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Corinne Curt

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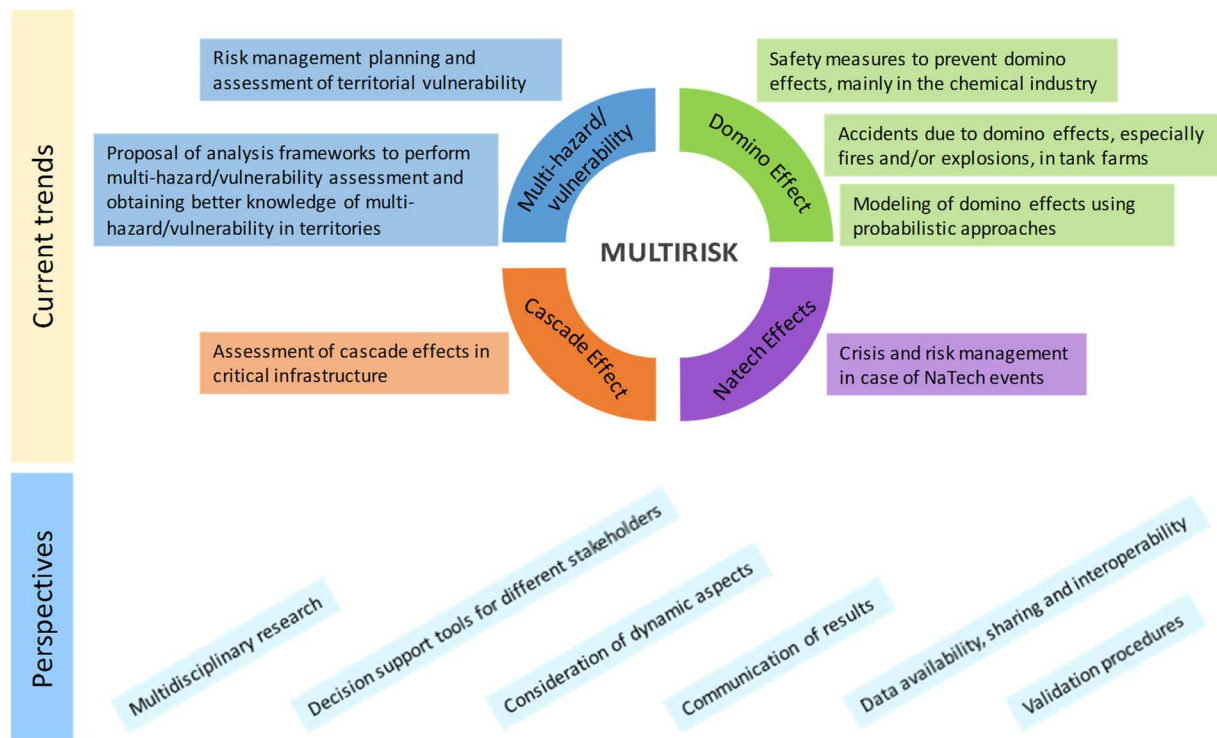
Multirisk: what trends in recent works? – A bibliometric analysis

Corinne Curt – INRAE, Aix Marseille Univ – RECOVER – 3275 Route Cézanne – CS 40061 – 13182
Aix-en-Provence – France
corinne.curt@inrae.fr

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.

20 Graphical abstract



21

22

23 Highlights

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

29

30 **Keywords**

31 Multirisk; Domino Effect; Cascade Effect; Natech event; Multi-hazard risk; Multi-vulnerability

32 **1. Introduction**

33 A recent United Nations report [1] specifically addressed the exposure of the world's urban population
34 (cities with 300,000 inhabitants or more) to several natural hazards: for example, in 2014, 100 million
35 people lived in areas that were highly exposed to multiple types of disaster, and 752 million people
36 (34 % of the total urban population) were exposed to the medium or low risk of one or more of the six
37 types of natural disaster. Of course, exposure in smaller cities must be added to these figures. The
38 consideration of technological risks further aggravates these situations, especially since the distance
39 between inhabited and industrial areas is rapidly decreasing [2] and the number of infrastructures and
40 their interrelations are increasing. Natural hazards can trigger technological accidents: these events are
41 referred to “NaTech” events. In addition, interactions due to the simultaneous or near-time occurrence
42 (before a system recovers from the first shock) of several independent hazards or even cascades
43 between events that are technological or natural must be emphasized: for example, the Philippines,
44 which suffered a volcanic eruption in 1991, followed by a typhoon; the combustion of buildings by
45 fire caused by an explosion of gas released from a pipeline ruptured by an earthquake, which
46 happened during the 1994 Northridge earthquake; the tsunamis triggered by earthquakes in the Indian
47 Ocean (2004) and Japan (2011), leading in the latter case to the accident of the Fukushima nuclear
48 plant; landslides caused by the occurrence of an earthquake, such as in New Zealand at the end of
49 2016. These phenomena rarely occur but always have catastrophic consequences: the potential risk
50 generated by several events is generally higher than the single aggregation of single risks [3], so this
51 consideration implies adopting quite a different outlook regarding classical single-risk analysis [4].
52 Finally, due to global changes, exposure has increased due to changes in the amplitudes, frequencies
53 and spatial distribution of hazards. The urbanization of an area including industries at risk can
54 transform an event into a disaster.

55

56 The concept of multirisk management emerged in Agenda 21 adopted at the Rio de Janeiro
57 Conference in 1992 [5], the Johannesburg Plan in 2002 and the Hyogo [6] and Sendai [7] Frameworks.
58 Taking into account multirisk was then identified as essential in various documents at the European
59 and global levels [8; 9]. Li et al (2017) demonstrated that, concerning the domino effect, increasing
60 attention on the topic is related to the growing attention paid worldwide to process safety and to
61 specific legislation requirements, such as the Seveso Directives in the European Union [10]. Scientific
62 studies have also reported that stakeholder interest in multirisk assessment is strong [11; 12].
63 However, there are still bottlenecks, as pointed out in recent OECD (Organization for Economic Co-
64 operation and Development) and ANR (French National Research Agency) reports, which classify this
65 issue as an open research question [13; 14].

66
67 Currently, there is no clear definition of “multirisk” either in science or in practice; decision-making
68 under multirisk is a nascent field [11]. In this article, the concept of multirisk refers to a set of different
69 hazards able to act in combination with or without coincidence over time (heavy rains can generate
70 floods and landslides; the occurrence of a hurricane in an area already affected by an earthquake but
71 not overcome by this first shock) and impacting, in a given territory, potentially dependent stakes (the
72 destruction of a hospital can lead to the over-saturation of other hospitals in the area; the failure of one
73 infrastructure may lead to the failure of other infrastructures) [15; 4; 16; 17]. Hazards can be natural
74 (earthquake, seism, flood, etc.) and/or technological (dam collapse, chemical explosion, etc.) and/or
75 due to anthropogenic processes (vegetation removal, mining, drainage, etc.) [18]. These can threaten
76 the same elements at risk. Malicious events (terrorism, arson, aspects of warfare, criminal activity) do
77 not belong to either anthropogenic processes or technological hazards/disasters, but may trigger the
78 occurrence of other hazards. Elements at risk are composed of human beings and natural or
79 anthropogenic elements presenting economic, social, technical, human, environmental vulnerabilities,
80 etc. The consequences can be direct (loss of human lives, destruction of resources, etc.) or indirect
81 (remote economic damage, etc.). Serious problems of pollution can occurred following the release of
82 hazardous substances in the environment due to Natech or domino events [19; 20; 21]. Environmental
83 pollutions can also be due to anthropogenic hazards [22].

84

85 The consideration of interactions is essential in multirisk issues and allows progressing from the
86 perception of multi-hazard risk toward multirisk management [4]: these interactions include the spatial
87 and temporal relationships between various hazards and other elements of the risk chain, and
88 unexpected effects and threats that are not captured by means of separate single-hazard analyses [11;
89 23; 4]. Different types of interaction can occur [24; 25]: a hazard triggered by another (domino effect);
90 the probability of a hazard is increased or decreased due to an initial event; events involving the spatial
91 and temporal coincidence of natural hazards (coupled events); events that increase the vulnerability of
92 the exposed elements-at-risk. Series and parallel events can occur [26]. Moreover, social and/or
93 physical vulnerability may progressively change due to the occurrence of events: they could increase,
94 thus reducing the capacity to cope, or decrease in the case of significant time intervals between
95 successive events, leading to better community awareness and preparation [18; 27; 25]. The different
96 situations exhibited in Figure 1 can be chained: a domino effect can be triggered by coupled events for
97 instance.

98 A multirisk approach entails seeing things within a multi-hazard and a multi-vulnerability perspective.
99 Considering such interactions allows better estimation of the final risk, incorporates possible
100 amplifications due to interaction with other hazards, and avoids significant bias and erroneous risk
101 hierarchization [28]. The multirisk approaches aim at providing decision support for better risk
102 management [15; 29; 30; 31].

103

104 To summarize, multirisk management is a relatively new field and formulating an integrated
105 framework for multirisk assessment is still a major challenge, notably due to the need to address
106 interactions [4; 16; 23]. These challenges have led to scientific production that has been growing over
107 the last 15 years. The purpose of this paper is to provide an analysis of this production, in particular by
108 identifying the scientific issues addressed in this body of articles, and ultimately to identify directions
109 for future research. It is based on a literature review focused on physical vulnerability: the analysis of
110 social and human vulnerability is a subject in its own right and is not covered here.

111

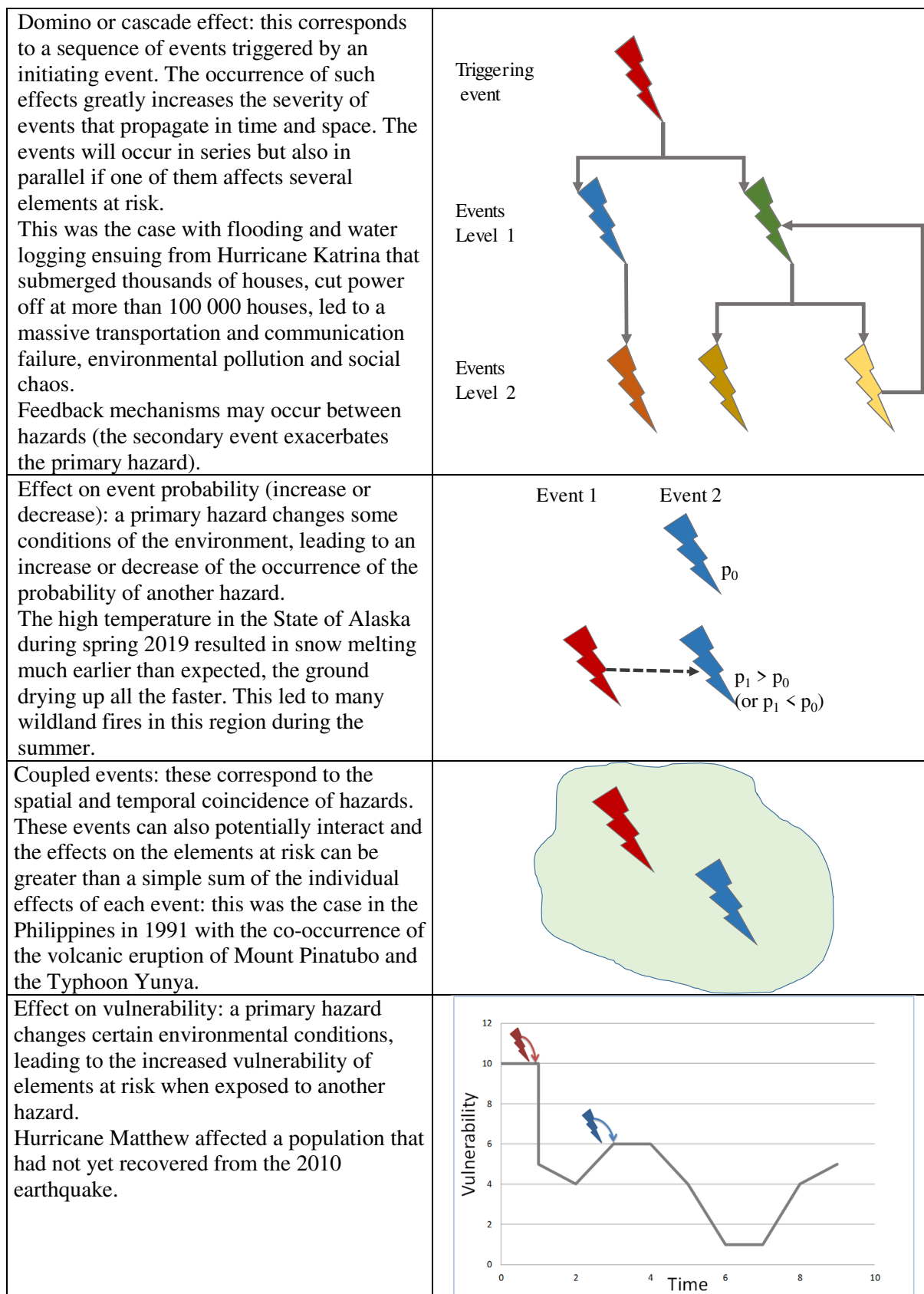


Figure 1. Different types of interactions – events are represented as flashes.

113 **2. Method**

114 **2.1 Selection of texts and distribution analyses**

115 To present the breadth of coverage of the literature review of multirisk studies and identify the
116 relevant papers, an analysis was first carried out of the Web of Science
117 (<https://www.webofknowledge.com>) and the SCOPUS databases
118 (<https://www.elsevier.com/solutions/scopus>), two comprehensive multidisciplinary content search
119 platforms for academic researchers. The requests are presented as Supplemental Materials. The
120 keywords used are (search in the article title): domino effect*, cascade effect*, cascading effect*,
121 natech, multi-risk*, multirisk*, "multi-hazard* risk*", "multihazard* risk*". Years considered are
122 2004-2020.

123

124 Duplicates were removed after which finer analyses were performed on abstracts and full reviews.
125 Articles related to other domains such as ecology, medicine, economy and mathematics or forum
126 articles were removed. This operation led to keeping 191 references. These comprised 13 review
127 articles [32; 33; 15; 23; 10; 34; 35; 36; 37; 38; 39; 40; 41] that will not be considered in the global
128 textual analysis (Sections 3 and 4) as this analysis is devoted to identifying the different research
129 themes present in the literature. Some of these 13 articles will be used further on in the discussion
130 section (Section 5) to highlight the results.

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

132 **2.2 Global textual analysis**

133 A textual analysis of the 178 abstracts was carried out using the IRaMuTeQ version 0.7 alpha 2
134 (Interface de R pour les Analyses Multidimensionnelles de Textes et de Questionnaires) [42]. The
135 software treats each of these abstracts as a text. The main themes present in these texts were searched:
136 the software makes distinctions between “full words” such as verbs, noun, adjectives, adverbs and
137 “tool words” such as pronouns, determiners, etc. With this distinction, only full words are included in

138 the main analysis. A lemmatization of the text corpus was performed. This consists in replacing a
139 word by its root term (e.g., 'risks' by 'risk'). This process decreases complexity.

140

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

154

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

161

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

166 **3. Distribution analyses**

167 The dynamics of academic research on multirisk issues are analyzed through their distribution over
168 time. The number of publications dealing with these issues has increased significantly since 2013 in
169 comparison to the previous years as they represent 75% of the total number of articles for the period
170 (2004-2020) and more than 50% since 2016 (cf. Supplementary Material – Figure 1SM).

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

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

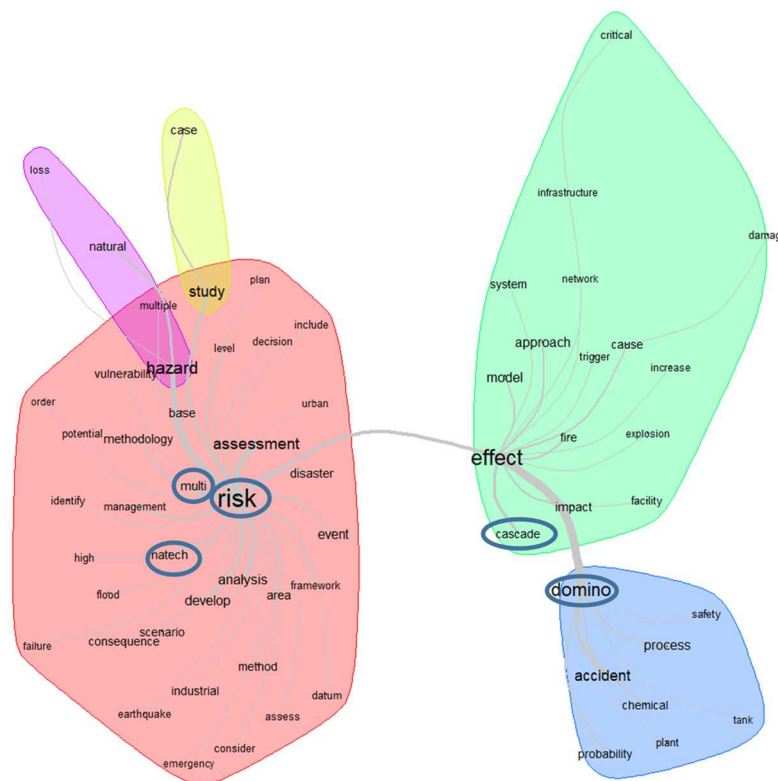
187 **4. Global textual analysis**

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

191 4.1 Analysis of similarity

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

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



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

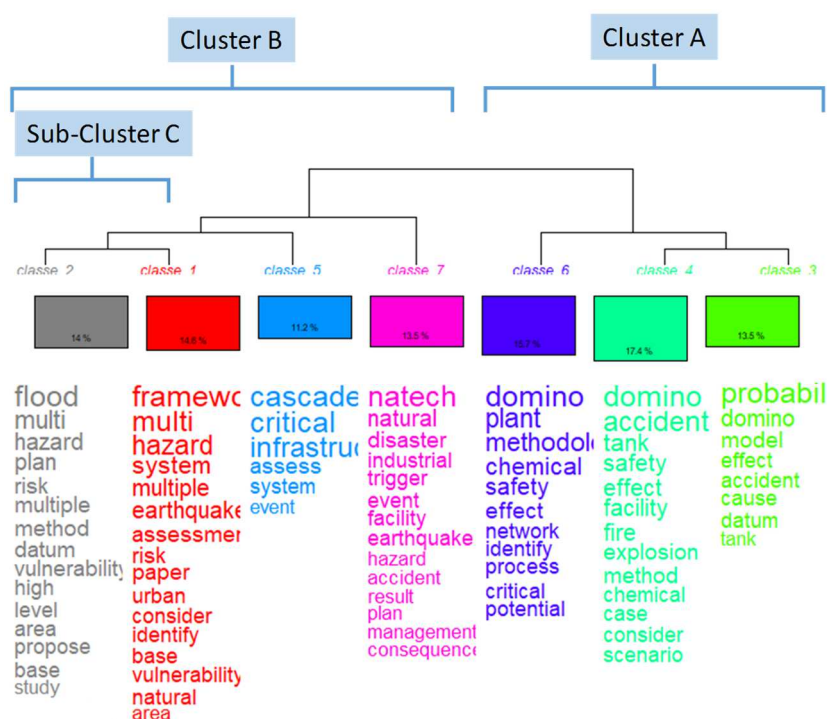
207

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

209 4.2 Reinert clustering

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

213



214 **Figure 3.** Dendrogram (only significant forms are shown for each class: $p < 0.05$) - Forms
 215 overrepresented in a cluster appeared with a larger character size

216

217 The clusters show the main research themes in the literature. The clustering separates two clusters.

218 Cluster A (classes 3, 4 and 6) represents 46.6% of the texts and gathers the texts dealing with “domino

219 effect”. Cluster B (classes 1, 2, 5 and 7) represents 53.4% (cf. Table 1 and Figure 3) and includes
 220 abstracts focusing on Natech issues, cascade effects and MHV issues (Cluster C). Classes 4 is the
 221 largest one and Class 5 the smallest. The main theme concerns Domino Effects (46.6%), then Multi-
 222 (hazard/vulnerability) Risk (28.7 %), Natech issues (13.5 %) and finally Cascade Effects in critical
 223 infrastructures (11.2 %).

224

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

228

- 229 - Class 2 (25 abstracts): Risk management planning and assessment of territorial vulnerability.
 230 Flooding (present in 17 abstracts – in combination with other hazards) is the hazard studied
 231 most;
- 232 - Class 1 (26 abstracts): Proposal of analysis frameworks allowing a multi-hazard/vulnerability
 233 assessment or better knowledge of multi-hazard/vulnerability in territories (identification of
 234 hazards, risks, interactions, etc.). The hazard considered most is earthquake (present in 10
 235 abstracts – in combination with other hazards). Urban areas are studied more particularly;
- 236 - Class 5 (20 abstracts): Assessment of cascade effects in critical infrastructures;
- 237 - Class 7 (24 abstracts): Crisis and risk management in case of NaTech events. The initiating
 238 hazard of such an event is mainly an earthquake (present in 11 abstracts);
- 239 - Class 6 (28 abstracts): Safety measures to prevent domino effects, mainly in the chemical
 240 industry. The word "network" refers to Bayesian network approaches (present in 10 abstracts);
- 241 - Class 4 (31 abstracts): Accidents due to domino effects, especially fires and/or explosions, in
 242 tank farms;
- 243 - Class 3 (24 abstracts): Modeling of domino effects using probabilistic approaches.

244

245 While the terms “domino” and “cascade” seem to be synonymous, the first is largely reserved for
 246 events occurring in an industrial environment while the second is reserved more for applications on

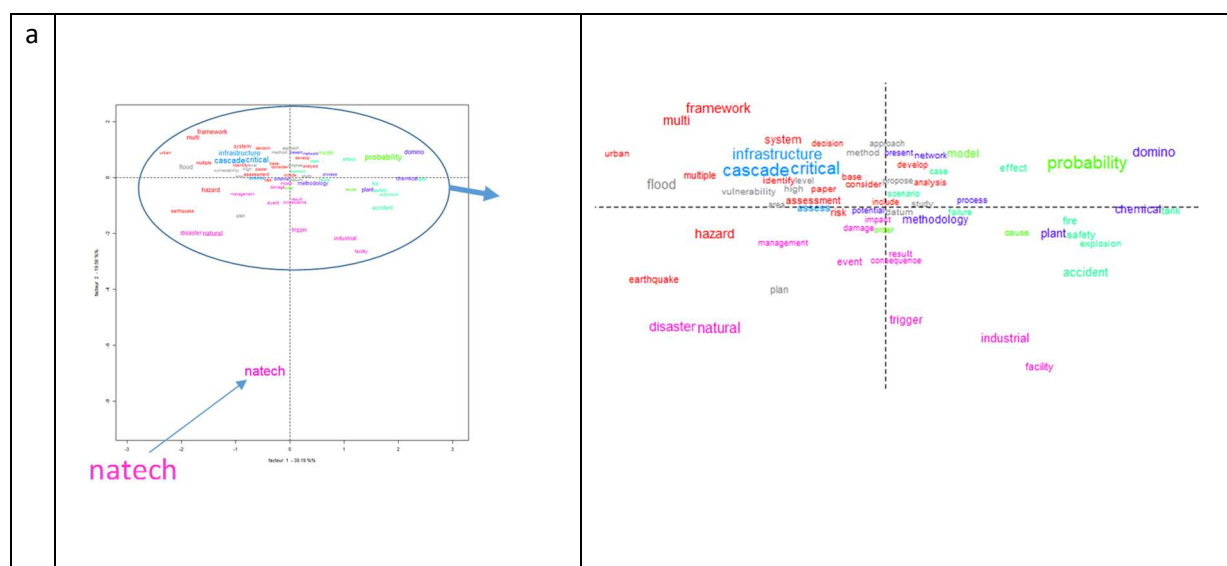
247 critical infrastructures (transport, energy, water networks, etc.). The key words "multirisk" and "multi-
 248 hazard risk" are used in the sense of natural hazards impacting a territory (MHV).

249 4.3 Factorial Correspondence Analysis (FCA)

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

258

259



277 Decision-support is linked to risk management through the planning of action plans, crisis measures,
278 etc. Research focused on risk analysis is more strongly orientated towards MHV and NaTech work;
279 works focused on knowledge production are mainly oriented towards domino effects. Works on
280 cascade effects are balanced between risk analysis and knowledge production. Advances in decision-
281 support concern all these themes. A few articles proposed tools or software (17 in total, shown in
282 brackets in Table 2).

283 **5.2 Hazards studied**

284 The hazards considered in the corpus are presented in Table 3. Three articles were not included in this
285 table: they analyze past cases considering different accidents involving domino effects. The natural
286 hazards studied most are floods and earthquakes, alone or in combination with other hazards. This, of
287 course, is not surprising: floods and earthquakes are recognized as the natural hazards causing the
288 most human, material and financial damage [43]. Almost one third of the works in the corpus consider
289 at least one of these two hazards. Some publications deal with specific accidents such as the
290 earthquake and tsunami in Japan in 2011, and the Kocaeli earthquake in Turkey in 1999. The other
291 natural hazards represent 12% of the hazards covered. Natural hazards are taken into account for
292 research performed on MHV (Classes 1 and 2) and when considering cascade effects involving
293 infrastructures (Class 5 - floods only) and NaTech issues (Class 7 - floods and earthquakes).
294 Nascimento et Alencar (2016) also found that these two phenomena overwhelmingly occur in the case
295 of Natech events [35]. Fires and/or explosions are the two technological hazards that are
296 overwhelmingly studied in terms of domino events and concern nearly 60% of the abstracts. Again,
297 this is hardly surprising as these two phenomena represent the majority of causes of accidents in
298 industrial installations according to past case analyses [43].

299
300 Some recent works (between 2014 and 2020) considered acts of terrorism as triggers of domino or
301 cascade effects.

302 **5.3 Elements at risk**

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

304

305 Most of the articles concern industrial installations (51.3%) and infrastructures and buildings (21.7%),
306 thus gathering nearly three-quarters of the publications. Industrial installations correspond to chemical
307 or process plants or complexes. The infrastructures considered are urban networks but also pipelines.
308 Industrial installations are major issues for the analysis of domino effects (Classes 3, 4 and 6) but also
309 Natech phenomena (Class 7). Infrastructures and buildings are of interest for the different themes (at
310 least 2 abstracts per class deal with infrastructures or buildings). Few articles consider population (less
311 than 7%), the environment (6%) or agriculture (4%). These are addressed in the articles dealing with
312 MHV (Classes 1 and 2). Finally, while articles on MHV, Natech phenomena and cascade effects
313 consider several issues, the articles on domino effects focus on the impacts on other plants in their
314 vicinity (the analysis of domino effects involving several industrial facilities is provided for in the
315 SEVESO directives [44]).

316 **5.4 Approaches developed or implemented**

317 The approaches used are presented in Table 5.

318

319 Probabilistic (including Bayesian networks) and statistical methods constitute the largest group,
320 accounting for more than one-third of the total. They are primarily used for work on domino effects in
321 industrial facilities. In addition, four other types of approach were used, each one counting for about
322 10% of all the methods. These are analytical frameworks (mainly for works focusing on MHV and to a
323 lesser extent on Natech effects), risk analysis and operational safety approaches (present in the
324 different classes but more strongly in studies dedicated to the cascade effects of infrastructures), and
325 finally the use of geographical information systems for MHV, Natech and cascade effects. Graph
326 theory and methods based on surveys or interviews each account for about 5% of the total. Finally, the
327 other types of methods are more marginal (less than 3% each): development of specific metrics,
328 lessons-learned and knowledge-based systems, analysis of existing tools, economic analysis, multi-
329 criteria analysis, serious games.

330 **6. Discussion**

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

332 **6.1 Multidisciplinary research is to be encouraged**

333 Three elements that act in favor of multidisciplinary research are highlighted below. Firstly, Table 2
334 shows that the governance of multirisk is poorly studied. However, risk management actors including
335 crisis managers are particularly interested in tools capable of managing multiple risks [11]. However,
336 two observations can be made: on the one hand, there is a lack of integrated practices for multirisk
337 governance, with little cooperation between communities working on different risk fields [44], and on
338 the other hand, the clear identification of responsibilities for the implementation of multirisk
339 approaches is necessary [45]. Secondly, very little work has considered the population, the
340 environment and agriculture as elements at risk but research has focused on anthropogenic works
341 (plants, infrastructures and buildings) (Table 4). However, an important subject is the consideration of
342 eco-socio-technical systems in the management of multirisk events. Thirdly, to address climate change
343 issues, Gallina et al (2016) indicated that multidisciplinary collaborations (e.g. modelers, natural
344 scientists, economists) should be promoted to develop a comprehensive multirisk assessment process
345 [15]. Research can therefore be encouraged in these directions and will be all the richer if it is carried
346 out by highly multidisciplinary teams.

347 **6.2 Decision support tools should be developed and adapted for different stakeholders**

348 Few tools, even as prototypes, are presented in the work: seven were identified for decision support
349 issues (Table 2). However, frameworks useful for the implementation of an approach can be added to
350 this list (23 frameworks were identified). These types of tool can help managers make wiser decisions,
351 gain better understanding of the various areas of risk in a territory, and support resource management
352 and emergency planning [46; 47]. As several stakeholders are usually involved in multirisk
353 management, tools should take this specificity into account and facilitate and improve communication
354 between them [48; 49]. Moreover, most likely domino scenarios and central events are company

355 specific and managers and operational staff need instruments to track the progress of scenarios, and
356 management tools to ensure the quality of barriers [39]. The development of new tools addressing
357 escalation effects and multi-level scenarios is needed [36]. It is clear that the development of tools
358 adapted to different stakeholders is a relevant challenge.

359 **6.3 Research should be oriented towards the necessary consideration of dynamic aspects**

360 The integration of dynamic issues in the different developments is a challenge, as MHV, domino,
361 NaTech and cascade phenomena occur over time. However, most of the work is mainly based on the
362 analysis of static vulnerability that assumes there is no change in the elements exposed. Another
363 challenge is related to the consideration of different temporal hazard scenarios and in particular those
364 related to global changes [15; 37; 40]. The use of bowtie methods to model MHV events was
365 mentioned above. This proposal is linked to a challenge: that of including dynamic and temporal
366 aspects in these approaches in order to fully represent these types of event [40].

367 **6.4 Communication of results is of great importance**

368 Communicating results is a major challenge contributing to successful multirisk management. Indeed,
369 “the successful implementation of disaster risk reduction options and strategies demand not only
370 comprehensive risk assessment schemes, but also an appropriate mechanism to communicate and
371 transfer knowledge on risk and its underlying drivers to the various stakeholders involved in the
372 decision-making process” [11]. The aim is to improve awareness of the multirisk issue (whether it is
373 due to domino, cascade, NaTech or MHV events). Communication must be adapted to different risk
374 management actors, whether they are decision-makers, managers, or the general public.

375

376 Spatial information systems are relevant tools: indeed, the spatial dimension is essential for MHV
377 phenomena as well as for Natech events and cascade effects between infrastructures. This was recently
378 underlined in particular by Naderpour et al (2019) [34]. The results presented by this type of system
379 are generally easily understood by different actors. However, a single map for all types of stakeholders
380 and showing all types of risks in the area concerned will probably not meet the needs of the different

381 stakeholders [23] and different representations should be proposed. Specifically, there is a need to
382 understand how to group and map MHV results in a way that they are usable, comprehensive and
383 easily applicable for stakeholders and non-expert users for assessment and management purposes [15].
384

385 Another type of representation that seems relevant to us stems from graphical methods such as fault
386 trees, cause trees and bowtie diagrams stemming from dependability analysis and Bayesian networks.
387 These methods originate from the industrial world. They have been implemented essentially to
388 characterize domino effects between industrial installations but seldom for MHV research. However,
389 these methods allow representing many variables and their interrelationships. Attempts have been
390 made in this direction [25]. It is thus possible to capture and communicate the breadth of the problem
391 simultaneously, while focusing on key processes at the local scale [40]. Different fields
392 (environmental, economic, social, etc.) can interact. Bayesian networks can also be coupled with
393 spatial approaches [36]. It would be relevant to develop work in this direction.
394

395 Moreover, appropriate communication of the uncertainties inherent to risk is crucial. There is a strong
396 need to present uncertainties so that they can be easily understood by the target audience(s), in order to
397 avoid decisions based on poorly evaluated information [15].
398

399 Finally, very few participatory approaches have been deployed and these have only involved decision-
400 makers [11; 45]. The involvement of the general public so that it can better understand the phenomena
401 that can have an impact on it, whether they are MHV, NaTech, cascade between infrastructures or
402 domino effects in industrial facilities, opens up a relevant avenue of research. This was noted for
403 example for Natech events [38]. In the same vein, serious games have seldom been used [50; 51] but
404 they are also a very relevant communication and learning vector. Work could be developed in this
405 direction.

406 **6.5 The issue of data availability, sharing and interoperability should be raised**

407 Most of the types of data needed for a multirisk assessment (hazards, vulnerabilities, defense
408 measures) are lacking in different parts of the world, with uneven quality due to a lack of international
409 standards and a lack of knowledge and resources in the institutes or agencies responsible for data
410 collection and management. However, initiatives to harmonize and standardize data are under way,
411 such as the IRDR (Integrated Research on Disaster Risk), EM-DAT (International Disaster Database)
412 and GEM (Global Earthquake Model) databases. Some research articles collected data on past events
413 [33; 41].

414
415 The issue of accessibility and data sharing between actors should be raised, especially since the lack of
416 accessibility has been exacerbated in recent years by the fear that groups might use information for
417 terrorist purposes [38]. Risk information produced by the insurance and catastrophe modeling industry
418 is still largely retained as intellectual property within each company and is rarely accessible to
419 governments, businesses or households [52]. A successful experience of reasoned information sharing
420 between different infrastructure managers was achieved during the DOMINO project [52] for the
421 management of cascading events.

422
423 Furthermore, information may have undergone transformations (e.g. data from models), and even if
424 the results are made widely accessible, it will not necessarily be easy to determine how the data has
425 been transformed and what assumptions were made to generate risk estimates [51]. For example, most
426 practitioners do not know how to use databases [9]. The question, therefore, is not whether the data are
427 available, but who uses and interprets the data and for what purpose – or, more fundamentally, who is
428 able to access and present the information in a meaningful and useful way. Another difficulty is the
429 inoperability of different data systems [53], making the coupled use of tools from different entities
430 complicated.

431 **6.6 Validation procedures have to be invented**

432 The question of the validation of the models developed seems interesting to discuss. Indeed, the best
433 way to carry out validation is a comparison with an independent set of observed data. However, on the

434 one hand, multirisk events occur in complex systems characterized by many variables of different
435 types (hazards, elements at risk, barriers or risk management actions) that must be considered in a
436 temporal and spatial dimension. On the other hand, especially for MHV, NaTech and cascades
437 between infrastructures, the events are not necessarily very numerous and, as previously mentioned,
438 the data are not always accessible. Few studies have identified and analyzed past cases: they are
439 essentially centered on domino events between industrial installations [54; 55; 56]. Validation must
440 therefore be thought out in a specific way and particular procedures must be set up.

441 **7. Conclusions**

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

456

457 **8. References**

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