Journal of Loss Prevention in the Process Industries 49 (2017) 103–110

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

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

# A bibliometric analysis of peer-reviewed publications on domino effects in the process industry

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ARTICLE INFO

*Article history:*
Received 24 March 2016
Received in revised form
2 June 2016
Accepted 3 June 2016
Available online 7 June 2016

*Keywords:*
Bibliometric study
Domino effects
Process industry

ABSTRACT

The topic of domino effects in the process industry started to receive attention in risk analysis and safety assessment studies over the last two decades. The popularity of the topic is partly due to the occurrence of catastrophic industrial accidents involving domino effects, e.g., the LPG-induced domino effects in Mexico City in 1984, and partly due to legislation (e.g. the so-called "Seveso Directives"), mandating the owners and managers of chemical plants to take the likelihood of domino effects into account when contemplating the prevention/mitigation of major accidents. The present study aims to take advantage of state-of-the-art bibliometric analysis tools to investigate the trend, the geographical and the authorial distributions of scientific papers on domino effects published in peer-reviewed journals around the globe. The result of this study can be used to identify the most influential research institutes and authors contributing to the domain of domino effects in the chemical industry.



## 1. Introduction

The chemical and process industry is affected, as many other human activities, by accidents whose impact may be amplified by the presence of hazardous substances. A few of such major accidents are commonly considered as milestones for the evolution of process safety. The Flixborough (1974) and Seveso (1976) accidents are worldwide recognized as the events that called the chemical and process industry and the regulatory authorities, at least in Europe, to introduce a structured approach to process safety management, also aimed at limiting the exposure of the population to major accident hazards.

In particular, the accident in Seveso, near Milan in Italy, where a few kilograms of 2,3,7,8-tetrachloro-dibenzo-dioxin were formed and released in the runaway of a chemical reactor, resulting in the permanent contamination of an area of several $km^2$, evidenced the huge impact potential of such accidents. As a legislative result of the Seveso accident in the European Union, a complex body of regulations requires the notification to public control authorities of the list of hazardous chemicals present in industrial sites, the identification of accident scenarios and the adoption of measures to prevent, control, and mitigate major accident hazards. Even now, 40 years after the Seveso accident, such regulations are still named "Seveso" Directives (Council Directive 82/501/EEC, 1982, Council Directive 96/82/EC, 1997, Council Directive 2012/18/EU, 2012).

The Seveso Directives were constantly updated in time, including the experience deriving from further milestone accidents, mostly occurring outside the European Union. The second Seveso Directive (Directive 96/82/EC, also known as "Seveso-II" Directive), issued after the Bhopal disaster (India, 1984) and the Mexico City accident (Mexico, 1984), introduced, besides other issues, land-use planning regulations and requirements for the identification and prevention of so-called "domino effects" in the chemical industry. The requirements concerning domino effects were recently further reinforced by the so-called "Seveso-III" Directive (Council Directive 2012/18/EU, 2012) which came into force on 1 June 2015 in the European Union, and forcing the owners

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http://dx.doi.org/10.1016/j.jlp.2016.06.003
0950-4230/

of different chemical facilities to more intensively exchange information aimed at the prevention of such escalation accident scenarios.

Although many different definitions exist, with the term "domino effect" in the chemical industry a sequence of accidents is indicated in which a primary accident, usually a fire or an explosion, triggers further accidents with an overall escalation of the consequences of the event. A detailed discussion of domino effects and of the features of domino accidents is reported elsewhere (Reniers and Cozzani, 2013). In comparison with other major accidents, the approaches proposed to the risk analysis and safety management of domino effects in the chemical industry were developed more recently. Actually this type of accident scenarios mainly gained attention since the notorious LPG disaster in Mexico City in 1984, where an LPG leakage resulted in an initial vapor cloud explosion followed by several secondary explosions and fires (Arturson, 1987). Many other less widely known accidents involving domino effects took place since (Reniers, 2010; Darbra et al., 2010; Abdolhamidzadeh et al., 2011; Reniers and Cozzani, 2013). More recently, the catastrophic accident that occurred in Tianjin, China, in August 2015, in which two initial explosions triggered fires burning for days and leading to about eight other explosions (Huang and Zhang, 2015) should be mentioned as an important domino effect accident involving chemical substances.

The increase in the attention paid to the risk analysis of domino effects in chemical plants has been driven on the one hand by the high impact of domino accidents on society, and on the other hand by technical standard requirements and law enforcement as that deriving from the application of the "Seveso" Directives in the European Union. However, due to both the data scarcity arising from the low frequency of domino effects and the complexity and interdependencies involved in such accidents, the modeling and incorporation of domino effects in quantitative risk analysis has been challenging. The need for the identification of primary accident scenarios, escalation mechanisms, escalation and damage probabilities, identification of secondary accident scenarios, and also modeling the safety measures in place are some of the main challenges that need to be afforded.

Nevertheless, recent studies dedicated to the determination of escalation probabilities (Cozzani and Salzano, 2004; Cozzani et al., 2005, 2006; Landucci et al., 2009, 2015) along with the development of advanced mathematical and probabilistic methods such as Monte Carlo simulation (Abdolhamidzadeh et al., 2010), Bayesian networks (Khakzad et al., 2013; Khakzad, 2015; Khakzad and Reniers, 2015a), graph theory (Khakzad and Reniers, 2015b), and event sequence diagrams (Zhou et al., 2016) resulted in a relevant improvement of risk assessment and safety management of domino effects.

Due to the importance of domino effects from either a safety or security perspective, in the present study a bibliometric analysis of attempts devoted to the description, management, modeling and risk assessment of domino effects in the chemical industry over the past decades was carried out.

## 2. Data and data mining techniques

The data used in the present study were retrieved from the Web of Science Core Collection on November 23, 2015 (the database was last updated on November 20, 2015), including Science Citation Index Expanded (1900 – present), Social Sciences Citation Index (1956 – present), Arts & Humanities Citation Index (1975 – present), Conference Proceedings Citation Index-Science (1994 – present) and Conference Proceedings Citation Index-Social Science and Humanities (1994 – present). Using "domino effect" and "chemical" as the search topics, a total of 112 records were found in the database, excluding books chapters, e.g., Reniers and Pavola (2013).

Bibliometric analysis of domino effects in the chemical industry was performed using methods such as outputs analysis, co-citations analysis (Marshakova, 1973; Small, 1973), and network visualization were used in the present work. For example, in the method of co-citation analysis, the more two papers are cited together the higher their co-citation score. The results obtained from the above-mentioned analyses can be categorized based on (i) the temporal trend of publications, (ii) their geographical distribution, and (iii) their authorial distribution. Accordingly, the bibliometric data was visualized using freely available mapping tools such as VOSviewer (Van Eck and Waltman, 2009), CiteSpace (Chen, 2006), and Gephi (Bastian et al., 2009).

## 3. Results

### 3.1. Temporal distribution

The cumulative trend of the publications over time can be used as an index of the popularity and the importance of domino effects in the process industry. According to Fig. 1, the publications in the domain of domino effects in the process industry can be divided into two distinguishable periods, that is, before 1996 and after 1996. Although some of the worst domino effects took place before 1996, e.g., LPG-induced fires and explosions in Mexico City in 1984, there is only one publication in the first period (Bagster and Pitblado, 1991). However, due to the requirements of the Seveso-II Directive (96/82/EC), issued in December 1996, that is, the "Article 8" of this Directive addressing the enforced inclusion of domino effects in risk analysis studies, the topic started to gain attention among the European risk and safety community. The trend has been almost constant with a notable increase between 2004 and 2008. However, the highest increase in the number of publications can be observed between 2013 and 2014, most likely due to the amendment of Seveso II which resulted in Seveso III (Council Directive 2012/18/EU, 2012) in July 2012. Article 10 of Seveso III explicitly requires the EU member states to account for the likelihood of domino effects in hazardous industries and for the more intensified exchange of information between facilities.

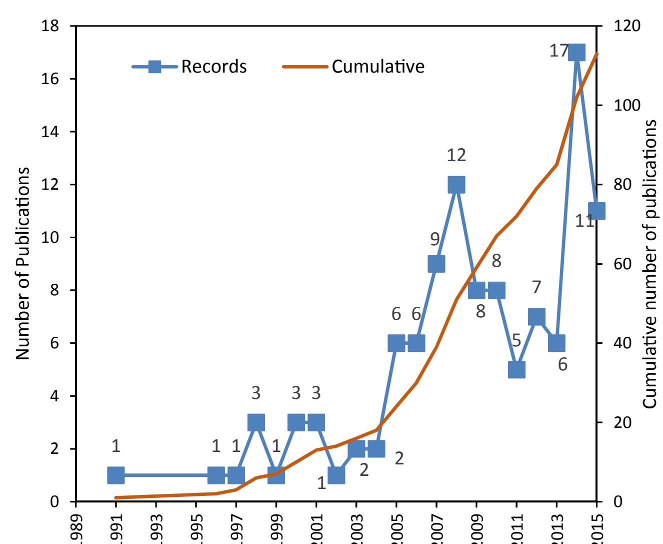


**Fig. 1.** Annual distribution of publications on domino effects in the chemical industry.

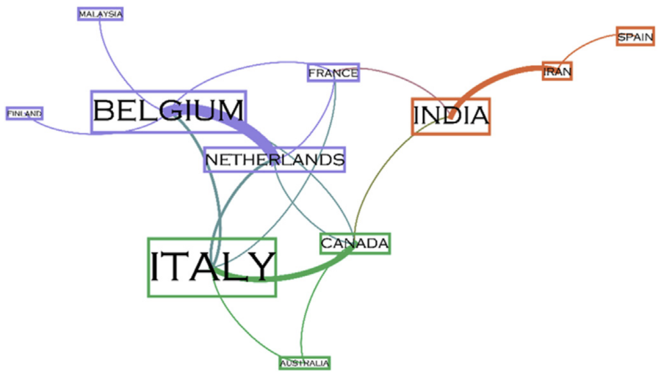


**Fig. 2.** The countries with the highest contribution/cooperation in the domain of domino effects in the chemical industry.

### 3.2. Geographical distribution

To the best of the authors' knowledge, there is no legislation requiring the assessment of domino effects in the chemical and process industry outside the European Union. As a result, the assumption of a strong correlation between the increasing trend of the publication in Fig. 1 and requirements of Seveso Directives should be supported by the geographical distribution of the publications. To this end, cooperation networks were analyzed to investigate affiliated countries, affiliated institutes, and authors. In the networks, a node is allocated to each co-author of a publication. The size and the color of a node respectively reflect the number of publications and the cluster to which the node belongs. It should be noted that for the sake of clarity only the largest sub-networks were considered in the analysis.

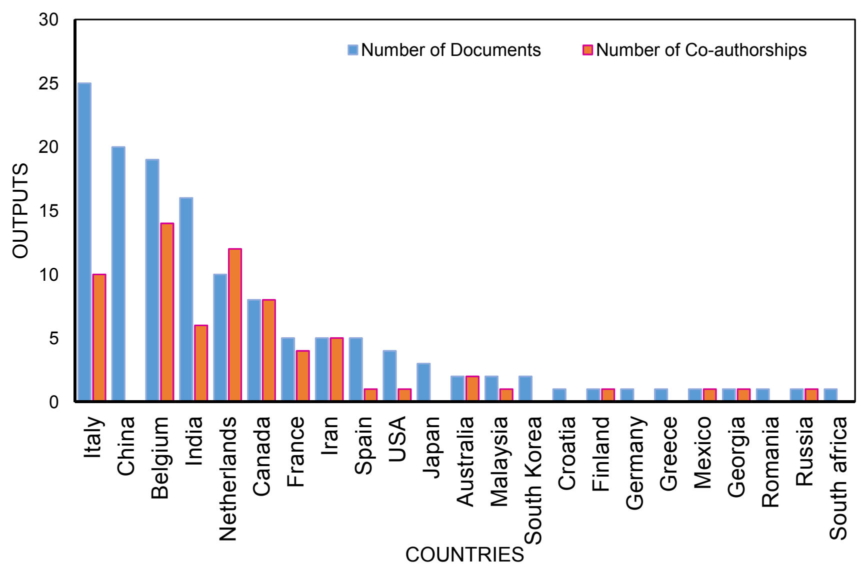


**Fig. 3.** Number of publications and co-authorships per country in the domain of domino effects in the chemical industry.

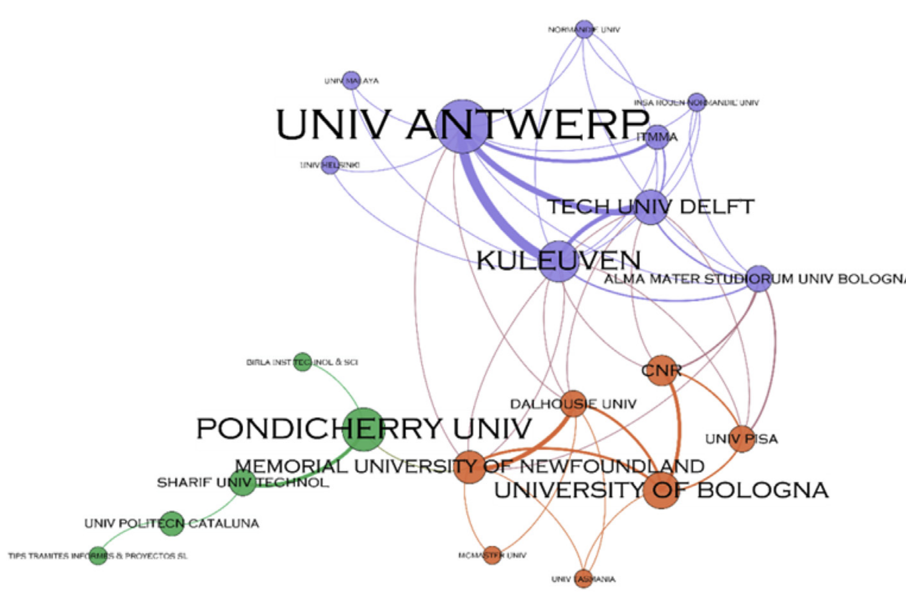


**Fig. 4.** Cooperation network of affiliated institutions in the domain of domino effects in the chemical industry.

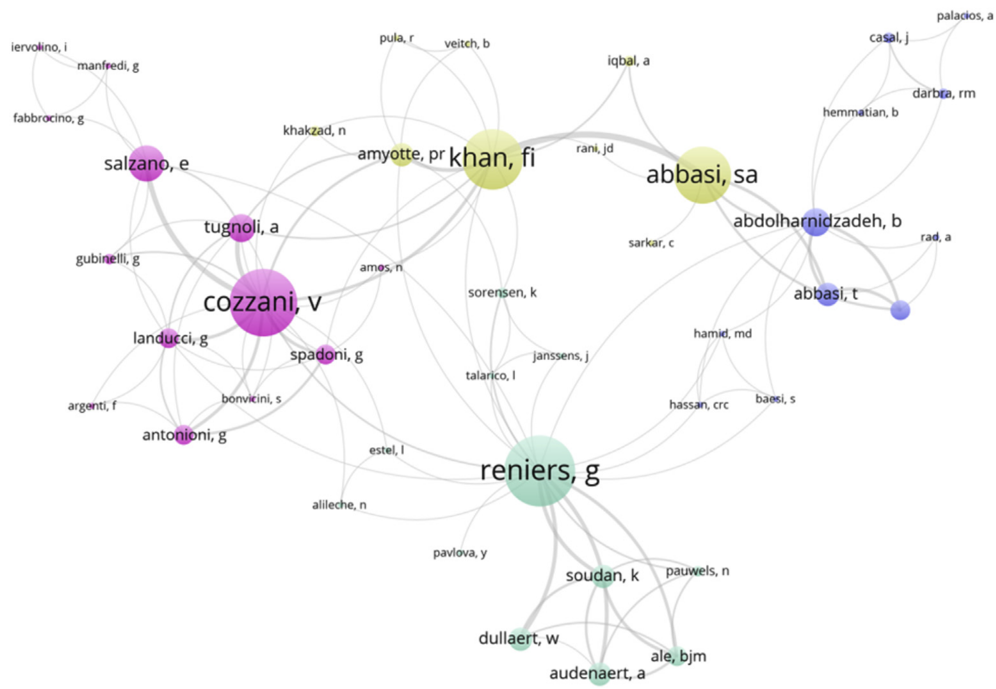


**Fig. 5.** Cooperation network of authors of peer reviewed publications in the domain of domino effects in the chemical industry.

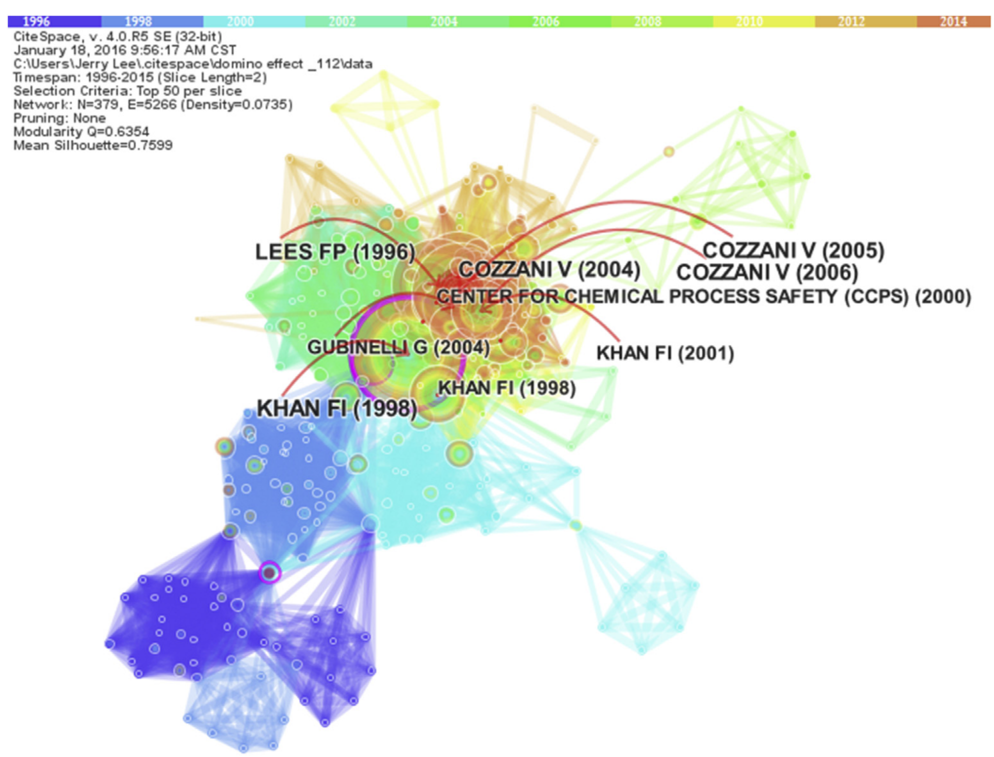


**Fig. 6.** The largest set of connected co-citation network of DEC research and the landmark nodes were shown in the network.

*3.2.1. Countries of affiliation*

Fig. 2 depicts the countries with the highest contribution to the topic of domino effects in the process industry. Being in line with the hypothesis of Seveso-induced domino effect studies in Europe, as can be seen from Fig. 2, European countries being Italy, Belgium, and The Netherlands are mainly affiliated with the research, followed by India and Canada. The connections between the nodes represent respective collaboration, with the highest collaborations between Belgium and The Netherlands (e.g., Janssens et al., 2015), Italy and Canada (e.g., Khakzad et al., 2013), and India and Iran (e.g., Abdolhamidzadeh et al., 2010).

Fig. 3 displays the number of publications per country along

**Table 1**
Detailed information of the landmark nodes (only publications with more than 15 citations are mentioned).

| Author | Title | Year | Document type | Cited frequencies |
|---|---|---|---|---|
| Khan FI | Models for domino effect analysis in chemical process industries | 1998 | Process Safety Progress | 34 |
| Cozzani V | The assessment of risk caused by domino effect in quantitative area risk analysis | 2005 | Journal of Hazardous Materials | 28 |
| Cozzani V | The quantitative assessment of domino effects caused by overpressure: Part I. Probit models | 2004 | Journal of Hazardous Materials | 27 |
| Lees FP | Loss Prevention in the Process Industries | 1996 | Book publication | 27 |
| Cozzani V | Escalation thresholds in the assessment of domino accidental events | 2006 | Journal of Hazardous Materials | 26 |
| Khan FI | An assessment of the likelihood of occurrence, and the damage potential of domino effect (chain of accidents) in a typical cluster of industries | 2001 | Journal of Loss Prevention in the Process Industries | 19 |
| Khan FI | DOMIFFECT (DOMIno eFFECT): user-friendly software for domino effect analysis | 1998 | Environmental Modeling & Software | 19 |
| Gubinelli G | A simplified model for the assessment of the impact probability of fragments | 2004 | Journal of Hazardous Materials | 19 |
| Center for Chemical Process Safety (CCPS) | Guidelines for Chemical Process Quantitative Risk Analysis | 2000 | Book publication | 16 |

with the number of co-authorships. A remarkable observation from Fig. 3 is that China with 20 publications seems to be disconnected from the cooperation network due to the lack of collaboration with other countries (zero number of co-authorships), thus not being visible in Fig. 2. This also holds true for the USA. However, it can be expected that owing to the recent catastrophic domino effect accident in China, that is, the Tianjin disaster in August 2015, and the increasing importance of security risks in the chemical industry,

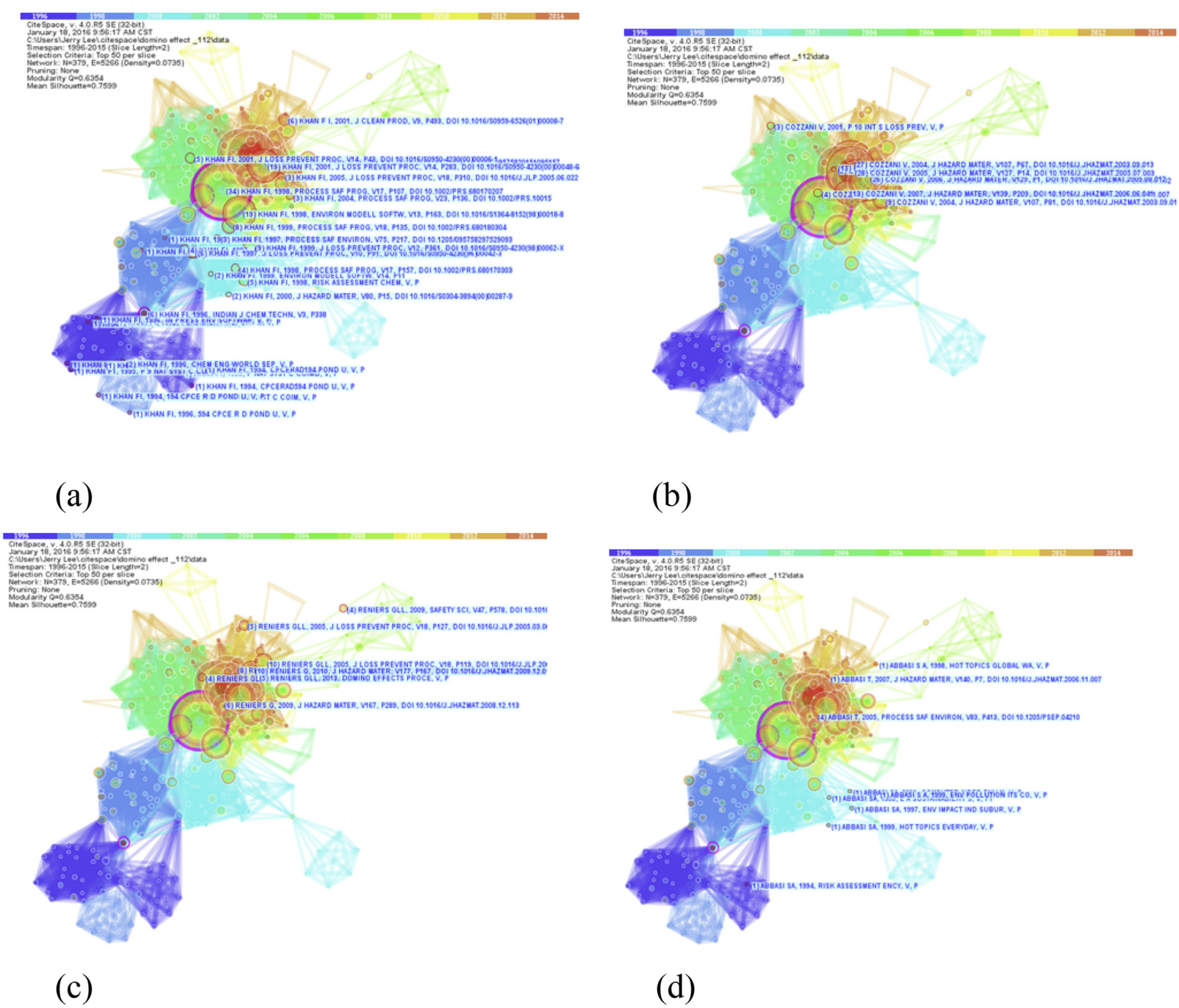


**Fig. 7.** Publications of Khan (a), Cozzani (b), Reniers (c), and Abbasi (d) within the co-citations Network.

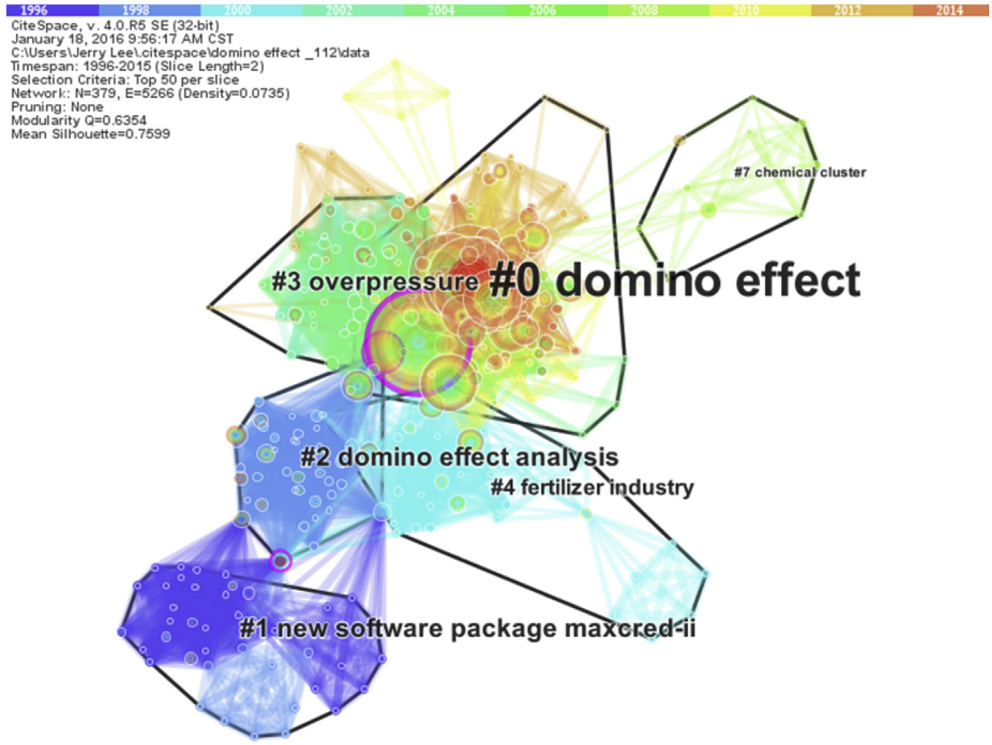


**Fig. 8.** Co-citation clusters of DEC research. Names of the clusters were extracted from title of the citing articles by using LLR algorithm.

**Table 2**
The eight largest clusters of co-cited references among the 20 clusters identified by bibliometric analysis.

| ID | Size | Silhouette | mean (Cited year) | Label by TF*IDF | Label by log-likelihood ratio |
|---|---|---|---|---|---|
| 0 | 121 | 0.72 | 2001 | (14.06) accident sequence; (14.06) main feature; (13.85) research; (13.85) method; (13.75) application | domino effect (276.53, 1.0E-4); art (176.04, 1.0E-4); state (176.04, 1.0E-4); |
| 1 | 43 | 0.916 | 1989 | (17.23) software package; (15.56) new software package maxcred-ii; (15.56) rapid quantitative risk analysis; (13.75) controlling environmental risk; (11.14) chemical process industries | new software package maxcred-ii (255.53, 1.0E-4); rapid quantitative risk analysis (255.53, 1.0E-4); tool (161.28, 1.0E-4); |
| 2 | 41 | 0.865 | 1989 | (17.49) domino effect analysis; (15.12) domiffect; (11.63) chemical process industries; (9.37) analysis; (9.15) software | domino effect analysis (360.05, 1.0E-4); domiffect (197.26, 1.0E-4); software (172.1, 1.0E-4); |
| 3 | 36 | 0.913 | 1986 | (15.56) use; (15.56) probit function; (13.61) overpressure; (13.36) domino accident; (12.61) quantitative risk assessment | overpressure (305.04, 1.0E-4); domino accident (269.27, 1.0E-4); use (235.15, 1.0E-4); |
| 4 | 34 | 0.844 | 1993 | (11.62) domino chemical accident; (11.62) statistical analysis; (10.32) rapid risk assessment; (10.32) computer-automated tool torap; (9.76) fertilizer industry | fertilizer industry (155.93, 1.0E-4); rapid risk assessment (127.36, 1.0E-4); computer-automated tool torap (127.36, 1.0E-4); |
| 5 | 27 | 1 | 1988 | (16.94) high proton affinity; (16.94) aromatic domino effect; (16.94) poly-2; (5.16) domino effect; (5.16) domino | high proton affinity (410.3, 1.0E-4); aromatic domino effect (410.3, 1.0E-4); poly-2 (410.3, 1.0E-4); |
| 6 | 19 | 1 | 1995 | (18.29) helix sense; (15.56) noncovalent chiral effect; (15.56) peptide helix sense; (15.56) temperature tuning; (15.56) noncovalent chiral domino effect | control (503.5, 1.0E-4); noncovalent chiral effect (250.95, 1.0E-4); peptide helix sense (250.95, 1.0E-4); |
| 7 | 11 | 0.984 | 2001 | (10.22) chemical cluster; (9.85) security; (9.41) man-made domino effect disaster; (8.28) managing domino; (8.28) industrial area | chemical cluster (88.05, 1.0E-4); need (67.76, 1.0E-4); man-made domino effect disaster (67.76, 1.0E-4); |

**Table 3**
Papers that cite at least 10 members of Cluster # 0.

| First author | Year | Title | References included in Cluster # 0 |
|---|---|---|---|
| Abdolhamidzadeh, B | 2010 | A new method for assessing domino effect in chemical process industry | 20 |
| Reniers, G | 2010 | An external domino effects investment approach to improve cross-plant safety within chemical clusters | 15 |
| Darbra, RM | 2010 | Domino effect in chemical accidents: main features and accident sequences | 13 |
| Cozzani, V | 2014 | Quantitative assessment of domino and Natech scenarios in complex industrial areas | 10 |

which seems to be an urgent concern especially in the context of domino effects, there will be more collaboration among research centers in the future.

*3.2.2. Institutes of affiliation*

To have a better look at the geographical distribution of the publications, the distributions per affiliated institutions have been

**Table 4**
Papers that cite the members of Cluster # 7.

| First author | Year | Title | References included in Cluster # 7 |
|---|---|---|---|
| Reniers, GLL | 2008 | Managing domino effect-related security of industrial areas | 6 |
| Reniers, GLL | 2009 | Man-made Domino Effect Disasters in the Chemical Industry: The Need for Integrating, Safety and Security in Chemical Clusters | 1 |
| Reniers, GLL | 2009 | Domino effects within a chemical cluster: A game-theoretical modeling approach by using Nash-equilibrium | 1 |
| Reniers, GLL | 2007 | DomPrevPlanning (c): User-friendly software for planning domino effects prevention | 1 |
| Reniers, GLL | 2010 | An external domino effects investment approach to improve cross-plant safety within chemical clusters | 1 |
| Reniers, GLL | 2008 | Knock-on accident prevention in a chemical cluster | 2 |
| Pavlova, Y | 2011 | A sequential-move game for enhancing safety and security cooperation within chemical clusters | 1 |

**Table 5**
Papers that cite the members of Cluster # 3.

| First author | Year | Title | References included in Cluster # 7 |
|---|---|---|---|
| Salzano, E | 2003 | The use of probit functions in the quantitative risk assessment of domino accidents caused by overpressure | 18 |
| Cozzani, V | 2004 | The quantitative assessment of domino effects caused by overpressure - Part I. Probit models | 10 |
| Salzano, E | 2005 | The analysis of domino accidents triggered by vapor cloud explosions | 2 |
| Abdolhamidzadeh, B | 2010 | A new method for assessing domino effect in chemical process industry | 2 |
| Cozzani, V | 2014 | Quantitative assessment of domino and NaTech scenarios in complex industrial areas | 1 |
| Khan, FI | 2001 | Risk analysis of a petrochemical industry using ORA (Optimal Risk Analysis) procedure | 1 |
| Chen, YT | 2012 | Investigation and analysis of historical Domino effects statistic | 1 |
| Alileche, N | 2015 | Thresholds for domino effects and safety distances in the process industry: A review of approaches and regulations | 1 |

presented in the cooperation network in Fig. 4, mainly consisting of European institutions. The main institutions are University of Bologna, Italy, Universities of Antwerp and KULeuven, Belgium, Delft University of Technology, The Netherlands, along with non-European universities such as Pondicherry University, India, Memorial University of Newfoundland, Canada, and Sharif University of Technology, Iran.

#### 3.2.3. Authors

The authors' cooperation network includes, as main researchers, V. Cozzani (University of Bologna, Italy), G. Reniers (University of Antwerp, Belgium), F. Khan (Memorial University of Newfoundland, Canada), and S.A. Abbasi (Pondicherry University, India) (see Fig. 5).

### 3.3. Co-citation analysis

#### 3.3.1. Co-citation network analysis

The co-citation network is a network of references that has been co-cited by a set of publications. The more cited together, the more similar the articles become in the network. In the present study, CiteSpace (Chen, 2006) was used to create the co-citation network of the publications in the domain of domino effects in the process industry. Compared to other bibliographic tools, CiteSpace can analyze the co-citation network by a single year, then integrate the time series of co-citation networks.

In the co-citation network analysis, the time line 1996–2015 was divided in 10 time intervals (2 years in each interval); the top 50 most cited publications were then extracted from each interval based on the time of citation. Finally, 2177 references were obtained from the 112 relevant articles, the co-citation network of which is depicted in Fig. 6. The network consists of 379 nodes and 5266 edges; small isolated groups are not shown in Fig. 6. The size of each node represents the number of citations of a certain document, indicating the work of Khan and Abbasi (1998), Cozzani et al. (2004, 2005), and Lees (1996) as the most cited publications. In this regard, Khan and Cozzani are the authors most referred to in the domain of domino effects in chemical industry (see also Table 1).

Furthermore, the publications of the top 4 productive authors (see Section 3.2.3) were marked in the co-citation network in Fig. 7. The results show 31 papers by Khan from 1992 to 2005, mainly published in the Journal of Loss Prevention in the Process Industries (6 papers) and in Process Safety Progress (5 papers). Likewise, the publications by Cozzani are from 2001 to 2009 (11 papers), being mainly published in the Journal of Hazardous Materials (5 papers), while those of Reniers, from 2005 to 2013 (9 papers), being published in Safety Science (2 papers), Journal of Loss Prevention in the Process Industries (2 papers), and Journal of Hazardous Materials (2 papers). Nine papers of Abbasi from 1994 to 2007 have been published in different journals. Among these four authors, Khan is the most widely cited scholar in the field of domino effect accidents in the chemical industry, followed by Abbasi, Reniers, and Cozzani (see Fig. 8).

#### 3.3.2. Co-citation cluster analysis

The co-citation network can be clustered using the modularity method, and named using TF*IDF (Salton et al., 1975) and log-likelihood ratio (Chen et al., 2010; Dunning, 1993) techniques. There are 8 large clusters identified within the documents co-citations network, and marked with the log-likelihood ratio results. The detail information of the clusters are listed in Table 2. ID is the rank of the clusters based on the size of the cluster, and the size is number of cited publications in a certain cluster. 'Mean' (cited year) is the average year of the cited publications in the cluster. In CiteSpace, Silhouettes is used to measure the homogeneity or consistency of the cluster (Rousseeuw, 1987).

The largest cluster, Cluster #0, is *domino effect*, with 121 references and an average year of publication as 2001. The majority of the most-cited documents are gathered in this cluster, implying that these publications can be considered as the main stream research in the field. Cluster #7 is *chemical cluster*, with an average year of publications as 2001, and including 11 publications. Cluster #1 is *new software package maxcred-ii*, cluster #2 is *domino effect analysis*, and cluster #3 is *overpressure*. Cited publications from these clusters are from 1986 to 1989. The average year of cited publications from #4 *fertilizer industry* is 1993.

The color of the links shows the first co-cited year of the members in a certain cluster. The blue links describing two publications were co-cited in 1996 while the most recent co-citation links are shown in yellow or orange. The current results demonstrate that the focus of research on domino effects in the chemical industry has changed from cluster #1 *new software package maxcred-ii* towards the more recent clusters #0, #3 and #7. The more recent papers citing the members in cluster #0, #3 and #7 were listed in Tables 3–5.

## 4. Conclusions

In the present study, a bibliometric analysis of available publications in the field of domino effects in the process industry was carried out. Investigating the countries, institutions, and the authors of peer-reviewed publications, it was demonstrated that the increasing attention on the topic is related to a growing attention paid worldwide to process safety and to specific legislation requirements, as the Seveso Directives in the European Union. As a result, most of the studies on the topic were promoted in European countries such as Italy, Belgium, The Netherlands, France and Spain, although researchers from non-European countries such as India, Canada, and Iran have also dedicated much attention to the topic. The state-of-the-art bibliometric tools used in the present study allowed the identification of the institutions and authors that provided the more cited publications on the topic. Research centers in public universities such as the University of Bologna (Italy), the University of Antwerp (Belgium), the Delft University of Technology (The Netherlands), the Memorial University of Newfoundland (Canada), Pondicherry University (India), and Sharif University of Technology (Iran) have played a key role in advancing the knowledge in this field.

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