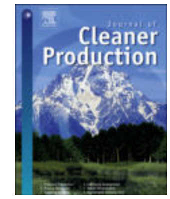
Journal of Cleaner Production 279 (2021) 123583

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro



Safety and security of oil and gas pipeline transportation: A systematic analysis of research trends and future needs using WoS

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ARTICLE INFO

Article history:
Received 27 October 2019
Received in revised form
22 July 2020
Accepted 31 July 2020
Available online 3 August 2020

Handling editor: Prof. Jiri Jaromir Klemeš

Keywords:
Oil and gas pipelines
Safety and security
Sustainable transportation
Bibliometric analysis
Research evolution

ABSTRACT

The terrorist attack on the Abqaiq oil plant in Saudi Arabia on September 14, 2019 attracted global attention to the significant role of safety and security in the sustainable oil and gas supply chain and the vulnerability of supply infrastructures subject to intentional and unintentional damages. Different from other oil and gas supply infrastructures, oil and gas pipelines may be more vulnerable to accidental, natural and intentional threats due to their widespread distribution. Therefore a systematic and thorough review is carried out to investigate safety and security of oil and gas pipelines based on bibliometric analysis. First, a total of 598 publications between 1970 and 2019 related to safety and security of oil and natural gas pipelines was retrieved and refined from the database of Web of Science (WoS). The 598 publications are analyzed by the bibliometric software VOSviewer to obtain the temporal and regional distribution of publications, to identify "productive institutions" and "productive authors", and create the cooperation networks between institutions and authors. Besides, the evolution of research topics and research methods are identified based on keywords and bibliographic analysis. Moreover, the main research topics and research methods are analyzed to obtain insight into the research evolutions and trends. Risk assessment, leakage, and corrosion are the main topics while QRA, fuzzy theory and the Bayesian network are the most frequently used research methods. To further improve the sustainability of oil and gas pipelines, this study provides and discusses future research needs such as pipeline security, environmental sustainability, pipeline system resilience. According to these results, the research on risk assessment based on Bayesian network and consequence analysis using CFD may increase in the future. Besides, more research and guidelines on pipeline security, resilience, and environmental impacts to better protect pipelines, are expected.

1. Introduction

Oil and natural gas are the most used energies in the world, contributing to 57.5% global primary energy consumption (Dudley, 2019). Pipelines are critical infrastructure for the transportation of oil and natural gas, connecting producing areas to refineries, chemical plants, home consumers and business needs (Shaikh et al., 2017). In the United States, there are more than 190,000 miles of liquid petroleum pipelines and over 2.4 million miles of natural gas pipelines (including the distribution lines that serve homes, offices and businesses). This constitutes the largest pipeline network in the world (START, 2019).

However, oil and natural gas are flammable and explosive substances, usually delivered in high-temperature high-pressure conditions via pipeline networks. As a result, major accidents (Chen et al., 2020; Yang et al., 2020; Zeng et al., 2020b, 2020a; Wang et al., 2018, 2020) such as fire, explosion, and toxic release are likely to occur at oil and gas pipelines, resulting in casualties, economic losses, and environmental problems, thus reducing the

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https://doi.org/10.1016/j.jclepro.2020.123583

sustainability of pipeline transportation. On November 22, 2013, a series of explosions and fires occurred in Qingdao, China, resulting in 62 fatalities, 136 injuries, 8000 people evacuated, and damages to nearby buildings and vehicles. The explosions occurred in a drain when the vaporized crude oil from a pipeline leak was ignited by a leak repair operation (Zhu et al., 2015). Besides, oil and gas pipelines may be damaged by natural hazards such as earthquakes, floods, and lightning, resulting in potential adverse secondary consequences to the population, the environment, or the industrial activity itself. These events are commonly referred to as Natech events, responsible for approximately 5% of major industrial accidents (Cozzani et al., 2010; Huang et al., 2020).

Different from unintentional events, intentional attacks on energy supply systems may result in more severe consequences. In Nigeria, a total of 15,718 deliberate attacks on oil pipelines occurred during 1993–2008 (Anifowose et al., 2012). Deliberate attacks have been an obstacle to the sustainability of pipelines and the petroleum industry in Nigeria. Most recently, the Abqaiq oil plant was attacked by drones on September 14, 2019, leading to a 50% reduction in Abqaiq's oil production and a nearly 15% increase in the crude oil price (BBC, 2019). Due to the essential role in the sustainability of energy supply chain, modern society and economy, pipelines may be attacked by adversaries (e.g., terrorist attackers, thieves and criminals) (Chen et al., 2020), resulting in economic losses, casualties, environmental pollution, public panic, etc. (Rezazadeh et al., 2019; Ge et al., 2019, 2020).

Process safety research can be divided into six parts: technical safety issues, human error/human factors, management focus on HSE, safety management systems, safety culture, and knowledge management/communication safety (Amyotte et al., 2016). To protect oil and gas pipelines, many attempts have been made on technical safety such as accident risk assessment (Shahriar et al., 2012), corrosion risk assessment (Bertuccio and Moraleda, 2012), seismic vulnerability (Lanzano et al., 2013), and security risk assessment (Moore, 2013). Besides, research work on non-technical safety issues (e.g. human error, management focus on HSE, and safety culture) can also be available in the literature (Meshkati, 2006). However, to the best of the authors' knowledge, no systematic review of the safety and security research related to oil and gas pipelines can be found in the literature. Literature analysis is an effective way to gain insights into a given research domain and put forward the needs for future research. Bibliometric analysis is a statistical tool that can provide an overview of a large number of publications and identify cooperation relationships, co-citation similarities, main research topics and methods, and research trends in a research field, in a relatively short time. In recent years, Bibliometric analysis has been used to different research domains such as the sustainable development in small and medium-sized enterprises (Prashar and Sunder M, 2020), urban environmental governance (Wu et al., 2018), domino effects (Li et al., 2017) and safety leadership (Jing et al., 2020), etc. There is no bibliometric analysis of safety or security research related to oil and gas pipelines.

This study aims to provide an overview of the research related to the safety and security of oil and gas pipelines. The research questions are summarized as follows: (i) what are the characteristics of publication distribution, active journals, productive institutions, productive authors, and cooperation networks? (ii) What are the evolutions and trends of research topics and methods? (iii) What are the safety and security needs for developing a sustainable pipeline transportation system? The research methodology and data are illustrated in Section 2, followed by the bibliometric analysis results for research question (i) in Section 3. Section 4 analyzes the evolutions and trends of research topics and methods. A discussion on future needs is conducted in Section 5 and the conclusions are drawn in Section 6.

2. Methodology

A literature review methodology based on bibliometric analysis is developed to analyze the research domain of the safety and security of oil and gas pipelines. The methodology includes five procedures, as shown in Fig. 1.

According to the procedure, the first step is to collect extensive literature from the online library of the Delft University of Technology. The bibliometric data were collected on September 15, 2019, from the Web of Science Core Collection, excluding books (BKCI–S and BKCI-SSH) and conference proceedings (CPCI–S and CPCI-SSH). The publications in local journals and unpublished academic documents are excluded due to language barriers, unavailable permission, etc. The timespan is set from 1970 to 2019. The searching topics were as follows:

Topic: Safety OR security OR accident OR risk OR consequence OR probability OR fire OR explosion OR release OR leak OR failure OR Vulnerability OR fragility OR damage OR sabotage OR intentional OR attack OR Threat;

AND Topic: pipeline OR pipe;

AND Topic: oil OR gas OR natural gas OR petroleum OR subsea OR hazardous OR offshore OR onshore OR transportation.

The search resulted in 7460 bibliographic records. Based on the records extracted from the databases, Step 2 examined all the titles and abstracts thoroughly to further filter out references that are not closely related to the topic. Finally, 598 publications were selected as the database for bibliometric analysis of international research trends. It should be remarked that this database may not fully display the research in underdeveloped areas (e.g., Africa) since authors in those areas may prefer to publish research in local journals. A bibliometric analysis for the refined database is conducted in Step 3 (Section 3) using VOSviewer. The VOSviewer is a widely used bibliometric software for analyzing co-authorship relationships, co-citation relationships, and co-occurrence relationships, etc. (van Eck and Waltman, 2019;Yang et al., 2019, 2020). Based on the bibliometric analysis, the research trends and evolutions are analyzed in step 4 (Section 4). Finally, future research needs are discussed in Step 5 (Section 5).

3. Bibliometric analysis

In this section, bibliographic analysis is used to analyze the distribution of the collected publications over time, by journals and by regions as well as the cooperation between institutions and authors.

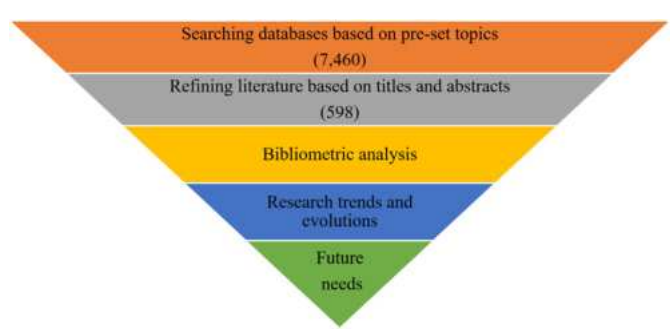

Fig. 1. Literature review methodology on the research related to safety and security of oil and gas pipelines in WoS.

3.1. Timeline distribution of publications

The temporal distribution of publication output is a significant indicator to reflect the popularity, importance and development trend of a scientific research issue, as shown in Fig. 2.

The cumulative number of publications is only 24 from 1970 to 2000 while it reached 598 in September 2019. The number of publications increased rapidly after 2004, following the severe pipeline explosion and fire accident at Ghislenghien, Belgium (Mahgerefteh and Atti, 2006). The publication trend is also consistent with the increasing trend of deliberate pipeline incidents in Nigeria (Anifowose et al., 2012). The annual number of publications reached 85 in 2018 which is over 21 times that in 2004. The average number of publications per year reached 31 during the most recent 15 years. The publication output follows exponential growth which indicates that the topic of safety and security of oil and gas pipelines has attracted increasing attention in the science and technology domain. Besides, the growth rate of the cumulative number of publications is increasing, indicating that the research on safety and security of oil and gas pipelines is still in the rapid development stage.

3.2. Regional distribution of publications

Based on institutional addresses, 56 countries are identified in the 598 publications related to safety and security of oil and natural gas pipelines. Fig. 3 shows the geographical distribution of these publications by countries. The number of publications is represented by a graduated color in the map, i.e., the darker the color, the larger the number of publications. These publications mainly originate from Asia (50.0%), Europe (32.8%) and North America (26.3%). It may be explained by the high consumption of oil and gas (70.4% in 2018) in the three areas. China has the most publications (192), followed by the USA (89), Canada (58), Italy (38), the UK (27), and Iran (22).

3.3. Source distribution of publications

The 598 publications were published in 247 academic journals. Only 22 journals published at least five papers on safety and security of oil and gas pipelines, which are called active journals in this study. Table 1 lists the top-10 most active journals concerning the domain of safety and security of oil and natural gas pipelines.

The Journal of Loss Prevention in the Process Industries with 75 publications and 1216 citations undoubtedly plays a dominant role in the domain, followed by Engineering Failure Analysis (25 publications) and Process Safety and Environmental Protection (23 publications). The Journal of Hazardous Materials and Reliability Engineering & System Safety have the highest citations per output (25), which may be related to their high impact factors (9.0 and 5.0). The analysis results indicate that the published research outcomes on the safety and security of oil and gas pipelines obtain more attention in safety and security (SS) journals than in engineering technical (ET) journals.

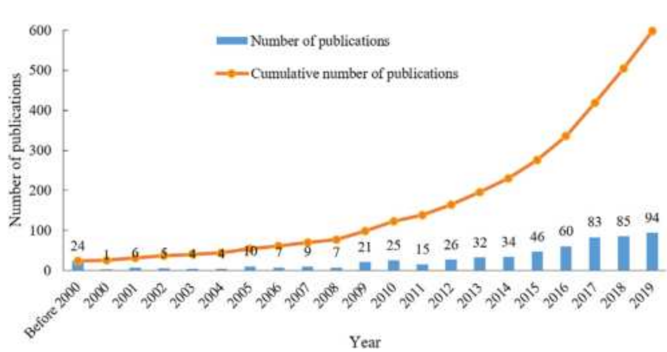

Fig. 2. Timeline distribution of the annual and cumulative number of publications on safety and security of oil and gas pipelines in WoS.

3.4. Cooperation network analysis

A total of 632 institutions and 1671 authors, identified from 56 countries, are involved in the 598 publications related to safety and security of oil and natural gas pipelines. To explore the research cooperation between different institutions and authors, two overlay visualization networks are developed using co-authorship analysis of VOSviewer, as shown in Fig. 4 and Fig. 5.

The nodes (circles) in the networks denote institutions (Fig. 4) or authors (Fig. 5) and their size depends on the number of publications of the institutions or authors. The curves represent the links between different institutions or different authors. The colors in the visualization networks represent cooperation clusters. As shown in Fig. 4, the institution cooperation network can be divided into three clusters. The largest cluster (in red) is around China University of Petroleum and Southwest Petroleum University. Most of the institutions in this cluster are located in China. Delft University of Technology and the University of Bologna lead the second cluster (in green) and play a bridge role in international cooperation on safety and security research related to oil and gas pipelines. The third cluster around Memorial University of Newfoundland consists of institutions mainly from North America and China. Fig. 6 shows the number of publications and citations in productive institutions with at least six publications. Nine of the sixteen institutions are in China and no single institution is from the USA. This observation reveals that scholars from the USA are widely distributed in different institutions while those research scholars in China are more centralized. Both the Memorial University of Newfoundland and the University of British Columbia are in Canada, and two other institutions are in Italy. The remaining three institutions are located in the Netherlands, Australia, and Italy, respectively. In total, only 76 in 632 institutions are presented in Fig. 4. It may be concluded that international cooperation in this domain needs to be improved.

In these productive institutions, multiple productive authors and their research cooperation can be identified, as shown in Fig. 5. The cooperation network consists of six clusters. Both the clusters led by Hong zhang (in red) and Laibin Zhang are from China University of Petroleum. The cluster led by Genserik Reniers and Valerio Cozzani (purple) consists of scholars in Europe. The authors from Iran form the cluster around Rouzbeh Abbassi (blue). Faisal Khan leads a cluster in Canada and has a lot of cooperation with scholars from China and Iran. The cluster around Guoming Chen consists of authors from China University of Petroleum (East China). Authors from the USA (the second productive country) and authors from Southwest Petroleum University (the second productive institution) are not labelled in the cooperation network due to limited cooperation. As a result, the research cooperation should be enhanced to better protect oil and gas pipelines. The most productive author is Faisal Khan (19), followed by Guoming Chen (12), Wei Liang (12) and Laibing Zhang (12). The publications authored by Faisal Khan, Wei Liang, Laibing Zhang, Rouzbeh Abbassi, Solomon Tesfamariam may obtain the most attention in terms of their high citations, as shown in Fig. 7.

4. Research trends and evolutions

To find out the main research topics related to the safety and security of oil and gas pipelines, a bibliographic coupling analysis is

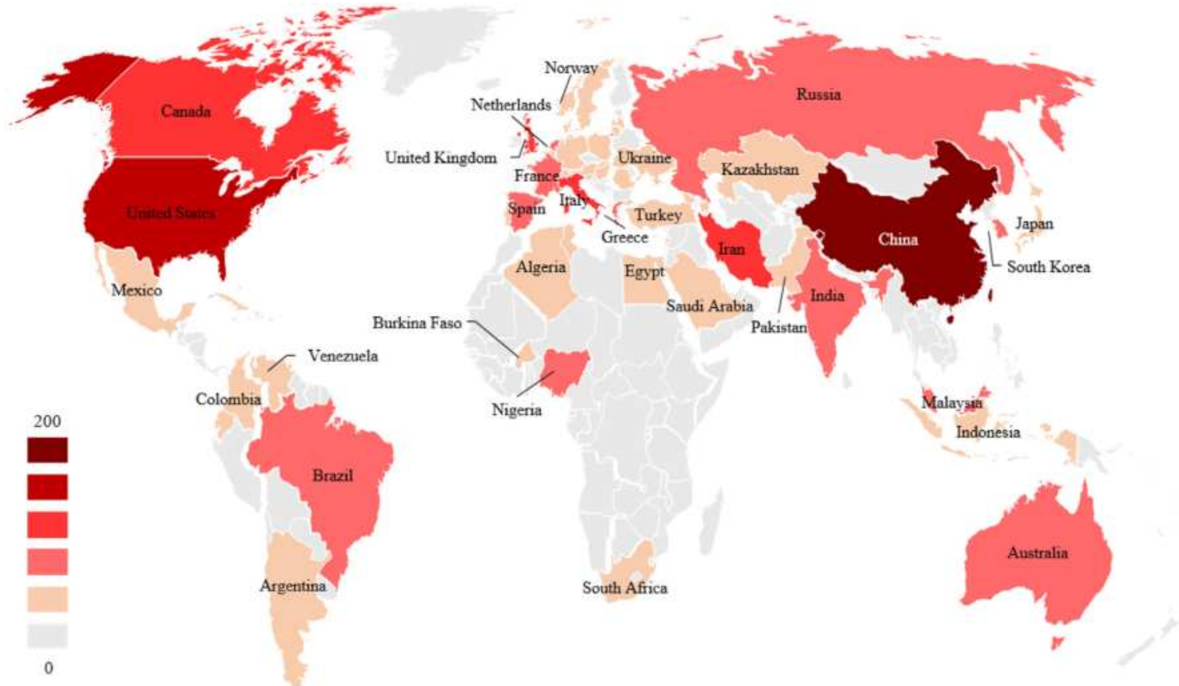

Fig. 3. Regional distribution of publications on safety and security of oil and gas pipelines in WoS.

Table 1
Top-10 most active journals on safety and security of oil and gas pipelines in WoS.

Journal	Journal categories	Papers	Citations	Average Citations	Impact factor (2019)
Journal of Loss Prevention in the Process Industries	SSJ	75	1216	16	2.8
Engineering Failure Analysis	SSJ	25	290	12	2.9
Process Safety and Environmental Protection	SSJ	23	150	7	5.0
Journal of Natural Gas Science and Engineering	ETJ	18	134	7	3.8
Journal Of Hazardous Materials	SSJ	16	404	25	9.0
Journal of Pressure Vessel Technology-transactions of the ASME	ETJ	16	58	4	1.1
International Journal of Pressure Vessels and Piping	ETJ	12	121	10	2.2
Journal of Machinery Manufacture and Reliability	ETJ	11	3	0	0.4
Journal of Pipeline Systems Engineering and Practice	ETJ	9	40	4	1.5
Reliability Engineering & System Safety	SSJ	9	228	25	5.0

SSJ**:** safety and security journals; ETJ: engineering technical journals.

conducted for the 598 publications. Fig. 8 shows the 116 publications with at least 10 citations. The circles denote publications and their size depends on the number of citations of the publications. Bibliographic coupling (represented by the link curve between publications) occurs when two publications reference an identical third publication. The color in the network represents a cluster. The network includes three clusters: red (top), green (left) and blue (right). The topic of each cluster can be determined by checking the title of all the publications in the network. The red (top) cluster consists of most publications (51), focusing on risk assessment and accident analysis. The topic of the green (left) cluster (38) is leakage while that in the blue (right) cluster (27) is corrosion. The results indicate that risk analysis, leakage, and corrosion obtained the most attention in the domain of safety and security of oil and natural gas pipelines.

To investigate the research evolutions and trends in the past decades, the keywords of publications are analyzed by using the co-occurring module in the software of VOSviewer. First, the publications are divided into four parts according to the publication time: (i) before 2005, (ii) 2005–2009, (iii) 2010–2014 and (iv) 2015–August 2019. Then the research topics (Fig. 9) and research methods (Fig. 10) are identified from keywords and visualized by density maps.

4.1. The evolution of research topics

The top-5 most frequent topics are considered to be hot topics in each period, excluding general description words such as “safety”, “pipeline” as well as “oil and gas”. Fig. 10a–d shows the topics of safety and security research related to oil and gas pipelines in four time periods.

4.1.1. Research topics before 2005

Fig. 9a shows the research topics before 2005. Obviously, “risk assessment” is the most frequent topic, including the risk analysis of natural gas releases (Arnaldos et al., 1998), the environmental risk assessment of pipelines (Zuniga-Gutierrez et al., 2002) and the quantitative assessment for pipeline route selection (Zuniga-Gutierrez and Ortega-Rubio, 2004), etc. The second hot research topic is pipeline leak and the relative research include mathematical modeling of accidental gas releases (Arnaldos et al., 1998), structural collapse calculations of old pipelines (Doglione and

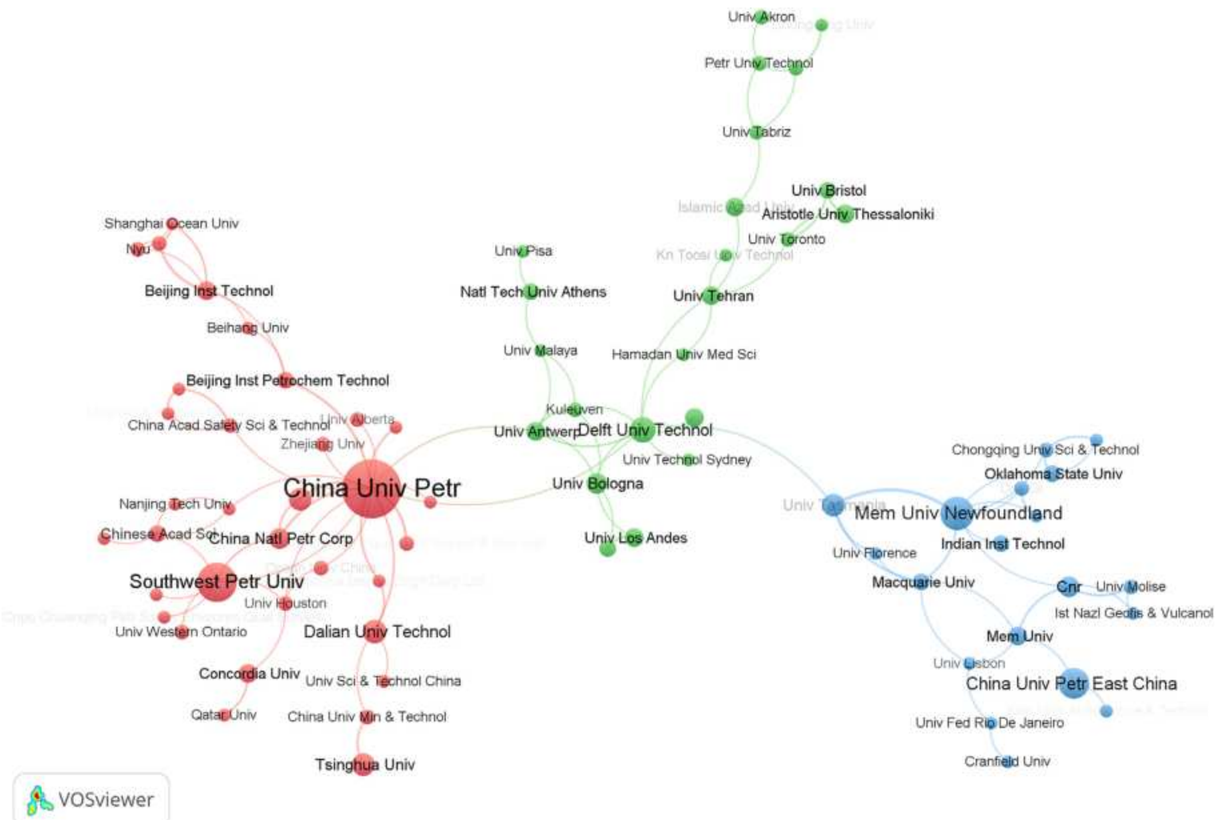

Fig. 4. Cooperation network between different institutions on safety and security of oil and gas pipelines in WoS.

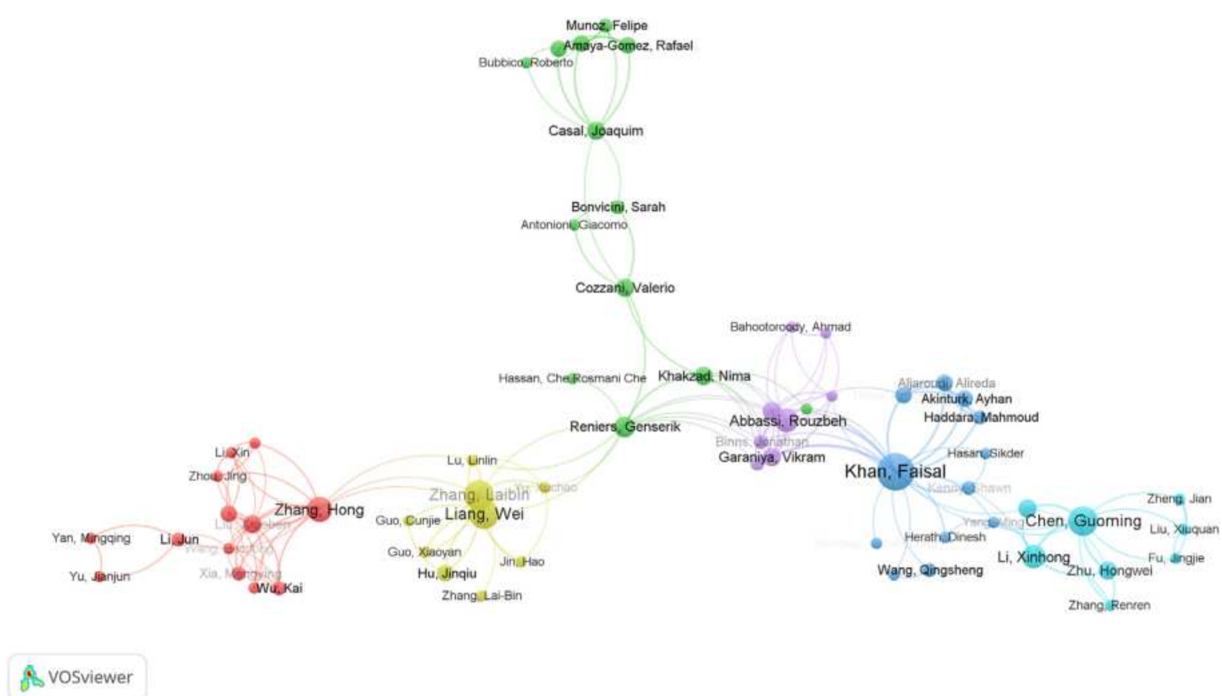

Fig. 5. Cooperation network between different authors on safety and security of oil and gas pipelines in WoS.

Firrao, 1998) and the impact of release rate on hazardous areas (Jo and Ahn, 2002). The third hot topic consists of the research related to the rupture consequence of natural gas pipelines (Cleaver et al., 2001) and accident consequence of city gas pipelines (Park et al., 2004). Other hot topics in this period include major hazard identification (Papadakis, 1999) and uncertainty analysis in risk

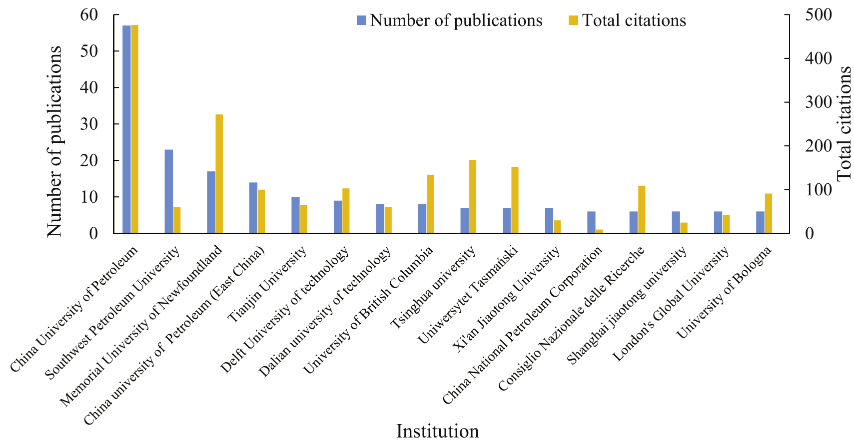

Fig. 6. The productive institutions that have a minimum of 6 documents on safety and security of oil and gas pipelines in WoS.

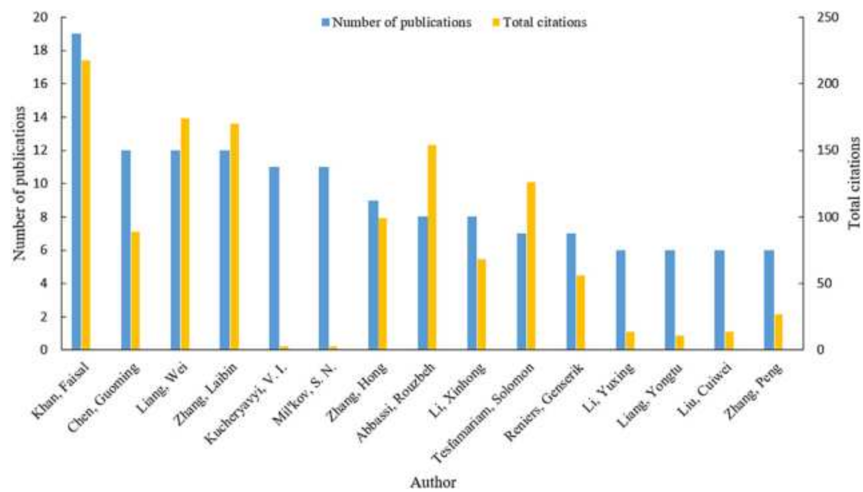

Fig. 7. The productive authors that have a minimum of 6 publications on safety and security of oil and gas pipelines in WoS.

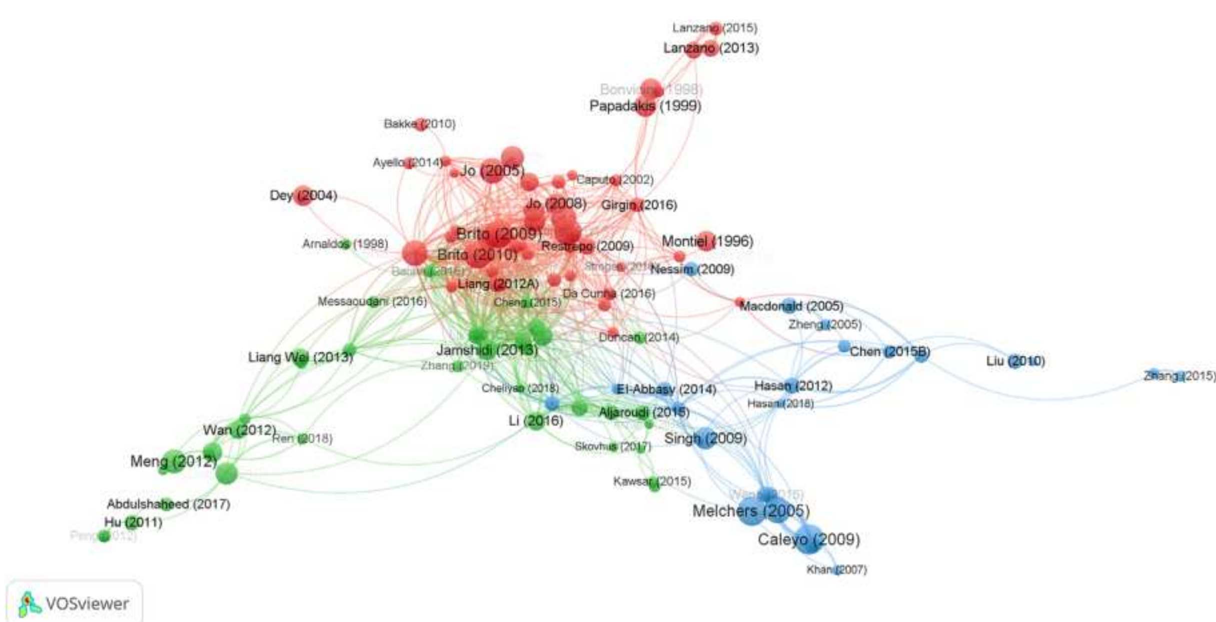

Fig. 8. Bibliographic coupling network between publications on safety and security of oil and gas pipelines on safety and security of oil and gas pipelines in WoS.

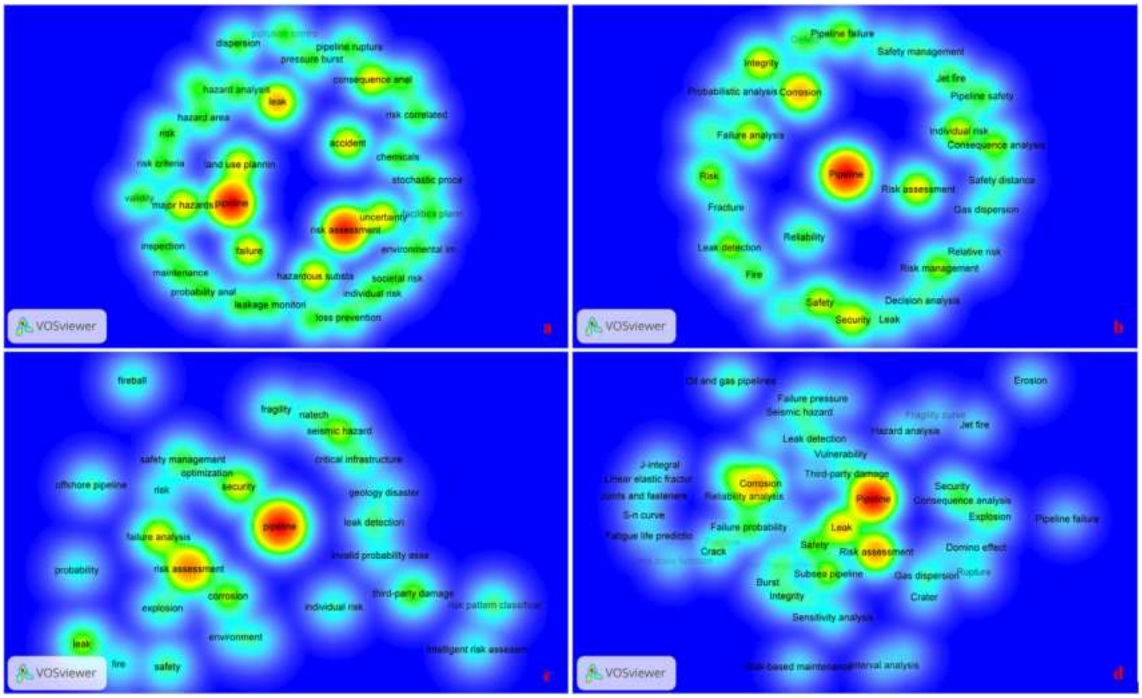

Fig. 9. Research topic evolution over time on safety and security of oil and gas pipelines in WoS: (a) before 2005, (b) 2005–2009, (c) 2010–2014 and (d) 2015–August 2019.

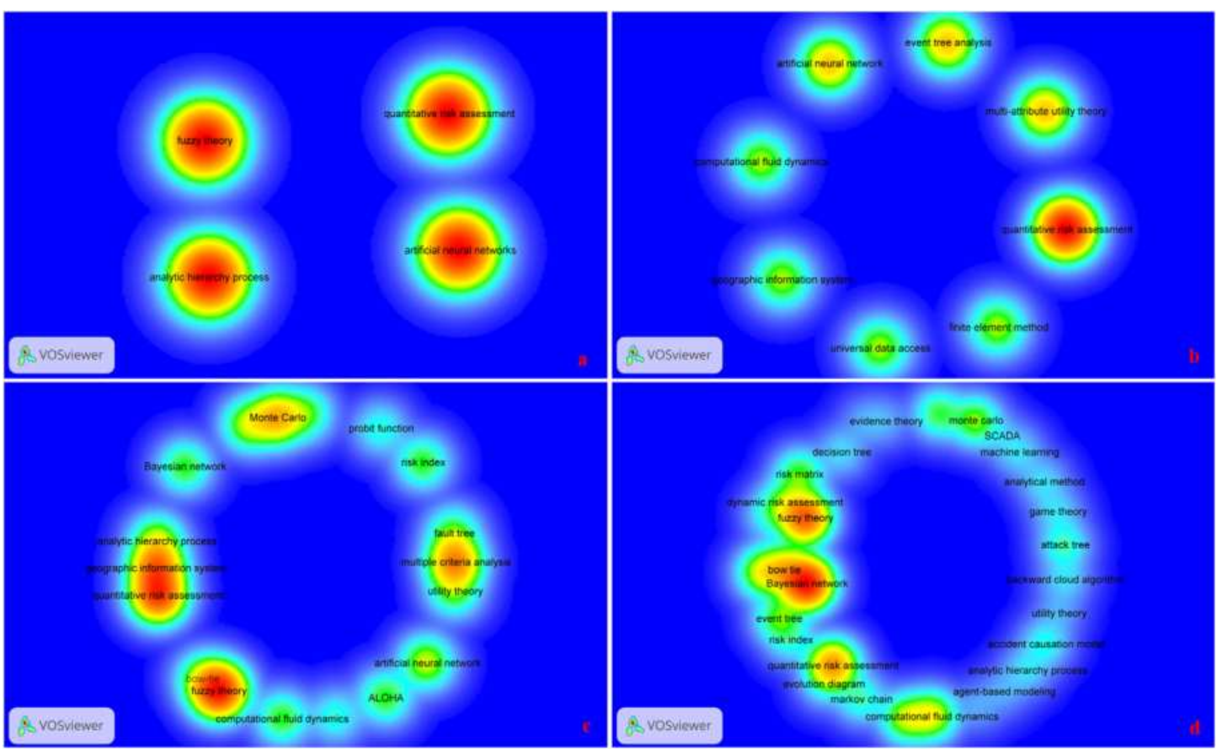

Fig. 10. Research method evolution over time on safety and security of oil and gas pipelines in WoS: (a) before 2005, (b) 2005–2009, (c) 2010–2014 and (d) 2015–August 2019.

assessment (Zhang, 2001).

4.1.2. Research topics between 2005 and 2009

The topics of safety and security research related to oil and gas pipelines from 2005 to 2009 are presented in Fig. 9b. In this period, the top-5 frequent topics are "corrosion", "integrity", "risk assessment", "security", and "failure analysis". The hot topic of integrity management in this period probably is due to the publication of integrity management standards such as "ASME B31.8S: Managing System Integrity of Gas Pipelines" (Macdonald and Cosham, 2005). Corrosion assessment is a key issue in integrity management received wide attention in this time period, including the probabilistic assessment of corrosion pit (Caleyo et al., 2009), and the failure estimation of corroded pipelines (Toth and Lenkey, 2009), etc. Compared with risk assessment before 2005, the research of risk assessment in this period highlights the role of quantitative risk (Jo and Ahn, 2005), individual risk (Jo and Crowl, 2008), and multi-attribute risk (Brito and de Almeida, 2009). After the "9/11" terrorist attack in 2001, the USA, the topic of security received increasing attention in scientific and technical literature. During this period, deliberate attacks on pipelines also increase rapidly (Anifowose et al., 2012). Moore (2006) applied the API/NPRA SVA methodology to transportation security issues. Onuoha (2009) studied the casualties induced by pipeline vandalization in Nigeria. The failure analysis is a basis for integrity management (Khan et al., 2006) and accident investigation (Fazzini and Otegui, 2009) of pipelines.

4.1.3. Research topics between 2010 and 2014

From 2010 to 2014, the hot topics are "risk assessment", "failure analysis", "security", "seismic hazard", "corrosion" and "leak" (the last three topics have an identical number of occurrences), as shown in Fig. 9c. Risk assessment research in this period includes urban pipeline risk assessment (Miao and Zhao, 2012), corrosion risk assessment (Bertuccio and Moraleda, 2012), and pipe network risk assessment (Tsitsifli et al., 2011), etc. The development of advanced tools such as the finite element method (FEM) (Liu et al., 2010b) and artificial neural networks (ANN) (Senouci et al., 2014) promote the research on pipeline failures. Security-related research on oil and gas pipelines in this period mainly focused on security risk assessment (Moore, 2013). After the 2008 Sichuan earthquake, a new seismic code for oil and gas transmission pipelines in China has been issued in 2009 (Liu et al., 2010a). Seismic hazard induced pipeline damage is a type of Natech event and the research related to seismic hazard includes seismic design (Liu et al., 2010a), vulnerability assessment (Lanzano et al., 2013) and consequence mitigation (Pasquare et al., 2011), etc. Besides, the stochastic nature of pitting corrosion was investigated in this period (Valor et al., 2013). In this period, leak related research mainly focused on leak detection possibly due to the development of acoustic emission theory (Davoodi and Mostafapour, 2014).

4.1.4. Research topics between 2015 and 2019

The safety and security research on oil and gas pipelines boomed in the last five years. As shown in Fig. 9d, the top-five topics are "risk assessment", "corrosion", "leak", "subsea pipeline" and "environmental damage". Risk assessment research in this period mainly paid attention to subsea (offshore) pipelines (Aljaroudi et al., 2015), and three-part damage (Omonefe and Oyetola, 2015), and Natechs caused by seismic hazards (Jahangiri and Shakib, 2018), and corroded pipelines (Shabarchin and Tesfamariam, 2016). The research related to pipeline corrosion included failure analysis of corrosion pipelines (Chen et al., 2015), corrosion monitoring (Ren et al., 2018), residual life assessment of corroded pipelines (Hu et al., 2014) and reliability assessment of corroded pipelines (Liu and Liu, 2019). In terms of the research of pipeline leak in this period, both leak detection (Meng et al., 2019) and consequence analysis (Ebrahimi-Moghadam et al., 2018) are the main issues. Besides, more attention was paid to environmental damage caused by pipeline spills and the measures to mitigate environmental consequences (Anifowose and Odubela, 2015). The research related to subsea pipelines is associated with increased petroleum activities in oceans and raising awareness of marine ecological protection (Arzaghi et al., 2018).

4.2. The evolution of research methods

To investigate the methods used in safety and security research related to oil and gas pipelines, the research methods used in past research are extracted from keywords. Fig. 10 shows the main safety and security research methods used in each period.

4.2.1. Research methods before 2005

As shown in Fig. 10a, four main research methods are identified before 2005: analytic hierarchy process (AHP), artificial neural networks (ANN), Fuzzy theory, and quantitative risk assessment (QRA). AHP is a multiple attribute decision-making technique that was used to develop a decision support system for inspecting and maintaining oil pipelines (Dey, 2004). Caputo and Pelagagge (2002) developed an inverse approach based on ANN for leakage monitoring of pipeline networks. ANN can be used to deal with nonlinear problems with a set of variables by mimicking human brains. However, this method needs large sample data and the behavior of networks is unexplained. Bonvicini et al. (1998) applied fuzzy logic in risk assessment to address uncertain input parameters using fuzzy numbers. But it needs subjective evaluation and it is a difficult task to select the exact fuzzy rules and membership functions. A QRA method is established for pipeline route selection in the design stage (Zuniga-Gutierrez and Ortega-Rubio, 2004). The application of the QRA method can obtain a comprehensive result but the result may be not precise and event confusing.

4.2.2. Research methods from 2005 to 2009

Fig. 10b shows the main research methods used from 2005 to 2009. QRA is the most frequent method in this period since it is able to quantify the likelihood and consequences of accidents. For example, Khan et al. (2006) established a QRA method to determine an optimal inspection and replacement interval. Jo and Crowl (2008) built an individual risk assessment method for high-pressure natural gas pipelines. The research results indicated that the risk from a natural gas pipeline is lower than that at the building with a minimum distance from chemical industries. Besides these QRA methods, an event tree approach was used to analyze possible outcomes of an accidental fuel gas release (Sklavounos and Rigas, 2006). Event tree analysis can show possible accident scenarios and event sequences but it may be extreme in size and complexity for an intricate problem. ANN was used for predicting wax deposition (Obanijesu and Omidiora, 2008), ensuring pipeline safety. Multi-attribute utility theory was used in ranking the risk of different sections of natural gas pipelines, incorporating decision-makers' preferences and behavior regarding risk (Brito and de Almeida, 2009). In this period, advanced tools such as the finite element method (FEM) was used to investigate the failure pressure of corroded pipelines while the computational fluid dynamics (CFD) was applied to model dispersion process of accidental release from pipelines. These advanced tools can obtain more accurate results but they are time-consuming and have higher requirements for operators.

4.2.3. Research methods from 2010 to 2014

The main research methods related to the safety and security of oil and gas pipelines in the period 2005–2009 are shown in Fig. 10c. As shown in this figure, the most frequent methods used in this period are fuzzy theory and QRA. Fuzzy theory combining with other risk assessment tools are usually used to deal with the uncertainty of input data. Bertuccio and Moraleda (2012) combines fuzzy logic theory and expert judgment to address the uncertainty in corrosion risk assessment of natural gas pipelines. Shahriar et al. (2012) used fuzzy logic in a bow-tie model to derive fuzzy probabilities of basic events and to estimate fuzzy probabilities of the consequences of output events. Jamshidi et al. (2013) integrated relative risk score (RRS) with fuzzy logic in pipeline risk assessment. Han and Weng (2011) demonstrated that the selection of qualitative or quantitative risk assessment methods depends on the available data of the gas pipelines and the precision requirements. Ma et al. (2013) used GIS in a QRA to aid pipeline management staff in demarcating high-risk areas. Besides, fuzzy theory, Monte Carlo simulation (MCS) also plays an important role in tackling uncertainty and also in simplifying the computation of analytical methods but it is time-consuming. Omidvar et al. (2013) used MCS to address the uncertainty in damage probability estimation of pipelines subject to earthquakes while Hu et al. (2014) applied MCS to simplify the lifetime prediction of corroded pipelines.

4.2.4. Research methods from 2015 to 2019

In the period 2014–2019, the Bayesian network played a dominant role in the research methods related to the safety and security of oil and gas pipelines, as shown in Fig. 10d. Compared with traditional risk assessment tools such as the fault tree, the Bayesian network has obvious advantages in explicitly representing the dependencies of events, updating probabilities, and coping with uncertainties (Khakzad et al., 2011). Shabarchin and Tesfamariam (2016) used a Bayesian network to assess the internal corrosion hazard of oil & gas pipelines. Wu et al. (2017) conducted an accident analysis of natural gas pipeline networks using the Bayesian network. The Bayesian network can also be used to model dynamic risks such as the time-dependent accident risk of subsea pipelines (Li et al., 2019). Besides, fuzzy theory (Biezma et al., 2018), quantitative risk assessment (Bonvicini et al., 2015) and bow tie (Chen and Wang, 2019) are also widely used for assessing the risks of oil and gas pipelines. With the development of computational resources, applying CFD and FEM methods in pipeline safety may become easier and wider in the future. Game theory and attack tree specially used in security risk research can also be found in Fig. 10d. Game theory is a decision-making tool to handle problems that contain intelligent players while it may be inaccurate due to subjective assumptions for attackers. Moreover, machine learning was also applied in this domain to assist in detecting and sizing of metal-loss defects in oil and gas pipelines. With the rapid development of machine learning techniques, their applications in pipeline safety and security may increase in the future.

5. Pathways for future sustainable pipeline transportation

This paper investigates current literature on safety and security research related to oil and natural gas pipelines to find out the most productive institutions and authors, cooperation networks between countries, institutions and authors, citation and co-citation networks, and research trends in different periods. This section aims to discuss possible research needs for developing a sustainable pipeline transportation system.

5.1. Safety and security

Safety-related incidents are unintentional whereas security-related incidents are intentional (the direct objective is to induce undesired incidents) (Chen et al., 2019). In terms of oil and gas pipelines, two main categories of security threats exist, i.e., theft and sabotage. Theft has been a long-standing security concern for oil and gas pipelines while the threat of terrorist attacks has become a more pressing priority in some regions (Reniers and Zamparini, 2013). Both theft and sabotage can lead to severe consequences, including public casualties, physical damage to the pipelines, interruption of energy supply, loss of oil and gas, environmental pollution, and the influence on socioeconomic and political stability, etc. (Onuoha, 2008). Nonetheless, less than 5% of the 589 publications focused on security issues involving oil and gas pipelines. Given the severe consequences caused by intentional incidents on oil and gas pipelines, safety and security are both important for protecting oil and natural gas pipelines. Therefore, more work on security or integrated safety and security should be carried out in the future, addressing the intelligent and strategic characteristics of attackers and considering the impacts of social, political and economic factors.

5.2. Technical safety issues and non-technical safety issues

According to the bibliometric analysis, most of the past research work related to the safety and security of oil and gas pipelines focused on technical safety issues such as corrosion risk assessment and leak detection. According to the historical pipeline accident research conducted by Restrepo et al. (2009), incorrect operation is one of the main pipeline accident causes. However, little attention has been paid to operation errors which are also one of the main accident causes. Besides, there is a lack of research on non-technical safety issues in the academic domain of safety and security topics related to oil and gas pipelines, such as safety management, safety economics, human factors, organizational factors, safety culture, and safety climate. As a result, more attention should be paid on non-technical safety issues listed above to better protect oil and gas pipelines in the future.

5.3. Environmental sustainability and oil spill cleanup technologies

Major accidents (fires, explosions, toxic leaks) of oil and gas pipelines may lead to casualties, the damage to the energy supply chain, and the damage to the environment, indirectly affecting the nearby population and other creatures by the contamination of soil, desert, surface water, underground water, and seawater. According to the research trend analysis, wide attention has been paid to risk assessment of major accidents of pipelines whereas little work was devoted to assessing and mitigating the environmental consequences of major accidents. Environmental risk assessment and quantitative environmental impacts should be integrated into pipeline safety management to improve environmental sustainability. Besides, oil spill cleanup technologies need to be developed to mitigate the impacts of major accidents on the environment and ecosystem. In addition, the research related to the reduction of carbon footprint should also be enhanced.

5.4. Pipeline system resilience

The resilience of oil and gas pipeline systems may be defined as the ability to absorb losses and maintain or improve energy supply despite pipeline damages. In light of the accidental hazards, natural hazards and intentional threats to oil and gas pipelines, enhancing the resilience of oil and gas pipeline systems is an important method to ensure the sustainability of the energy supply chain. Once a damage to an oil and gas pipeline is inevitable, a resilient pipeline system can effectively mitigate the consequences of the damage and rapidly recover from the supply interrupt. However, limited research has been done on the resilience of oil and gas pipeline systems. As a result, more attention should be paid to enhance the resiliency of an oil and gas pipeline system, such as formulating a resilient emergency response strategy and developing a robust pipeline system.

5.5. International cooperation

Research cooperation networks in this research domain tend to be geographically concentrated around the most productive institutions and they seem to lack international communications. For example, cooperation between China and the USA is rare while they are the most productive countries in the field. The publications in international journals from developing areas such as Africa are limited. As a result, enhancing academic cooperation and communication in the future may promote the safety and security research related to oil and natural gas pipelines.

6. Conclusions

This study conducted a systematic analysis of the research related to the safety and security of oil and natural gas pipelines. Three main conclusions to answer the research questions proposed in the Introduction are as follows.

China contributed the most publications in this domain, followed by the USA, Canada, Italy, the UK, and Iran. The top-3 productive institutions include China University of Petroleum, Southwest Petroleum University, and the Memorial University of Newfoundland. The research cooperation networks tend to be geographically concentrated around the most productive institutions and authors in each cooperative cluster. The cooperation in China led by China University of Petroleum and Southwest Petroleum University consists of the largest research cooperation cluster. Delft University of Technology leads the cooperative cluster in Europe, playing a bridge role in international cooperation on safety and security research related to oil and gas pipelines.

The bibliographic coupling analysis indicates that risk assessment, leakage, and corrosion are the main topics in the domain of safety and security research related to oil and gas pipelines. QRA, fuzzy theory and the Bayesian network are the most frequently used research methods. Before 2005, the methods of AHP, fuzzy theory, and QRA are used for risk assessment. From 2005 to 2009, QRA is the most frequent method and hot topics include corrosion, integrity management, risk assessment, security, and failure analysis. Fuzzy theory combined with other risk assessment tools were usually used to deal with the uncertainty of input data in the period from 2010 to 2014. In this period, risk assessment, failure analysis, security, seismic hazard, corrosion, and leak are hot topics. From 2015 to 2019, the Bayesian network method played a dominant role in risk assessment, followed by quantitative risk assessment and bow-tie. Subsea pipelines and environmental damage have received increasing attention in the last five years.

Most of the past research focused on technical safety issues, more attention should be paid to the security and non-technical issues such as safety culture and human factors. Environmental risk assessment and quantitative environmental impacts should be integrated into pipeline safety management to improve environmental sustainability. New oil spill cleanup technologies and the research related to the reduction of carbon footprint should also be enhanced. The resilience of the oil and gas pipeline system may be another research issue in the future to further mitigate the consequences of damages to pipelines and to rapidly recover from supply interrupts. Besides, international cooperation in developing areas may be improved to create a sustainable pipeline transportation system for oil and gas in the future. Research methods such as machine learning, Bayesian network, and CFD are gaining attention and possibly be widely used in future research.

In general, this study shows a clear picture of the evolution of the research related to the safety and security of oil and gas pipelines. Safety research tools such as Bayesian network and CFD may be widely used while the research and guidelines on pipeline security, resilience and environmental impacts may be enhanced in the future. The results of this study can provide valuable insights to both safety and security researchers and practitioners in the petroleum industry, thus creating safer, resilient, and sustainable oil and gas pipelines in the future.

CRediT authorship contribution statement

Chao Chen: Data curation, Writing - original draft. **Changjun Li:** Methodology, Conceptualization. **Genserik Reniers:** Supervision, Writing - review & editing. **Fuqiang Yang:** Visualization, Resources, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing for financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (Grant No. 51974269, 51674213 and 51604233); a subproject of the National Science and Technology Major Project of China (Grant No. 2016ZX05028-001-006); and the Chinese Scholarship Council (Grant No: 201708510111). We also appreciate the editor and anonymous reviewers.

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