reliability analysis of industrial plants. Let x, a_1, b_1, c_1, $d_1 \in R$. A triangular fuzzy numbers is defined by three numbers expressed as (a_1, b_1, c_1), where $a_1 \leq b_1 \leq c_1$ represent the lower bound, mean bound and upper bound, respectively. The fuzzy membership function $\mu_{\tilde{a}}(x)$ is a continuous function defined on a closed interval [0, 1], and its mathematical function is expressed as:

$$\mu_{\tilde{a}}(x) = \begin{cases} \dfrac{x-a_1}{b_1-a_1} & for \quad a_1 < x \leq b_1 \\ \dfrac{c_1-x}{c_1-b_1} & for \quad b_1 < x < c_1 \\ 0 & otherwise \end{cases} \tag{2}$$

Similarly, the trapezoidal fuzzy numbers can be defined by four numbers expressed as (a_1, b_1, c_1, d_1), and its membership function is given by:

$$\mu_{\tilde{a}}(x) = \begin{cases} \dfrac{x-a_1}{b_1-a_1} & for \quad a_1 < x < b \\ 1 & for \quad b_1 \leq x \leq c_1 \\ \dfrac{d_1-x}{d_1-c_1} & for \quad c_1 < x < d_1 \\ 0 & otherwise \end{cases} \tag{3}$$

Over the years, fuzzy set theory has been combined with classical risk assessment tools to produce fuzzy based risk assessment methodologies for assessing the risk and reliability of complex systems in safety critical industries. Fuzzy ETA (Kenarangui, 1991; Fu *et al.*, 2018), fuzzy FTA (Yuhua and Datao, 2005; Yazdi *et al.*, 2017; Moeinedini *et al.*, 2018; Piadeh *et al.*, 2018), fuzzy FMEA (Baykasoğlu and Gölcük, 2017; Karatop and Sinan, 2017; Orouei and Jahan, 2017), fuzzy BN, fuzzy PN (Chang *et al.*, 2018; Zhou and Reniers, 2017; Zhou *et al.*, 2017; Zhou *et al.*, 2017) and fuzzy Markov chain (Fu *et al.*, 2012) are examples of the common fuzzy based risk assessment tools.

3.2.11 Markov chain model

This is a sophisticated quantitative method based on diagrammatic modelling which allows for inclusion of transitions between different states. This approach is suitable for modelling the risk of dynamic systems. A Markov chain describes a system whose state changes over time. The changes can be modelled by probability distributions with a simple sort of dependence structure, where the conditional distribution of future states of the system depends only on its present state and not at all on its past states. According to Kabir and Papadopoulos (2018), information such as components' failure modes, failure sequence and spare parts availability can also be incorporated into Markov model for safety and reliability analysis, where the failure or repair rate of components denote the transition rates.

3.2.12 Computational fluid dynamics (CFD)

The use of computational fluid dynamics (CFD) as a risk analysis tool is gaining popularity in the LNG sector. This is because CFD models can take different factors such as wind speed, wind direction, leak rate, location of leaks, path of release and other obstacles into account for risk evaluation. In addition, CFD models are suitable when a comprehensive risk analysis study with sensitivity analysis is required. In the application of CFD for risk analysis, a number of mathematical models are formulated. These models combine the probability of failure of an event and its corresponding consequences with environmental factors to evaluate the risk. The use of this powerful tool does not only enable LNG facilities to set the appropriate safety tolerance limits for accident events during siting and operations but also can provide decision makers with appropriate information for risk reduction.

3.2.13 Hybrid decision making tools

Majority of the individual risk analysis tools have practical limitations. In order to overcome the limitations of the individual tools and enhance their performance, some studies have integrated two or more individual risk analysis tools. Some of the common hybrid risk analysis tools used in the LNG sector include: combined FTA and ETA, check list and FMEA, ETA and PHAST simulation (https://www.usgs.gov/software/phast-a-computer-program-simulating-groundwater-flow-solute-transport-and-multicomponent), Bayesian–LOPA, non-linear finite element method (FEM) and BN, formal safety assessment (FSA) and fuzzy evidential reasoning (FER), FTA and cause-consequence diagram, risk matrix and FER and FTA, dynamic process simulation and Monte Carlo method, FMECA and HAZOP, ETA and CFD, etc.

The results of the review for risk analysis tools are shown in Table 3. The results indicate that majority of the papers have applied integrated risk analysis tools (19 out of 66), followed by individual risk analysis tools (18 out of 66) and then fuzzy-based analysis tools (7 out of 66). The rest of the papers were not clear on the type of tools they used for risk analysis. Among the individual risk analysis tools, ETA was found to be the most commonly used tool, followed by BN and CFD, whereas Markov chain method and PN have been rarely used for risk analysis in the LNG sector.

3.3 Data sources

In order to make appropriate decision, risk analysts requires good quality quantitative and qualitative data. In many cases, these data are obtained from some popular sources such as OREDA handbook, UK HSE databases, regulatory agencies' reports, industry datasets, and experts' consultations. In what follows, some of the popular data sources used for risk analysis in the LNG sector are briefly described.

3.3.1 Offshore and onshore reliability data (OREDA)

The OREDA database (https://www.oreda.com/) contains high quality reliability data collected from both offshore and onshore oil and gas equipment over a period of time. The reliability information in OREDA handbook has been used by researchers, practitioners, scholars and other stakeholders in the oil and gas industry in order to evaluate the reliability, availability, maintainability (RAM) of safety, production and environmental critical systems. There are two volumes of the handbook, volume 1 presents information on topside equipment and volume 2 presents information on subsea equipment. Since the beginning of the OREDA project in the 80's, six different editions of the handbook have been published; 1984 (1st edition), 1992 (2nd edition), 1997 (3rd edition), 2002 (4th edition), 2009 (5th edition) and 2015 (6th edition). The structure of the newest edition published in 2015 includes two parts. The first part describes the OREDA project and the second part presents the data collection process as well as the procedures employed to obtain the reliability data.

3.3.2 Pipeline and riser loss of containment (PARLOC)

Over the years, the pipeline and riser loss of containment (PARLOC) database (https://oilandgasuk.co.uk/parloc/) has become a preferred source of information for risk assessment of pipelines and risers in the oil and gas industry. It contains data on generic loss of containment incidents that have occurred on pipelines and risers in the UK continental shelf (UKCS). PARLOC data can help designers and operators to validate design and operational safety requirements for pipelines in the LNG sector.

3.3.3 UK HSE databases

The UK HSE databases (http://www.hse.gov.uk/pesticides/topics/databases.htm) contain details of equipment used in the petroleum industry and their corresponding failure rates and event data for risk assessment. The failure rate and event data present in these databases are generic, since they are obtained from risk assessment tools. In the absence of failure rate data for some specific systems or components, the information contained in the failure rate and event document can be a good starting point for risk analysis in the LNG sector.

3.3.4 Experts' consultations

Risk analysts require the use of good quality data for decision making with high degree of confidence. However, in some instances, when the required data is not available, limited or difficult to collect, experts' judgements become the only source of information. The experts' judgement is based on the knowledge and experience of experts in a particular field. Elicitation of experts' opinion is the frequent method used to obtain data. According to Rosqvist (2003), the elicitation process requires the use of decision makers, facilitators, normative experts, domain experts and stakeholders. In order to obtain the required data through the elicitation process, there should be a structured interaction (i.e. face to face, telephone, etc.) between the facilitator and experts. In the LNG sector, failure modes and causes, failure rates, mean time to failure (MTTF), economic impact of incidents, type of model to be used for analysis as well as interpreting data from sensors are examples of data that may be obtained through experts' consultations for risk assessment. For more details on how to use experts' judgement for risk assessment, see Mayer and Booker (1991).

From Table 3, we observe that several databases have been used for risk analysis in the LNG sector. Out of 59 papers reviewed under this category, eight papers utilized historical data, 11 papers relied on experts' judgments, one paper used experimental data, three papers utilized reliability data, one paper used data from software packages, 4 papers applied OREDA dataset, two papers used datasets in safety organizations, one paper combined data from literature with experts' judgment, and four papers utilized generic data from published literature and industry reports. In addition, ten studies used data from two or more databases for their analysis and the rest of the studies did not indicate the source of the data used in their analysis.

3.4 Output/strategy

While reviewing the literature, we found that risk analysis methodologies and tools in the LNG sector have been applied as a decision support tool for risk assessment, risk-based maintenance (RBM) strategy, risk-based inspection (RBI) strategy, risk-based inspection and maintenance (RBIM) strategy, risk verification strategy, safety analysis, shutdown strategy, availability estimation, accident modelling, hazard ranking, etc.

The results of the review for risk analysis outputs and strategies are shown in Table 3. 39 papers proposed methods for risk assessment, whereas the rest of the papers proposed methods for safety analysis, risk verification, risk reduction, risk-based shutdown management strategy, RBM, accident modelling, hazard ranking, risk-based availability estimation, dynamic risk failure monitoring, risk-based design, corrosion protection and maintenance optimization.

Table 3. Output, analysis tools and data sources

3.5 Applications

LNG as fuel is used in wide range of safety critical industries with additional responsibility of environmental management being core to their operations. This study identified four different subsectors in the LNG sector that have reported conducting risk assessments for their own systems or assets. These include: LNG carriers and LNG fuelled ships, LNG terminals and stations, LNG offshore floating units, and LNG plants. In what follows, the most important publications in each subsector are briefly reviewed.

3.5.1 LNG carriers and LNG fuelled ships

Han *et al.* (2008) performed structural risk analysis of Gaz Transport/Technigas (GTT) NO96 membrane-type LNG carriers operating from the Baltic Sea to Quebec, Canada. Vanem *et al.* (2008) presented a risk assessment model to support operations of sea-going LNG carriers. Montewka *et al.* (2010) calculated the collision risk between an LNG tanker and a harbour tug during mooring operations. Nwaoha *et al.* (2010) developed a genetic algorithm (GA) to model the cost of maintenance and repair of LNG carrier systems. Nwaoha *et al.* (2011) investigated the risk levels of LNG carrier systems by means of fuzzy evidential reasoning method. Parihar *et al.* (2011) applied CFD dispersion methodology to perform consequence analysis for an LNG deepwater port facility. Li and Huang (2012) evaluated the fire and explosion risk associated with LNG ships. Roldán *et al.* (2012) presented a risk-based approach to analyse the failure modes and consequences associated with cargo handling operation of LNG carrier. Berle *et al.* (2013) addressed the vulnerability in maritime transportation system by applying the formal vulnerability assessment approach using quantitative data. The approach was illustrated using a maritime LNG transportation system. Nwaoha *et al.* (2013) developed a new framework by combining risk matrix and FER method to identify and rank hazards associated with LNG carrier operations. Elsayed *et al.* (2014) used a fuzzy TOPSIS methodology to assess the risk of LNG carriers. Melani *et al.* (2014) applied BN to support risk-based analysis of LNG carrier operations. Noh *et al.* (2014) developed a risk-based approach by combining dynamic process method with Monte Carlo simulation to determine the risk of LNG fuel storage tanks in LNG-fuelled ships. Lee *et al.* (2015) assessed and compared the fire risk of two types of LNG fuel gas supply (FGS) systems used in marine vessels. Zhao *et al.* (2015) applied BN to assess the risk of accidents in LNG carrier anchoring system. Fu *et al.* (2016) proposed a quantitative risk assessment framework for determining the potential risk of leakage events in LNG-fueled vessels. Ahn *et al.* (2017) applied a fuzzy-based FMEA to conduct risk analysis of hybrid systems possessing an MCFC (molten carbonate fuel cell) and a gas turbine for marine propulsion. Jeong *et al.*

(2017) adopted probabilistic risk assessment approaches to determine the safety exclusion zone for LNG bunkering stations on LNG-fuelled ships. Souza *et al.* (2012) conducted risk analysis of a header failure in LNG carriers. Li and Tang (2019) proposed a structural risk analysis model based on Bayesian belief network (BBN) to assess the risk of hull girder collapse of a membrane LNG carrier after grounding. Sultana *et al.* (2019) assessed the feasibility of replacing conventional HAZOP analysis with a method called System Theoretical Process Analysis (STPA). The study further compared the results from applying STPA and conventional HAZOP analysis to ship-to-ship transfer system of LNG.

3.5.2 LNG terminals and stations

Shindo *et al.* (2000) developed an approach by combining FTA and ETA for risk analysis of a networked chemical plant. The validity of the approach was tested by applying it to assess the risks of LNG receiving terminal. Ochiai *et al.* (2005) applied the ASME's risk-based maintenance concept to quantitatively analyse the risks of LNG terminal. Ronza *et al.* (2006) presented a methodology for performing quantitative risk analysis on marine hydrocarbon terminals sited in harbours. Spitzenberger (2009) used comparative risk assessment approach to assess four different pipe-in-pipe alternatives for loading line design of LNG liquefaction offshore jetty system. Yun *et al.* (2009) estimated the potential risks of LNG terminals using LOPA. Chin and Saetren (2010) presented the results of a detailed risk analysis for an LNG export loading operation at a Jetty. Chu *et al.* (2013) developed a risk prediction model for LNG terminal station using the information diffusion theory. Sun *et al.* (2013) applied CFD simulations based on NFPA 59A (2013) to conduct risk assessment for most likely spill scenarios at LNG terminals/stations. Aneziris *et al.* (2014) presented an integrated risk assessment model for LNG terminals. Chu *et al.* (2014) assessed the risk of fire in LNG terminal stations using the information diffusion model. Vianello and Maschio (2014b) applied a quantitative risk assessment methodology to a case study of an FSRU terminal. Hamedifar *et al.* (2015) provided an overview of quantitative risk analysis methods for LNG and LPG marine terminals and transportation projects in North America. Martinez and Lambert (2015) proposed a risk assessment framework to identify, screen and prioritise different sources of risks in an LNG storage terminal. George *et al.* (2019) applied FMECA method to assess the risks of LNG unloading facility in an LNG terminal in South India. Yoon *et al.* (2019) proposed a collaborative quantitative risk analysis framework and applied it to three large LNG import terminals.

3.5.3 LNG offshore floating units

Dogliani (2002) performed a safety assessment on an offshore LNG storage and regasification unit. Ballesio *et al.* (2009) assessed risk of subsea cryogenic pipeline design and concluded that the pipeline is technically feasible from safety and functional point of view. Skramstad *et al.* (2010) presented a risk-based verification approach for process systems on an FLNG producing unit. Benyessaad *et al.* (2013) presented a risk and safety analysis study for a new LNG floating unit project in the offshore LNG industry. Dan *et al.* (2014) applied a quantitative risk assessment method to evaluate the risk of fire and explosion in an LNG-FPSO. Martins *et al.* (2014) proposed a hybrid BN model to analyse the risk of LNG regasification system on board FSRU vessels. Yeo *et al.* (2016) developed an approach employing BN to perform dynamic safety analysis for offloading process in FLNG platforms.

3.5.4 LNG plants

Bozzolsco (2005) applied quantitative risk assessment at the early stages of a project to select site for the construction of LNG plant. Kim *et al.* (2005) employed FTA to identify and estimate the risks associated with membrane-type LNG storage tank. Kolodziej *et al.* (2009)

applied a concept risk assessment (CRA) technique to generic FLNG, Compressed Natural Gas (CNG), and Floating Gas to Liquids (FGTL) technology concepts by estimating the comparative risk measurement of Personnel Risk Exposure (PRE) and Cumulative Risk Factor (CRF). Raj and Lemoff (2009) discussed the risk evaluation approach incorporated into the mandatory annex in the 2009 edition of NFPA 59A (2013) and other possible approaches for conducting risk assessment on LNG facilities. Vinnem (2010) applied the Norwegian risk analysis approach to support risk-informed decision making in siting LNG facilities of urban areas in Norway. Tanabe and Miyake (2011) proposed an approach for functional safety requirement evaluation as a criterion for design of emergency systems. The approach was verified by applying it to an onshore LNG plant, in order to provide the risk reduction criteria and establish the design requirements for the emergency system. Keshavarz *et al.* (2012) developed a risk-based shutdown management strategy for LNG units. Khalil *et al.* (2012) presented a novel cascaded fuzzy-LOPA method for risk assessment in the natural gas industry. In Rathnayaka *et al.* (2012), a novel accident investigation model was developed using the System Hazard Identification and Prediction and Prevention (SHIPP) methodology. The methodology was tested and validated using LNG facility. Ahmed *et al.* (2015) developed a risk-based availability model using Markov method. The model was applied to evaluate the availability of gas sweetening unit of a natural gas plant. Mcinerney *et al.* (2014) proposed a new quantitative risk criteria for US LNG facilities. Vianello and Maschio (2014a) applied a quantitative risk assessment technique to analyse the risk of Italy's high pressure natural gas distribution network. Vianello and Maschio (2014b) determined the safety and security risks of new and alternative technologies for LNG re-gasification unit. Giardina and Morale (2015) applied an integrated FMECA and HAZOP methodology to analyse the risk of LNG storage facilities under construction in Porto Empedocle, Italy. Stavrou *et al.* (2016) employed a Fuzzy Inference System (FIS) methodology for dynamic monitoring of risk of failures in LNG site operations. Renjith *et al.* (2018) applied fuzzy FMECA to assess the risks of LNG storage facilities. Baalisampang *et al.* (2019) proposed a framework and applied it to assess the risks of LNG processing plant considering accidental LNG release, including vaporisation, a pool fire and Vapour Cloud Explosion (VCE). Badida *et al.* (2019) applied a fuzzy FTA method to evaluate the risks of oil and natural gas pipelines. Kong *et al.* (2019) provided a vital guide for formulating energy policy aimed at assessing the risks associated with natural gas importation.

4. Discussion of findings

This paper provides an overview of risk analysis application in the LNG sector. A total of 66 papers have been reviewed, comprising 47 journal articles and 19 conference proceedings. Figure 1 represented a bar chart showing the number of scientific works by year of publication. It was observed that literature on risk analysis application in the LNG sector has been growing in the last two decades with majority of the papers appearing during the last decade (2009– 2019). It can therefore be projected that more publications in this field of study may be expected in the next coming years. In Figure 2, the proposed framework underpinning the categorization of the state-of-the-art publications on risk analysis application in the LNG sector is introduced. To this end, the categories, listed in Section 2.2 are used as the structure to further discuss the findings of the review.

4.1 Risk analysis methods

On comparing qualitative, quantitative and semi-qualitative risk analysis methods (Table 1), qualitative risk analysis methods which are considered the quickest and the simplest, are least reported in literature among the three categories of risk analysis methods applied in the LNG sector. This may imply that qualitative risk analysis methods are deficient in their application because of the high hazards in the LNG sector which can lead to catastrophic accidents resulting in injuries, fatalities, significant economic loss and reputation damage. It can also be observed from Table 1 that semi-qualitative risk assessment methods which have advantage of compensating for the limitations of the both qualitative and quantitative methods is gradually gaining popularity in the LNG sector, although international regulations advocate for the use of quantitative risk assessment methods for risk analysis in safety critical industries such as the LNG sector (CCPS, 1999; NFPA 59A, 2013).

On comparing probabilistic and deterministic risk analysis methods (Table 1), it is not surprising that 46.8% of the studies have reported on the application of probabilistic methods as opposed to 43.5% for deterministic methods. This is because probabilistic risk assessment methods are suitable for evaluating the risk of complex engineering assets with multiple risks such as LNG facilities, nuclear plants and chemical processing plants (Tixier *et al.*, 2002). Also, very few studies have utilized the hybrid probabilistic and deterministic methods for risk assessment in the LNG sector.

Risk analysis methods continue to play a critical role throughout the life cycle of safety critical assets from design, construction, installation, operation, maintenance to decommissioning. CRA approaches have some limitations and key amongst them is the inability to update risk analysis results when new information emerges. This has led to the development of DRA approaches with the potential of overcoming the limitations of the CRA approaches. DRA approaches are capable of dynamically updating risk analysis results when new information emerges. However, as can be seen in Table 2, significant number of studies continues to apply the CRAs during risk analysis in the LNG sector, regardless of the limitations. This means that a lot more research is required to demonstrate the capabilities and advantages of using DRA to practitioners and researchers.

4.2 Risk analysis tools, output strategies and data sources

It can clearly be seen from Table 3 that integrated risk analysis tools are the greatest contributor in literature as far as risk analysis application in the LNG sector is concerned. Although it is well established in literature that fuzzy based approaches can deal with uncertainties, vagueness and imprecisions associated with human judgement during risk assessment, the result indicates that less studies have applied fuzzy based approaches to support risk analysis in the LNG sector.

Fuzzy risk analysis tools such as FER, fuzzy-LOPA, fuzzy-TOPSIS, Fuzzy Inference System (FIS) and fuzzy-based FMEA/FMECA are some fuzzy based approaches developed for risk analysis in the LNG sector, whereas ETA, FTA, BN and CFD are some of the individual tools combined with others. This is not surprising because these tools are very suitable in tackling complex risk problems, and therefore, combining them with certain tools can help overcome the limitations of those tools by enhancing their performance.

As can be seen from Table 3, expert judgment appears to be the most dominant source of data for risk analysis in the LNG sector. The implication of this finding is that there may be paucity of good quality data to support risk analysis in the LNG sector. Furthermore, when linking data sources to risk analysis tools, it is observed that most studies utilizing DRA approaches such BN and Monte Carlo simulation rely on information from data handbooks, technical reports and historical data for risk analysis. Thus, in order for the LNG sector to shift toward the use of DRA approaches for risk analysis, good quality data must be available to decision makers.

4.3 Applications

The adoption of LNG as an environmentally friendly source of fuel across several industries has led to dramatic development of LNG infrastructure such as LNG carriers, LNG terminals, stations and jetties and onshore and offshore LNG processing facilities. Figure 3 represents a pie chart showing percentages of studies in relation to risk analysis in different LNG subsectors.

Figure 3. Distribution of papers according to their application areas in the LNG sector.

As shown in Figure 3, the LNG carriers and LNG fuelled ships sector with 21 reported studies has received the most attention in the LNG sector, followed by LNG plants (19), terminals and stations (15) and LNG offshore floating units (7).

The statistics above indicate wide acceptance of LNG as an alternative environmentally friendly fuel with the potential of reducing emissions compared to conventional fuels. Thus, a number of ships are now handling LNG as cargo or fuel for running shipboard machinery. This may have accounted for the increase in number of papers reporting on risk assessment for LNG carriers and LNG fuelled ships. According to Animah *et al.* (2018), the use of LNG by ships as an alternative fuel is considered as one of the most viable ways ships can comply with the strict emission requirements set out by the International Maritime Organization (IMO). On another hand, the increase in LNG infrastructure will mean that assets and personnel working in the LNG sector will be exposed increased health and safety risks. Thus, stakeholders must make conscious effort to enhance the safety of LNG facilities through the application of proven risk analysis methodologies.

5. Conclusions

The use of risk analysis has contributed to accident prevention as well as enhancing the safety and reliability of critical systems in the LNG sector over the past two decades. In this paper, we have reviewed 66 international journal articles and conference papers published between January 2000 and June 2019 about the application of risk analysis in the LNG sector. Based on the current practices in the LNG sector, we proposed a comprehensive classification framework according to risk analysis methods, risk analysis tools, output/strategy, data sources and application.

The proposed classification framework covered more aspects of risk analysis process compared with the existing review articles on risk analysis which classified scientific literature according to only risk assessment methods. Thus, this paper reveals the holistic issues and future perspectives on application of risk analysis in the LNG sector. Our classification scheme will not only help researchers and practitioners to identify and classify potential risk factors in the LNG sector but can also serve as a starting point in risk decision-making, since it provides useful insights on the type of risk analysis method, risk assessment tool, and the data sources may be applicable for a particular case.

The review of scientific literature revealed that the number of publications on risk analysis application in the LNG sector is gradually increasing, with the year 2014 recording the highest number of publications. In spite of remarkable progress in the application of risk analysis in the LNG sector, there are still opportunities for further research in this area of study. Some of the potential future research directions are provided below:

1. There is clear research gap in the area of risk assessment type, where approximately 71% of the published literature on LNG risk analysis have used conventional type of risk assessment as opposed to 29% which have employed dynamic risk assessment.
2. The difficulty in obtaining good quality real-life data has been expressed by researchers as one of the key challenges in relation to conducting risk analysis in safety critical

industries (Berle *et al.*, 2013). The introduction of electronic data collection platforms in different industries including the LNG sector can provide a solution to this problem. Electronic data collection platforms have the capability of providing decision makers with good quality data for the right decision.

3. Though Petri net and Markov chain are two powerful quantitative risk assessment tools, this review revealed that very few papers have reported using these methods for risk analysis in the LNG sector. Therefore, future research on risk analysis in the LNG sector can use these methods.
4. Our findings indicated that few attempts have been made to use MCDM methods to solve risk-based problems in the LNG sector. Therefore, there is a critical need to develop MCDM methods which can take into account environmental, safety, economic and social issues into risk-based decision making. MCDM has the capability of overcoming the limitations of some risk analysis methodologies.
5. The trend towards the development of more efficient integrated risk analysis tools (combining techniques) to evaluate risk of complex and dynamic assets such as LNG plants is growing steadily. We suggest that these tools should be further developed to incorporate sensitivity analysis to deal with uncertainties associated risk analysis in the LNG sector.

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Table 1. Distribution of the papers utilizing risk analysis methodologies.

Reference	Qualitative	Quantitative	Semi-qualitative	Probabilistic	Deterministic	Hybrid Deterministic-Probabilistic
Shindo *et al.* (2000)	√				√	
Dogliani (2002)			√			√
Bozzolsco (2005)		√		√		
Kim *et al.* (2005)		√		√		
Ochiai *et al.* (2005)		√			√	
Ronza *et al.* (2006)		√		√		
Han *et al.* (2008)		√			√	
Vanem *et al.* (2008)			√			√
Ballesio *et al.* (2009)	√				√	
Kolodziej *et al.* (2009)		√			√	
Raj and Lemoff (2009)		√		√		
Spitzenberger (2009)		√		√		
Yun *et al.* (2009)			√	√		
Chin and Saetren (2010)			√			√
Nwaoha *et al.* (2010)		√			√	
Montewka *et al.* (2010)		√		√		
Skramstad *et al.* (2010)	√				√	
Vinnem (2010)			√			√
Nwaoha *et al.* (2011)			√		√	
Tanabe and Miyake (2011)		√		√		
Keshavarz *et al.* (2012)		√			√	
Khalil *et al.* (2012)			√	√		
Li and Huang (2012)		√			√	
Rathnayaka *et al.* (2012)			√	√		
Roldán *et al.* (2012)			√	√		
Souza *et al.* (2012)		√		√		
Berle *et al.* (2013)		√		√		
Benyessaad *et al.* (2013)			√		√	
Chu *et al.* (2013)		√				
Nwaoha *et al.* (2013)			√		√	
Sun *et al.* (2013)		√			√	
Aneziris *et al.* (2014)			√	√		

Chu *et al*. (2014)		√				
Dan *et al*. (2014)		√		√		
Devkaran (2014)		√		√		
Elsayed *et al*. (2014)			√		√	
Melani *et al*. (2014)			√			√
Martins (2014)		√		√		
Noh *et al*. (2014)		√		√		
Vianello and Maschio (2014a)		√			√	
Vianello and Maschio (2014b)		√		√		
Ahmed *et al*. (2015)		√		√		
Hamedifar *et al*. (2015)			√	√		
Giardina and Morale (2015)			√		√	
Lee *et al*. (2015)		√		√		
Martinez and Lambert (2015)			√		√	
Zhao *et al*. (2015)			√	√		
Fu *et al*. (2016)		√		√		
Jewitt (2016)		√			√	
Martins *et al*. (2016)		√		√		
Yeo *et al*. (2016)			√	√		
Stavrou *et al*. (2016)			√		√	
Ahn *et al*. (2017)			√		√	
Jeong *et al*. (2017)		√		√		
Hogelin *et al*. (2018)	√				√	
Renjith *et al*. (2018)			√		√	
Baalisampang *et al*. (2019)			√	√		
Badida *et al*. (2019)			√		√	
George *et al*. (2019)			√		√	
Leoni *et al*. (2019)			√			√
Li and Tang (2019)		√		√		
Kong *et al*. (2019)			√		√	
Sultana *et al*. (2019)	√				√	
Yoon *et al*. (2019)		√			√	

Table 2. Distribution of the papers utilizing conventional and dynamic risk analysis.

Year	No	Conventional	No	Dynamic
2000	1	(Shindo *et al.*, 2000)	0	
2001			0	
2002	1	(Dogliani, 2002)	0	
2003	0		0	
2004	0		0	
2005	3	(Bozzolsco, 2005; Kim *et al.*, 2005; Ochiai *et al.*, 2005)	0	
2006	1	(Ronza *et al.*, 2006)	0	
2007	0		0	
2008	2	(Han *et al.*, 2008; Vanem *et al.*, 2008)	0	
2009	3	(Ballesio *et al.*, 2009; Kolodziej *et al.*, 2009; Spitzenberger, 2009)	1	(Yun *et al.*, 2009)
2010	2	(Skramstad *et al.*, 2010; Vinnem, 2010)	2	(Chin and Saetren, 2010; Montewka *et al.*, 2010)
2011	2	(Nwaoha *et al.*, 2011; Tanabe and Miyake, 2011)	0	
2012	6	(Keshavarz *et al.*, 2012; Khalil *et al.*, 2012; Li and Huang, 2012; Rathnayaka *et al.*, 2012; Roldán *et al.*, 2012; Souza *et al.*, 2012)	0	
2013	3	(Benyessaad *et al.*, 2013; Chu *et al.*, 2013; Nwaoha *et al.*, 2013)	2	(Berle *et al.*, 2013; Sun *et al.*, 2013)
2014	6	(Aneziris *et al.*, 2014; Dan *et al.*, 2014; Devkaran, 2014; Elsayed *et al.*, 2014; Vianello and Maschio, 2014a, 2014b)	3	(Martins et al., 2014; Melani *et al.*, 2014; Noh *et al.*, 2014)
2015	5	(Ahmed *et al.*, 2015; Giardina and Morale, 2015; Hamedifar *et al.*, 2015; Lee *et al.*, 2015; Martinez and Lambert, 2015)	1	(Zhao *et al.*, 2015)
2016	3	(Fu *et al.*, 2016; Jewitt, 2016; Martins *et al.*, 2016)	2	(Stavrou *et al.*, 2016; Yeo *et al.*, 2016)
2017	2	(Ahn *et al.*, 2017; Jeong *et al.*, 2017)	0	
2018	2	(Hogelin *et al.*, 2018; Renjith *et al.*, 2018)	0	
2019	6	(Baalisampang *et al.*, 2019; Badida *et al.*, 2019; George *et al.*, 2019; Kong *et al.*, 2019; Sultana *et al.*, 2019; Yoon *et al.*, 2019)	2	(Leoni *et al.*, 2019; Li and Tang, 2019)

Table 3. Output, analysis tools and data sources

Ref	Output/strategy	Tools applied	Data sources
Shindo *et al.* (2000)	Risk assessment	Combination of FTA and ETA	-
Dogliani (2002)	Safety analysis	Application of IGC code	-
Bozzolsco (2005)	Site selection and plant layout	Software tool	-
Kim *et al.* (2005)	Risk assessment	FTA	Generic data
Ochiai *et al.* (2005)	Risk assessment	API and ASME quantitative risk evaluation method	-
Ronza *et al.* (2006)	Risk assessment	ETA	Historical data
Han *et al.* (2008)	Risk assessment		-
Vanem *et al.* (2008)	Risk assessment	ETA	Historical data, published damage statistics and expert judgement
Ballesio *et al.* (2009)	Risk assessment	Check list and FMEA	Expert knowledge and Engineering judgement
Kolodziej *et al.* (2009)	Risk assessment	Concept risk assessment (CRA) model	General arrangement drawings and a 3D CADView model
Spitzenberger (2009)	Risk assessment	ETA and PHAST simulation software	Historical data
Yun *et al.* (2009)	Risk assessment	Bayesian–LOPA	OREDA database
Chin and Saetren (2010)	Risk assessment	BN	Expert judgement
Montewka *et al.* (2010)	Risk assessment	Non-linear finite element method (FEM) and BN	Historical data
Nwaoha *et al.* (2010)	Risk based maintenance	Genetic algorithm	Literature review
Skramstad *et al.* (2010)	Risk based verification	Expert technical assessment and literature review	-
Nwaoha *et al.* (2011)	Risk assessment	Combination of the FSA methodology and fuzzy evidential reasoning (FER)	Expert judgement
Tanabe and Miyake (2011)	Risk reduction	IEC 61508 and 61511	Historical data
Keshavarz *et al.* (2012)	Risk-based shutdown management strategy	Parameter estimation	OREDA database
Khalil *et al.* (2012)	Risk assessment	Cascaded-fuzzy-LOPA	Data obtained from PHA along with that from the look up tables.
Li and Huang (2012)	Risk assessment	Dow method, BLEVE model and VCE model	-
Rathnayaka *et al.* (2012)	Accident modelling	Combination of FTA and ETA	Historical data
Roldán *et al.* (2012)	Risk assessment	FTA and cause-consequence diagram	OREDA and UK HSE databases
Berle *et al.* (2013)	Risk assessment	Monte Carlo simulation	Expert judgment
Benyessaad *et al.* (2013)	Risk and safety studies	Design risk assessment flowchart	Historical data
Chu *et al.* (2013)	Risk assessment	Information diffusion theory	-
Nwaoha *et al.* (2013)	Hazards ranking in LNG carrier operations	Risk matrix and fuzzy evidential reasoning (FER) method and FTA	Expert judgement
Sun *et al.* (2013)	Risk assessment	CFD	Experimental data
Aneziris *et al.* (2014)	Risk assessment	Parameter estimation, ETA and FTA	OREDA database
Dan *et al.* (2014)	Risk assessment	ETA and PHAST software	E&P Forum and OGP data
Devkaran (2014)	Risk assessment	Risk assessment calculation in line with international	-

		standards (IEC 62305)	
Elsayed *et al.* (2014)	Risk assessment	Fuzzy-TOPSIS	Expert Judgement
Melani *et al.* (2014)	Risk assessment	Cause-Consequence Diagram and BN	OREDA and UK HSE databases
Martins *et al.* (2014)	Risk assessment	Hybrid BN	-
Noh *et al.* (2014)	Risk-based information	Dynamic process simulation combined with Monte Carlo method	OREDA database
Vianello and Maschio (2014a)	Risk assessment	ETA	Generic data
Vianello and Maschio (2014b)	Risk assessment	ETA and PHAST software	Generic data
Ahmed *et al.* (2015)	Risk-based availability estimation	Markov method	Available plant data and OREDA database
Hamedifar *et al.* (2015)	Risk assessment	Modelling	Historical data
Giardina and Morale (2015)	Safety analysis	Integrated FMECA and HAZOP	Data from risk analysis database software
Lee *et al.* (2015)	Risk assessment	ETA and CFD	Actual navigation data and UK HSE database
Zhao *et al.* (2015)	Risk assessment	BN	Experts' judgement
Fu *et al.* (2016)	Risk assessment	Integrated ETA and CFD	China academy of safety science and technology
Jewitt (2016)	Safety design analysis	CFD	-
Martins *et al.* (2016)	Risk assessment	PHAST Risk software	-
Yeo *et al.* (2016)	Risk assessment	BN	Generic data
Stavrou *et al.* (2016)	Dynamic risk failure monitoring	Fuzzy Inference System	Experimental data
Ahn *et al.* (2017)	Risk-based design	Fuzzy-based FMEA	Reliability data
Jeong *et al.* (2017)	Identify potential risks of LNG bunkering	Bespoke IQRA software	DNV frequency failure datasheets
Hogelin *et al.* (2018)	Safety and corrosion protection	Risk Assessment Process Flowchart	Historical data
Renjith *et al.* (2018)	Risk assessment	Fuzzy FMECA	Expert judgement
Baalisampang *et al.* (2019)	Consequence modelling and risk assessment	Grid based approach	Expert judgement
Badida *et al.* (2019)	Risk assessment	Fuzzy FTA	Expert judgement
George *et al.* (2019)	Risk assessment	Fuzzy FMECA	Expert judgement
Leoni *et al.* (2019)	Optimization of maintenance time schedule	BN	Combination of literature and experts judgement.
Li and Tang (2019)	Risk assessment	BBN	Statistical data
Sultana *et al.* (2019)	Hazard analysis	System Theoretical Process Analysis (STPA)	Expert judgement
Yoon *et al.* (2019)	Risk assessment	Collaborative QRA	LNG equipment reliability data book of Korea gas corporation (KOGAS) and technical assessment reports

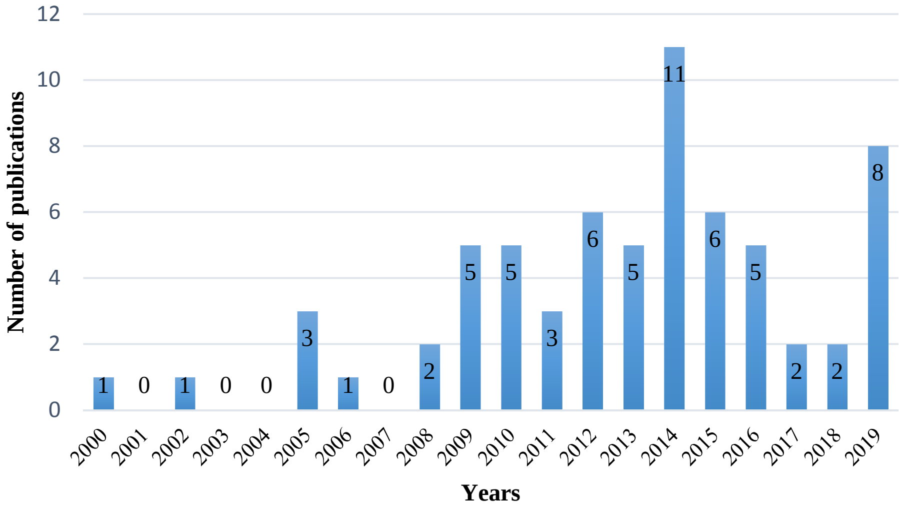

Figure 1. Distribution of the number of papers over the past two decades.

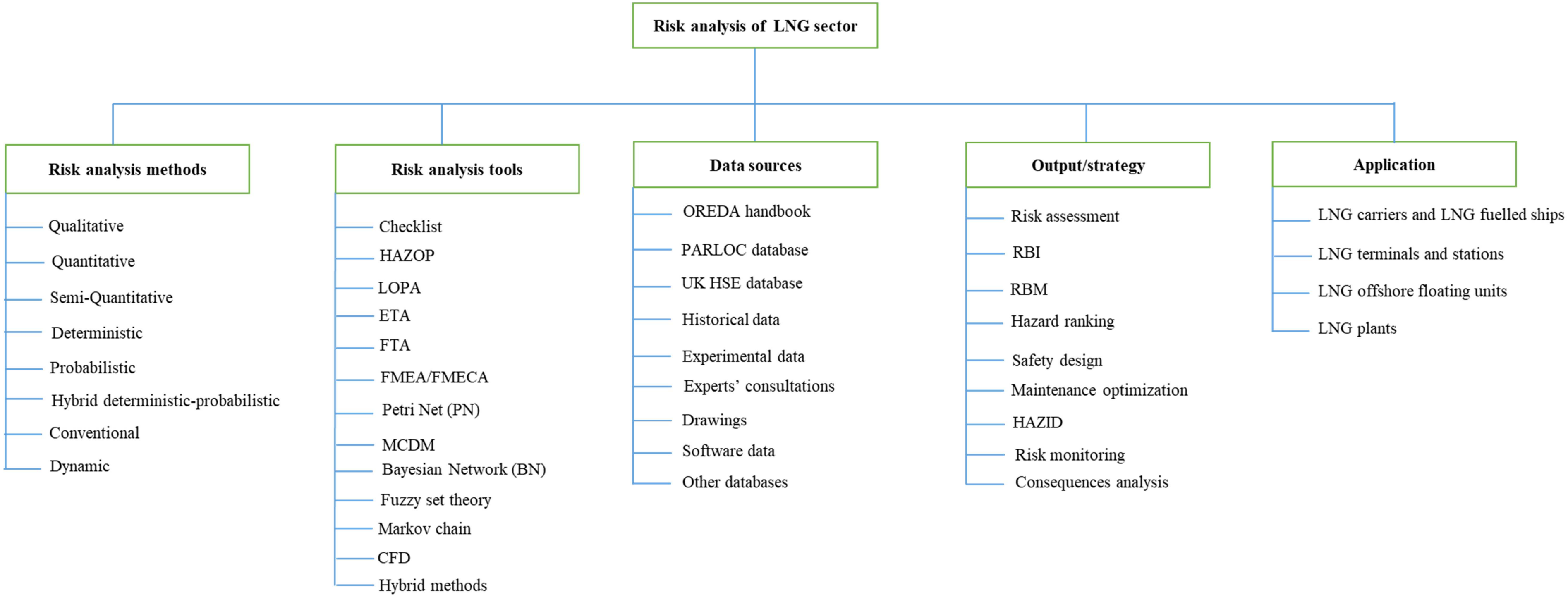

Figure 2. Classification framework for risk analysis in the LNG sector

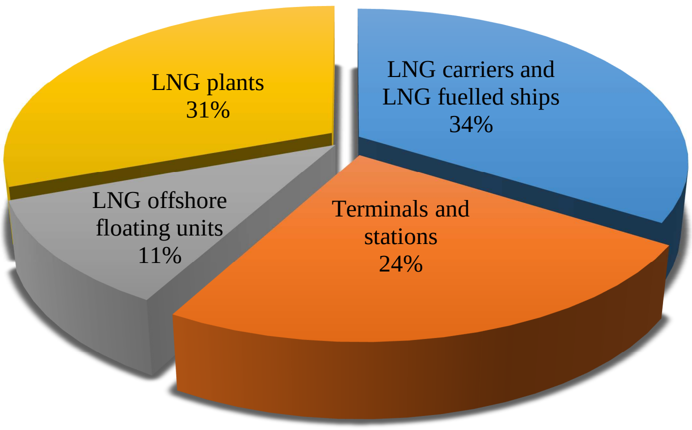

Figure 3. Distribution of papers according to their application areas in the LNG sector.

RESEARCH HIGHLIGHTS

- To systematically review the published literature about risk analysis in the LNG sector.
- To identify various applications of risk analysis in LNG carriers, LNG fuelled ships, LNG terminals and stations, LNG offshore floating units, LNG plants, etc.
- To analyse the state-of-the-art of risk analysis strategies, methods, tools and techniques in the LNG sector.
- To identify application areas and data sources (OREDA handbook, published literature, UK HSE databases, regulatory agencies' reports, industry datasets, and experts' consultations) to apply risk analysis to the LNG sector.