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Multirisk: What trends in recent works? – A bibliometric analysis

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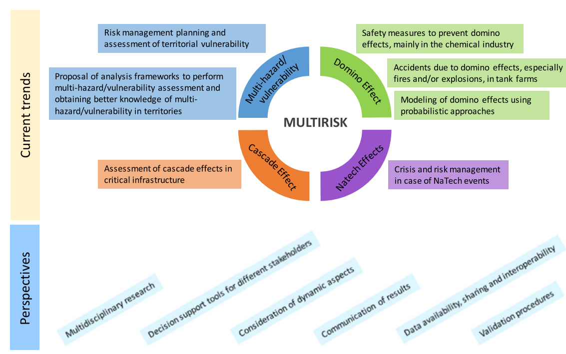
HIGHLIGHTS

- Multirisk embraces domino, cascade, Natech and multi-hazard/vulnerability risks.
- Distribution and global textual analyses are performed on the abstracts selected.
- The literature has focused on seven issues since 2004.
- A cross-issue analysis (objective, hazard, element at risk, approach) is presented.
- Six themes are discussed of which some could be future research themes.

GRAPHICAL ABSTRACT



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ABSTRACT

The issue of multirisk is coming under increasing scrutiny in the scientific literature and is of great concern for governments. Multirisk embraces different meanings: domino and cascade effects, NaTech events and the consideration of several natural hazards and their interactions. Scientific production relating to multirisk has been growing over the last 15 years. This review, based on 191 articles, proposes a new way of analyzing and presenting bibliographic results by the use of a global textual analysis. This analysis leads to identify seven main themes of research in the literature: three concern Domino Effects (46.6% of the articles), two are dedicated to the assessment of Multi-(hazard/vulnerability) Risk (28.7%), one deals with Natech issues (13.5%) and one concerns Cascade Effects in critical infrastructures (11.2%). A cross-issue analysis was performed on the basis of four criteria: objectives, hazards, the elements at risk considered, and the approaches used or developed in the articles. It provides general lessons on these items and proposes themes for future research on the topic of multirisk.

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1. Introduction

A recent United Nations report (United Nations/Department of Economic and Social Affairs, 2015) specifically addressed the exposure of the world's urban population (cities with 300,000 inhabitants or more) to several natural hazards: for example, in 2014, 100 million people lived in areas that were highly exposed to multiple types of disaster, and 752 million people (34% of the total urban population) were exposed to the medium or low risk of one or more of the six types of natural disaster. Of course, exposure in smaller cities must be added to these figures. The consideration of technological risks further aggravates these situations, especially since the distance between inhabited and industrial areas is rapidly decreasing (Rad et al., 2014) and the number of infrastructures and their interrelations are increasing. Natural hazards can trigger technological accidents: these events are referred to "NaTech" events. In addition, interactions due to the simultaneous or near-time occurrence (before a system recovers from the first shock) of several independent hazards or even cascades between events that are technological or natural must be emphasized: for example, the Philippines, which suffered a volcanic eruption in 1991, followed by a typhoon; the combustion of buildings by fire caused by an explosion of gas released from a pipeline ruptured by an earthquake, which happened during the 1994 Northridge earthquake; the tsunamis triggered by earthquakes in the Indian Ocean (2004) and Japan (2011), leading in the latter case to the accident of the Fukushima nuclear plant; landslides caused by the occurrence of an earthquake, such as in New Zealand at the end of 2016. These phenomena rarely occur but always have catastrophic consequences: the potential risk generated by several events is generally higher than the single aggregation of single risks (Marzocchi et al., 2009), so this consideration implies adopting quite a different outlook regarding classical single-risk analysis (Garcia-Aristizabal et al., 2015). Finally, due to global changes, exposure has increased due to changes in the amplitudes, frequencies and spatial distribution of hazards. The urbanization of an area including industries at risk can transform an event into a disaster.

The concept of multirisk management emerged in Agenda 21 adopted at the Rio de Janeiro Conference in 1992 (United Nations Conference on Environment and Development, 1992), the Johannesburg Plan in 2002 and the Hyogo (United Nations/International Strategy for Disaster Reduction (UNISDR), 2005) and Sendai (United Nations/International Strategy for Disaster Reduction (UNISDR), 2015) Frameworks. Taking into account multirisk was then identified as essential in various documents at the European and global levels (The World Bank, 2014; European Commission, 2010). Li et al. demonstrated that, concerning the domino effect, increasing attention on the topic is related to the growing attention paid worldwide to process safety and to specific legislation requirements, such as the Seveso Directives in the European Union (Li et al., 2017). Scientific studies have also reported that stakeholder interest in multirisk assessment is strong (Komendantova et al., 2016; Scolobig et al., 2013a). However, there are still bottlenecks, as pointed out in recent OECD (Organization for Economic Co-operation and Development) and ANR (French National Research Agency) reports, which classify this issue as an open research question (ANR, 2019; OECD, 2012).

Currently, there is no clear definition of "multirisk" either in science or in practice; decision-making under multirisk is a nascent field (Komendantova et al., 2014). In this article, the concept of multirisk refers to a set of different hazards able to act in combination with or without coincidence over time (heavy rains can generate floods and landslides; the occurrence of a hurricane in an area already affected by an earthquake but not overcome by this first shock) and impacting, in a given territory, potentially dependent stakes (the destruction of a hospital can lead to the over-saturation of other hospitals in the area; the failure of one infrastructure may lead to the failure of other infrastructures) (Gallina et al., 2016; Garcia-Aristizabal et al., 2015; Garcia-Aristizabal and Marzocchi, 2012a; Garcia-Aristizabal and Marzocchi, 2012b). Hazards can be natural (earthquake, seism, flood, etc.) and/or technological (dam collapse, chemical explosion, etc.) and/or due to anthropogenic processes (vegetation removal, mining, drainage, etc.) (Gill and Malamud, 2016). These can threaten the same elements at risk. Malicious events (terrorism, arson, aspects of warfare, criminal activity) do not belong to either anthropogenic processes or technological hazards/disasters, but may trigger the occurrence of other hazards. Elements at risk are composed of human beings and natural or anthropogenic elements presenting economic, social, technical, human, environmental vulnerabilities, etc. The consequences can be direct (loss of human lives, destruction of resources, etc.) or indirect (remote economic damage, etc.). Serious problems of pollution can occurred following the release of hazardous substances in the environment due to Natech or domino events (Basco and Ernesto, 2017; Duan and He, 2015; Krausmann et al., 2019). Environmental pollutions can also be due to anthropogenic hazards (Garcia-Aristizabal et al., 2019).

The consideration of interactions is essential in multirisk issues and allows progressing from the perception of multi-hazard risk towards multirisk management (Garcia-Aristizabal et al., 2015): these interactions include the spatial and temporal relationships between various hazards and other elements of the risk chain, and unexpected effects and threats that are not captured by means of separate single-hazard analyses (Komendantova et al., 2016; Kappes et al., 2012; Garcia-Aristizabal et al., 2015). Different types of interaction can occur (Gill and Malamud, 2014; Yordanova and Curt, 2018): a hazard triggered by another (domino effect); the probability of a hazard is increased or decreased due to an initial event; events involving the spatial and temporal coincidence of natural hazards (coupled events); events that increase the vulnerability of the exposed elements-at-risk. Series and parallel events can occur (Liu et al., 2016). Moreover, social and/or physical vulnerability may progressively change due to the occurrence of events: they could increase, thus reducing the capacity to cope, or decrease in the case of significant time intervals between successive events, leading to better community awareness and preparation (Gill and Malamud, 2014; Liu et al., 2015; Yordanova and Curt, 2018). The different situations exhibited in Fig. 1 can be chained: a domino effect can be triggered by coupled events for instance.

A multirisk approach entails seeing things within a multi-hazard and a multi-vulnerability perspective. Considering such interactions allows better estimation of the final risk, incorporates possible amplifications due to interaction with other hazards, and avoids significant bias and erroneous risk hierarchization (Selva, 2013). The multirisk approaches

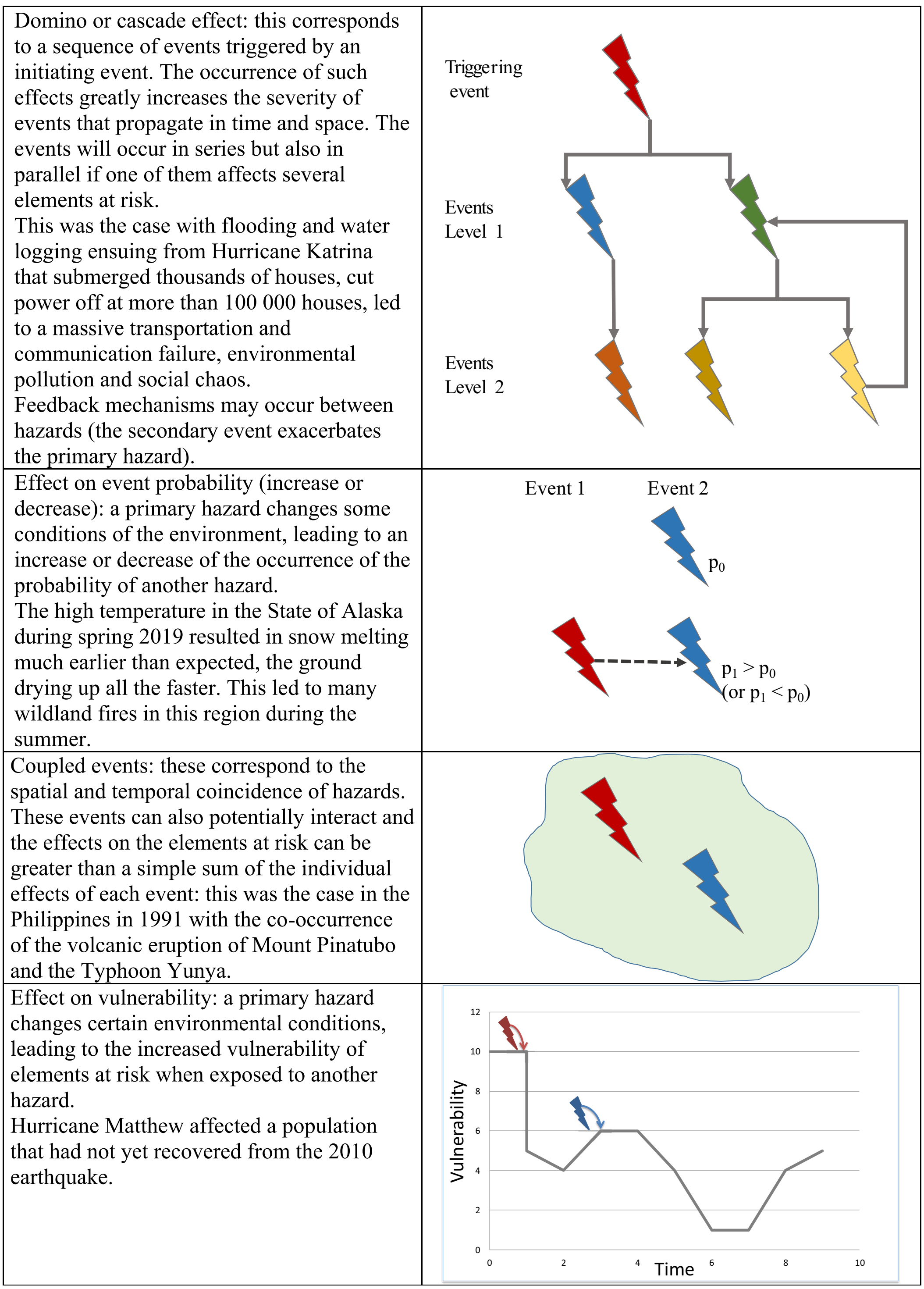

Fig. 1. Different types of interactions – events are represented as flashes.

aim at providing decision support for better risk management (Gallina et al., 2016; Greiving, 2006; Marzocchi et al., 2012; Scolobig et al., 2013b).

To summarize, multirisk management is a relatively new field and formulating an integrated framework for multirisk assessment is still a major challenge, notably due to the need to address interactions (Garcia-Aristizabal et al., 2015; Garcia-Aristizabal and Marzocchi, 2012a; Kappes et al., 2012). These challenges have led to scientific production that has been growing over the last 15 years. The purpose of this paper is to provide an analysis of this production, in particular by identifying the scientific issues addressed in this body of articles, and ultimately to identify directions for future research. It is based on a literature review focused on physical vulnerability: the analysis of social and human vulnerability is a subject in its own right and is not covered here.

2. Method

2.1. Selection of texts and distribution analyses

To present the breadth of coverage of the literature review of multirisk studies and identify the relevant papers, an analysis was first carried out of the Web of Science (https://www.webofknowledge.com) and the SCOPUS databases (https://www.elsevier.com/solutions/scopus), two comprehensive multidisciplinary content search platforms for academic researchers. The requests are presented as Supplemental Materials. The keywords used are (search in the article title): "domino effect*", "cascade effect*", "cascading effect*", natech, multi-risk*, multirisk*, "multi-hazard* risk*", "multihazard* risk*". Years considered are 2004–2020.

Duplicates were removed after which finer analyses were performed on abstracts and full reviews. Articles related to other domains such as ecology, medicine, economy and mathematics or forum articles were removed. This operation led to keeping 191 references. These comprised 13 review articles (Alileche et al., 2017; Darbra et al., 2010; Gallina et al., 2016; Kappes et al., 2012; Li et al., 2017; Naderpour et al., 2019; Nascimento and Alencar, 2016; Necci et al., 2015; Sperotto et al., 2017; Steinberg et al., 2008; Swuste et al., 2019; Terzi et al., 2019; Zhang et al., 2019) that will not be considered in the global textual analysis (Sections 3 and 4) as this analysis is devoted to identifying the different research themes present in the literature. Some of these 13 articles will be used further on in the discussion section (Section 5) to highlight the results.

Distribution analyses were performed by year of publication, journals and keywords.

2.2. Global textual analysis

A textual analysis of the 178 abstracts was carried out using the IRaMuTeQ version 0.7 alpha 2 (Interface de R pour les Analyses Multidimensionnelles de Textes et de Questionnaires) (Ratinaud, 2014). The software treats each of these abstracts as a text. The main themes present in these texts were searched: the software makes distinctions between "full words" such as verbs, noun, adjectives, adverbs and "tool words" such as pronouns, determents, etc. With this distinction, only full words are included in the main analysis. A lemmatization of the text corpus was performed. This consists in replacing a word by its root term (e.g., 'risks' by 'risk'). This process decreases complexity.

A cluster analysis using the Reinert method was carried out. This method allows the investigation of links between topics. First, a binary matrix (abstracts in rows, full words in columns) is built. Then a hierarchical divisive clustering is performed, using bipartition: at each step of the process, the larger remaining cluster is divided into 2 parts. The texts are grouped according to the co-occurrence of forms with a homogeneity property into a cluster and a heterogeneity property between clusters. The results are presented as a dendrogram that represents the quantity and lexical composition of the clusters arising from the grouping of terms. The software searches for patterns of co-occurrence of words/lexemes through successive Chi square tests, and organizes themes/clusters based on them. Forms overrepresented in a cluster appear with a larger character size. To determine the number of forms to be kept, we sought to optimize the number of abstracts classified in clusters. The analysis was performed for different values of occurrences: words with at least 10, 20, 30, 40, 45, 50, 60 occurrences were kept. The best result was obtained using the 64 words presenting at least 45 occurrences in the corpus: 100% of the texts are clustered.

Correspondence factorial analysis creates graphs that allow the visualization of classes and their proximity. This analysis identifies a small number of independent factors representing the main deviations from independence. Factor 1 represents the largest amount of explained inertia from independence; Factor 2, the second largest, and so on. This analysis aims at representing the clusters in a low-dimensional space. Clusters with similar distributions are close in space contrary to clusters with dissimilar distributions.

The analysis of similarity is a technique based on graph theory that shows co-occurrences of, and connections between, words and helps to identify the representation structure. Font size is proportional to the term's frequency of occurrence and line thickness reflects the strength of the relationship between two forms. The analysis was performed with the same words as the cluster analysis.

3. Distribution analyses

The dynamics of academic research on multirisk issues are analyzed through their distribution over time. The number of publications dealing with these issues has increased significantly since 2013 in comparison to the previous years as they represent 75% of the total number of articles for the period (2004–2020) and more than 50% since 2016 (cf. Supplementary Material – Fig. 1SM).

Sixty-three different journals from various disciplines were included in this literature review. Fourteen journals contributed at least 3 articles examined in this literature review: 22% of the journals published more than 65% of the articles. Among these, *Journal of Loss Prevention in the Process Industries* is the most significant source, followed by *Reliability Engineering & System Safety*. To complete the list, 14 (resp. 35) different journals published 2 (resp. 1) articles. These results are presented as Supplementary Material (Table 1SM).

The distribution of papers is analyzed following the four keywords used in the survey: Multi-risk/multirisk/multi-hazard risk; Domino; Cascade Effect; Natech. Domino effect is the main theme studied, followed by Multi-risk/Multi-hazard risk. Cascade and Domino effects can be considered as similar concepts; however, in the articles studied the former mainly consider infrastructures while the latter focus on industries or parks of industries. In the literature, the terms "multi-risk", "multirisk" and "multi-hazard" are used with a territorial meaning. They are more linked to natural hazards and differ from domino, cascade or NaTech effects. When we mention this type of event in the following, the term "multi-hazard/vulnerability" will be used (abbreviated as MHV). Conversely, the term "multirisk" will be kept when considering all types of event: domino, cascade, Natech effects and MHV. These results are presented as Supplementary Material (Table 2SM).

4. Global textual analysis

The content of the corpus analyzed was composed of 178 texts. Unsurprisingly, the keywords used for the search are the top twenty-seven most active frequent forms: risk is the most frequent form (576 occurrences) and cascade the least (98 occurrences) (cf. Supplementary Material – Table 3SM).

4.1. Analysis of similarity

Fig. 2 shows the result of the similarity analysis performed on forms whose occurrence is higher or equal to 45 (68 forms – this choice was retained as it allows classing all the abstracts with the Reinert clustering). Five communities are identified based on 64 forms. Four words were removed from the analysis: Propose, Present, Paper and Result, which are not significant for this study. Three main themes can be distinguished:

- Domino events in industrial plants, mainly process and chemical ones;
- Cascade effects involving infrastructures;
- Multi-(hazard/vulnerability)risk and Natech events. "Risk" is strongly associated with the form "Assessment", revealing that this activity is a specific issue of the scientific research on multirisks. Two smaller clusters are partially superimposed: one indicates that natural risks are specifically considered; "case + study" shows that articles often present an example of application.

A deeper analysis relying on clustering is proposed in the next section.

4.2. Reinert clustering

The Reinert analysis retains all the texts. Seven classes were generated that are analyzed based on their characteristics (cf. Fig. 3 – only significative forms are shown). They show the main themes of research in the literature.

The clusters show the main research themes in the literature. The clustering separates two clusters. Cluster A (classes 3, 4 and 6) represents 46.6% of the texts and gathers the texts dealing with "domino effect". Cluster B (classes 1, 2, 5 and 7) represents 53.4% (cf. Table 1 and Fig. 3) and includes abstracts focusing on Natech issues, cascade effects and MHV issues (Cluster C). Classes 4 is the largest one and Class 5 the smallest. The main theme concerns Domino Effects (46.6%), then Multi-(hazard/vulnerability) Risk (28.7%), Natech issues (13.5%) and finally Cascade Effects in critical infrastructures (11.2%).

From this analysis, it can be stated that 7 main themes are present in the literature (from left to right in Fig. 3). Three articles have been moved from one class to another in order to better correspond to the categories identified. The 7 classes are:

- Class 2 (25 abstracts): Risk management planning and assessment of territorial vulnerability. Flooding (present in 17 abstracts – in combination with other hazards) is the hazard studied most;
- Class 1 (26 abstracts): Proposal of analysis frameworks allowing a multi-hazard/vulnerability assessment or better knowledge of multi-hazard/vulnerability in territories (identification of hazards, risks, interactions, etc.). The hazard considered most is earthquake (present in 10 abstracts – in combination with other hazards). Urban areas are studied more particularly;
- Class 5 (20 abstracts): Assessment of cascade effects in critical infrastructures;

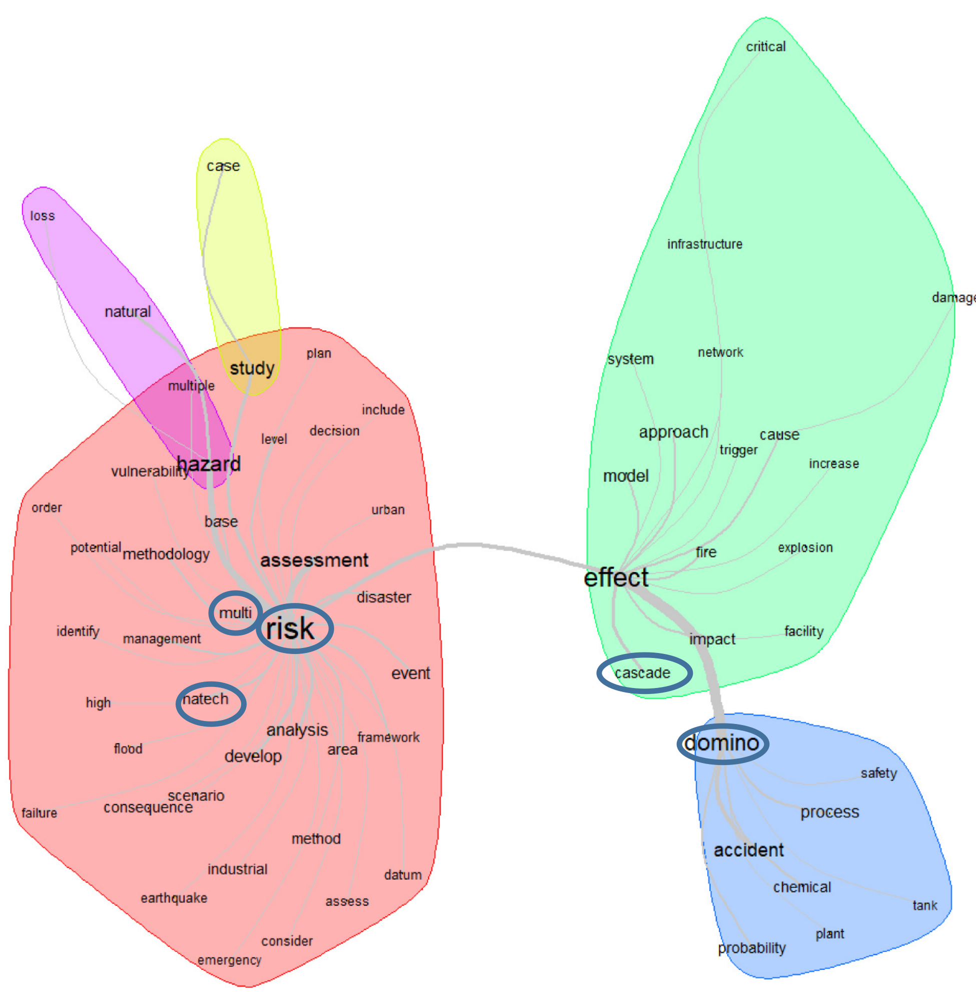

Fig. 2. Graph of similarities (only forms whose occurrence was higher or equal to 45 were considered – Keywords used for the search are indicated).

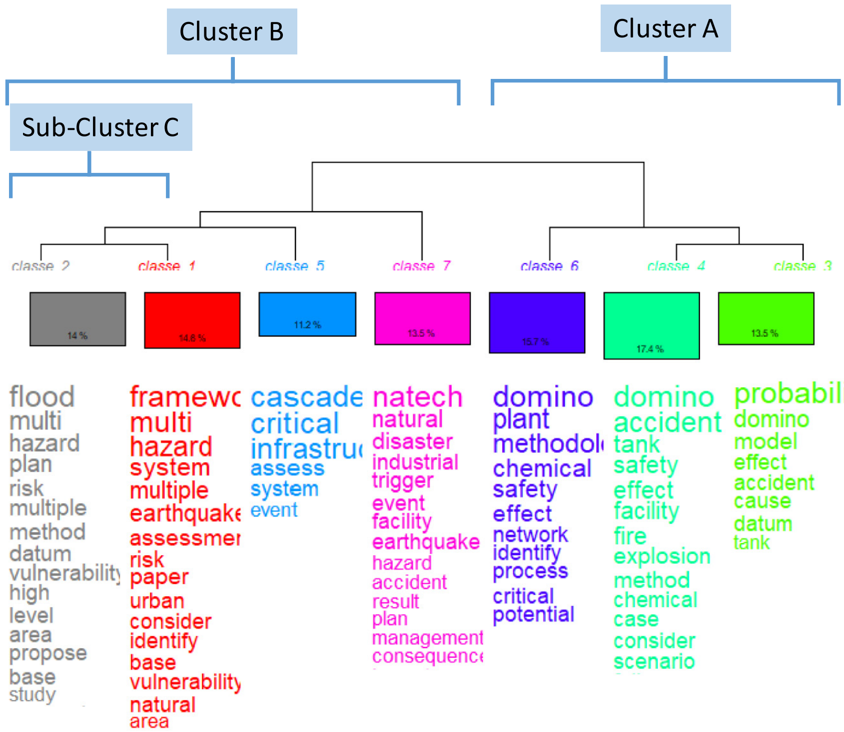

Fig. 3. Dendogram (only significative forms are shown for each class: $p < 0.05$) - Forms overrepresented in a cluster appeared with a larger character size.

- Class 7 (24 abstracts): Crisis and risk management in case of NaTech events. The initiating hazard of such an event is mainly an earthquake (present in 11 abstracts);
- Class 6 (28 abstracts): Safety measures to prevent domino effects, mainly in the chemical industry. The word "network" refers to Bayesian network approaches (present in 10 abstracts);
- Class 4 (31 abstracts): Accidents due to domino effects, especially fires and/or explosions, in tank farms;
- Class 3 (24 abstracts): Modeling of domino effects using probabilistic approaches.

While the terms "domino" and "cascade" seem to be synonymous, the first is largely reserved for events occurring in an industrial environment while the second is reserved more for applications on critical infrastructures (transport, energy, water networks, etc.). The key words "multirisk" and "multi-hazard risk" are used in the sense of natural hazards impacting a territory (MHV).

4.3. Factorial correspondence analysis (FCA)

The FCA resulted in six factors, the first three represent more than 75% of the total variance. The first factor (F1–39.19% of the total variance) discriminates according to the scale of study: territory, urban scales and associated hazards are represented by negative values ("urban", "infrastructure", "earthquake", "flood", etc.) while industrial plants are represented by positive ones ("plant", "tank", "fire"). The second factor (F2–19.55% of the total variance) differentiates "one-type" risks, i.e. industrial or natural ones (positive values) from "compounded" risks, i.e. Natech ones (negative values) (cf. Fig. 4). Finally, the third factor (F3–18.89% of the variance) positions critical infrastructures as specific elements of the territory.

Table 1
Number of abstracts per cluster.

Cluster	1	2	3	4	5	6	7	Total
Number of abstracts	26	25	24	31	20	28	24	178
Domino			24	31		28		83
Multi-(hazard/vulnerability) risk	26	25						51
Natech							24	24
Cascade					20			20

5. Cross-class analysis

A comparative analysis of the seven groups obtained by Reinert's classification was performed. Four issues were addressed: objectives of the work, hazards and elements at risk considered, and methods implemented. Synthesis tables are presented below (some articles may have been considered in 2 issues, for example, an article with a dual objective oriented towards risk analysis and decision support – the number of articles per class does not therefore necessarily correspond to the numbers shown above).

5.1. Objectives of the research

Five objectives can be defined for the works; their distribution following each Reinert class is represented in Table 2. They mainly concern three fields – risk analysis, knowledge production and decision support – and consider governance analysis or training very marginally. Knowledge production corresponds to the modeling of domino or cascade effects or the analysis of past cases. Decision-support is linked to risk management through the planning of action plans, crisis measures, etc. Research focused on risk analysis is more strongly orientated towards MHV and NaTech work; works focused on knowledge production are mainly oriented towards domino effects. Works on cascade effects are balanced between risk analysis and knowledge production. Advances in decision-support concern all these themes. A few articles proposed tools or software (17 in total, shown in brackets in Table 2).

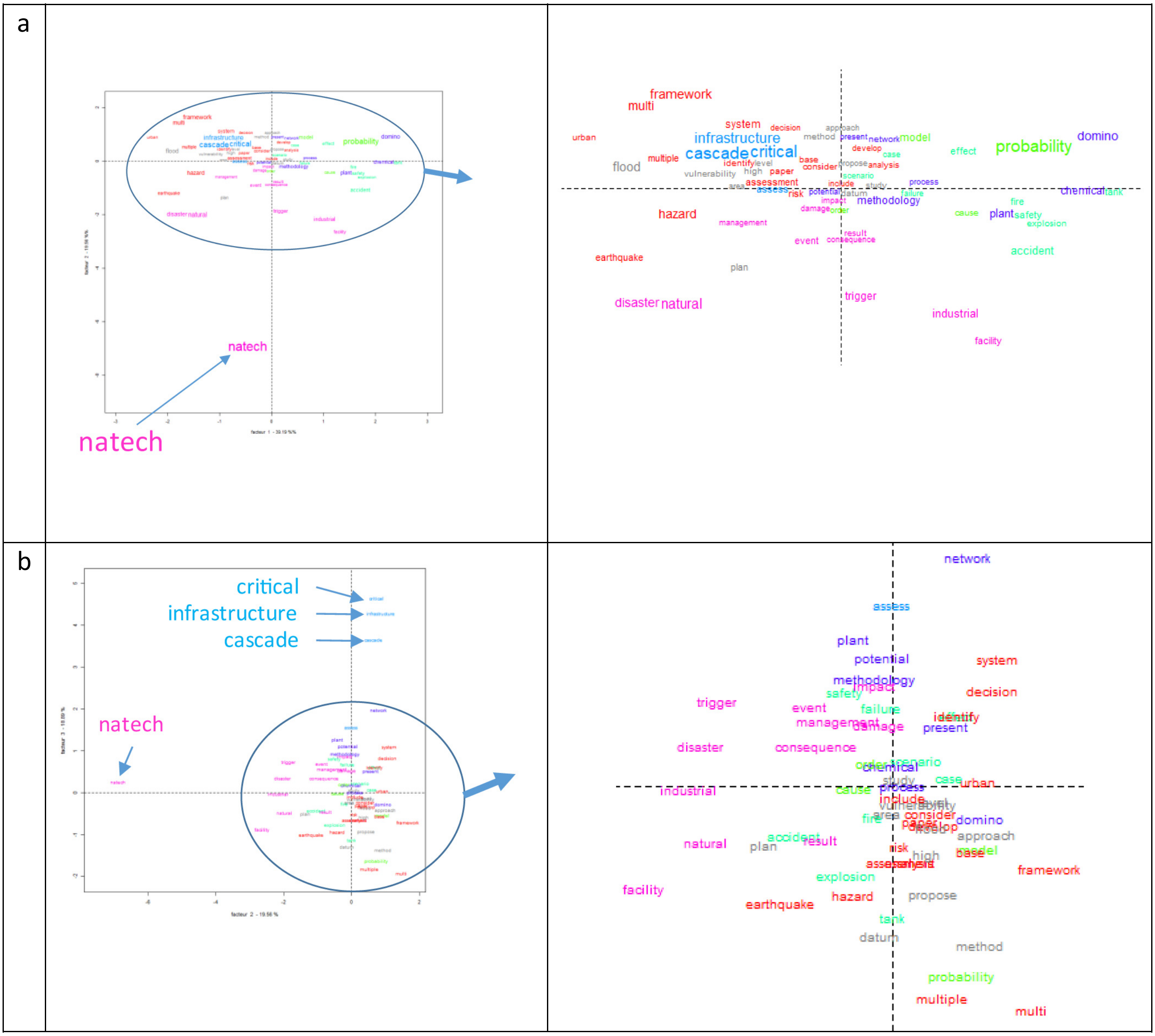

Fig. 4. (a) Projection on the first two factors of the FCA – (b) Projection on axes 2 and 3 (clusters are indicated by colors: Red: Class 1; Grey: Class 2; Neon green: Class 3; Green: Class 4; Light blue: Class 4; Dark blue: Class 6; Pink: Class 7) – forms with an occurrence higher or equal to 45 are analyzed.

5.2. Hazards studied

The hazards considered in the corpus are presented in Table 3. Three articles were not included in this table: they analyze past cases considering different accidents involving domino effects. The natural hazards studied most are floods and earthquakes, alone or in combination with other hazards. This, of course, is not surprising: floods and earthquakes are recognized as the natural hazards causing the most human, material and financial damage (UNISDR (United Nations Office for Disaster Risk Reduction), 2017). Almost one third of the works in the corpus consider at least one of these two hazards. Some publications deal with specific accidents such as the earthquake and tsunami in Japan in 2011, and the Kocaeli earthquake in Turkey in 1999. The other natural hazards represent 12% of the hazards covered.

Table 2
Objectives addressed in the corpus work (numbers in brackets indicate the number of tools developed).

	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7	Total
Risk analysis	14 (2)	21 (2)	3		7	8	22	75
Knowledge production			12 (1)	24 (2)	14 (1)	8 (1)		58
Decision-support	11 (1)	2	10 (1)	7 (2)	2	15 (3)	3	50
Governance analysis	2							2
Training		1 (1)						1

Table 3
Hazards considered in the abstracts.

	Cl 1	Cl 2	Cl 3	Cl 4	Cl 5	Cl 6	Cl 7	Total
Intense flooding or precipitation combined with other hazards	5	14						19
Intense flooding or precipitation					6		5	10
Earthquake combined with other hazards	11	6						17
Earthquake/tsunami							12	12
Geological hazards	1	2					3	6
Coastal hazards	2	2						4
Volcanism	1				1		1	2
Fire			6	7	1	8	1	23
Explosion			12	5	1	3		21
Fire and explosion				10		5		15
Effects between infrastructures			2	1		2		5
Terrorism				1	1	4		6
Miscellaneous					11			12
Others		2		2				4
Versatile approaches	7	1	2	2		6	6	24

Natural hazards are taken into account for research performed on MHV (Classes 1 and 2) and when considering cascade effects involving infrastructures (Class 5 - floods only) and NaTech issues (Class 7 - floods and earthquakes). Nascimento et Alencar also found that these two phenomena overwhelmingly occur in the case of Natech events (Nascimento and Alencar, 2016). Fires and/or explosions are the two technological hazards that are overwhelmingly studied in terms of domino events and concern nearly 60% of the abstracts. Again, this is hardly surprising as these two phenomena represent the majority of causes of accidents in industrial installations according to past case analyses (UNISDR (United Nations Office for Disaster Risk Reduction), 2017).

Some recent works (between 2014 and 2020) considered acts of terrorism as triggers of domino or cascade effects.

5.3. Elements at risk

The different elements at risks studied can be grouped under 8 categories (Table 4).

Most of the articles concern industrial installations (51.3%) and infrastructures and buildings (21.7%), thus gathering nearly three-quarters of the publications. Industrial installations correspond to chemical or process plants or complexes. The infrastructures considered are urban networks but also pipelines. Industrial installations are major issues for the analysis of domino effects (Classes 3, 4 and 6) but also Natech phenomena (Class 7). Infrastructures and buildings are of interest for the different themes (at least 2 abstracts per class deal with infrastructures or buildings). Few articles consider population (less than 7%), the environment (6%) or agriculture (4%). These are addressed in the articles dealing with MHV (Classes 1 and 2). Finally, while articles on MHV, Natech phenomena and cascade effects consider several issues, the articles on domino effects focus on the impacts on other plants in their vicinity (the analysis of domino effects involving several industrial facilities is provided for in the SEVESO directives (Komendantova et al., 2016)).

Table 4
Elements at risk studied.

	Cl 1	Cl 2	Cl 3	Cl 4	Cl 5	Cl 6	Cl 7	Total
Population	7	6						13
Buildings and infrastructures	10	7	2	4	14	2	2	41
Socio-economic issues	3							3
Industrial installations			26	25	3	27	16	97
Mining and extraction activities							4	4
Agriculture		4						4
Environment	4	2						6
Multiple elements	6	7			3		5	21

5.4. Approaches developed or implemented

The approaches used are presented in Table 5.

Probabilistic (including Bayesian networks) and statistical methods constitute the largest group, accounting for more than one-third of the total. They are primarily used for work on domino effects in industrial facilities. In addition, four other types of approach were used, each one counting for about 10% of all the methods. These are analytical frameworks (mainly for works focusing on MHV and to a lesser extent on Natech effects), risk analysis and operational safety approaches (present in the different classes but more strongly in studies dedicated to the cascade effects of infrastructures), and finally the use of geographical information systems for MHV, Natech and cascade effects. Graph theory and methods based on surveys or interviews each account for about 5% of the total. Finally, the other types of methods are more marginal (less than 3% each): development of specific metrics, lessons-learned and knowledge-based systems, analysis of existing tools, economic analysis, multi-criteria analysis, serious games.

6. Discussion

Several issues are discussed in this section and they could be the subject of future research.

6.1. Multidisciplinary research is to be encouraged

Three elements that act in favor of multidisciplinary research are highlighted below. Firstly, Table 2 shows that the governance of multirisk is poorly studied. However, risk management actors including crisis managers are particularly interested in tools capable of managing multiple risks (Komendantova et al., 2014). However, two observations can been made: on the one hand, there is a lack of integrated practices for multirisk governance, with little cooperation between communities working on different risk fields (Komendantova et al., 2016), and on the other hand, the clear identification of responsibilities for the implementation of multirisk approaches is necessary (Scolobig et al., 2017). Secondly, very little work has considered the population, the environment and agriculture as elements at risk but research has focused on anthropogenic works (plants, infrastructures and buildings) (Table 4). However, an important subject is the consideration of eco-

Table 5
Methods developed or implemented.

	Cl 1	Cl 2	Cl 3	Cl 4	Cl 5	Cl 6	Cl 7	Total
Geographic Information System	5	7	1		3		3	19
Probabilistic approach	5	5	12	15	2	5	4	48
Bayesian networks				3	1	9	2	15
Statistical approach	2	1	5					8
Petri nets			2	1				3
Development of specific metrics	2			1		1	1	5
Framework	14	1			2		6	23
Dependability analysis		2	2	4	7	2	1	18
Graph theory					3	7		10
Risk analysis		6		4		6	3	19
Multicriteria analysis		2						2
Lessons learned – Knowledge-based system				1	1		3	5
Survey – Interview		1		3	1		4	9
Serious game			1			1		2
Analysis of existing tools	4						1	5
Economic analysis	1					1	1	3
Others		1	1		1			3

socio-technical systems in the management of multirisk events. Thirdly, to address climate change issues, Gallina et al. indicated that multidisciplinary collaborations (e.g. modelers, natural scientists, economists) should be promoted to develop a comprehensive multirisk assessment process (Gallina et al., 2016). Research can therefore be encouraged in these directions and will be all the richer if it is carried out by highly multidisciplinary teams.

6.2. Decision support tools should be developed and adapted for different stakeholders

Few tools, even as prototypes, are presented in the work: seven were identified for decision support issues (Table 2). However, frameworks useful for the implementation of an approach can be added to this list (23 frameworks were identified). These types of tool can help managers make wiser decisions, gain better understanding of the various areas of risk in a territory, and support resource management and emergency planning (Lozoya et al., 2011; Ravankhah et al., 2017). As several stakeholders are usually involved in multirisk management, tools should take this specificity into account and facilitate and improve communication between them (Gerkensmeier and Ratter, 2018; Grandjean et al., 2018). Moreover, most likely domino scenarios and central events are company specific and managers and operational staff need instruments to track the progress of scenarios, and management tools to ensure the quality of barriers (Swuste et al., 2019). The development of new tools addressing escalation effects and multi-level scenarios is needed (Necci et al., 2015). It is clear that the development of tools adapted to different stakeholders is a relevant challenge.

6.3. Research should be oriented towards the necessary consideration of dynamic aspects

The integration of dynamic issues in the different developments is a challenge, as MHV, domino, NaTech and cascade phenomena occur over time. However, most of the work is mainly based on the analysis of static vulnerability that assumes there is no change in the elements exposed. Another challenge is related to the consideration of different temporal hazard scenarios and in particular those related to global changes (Gallina et al., 2016; Sperotto et al., 2017; Terzi et al., 2019). The use of bowtie methods to model MHV events was mentioned above. This proposal is linked to a challenge: that of including dynamic and temporal aspects in these approaches in order to fully represent these types of event (Terzi et al., 2019).

6.4. Communication of results is of great importance

Communicating results is a major challenge contributing to successful multirisk management. Indeed, “the successful implementation of disaster risk reduction options and strategies demand not only comprehensive risk assessment schemes, but also an appropriate mechanism to communicate and transfer knowledge on risk and its underlying drivers to the various stakeholders involved in the decision-making process” (Komendantova et al., 2014). The aim is to improve awareness of the multirisk issue (whether it is due to domino, cascade, NaTech or MHV events). Communication must be adapted to different risk management actors, whether they are decision-makers, managers, or the general public.

Spatial information systems are relevant tools: indeed, the spatial dimension is essential for MHV phenomena as well as for Natech events and cascade effects between infrastructures. This was recently underlined in particular by Naderpour et al. (2019). The results presented by this type of system are generally easily understood by different actors. However, a single map for all types of stakeholders and showing all types of risks in the area concerned will probably not meet the needs of the different stakeholders (Kappes et al., 2012) and different representations should be proposed. Specifically, there is a need to understand how to group and map MHV results in a way that they are usable, comprehensive and easily applicable for stakeholders and non-expert users for assessment and management purposes (Gallina et al., 2016).

Another type of representation that seems relevant to us stems from graphical methods such as fault trees, cause trees and bowtie diagrams stemming from dependability analysis and Bayesian networks. These methods originate from the industrial world. They have been implemented essentially to characterize domino effects between industrial installations but seldom for MHV research. However, these methods allow representing many variables and their interrelationships. Attempts have been made in this direction (Yordanova and Curt, 2018). It is thus possible to capture and communicate the breadth of the problem simultaneously, while focusing on key processes at the local scale (Terzi et al., 2019). Different fields (environmental, economic, social, etc.) can interact. Bayesian networks can also be coupled with spatial approaches (Necci et al., 2015). It would be relevant to develop work in this direction.

Moreover, appropriate communication of the uncertainties inherent to risk is crucial. There is a strong need to present uncertainties so that they can be easily understood by the target audience(s), in order to avoid decisions based on poorly evaluated information (Gallina et al., 2016).

Finally, very few participatory approaches have been deployed and these have only involved decision-makers (Komendantova et al., 2014; Scolobig et al., 2017). The involvement of the general public so that it can better understand the phenomena that can have an impact on it, whether they are MHV, NaTech, cascade between infrastructures or domino effects in industrial facilities, opens up a relevant avenue of research. This was noted for example for Natech events (Steinberg et al., 2008). In the same vein, serious games have seldom been used (Reniers, 2010; Reniers et al., 2009) but they are also a very relevant communication and learning vector. Work could be developed in this direction.

6.5. The issue of data availability, sharing and interoperability should be raised

Most of the types of data needed for a multirisk assessment (hazards, vulnerabilities, defense measures) are lacking in different parts of the world, with uneven quality due to a lack of international standards and a lack of knowledge and resources in the institutes or agencies responsible for data collection and management. However, initiatives to harmonize and standardize data are under way, such as the IRDR (Integrated Research on Disaster Risk), EM-DAT (International Disaster Database) and GEM (Global Earthquake Model) databases. Some research articles collected data on past events (Darbra et al., 2010; Zhang et al., 2019).

The issue of accessibility and data sharing between actors should be raised, especially since the lack of accessibility has been exacerbated in recent years by the fear that groups might use information for terrorist purposes (Steinberg et al., 2008). Risk information produced by the insurance and catastrophe modeling industry is still largely retained as intellectual property within each company and is rarely accessible to governments, businesses or households (UNISDR (United Nations Office for Disaster Risk Reduction), 2015). A successful experience of reasoned information sharing between different infrastructure managers was achieved during the DOMINO project (UNISDR (United Nations Office for Disaster Risk Reduction), 2015) for the management of cascading events.

Furthermore, information may have undergone transformations (e.g. data from models), and even if the results are made widely accessible, it will not necessarily be easy to determine how the data has been transformed and what assumptions were made to generate risk estimates (Reniers et al., 2009). For example, most practitioners do not know how to use databases (The World Bank, 2014). The question, therefore, is not whether the data are available, but who uses and interprets the data and for what purpose – or, more fundamentally, who is able to access and present the information in a meaningful and useful way. Another difficulty is the inoperability of different data systems (Vinchon et al., 2011), making the coupled use of tools from different entities complicated.

6.6. Validation procedures have to be invented

The question of the validation of the models developed seems interesting to discuss. Indeed, the best way to carry out validation is a comparison with an independent set of observed data. However, on the one hand, multirisk events occur in complex systems characterized by many variables of different types (hazards, elements at risk, barriers or risk management actions) that must be considered in a temporal and spatial dimension. On the other hand, especially for MHV, NaTech and cascades between infrastructures, the events are not necessarily very numerous and, as previously mentioned, the data are not always accessible. Few studies have identified and analyzed past cases: they are essentially centered on domino events between industrial installations (Abdolhamidzadeh et al., 2011; Hemmatian et al., 2014; Hou et al., 2020). Validation must therefore be thought out in a specific way and particular procedures must be set up.

7. Conclusions

The scientific literature is increasingly focusing on multirisk issues that are of great concern for governments. Multirisk embraces different meanings: domino and cascade effects, Natech events and the consideration of several natural hazards and their interactions. This bibliographic review based on a textual analysis of 178 abstracts proposed a new way of analyzing and presenting bibliographic results. Using Iramuteq software, it was possible to extract the main themes that have been considered in the literature for the last 15 last years: risk management planning and assessment of territorial vulnerability; the proposal of analysis frameworks to perform multi-hazard/vulnerability risk assessments and obtain better knowledge of multi-hazard/vulnerability in territories; the assessment of cascade effects in critical infrastructures; crisis and risk management in the case of NaTech events; safety measures to prevent domino effects, mainly in the chemical industry; accidents due to domino effects, especially fires and/or explosions in tank farms; and the modeling of domino effects using probabilistic approaches. Then, the cross-class analysis was carried out on the hazards and elements at risk considered in the 178 articles and the approaches used or developed in them. These analyses will allow proposing themes for future research on the topic of multirisk.

Declaration of competing interest

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

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Appendix A. Supplementary data

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References

Abdolhamidzadeh, B., Abbasi, T., Rashtchian, D., Abbasi, S.A., 2011. Domino effect in process-industry accidents - an inventory of past events and identification of some patterns. J. Loss Prev. Process Ind. 24 (5), 575–593. https://doi.org/10.1016/j.jlp.2010.06.013.

Alileche, N., Olivier, D., Estel, L., Cozzani, V., 2017. Analysis of domino effect in the process industry using the event tree method. Saf. Sci. 97, 10–19. https://doi.org/10.1016/j.ssci.2015.12.028.

ANR, 2019. Risques et catastrophes naturels - Bilan des projets financés sur la période 2010–2018.

Basco, A., Ernesto, S., 2017. The vulnerability of industrial equipment to tsunami. J. Loss Prev. Process Ind. 50, 301–307. https://doi.org/10.1016/j.jlp.2016.11.009.

Darbra, R.M., Palacios, A., Casal, J., 2010. Domino effect in chemical accidents: main features and accident sequences. J. Hazard. Mater. 183, 565–573. https://doi.org/10.1016/j.jhazmat.2010.07.061.

Duan, W., He, B., 2015. Emergency response system for pollution accidents in chemical industrial parks, China. International Journal of Environmental Research and Public Health 12, 7868–7885. https://doi.org/10.3390/ijerph120707868.

European Commission, 2010. Risk assessment and mapping guidelines for disaster management.

Gallina, V., Torresan, S., Critto, A., Sperotto, A., Glade, T., Marcomini, A., 2016. A review of multi-risk methodologies for natural hazards: consequences and challenges for a climate change impact assessment. J. Environ. Manag. 168, 123–132. https://doi.org/10.1016/j.jenvman.2015.11.011.

Garcia-Aristizabal, A., Marzocchi, W., 2012a. MATRIX Project - Deliverable 5.1: State-of-the-Art in Multi-risk Assessment.

Garcia-Aristizabal, A., Marzocchi, W., 2012b. MATRIX Project - Deliverable 3.1: Review of Existing Procedures for Multi-Hazard Assessment.

Garcia-Aristizabal, A., Gasparini, P., Uhinga, G., 2015. Multi-risk assessment as a tool for decision-making. Urban Vulnerability and Climate Change in Africa - a Multidisciplinary Approach. Springer https://doi.org/10.1007/978-3-319-03982-4_7.

Garcia-Aristizabal, A., Kocot, J., Russo, R., Gasparini, P., 2019. A probabilistic tool for multi-hazard risk analysis using a bow-tie approach: application to environmental risk assessments for geo-resource development projects. Acta Geophysica 67 (1), 385–410. https://doi.org/10.1007/s11600-018-0201-7.

Gerkensmeier, B., Ratter, B.M.W., 2018. Multi-risk, multi-scale and multi-stakeholder - the contribution of a bow-tie analysis for risk management in the trilateral Wadden Sea Region. J. Coast. Conserv. 22 (1), 145–156. https://doi.org/10.1007/s11852-016-0454-8.

Gill, J.C., Malamud, B.D., 2014. Reviewing and visualizing the interactions of natural hazards. Rev. Geophys. 52 (4), 680–722. https://doi.org/10.1002/2013RG000445.

Gill, J.C., Malamud, B.D., 2016. Hazard interactions and interaction networks (cascades) within multi-hazard methodologies. Earth System Dynamics 7, 659–679. https://doi.org/10.5194/esd-7-659-2016.

Grandjean, G., Thomas, L., Bernardie, S., Team, S., 2018. A novel multi-risk assessment web-tool for evaluating future impacts of global change in mountainous areas. Climate 6 (4). https://doi.org/10.3390/cli6040092.

Greiving, S., 2006. Integrated risk assessment of multi-hazards: a new methodology. In: Schmidt-Thomé, P. (Ed.), Natural and Technological Hazards and Risks Affecting the Spatial Development of European Regions. Geological Survey of Finland.

Hemmatian, B., Abdolhamidzadeh, B., Darbra, R.M., Casal, J., 2014. The significance of domino effect in chemical accidents. J. Loss Prev. Process Ind. 29, 30–38. https://doi.org/10.1016/j.jlp.2014.01.003.

Hou, L., Wua, X., Wua, Z., Wu, S., 2020. Pattern identification and risk prediction of domino effect based on data mining methods for accidents occurred in the tank farm. Reliability Engineering & System Safety 193, 106646. https://doi.org/10.1016/j.ress.2019.106646.

Kappes, M.S., Keiler, M., von Elverfeldt, K., Glade, T., 2012. Challenges of analysing multi-hazard risk: a review. Nat. Hazards 64, 1925–1958. https://doi.org/10.1007/s11069-012-0294-2.

Komendantova, N., Mrzyglocki, R., Mignan, A., Khazai, B., Wenzel, F., Patt, A., Fleming, K., 2014. Multi-hazard and multi-risk decision-support tools as a part of participatory risk governance: feedback from civil protection stakeholders. International Journal of Disaster Risk Reduction 8, 50–67. https://doi.org/10.1016/j.ijdrr.2013.12.006.

Komendantova, N., Scolobig, A., Garcia-Aristizabal, A., Monfort, D., Fleming, K., 2016. Multi-risk approach and urban resilience. International Journal of Disaster Resilience in the Built Environment 7 (2), 114–132. https://doi.org/10.1108/IJDRBE-03-2015-0013.

Krausmann, E., Girgin, S., Necci, A., 2019. Natural hazard impacts on industry and critical infrastructure: Natech risk drivers and risk management performance indicators. International Journal of Disaster Risk Reduction 40, 9. https://doi.org/10.1016/j.ijdrr.2019.101163.

Li, J., Reniers, G., Cozzani, V., Khan, F., 2017. A bibliometric analysis of peer-reviewed publications on domino effects in the process industry. J. Loss Prev. Process Ind. 49, 103–110. https://doi.org/10.1016/j.jlp.2016.06.003.

Liu, Z.Q., Nadim, F., Garcia-Aristizabal, A., Mignan, A., Fleming, K., Luna, B.Q., 2015. A three-level framework for multi-risk assessment. Georisk-Assessment and Management of Risk for Engineered Systems and Geohazards 9 (2), 59–74. https://doi.org/10.1080/17499518.2015.1041989.

Liu, B., Siu, Y.L., Mitchell, G., 2016. Hazard interaction analysis for multi-hazard risk assessment: a systematic classification based on hazard-forming environment. Nat. Hazards Earth Syst. Sci. 16, 629–642. https://doi.org/10.5194/nhess-16-629-2016.

Lozoya, J.P., Sarda, R., Jimenez, J.A., 2011. A methodological framework for multi-hazard risk assessment in beaches. Environ. Sci. Pol. 14 (6), 685–696. https://doi.org/10.1016/j.envsci.2011.05.002.

Marzocchi, W., Mastellone, M., Di Ruocco, A., Novelli, P., Romeo, E., & Gasparini, P. (2009). Principles of Multi-risk Assessment - Interaction amongst Natural and Man-induced Risks.

Marzocchi, W., Garcia-Aristizabal, A., Gasparini, P., Mastellone, M., Di Ruocco, A., 2012. Basic principles of multi-risk assessment: a case study in Italy. Nat. Hazards 62, 551–573. https://doi.org/10.1007/s11069-012-0092-x.

Naderpour, M., Rizeei, H.M., Khakzad, N., Pradhan, B., 2019. Forest fire induced Natech risk assessment: a survey of geospatial technologies. Reliability Engineering & System Safety 191. https://doi.org/10.1016/j.ress.2019.106558.

Nascimento, K.R.D.S., Alencar, M.H., 2016. Management of risks in natural disasters: a systematic review of the literature on NATECH events. J. Loss Prev. Process Ind. 44, 347–359. https://doi.org/10.1016/j.jlp.2016.10.003.

Necci, A., Cozzani, V., Spadoni, G., Khan, F., 2015. Assessment of domino effect: state of the art and research needs. Reliab. Eng. Syst. Saf. 143, 3–18. https://doi.org/10.1016/j.ress.2015.05.017.

OECD, 2012. Global Modelling of Natural Hazard Risks - Enhancing Existing Capabilities to Address New Challenges.

Rad, A., Abdolhamidzadeh, B., Abbasi, T., Rashtchian, D., 2014. FREEDOM II: an improved methodology to assess domino effect frequency using simulation techniques. Process Saf. Environ. Prot. 92, 714–722. https://doi.org/10.1016/j.psep.2013.12.002.

Ratinaud, P., 2014. IRaMuTeQ: interface de R pour les analyses Multidimensionnelles de Textes et de questionnaires (version 0.7 alpha 2) [R Interface for multidimensional analyzes of texts and questionnaires. Free software built with free software]. URL. http://www.iramuteq.org/.

Ravankhah, M., Schmidt, M., Will, T., 2017. Multi-hazard disaster risk identification for world cultural heritage sites in seismic zones. Journal of Cultural Heritage Management and Sustainable Development 7 (3), 272–289. https://doi.org/10.1108/jchmsd-09-2015-0032.

Reniers, G., 2010. An external domino effects investment approach to improve cross-plant safety within chemical clusters. J. Hazard. Mater. 177 (1–3), 167–174. https://doi.org/10.1016/j.jhazmat.2009.12.013.

Reniers, G., Dullaert, W., Karela, S., 2009. Domino effects within a chemical cluster: a game-theoretical modeling approach by using Nash-equilibrium. J. Hazard. Mater. 167 (1–3), 289–293. https://doi.org/10.1016/j.jhazmat.2008.12.113.

Scolobig, A., Garcia-Aristizabal, A., Komendantova, N., Patt, A., Di Ruocco, A., Gasparini, P., ... Fleming, K., 2013a. From multi-risk assessment to multi-risk governance: recommendations for Future Directions. Global Assessment Report on Disaster Risk Reduction 2015.

Scolobig, A., Vinchon, C., Komendantova, N., Bengoubou-Valerius, M., Patt, A., 2013b. MATRIX Project - Deliverable 6.3: Social and Institutional Barriers to Effective Multi-hazard Decision Making.

Scolobig, A., Komendantova, N., Mignan, A., 2017. Mainstreaming multi-risk approaches into policy. Geosciences 7 (4). https://doi.org/10.3390/geosciences7040129.

Selva, J., 2013. Long-term multi-risk assessment: statistical treatment of interaction among risks. Nat. Hazards 67, 701–722. https://doi.org/10.1007/s11069-013-0599-9.

Sperotto, A., Molina, J.L., Torresan, S., Critto, A., Marcomini, A., 2017. Reviewing Bayesian networks potentials for climate change impacts assessment and management: a multi-risk perspective. J. Environ. Manag. 202, 320–331. https://doi.org/10.1016/j.jenvman.2017.07.044.

Steinberg, L., Sngul, H., Cruz, A., 2008. Natech risk and management: an assessment of the state of the art. Nat. Hazards 46, 143–152. https://doi.org/10.1007/s11069-007-9205-3.

Swuste, P., van Nunen, K., Reniers, G., Khakzad, N., 2019. Domino effects in chemical factories and clusters: an historical perspective and discussion. Process Saf. Environ. Prot. 124, 18–30. https://doi.org/10.1016/j.psep.2019.01.015.

Terzi, S., Torresan, S., Schneiderbauer, S., Critto, A., Zebisch, M., Marcomini, A., 2019. Multi-risk assessment in mountain regions: a review of modelling approaches for climate change adaptation. J. Environ. Manag. 132, 759–771. https://doi.org/10.1016/j.jenvman.2018.11.100.

The World Bank, 2014. Understanding Risk in an Evolving World - Emerging Best Practives in Natural Disaster Risk Assessment.

UNISDR (United Nations Office for Disaster Risk Reduction), 2015. Réduction du risque de catastrophe: Bilan mondial.

UNISDR (United Nations Office for Disaster Risk Reduction), 2017. Words into Action Guidelines National Disaster Risk Assessment.

United Nations/Department of Economic and Social Affairs, 2015. Risks of Exposure and Vulnerability to Natural Disasters at the City Level: A Global Overview.

United Nations Conference on Environment and Development, 1992. The Rio Declaration on Environment and Development.

United Nations/International Strategy for Disaster Reduction (UNISDR), 2005. Hyogo Framework for Action 2005–2015: Building the Resilience of Nations and Communities to Disasters - Extract from the Final Report of the World Conference on Disaster Reduction.

United Nations/International Strategy for Disaster Reduction (UNISDR), 2015. Sendai Framework for Disaster Risk Reduction 2015–2030.

Vinchon, C., Carreño, M.L., Contreras-Mojica, D.M., Kienberger, S., Schneiderbauer, S., Alexander, D., ... Welle, T., 2011. MOVE Project - Assessing vulnerability to natural hazards in Europe:From Principles to Practice - A manual on concept, methodology and tools.

Yordanova, R., Curt, C., 2018. Towards a systematic qualitative methodology for multi-hazards risk representation and preliminary assessment. 10èmes journées Fiabilité des Matériaux et des Structures, Bordeaux, France. JFMS.

Zhang, M.G., Zheng, F., Chen, F.Z., Pan, W.J., Mo, S.F., 2019. Propagation probability of domino effect based on analysis of accident chain in storage tank area. J. Loss Prev. Process Ind. 62. https://doi.org/10.1016/j.jlp.2019.103962.