Identification and Evaluation of Main Research Themes for Earthquake Studies in Material and Energy Fields by Science Maps and Scientometric Methods

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ABSTRACT

Finding new research themes in any branch of science is vital for researchers, universities, research institutes, research sponsors, administrators and research policymakers. Powerful tools for this purpose are the well-defined science maps and keyword networks, as well as appropriate scientometric indices and diagrams. Interpreting such maps and diagrams will present an overall outlook of the research area, and the most important or challenging research topics of the field are revealed. Earthquake studies in two economically important fields of energy and material are visualized to identify new research topics with high commercial potentials. After research documents are retrieved from SCOPUS for 2010-2020, meta-dataset is used to present science maps and scientometric diagrams by use of VOSViewer and Biblometrix. They are then analyzed and interpreted qualitatively and quantitatively for three main tasks: Identification of the main research topics; Evaluation of the topics for research and commercial capacity; Determination of main research themes. The results of both qualitative and quantitative methods are well close to each other. Based on the results, four main research themes are characterized as up-to-date recent trends in Earthquake studies for both fields: nonlinear analyses, experimental modellings, different types of seismic assessment, and resilience. The results of the method are fruitful for research planning of associative earthquake institutes and researchers.

Keywords:
Energy; Earthquake; Keyword network; Material; Science map

1. Introduction

Science map is a tool to reveal and analyze the knowledge structure of a scientific field from different points of view. It provides a general perspective of the science domain, which may effectively highlight its different subject areas, helps to discriminate subfields of a domain from each other, and can illustrate renovation and changes of a domain as well. Illustrating scientific information in the form of a science map can disclose hidden information, relations and templates of the complex body of the knowledge and uncovers the scientists and researchers' layers of mind. In this way, one may identify, in addition to the relationship between subdomains of the science field, the most influential individuals and institutions. Most important of all, by the help of science maps, researchers can benefit previous experiments and organize their future study more effectively. For research funding organizations, science maps may ensure long-term investments for research development, enhance policy assessment procedures, and improve decision-making and research funding models. Industry managers can use such maps to appreciate academic research more easily and efficiently. They can also identify their needs and research potentials, and design research projects and grants to enhance their industry.

Identification of current research trends in earthquake sciences is especially important for research institutes. While the devastating phenomenon of earthquake is one of the main challenges of the world, especially for the countries that experience destructive earthquakes from time to time, the rapid and dramatic growth of technology in various fields of engineering and geophysics, the growing research interest to work on this field, as well as the huge investment of developed countries on this subject, all indicate a new epoch in dominating the earthquakes. It is therefore worthwhile for researchers and research institutes active in this field, to have a clear view of the current research environment and the perspective ahead of earthquake science studies, in order to reorganize their research procedures and trends. To the authors' knowledge, there is no study on science mapping and thematic analysis of the entire field by using new tools of knowledge visualization. We should only mention some new science-mapping studies on specialized subjects in the field such as safety [1], vulnerability [2-3] and crisis management [3-5].

Bibliometric analysis has long been an approach for exploring the state-of-the-art, research frontiers and thematic trends of a particular subject area [6-12]. Science mapping among different techniques of bibliometric analysis would benefit domain experts in identifying the knowledge structure of a field [13-14]. In this research, an attempt is made to establish a proper view of the science map in the field of earthquake sciences, and by performing appropriate interpretations, the main research topics are identified and classified from a research and commercial perspective. Since Earthquake is a very broad field of knowledge, this study is limited to only two applied parts of the field, i.e. earthquake studies in Materials and Energy sciences[1] and their respective documents indexed in Scopus during 2010 to 2020. The study pursues two main objectives: first, to identify important and valuable research topics in these two areas over the past decade and to examine how they relate to each other through the construction and interpretation of keyword co-occurrence networks; and second, evaluating the research topics according to their potential for research and industry. In Section 2, in the three subsections of Data, Analysis, and Interpretation, the method of collecting and refining the bibliometric data, map visualization and scientometric analysis by VOSViewer and Bibliometrix, and approaches for quantitative and qualitative interpretations are explained. In Section 3, visualized maps and diagrams, as well as their quantitative and qualitative interpretations are reported for both fields, and the most important research topics and themes with positive research and business perspective are presented.

2. Data and Methodology

This research includes the following three basic steps:

1. Data extraction from SCOPUS database based on two themes “MATE” and “ENER”
2. Preparing a database from the extracted data through filtering and refining keywords of the documents.
3. Data analysis, including the drawing of the science map and preparing appropriate graphs in the field of knowledge.
4. Interpretation of the results, which is done in two ways: qualitative (interpretation of the map and inference of research trends by the expert) and quantitative (extraction of research trends based on scientometric indicators); the results of these two interpretations are ultimately compared.

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1. This approach is applied time to time as Mahi et al. [15] have also narrowed their methodologically similar study on the energy field.

2.1. Data

In this study, review and research papers are limited to those published in scientific journals indexed in Scopus citation database, during 2010 to 2020. This ten-year period seems to be sufficient to reveal new research themes and trends of the scientific area of interest. To establish a bibliometric meta-database, documents were queried for by a keyword search for “Earthquake” in Scopus, under the two categories of materials (MATE) and energy (ENER), restricted to “original” and “review” papers. Since bibliometric data for up to 2000 documents may only be loaded at each instance, database was constructed step by step based on the selection of the appropriate number of journals in csv format, and the files were merged in to one complete file at the end.

After all metadata was loaded and saved, appropriate editions were performed in the Sublime text editor. As a crucial task for a valid and efficient analysis in the next step, a thesaurus for equivalent terms and synonyms was provided, since different authors may point to a unique scientific concept (e.g. Finite Element Method) with different terms (such as Finite Element Analysis, Finite Element Modeling, FEM, FEA and …). In this study, a thesaurus with about 2000 equivalent terms was organized and used for data visualization.

2.2. Analysis

In this research, VOSViewer software is employed to visualize science maps and keyword co-occurrence networks [16-17]. The software, due to its promising capability in network illustration, has received much reputation in scientometrics community, and is widely used for visualizing scientific knowledge. It may convert csv Scientific Documentation database into co-occurrence matrices, which are represented as networks or density maps as well. In order to facilitate the process of qualitative interpretation of maps by the human expert, the following words are considered as stop list:

1. The canonical keyword “Earthquake”
2. General words and concepts such as “seismic” or” seismic performance”
3. Keywords that represent familiar and widely used technologies, which span a long history of the science domain, e.g. FEM or Numerical analysis.

In the research, some diagrams and indicators are provided by the recently developed R-based Bibliometrix package. R, as a programming language and open-source statistical interface, is sponsored by the Foundation for Statistical Computation R and is free to all users. R packages are a set of commands and functions developed and shared for public use by R programmers. The Bibliometrix package contains featured and extensive tools for depicting a variety of tables, diagrams and maps such as word clouds, tree maps, thematic maps, collaboration networks etc.

2.3. Interpretation

In this section, using different outputs obtained from the data analysis stage, the following three important questions about Earthquake studies in the fields of materials and energy are answered:

1. What are the important research topics that have been studied in this field of knowledge during the last 10 years? In fact, the first special task of interpretation is to select important and valuable research topics from the many keywords contained in the articles in the last ten years.
2. What is the position of the selected topics and technologies from a research and commercial perspective? In fact, the second task of interpretation is to position the selected themes, and to determine their current position and value as research topics or technologies.
3. The third feature of interpretation is the introduction of research themes arising from research topics and how they evolve.

These three special tasks are performed in two ways: qualitatively (by examining the keyword network-map by an expert in earthquake sciences) and quantitatively (by drawing diagrams and determining appropriate indicators, which will be explained in Section 2.3.2). Finally, the results of these two interpretations are compared and summarized in each of the two branches of earthquake science.

2.3.1. Qualitative Interpretation

In this research, the science map drawn with VOSViewer is interpreted qualitatively; This interpretation is based on the co-occurrence network map of keywords, which is colored based on the average year of publication. As will be seen in the next section, the Earthquake Science Expert has listed important and valuable research topics in the following seven categorizations based on his map review:

1. Research topics approaching the commercialization stage.
2. Research topics at the beginning of the commercialization phase or business topics on which extensive research work is still going on.
3. Research topics that have recently entered the commercial stage and more or less a research work is carried on them. These topics are close to the research maturity stage.
4. Research topics that have been commercialized for a long time, with no significant research work in process. These are topics that have reached full research maturity.
5. Emerging concept or technology with a considerable growth potential.
6. An emerging concept or idea that is not developed yet, and has not found a strong connection with other research topics and concepts.
7. A term in another science that has appeared in specific interdisciplinary research and usually introduces a particular innovation.

The above classification is suggested by an earthquake expert, based on his perspective on earthquake knowledge, research, industry and trade, as well as his understanding of the keyword map drawn by VOSViewer (including information on word position, frequency and links, and average year of word emergence over a decade).

The expert, in addition to selecting vocabulary related to research topics and important technologies from the many keywords available in the articles, has also evaluated their position in terms of research and commercial status and placed them in the above categories. Finally, the expert summarizes his views on the research topics, and introduces most important research themes in the field by labeling them as: basic, up-to-date or specific subjects, and explains how they evolve and proceed over the last decade.

2.3.2. Quantitative Interpretation

In this section, as in the previous section, three interpretive tasks are performed: (a) selection of important research topics, (b) determination of their position, and (c) determination of research themes and how they have evolved in recent years. These three special tasks, unlike the previous section, which is done by a human expert, are performed with the help of appropriate diagrams and indicators obtained from scientometric processes in Bibliometrix (R) software.

The selection of research topics and their hierarchical structure is performed by using indicators related to the frequency and number of links and hierarchical diagrams and clustering operations. Positioning of technologies and research topics is also based on the current position of the selected keywords in the research S diagram and the technology S (adoption curve) diagram, as depicted in Figure (1). Both diagrams follow an S-shaped pattern. The horizontal axis of the charts is time (usually by year), and the vertical axis is a suitable cumulative indicator, indicating the performance of the subject from a research or commercial perspective. In this research, the diagram of keyword frequency-year is used as the research S chart, and the number of sponsors-year diagram is used as the technology (business) S chart.

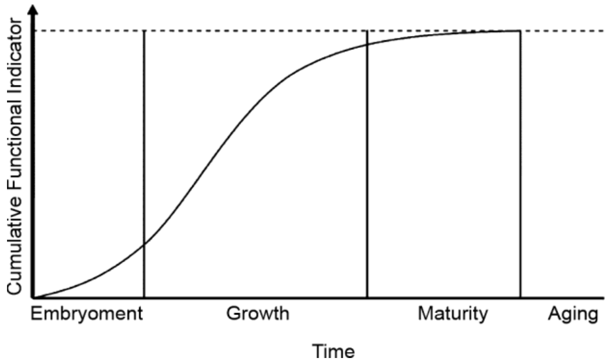

Figure 1. Schematic view of S-diagram.

Based on this, four stages can be observed in both diagrams: embryoment, growth, maturity and aging. In this study, for the sake of simplicity, S charts are examined with only the three first stages.

Research topics without sponsorship are assumed to be in technologically embryoment (or aging) stage. Based on this, nine positions for the research topic are conceivable, as illustrated in Table (1).

This nine-item classification is, in some cases, consistent with the seven-item classification provided by the earthquake science expert. The numbers written in some of the cells in Table (2) are the category numbers introduced by the human expert (Section 2.3.1) that have relative coordination with a corresponding category of the nine-item classification. Qualitative category number 7 does not correspond to any of the quantitative categories, and quantitatively, it must be identified in another way. Qualitative categories 5 and 6 are both in the research and commercial embryoment stage; the difference is that in category 5, the number of links is higher compared to that of category 6. In other words, category 5 topics are research subjects that have been recognized by the industry as having high economic profitability from the very beginning.

Table 1. 9-item quantitative classification of research topics.

		Industry		
		E	G	M
Research	E	EE	EG	EM
	G	GE	GG	GM
	M	ME	MG	MM

Table 2. Correspondence of 7-item qualitative and 9-item quantitative classifications for research topics.

		Industry		
		E	G	M
Research	E	5-6 EE	EG	EM
	G	1 GE	2 GG	GM
	M	ME	3 MG	4 MM

In the examples of Section 3, the two classifications will be compared, and their compatibility will be examined.

Another useful diagram employed to position research topics is the frequency-year chart, which is reported by the Bibliometrix package. This diagram, with a schematic pattern shown in Figure (2), provides useful information about the frequency of a keyword and the average year of its occurrence, which is, in fact, an alternative representation of some information given by the VOSViewer map.

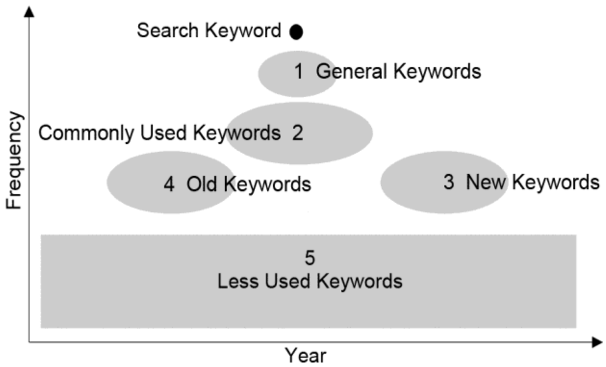

Figure 2. General template for frequency-year diagram of research topics.

Extraction of research themes and their status and evolution is undertaken using the diagrams obtained from Thematic Analysis. In fact, in the keyword network-map, three groups of entities can be seen in three different levels:

1. Keyword (research concept): The most important concepts of any research article are reported as keywords by the authors (Author keywords) or machine algorithms (Indexed keyword/keyword Plus). Keywords are the basic and visible elements of a co-occurrence network-map.
2. Research topic: A bunch of related keywords can be considered as a research topic. In fact, keywords that are highly related to other keywords might be considered as a research topic.
3. Research theme: A set of research topics form a cluster or research theme.

As the third task of interpretation, research themes are determined and evaluated by drawing Thematic Map in Bibliometrix. The general pattern of this diagram and its four regions is shown in Figure (3). Research themes in this diagram are introduced in terms of density (a measure for the development of the research theme, which represents internal links within the research cluster) and centrality (a measure of the significance of the theme to introduce the science field, which is an estimation of the external links of the cluster) [18]. The four regions of this diagram are defined as follows:

– Zone 1): Motor themes are high-density, centrally concentrated clusters; that is, research clusters that have reached full maturity and development due to high internal linkages; and due to the large number of external links, they can be considered influential on other research topics. These clusters mainly contain topics that have been studied by researchers for a long period of time.
– Zone 2) Research themes with high internal but low external links, can be assumed as developed but isolated topics that have side effects on the science field, and are possibly very specialized topics. Of course, these themes have the potential to enter the Zone 1 in the future.
– Zone 3) Research clusters with low density (internal links) and high centrality (external links) indicate basic and general topics that have been developed for a long time.
– Zone 4) Research clusters with low density and centrality imply immature and ineffective topics, which might be emerging or declining scientific topics.

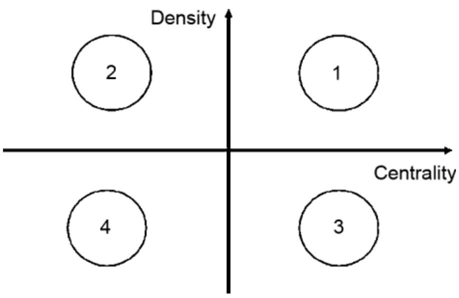

Figure 3. General template of thematic map.

3. Results and Discussion

In this section, the results of qualitative and quantitative analyzes, along with the interpretations performed on them are displayed for the two fields of: 1) Earthquake studies in Material Sciences, and 2) Earthquake studies in Energy Sciences, according to the explanations given in Section 2-3. Finally, the interpretations made are compared and summarized.

3.1. Earthquake Studies in Material Sciences

3.1.1. Qualitative Approach

The keyword map, based on the focal keyword earthquake in the field of materials science (for the years 2021-2010), is shown in Figure (4). In this map, keywords with a frequency of more than 3 co-occurrences are shown. Keywords are colored based on the average years of publication. A magnified view of the main stack of this glossary (Figure 4), after applying the refinements described in Section 2.2., is shown in Figure (5).

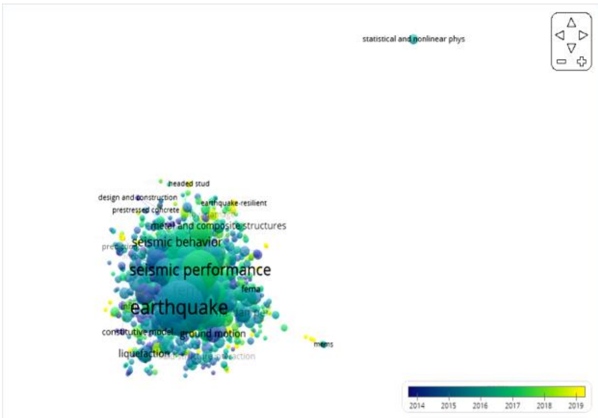

Figure 4. Keyword map for the domain of Earthquake studies in Materials Science (2010-2020).

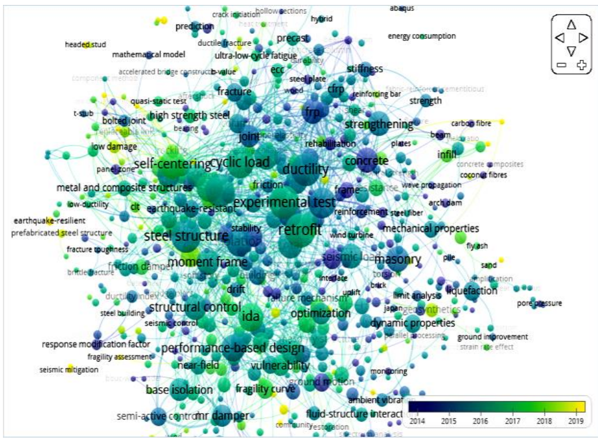

Figure 5. Magnified view of the main stack of the Keyword map for the domain of Earthquake studies in Materials Science.

It is now possible to examine and interpret this graph-like map. As can be seen from Figure (5), the general research topics are mostly in the middle of the stack, and the emerging words and concepts are scattered around it. Hence, the middle of the stack is mostly blue-green, surrounded by yellow or light green keywords.

In keyword networks, the greater the number of the links, the more the keyword is drawn to the center. Keywords with more links usually have more frequency.

The larger circles, which here represent higher frequencies of a keyword, must actually be considered as research topics that are formed by the aggregation of a number of research concepts (keywords). In contrast, smaller circles are research concepts. For example, as shown in Figure (6), the research subject of self-centering is related on the one hand to a number of research concepts (small circles) and on the other hand to a number of research subjects (large circles); in other words, this issue has a kind of betweenness centrality. These two types of linkages actually operate on two levels. The gathering of small concepts forms the research topic of self-centering, which actually resides on a higher level. This topic then relates to other research topics as well.

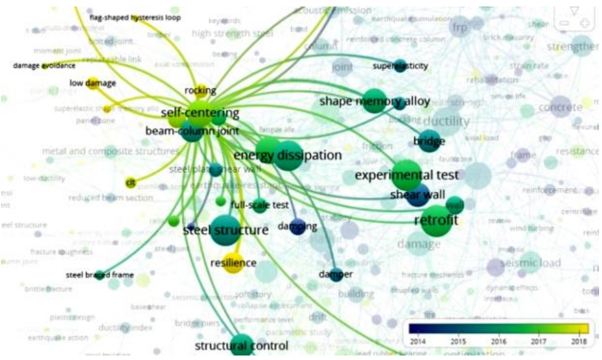

Figure 6. Representation of the relationship between the research topic: self-centering with other research topics and concepts.

Valuable research keywords in the field of earthquake studies in materials sciences, based on the qualitative classification introduced in Section 2-3-1, are as follows:

1. New research topics, which are mainly in the form of large circles with light green color in the middle of the main stack. These research topics are about to approach the commercialization stage. In the field of knowledge, these research topics are:
   – Resilience
   – Self-centering
2. Research topics that are at the beginning of the commercialization phase or are business topics that are still being extensively researched. These topics are mostly in the form of large green circles in the middle of the main stack. These research topics include:
   – Hysteresis, Cyclic load
   – Retrofit
   – Experimental test
   – Shape memory alloy
   – Fragility, Vulnerability
3. Research topics that have recently entered the commercial stage and more or less a research work is carried on them. These topics are mostly in the form of large blue-green circles in the middle of the main stack. These research topics include:
   – Energy dissipation, Isolation, Structural control
   – Performance-based design
   – Liquefaction
   – Strengthening
4. Research topics that have been commercialized for a long time and no significant research work is being done on them. These topics, which have reached full research maturity, are mostly in the form of large circles with a bluish or purple color in the middle of the main stack. These research topics include:
   – Ductility, Damage
   – FRP
   – Joint
   – Shear wall
5. Keywords in the form of small brightly-colored circles, residing in the main stack, which mainly represent emerging concepts or technologies with considerable research potential. These words usually have a frequency of more than 4 and a high number of links. In the field of research, these words are (numbers in the parenthesis denote keyword frequencies):

– Geosynthetics (18) → Soil → Construction Material
– Lead rubber bearing (8) → Base isolation → Isolation
– Vulnerability assessment (8), Risk analysis (8) → Fragility → Resilience
– Mortar (5) →Masonry →Construction Material
– Steel reinforced concrete (4) → rc Concrete → Construction Material
– Unreinforced Masonry (13) → Masonry → Construction Material
– High strength steel (17) → Steel → Construction Material / → Composite → Construction Material
– Replaceable link (10) → Resilience
– Low damage (13) → Resilience
– Rocking (17) → Resilience
– Friction damper (19) → Damping → Isolation / → Resilience
– Buckling restrained brace (28), concentrically braced frame (21) → Damping → Isolation
– Infill (17) → Retrofit / → Masonry / → rc Concrete / → Strengthening

In the above glossary, the dependence of each research concept on the hierarchical structure of the research topic is shown with the symbol →.

1. Brightly-colored keywords around the main stack represent emerging concepts or ideas that are not yet well developed. These keywords are:
   – Textile reinforced mortar (3)
   – Seismic metamaterial (4)
   – Derailment (4)
   – Friction Pendulum Bearing (3) ‹End-plate connection (4) ‹Headed stud (4)
2. Keywords outside the main stack (Figure 7) are mainly related to other sciences and may appear in specific interdisciplinary research and usually imply special innovation. These keywords usually have Link Strength of zero or near zero. The keywords in this category are:
   – MEMS (3)
   – Energy harvesting (3), Electromagnetic generator (3), Triboelectric Nano-generator (3)
   – Statistical and nonlinear physics (11)
   – Shear panel damper (3)
   – Coupled shear wall (3)

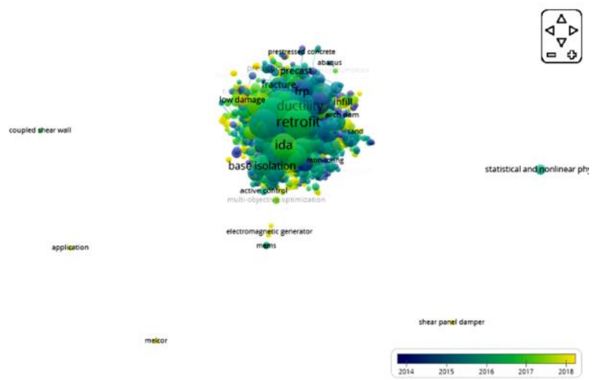

Figure 7. Keywords outside the main stack of the keyword map for the domain of Earthquake studies in Materials Science.

On this basis, research trends in this science field is reviewed by human expert and identified in the following four areas as below:

1. Materials: Among the three basic groups of building materials, most research work is now directed toward steel, masonry and mortars; research activities in the field of concrete materials have decreased. Researchers now seem to be turning to more advanced materials such as high-strength steels, ECC, and geosynthetics.
2. Loading: Special attention is recently paid to cyclic loads. This, as will be noted in the next section, is due to the ability of researchers to perform more complex nonlinear analyzes and to consider the hysteretic behaviors of materials.
3. Analysis and Assessment: Referring to the prominent bold keywords such as Simulation, FEM, and Dynamic analysis at the center of the keyword stack (Figure 8), one can clearly conclude that computer simulations and numerical analysis, especially Finite Element Method are still widely used for research in this field. However, two new approaches can also be traced for analysis. In fact, due to researchers dealing with more complex phenomena in the field of earthquake sciences (such as Fracture and Damage, Friction, Ductility, etc.), numerical simulations are mainly shifted towards nonlinear analysis, especially nonlinear dynamic analysis (IDA); most attempts are now made to represent complex behaviors of materials through defining

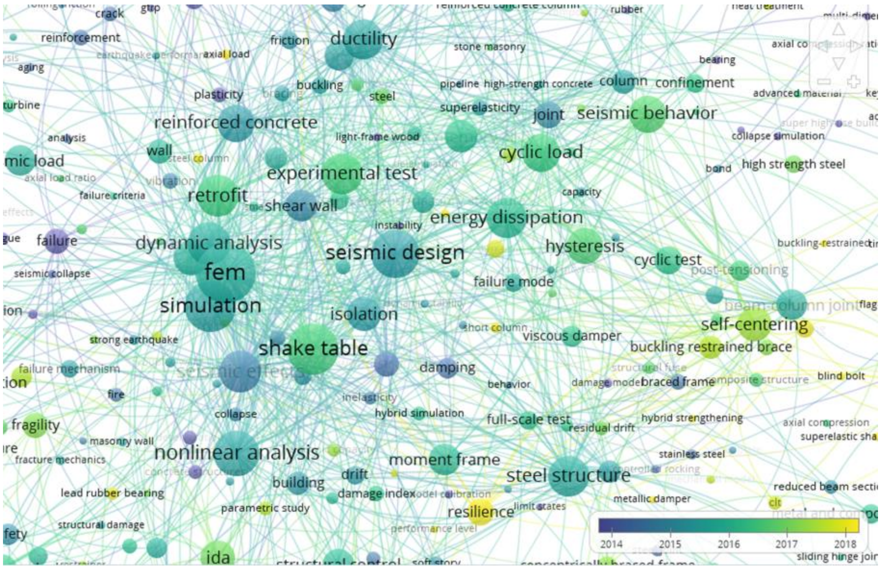

Figure 8. Magnified view of the middle part of the main stack of the Keyword map for the domain of Earthquake studies in Materials Science.

sophisticated nonlinear relationships; On the other hand, due to inadequate efficiency of numerical methods in dealing with very complex nonlinearities, attention to experimental and laboratory methods in this field is increasing. This shift in research process is implied by the rapid growth of keywords such as Experimental test or Shake table. In the field of assessment, much research is now undertaken, especially in the fields of Risk, Vulnerability, Fragility, Damage, etc., all of which indicate an arising attention to the field of seismic assessment, especially with the inclusion of damages and complex nonlinear behaviors.

4. Design, Retrofit and Resilience: According to the keyword map, researchers are interested in the two following domains in Seismic design:

The first domain includes the reduction of earthquake input energy to the building (energy dissipation) and structural control. Active control does not seem to be of much interest to researchers anymore, and passive or semi-active controls are more attractive. The focus of this research is now more on new vibration damping devices; especially those with complex mechanical structures which are sometimes used in other industries such as automotive as well.

The second domain is the design approaches. From the keywords map, it can be seen that research is still undertaken in the field of performance-based design; though, it seems to be approaching its research maturity.

It is interesting to note here that due to the research maturity of the field of design (design of non-existent buildings), attention has recently been drawn to the field of retrofit (design for existing buildings). In this area of research, studies have shifted to experimental experiments and cyclic loading. The seismic retrofit also seems to be close to its research maturity.

But the interesting part in this science field is Seismic Resilience, which has just recently become the focus of research and is on the verge of research growth and leap (Figure 9).

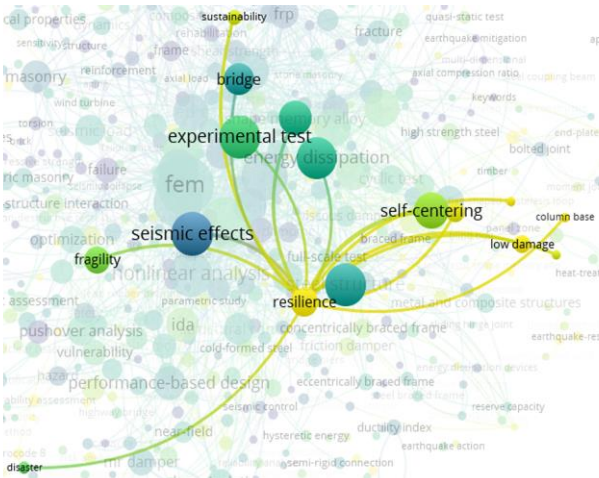

Figure 9. Rapid growth of the research topic: Resilience in the keyword map of Earthquake studies in Materials Science.

3.1.2. Quantitative Study

In this section, the three tasks defined for the interpretation stage are performed using appropriate diagrams derived from Bibliometrix. In Figures (10a) and (10b), diagrams of keyword frequencies in terms of their mean years of occurrence are plotted for the two cases of with and without applying the thesaurus (described in Section 2.1). In both diagrams, the search keyword "Earthquake" has the highest frequency, far distant from other keywords and is not shown in the diagrams. The keyword arrangement in these diagrams is relatively consistent with the pattern shown in Figure (2). The numbers shown on keyword clusters of the diagrams coincide with those in Figure (2).

It can be seen from the diagrams that general keywords (keyword-group 1) such as seismic, seismic performance, seismic response, and seismic design are rested in the top middle of the chart, and are occasionally mixed with commonly used keywords (keyword-group 2). Keywords in

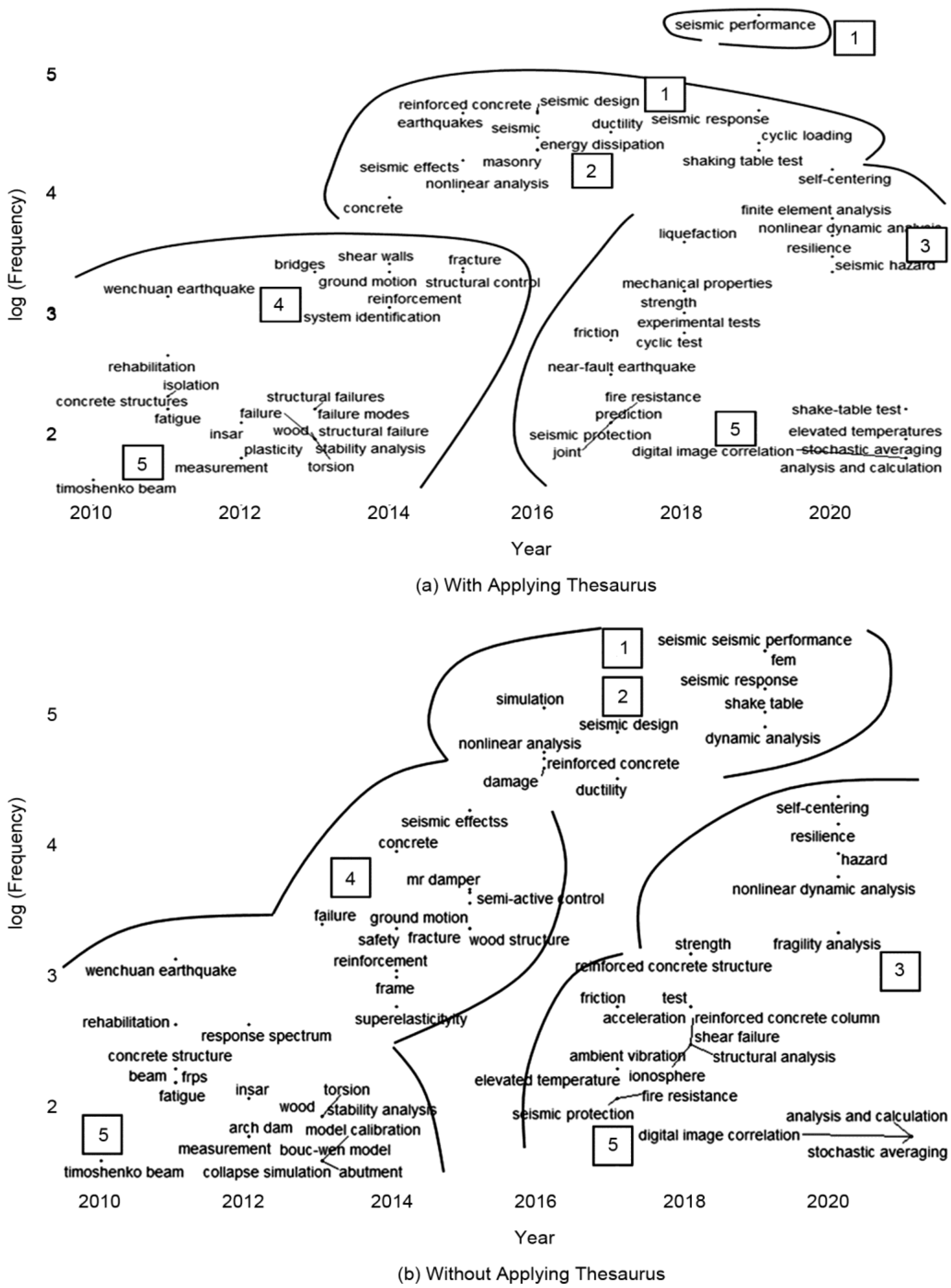

Figure 10. Keyword frequencies (Earthquake in Materials science) in terms of their mean years of occurrence.

group 2 are mostly related to applied technologies in the field, including numerical analysis (such as FEM, dynamic analysis, etc.), laboratory analysis (shake table), energy dissipation and construction materials (concrete and masonry).

In both diagrams (a and b) of Figure (10), it can be seen that keyword groups, though are consistently arranged with that of Figure (2), have a degree of intermingling. For example, terms such as cyclic loading might be considered to belong to both keyword-groups 2 and 3. From this perspective, it should be said that keywords have a fuzzy behavior and can be attributed to both neighboring clusters. This issue will be further explored in Section 3-2-2. Keywords in cluster number 2 in the diagrams of Figure (10) introduce general research disciplines of the field, including: loading (with emphasis on cyclic loading), numerical and laboratory analysis, materials (masonry and concrete), and seismic design (especially energy dissipating methods). These keywords are well consistent with the classification provided by the expert in introducing research trends.

Up to this point, research topics in this science field, in the form of three: new, widely used and old vocabulary clusters, are selected from the diagrams in Figure (10). In the next step, the position of research topics according to the nine groups described in Section 2-3-2, are determined. Here, we investigate, as samples, some research topics, which were previously evaluated and accordingly positioned by the expert in Section 3.1.1.

Figure (11) shows a cumulative frequency chart of selected keywords for the years of the last decade. It is clear that while the subject of Resilience is at the embryoment stage of its research process, Retrofit, Masonry, and Shake table topics are in the research growth phase, albeit with different growth rates (especially in the last three years). Retrofit, Resilience, and Shake table topics are experiencing high growth rates, and Masonry, with a lower growth rate, follows an upward trend in research studies. The subject of seismic effects is also at its end of maturity and is beginning its aging phase.

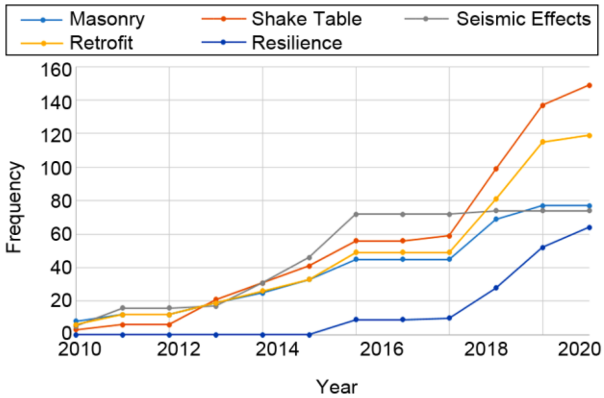

Figure 11. Cumulative frequency – year diagram for selected keywords.

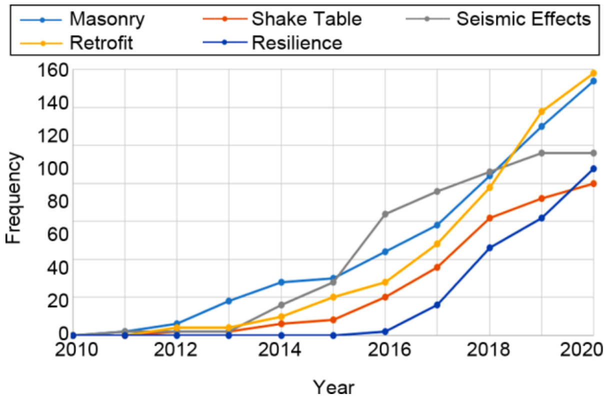

Figure 12. Cumulative number of sponsors - year diagram for selected keywords.

Figure (12) shows the graphs of the number of sponsors by year for the five aforementioned research topics. Based on these charts, financial support for the research term Seismic effects has been declining in recent years, which is consistent with the declining trend in the number of research studies on the subject. Thus, this research topic can be considered in its research aging phase and the end of its business maturity stage. The three keywords Shake Table, Masonry and Retrofit are at the end of the embryoment phase and the beginning of the business growth stage. The subject of Resilience seems to reside on the commercial embryoment stage.

Based on the information obtained from Figures (11) and (12), in Table (3), the selected research topics are classified based on quantitative and qualitative categories. The classes found based on both classifications, according to Table (2), are in good agreement with each other. Based on these classes, researchers can evaluate and draw conclusions about the value of the research topic and their future research and business prospects.

Table 3. Qualitative and quantitative classifications for selected keywords.

Qualitative Category	Quantitative Category	Keyword
1	GE	Resilience
2	GG	Hydraulic Fracturing
5	EE	Retrofit
3	GG	Induced Earthquake
4	MM	Hydraulic Structure

We now consider the third task of interpretation. Figure (13) shows the main research themes of the field. The topics under the cluster title Earthquake have a high centrality and moderate density. This research theme, thus, introduces moderately developed topics with high influence on the science field. The topics under the title seismic design are well-formed, fully-developed subjects, with moderate influence on other topics of the field. Topics under the title seismic performance are specific and relatively new issues that have not yet been sufficiently coherent and consistent.

3.2. Earthquake Studies in Energy Sciences

3.2.1. Qualitative Study

In setting up the keyword map of science in this field, keywords with frequencies greater than 2 are used. Also, here some general concepts such as Seismic performance or Seismic behavior, as well as some well-known high-frequency topics such as FEM, Simulation and Shake table have been omitted for a better visualization, to facilitate human qualitative interpretation; such keywords, however, are considered in the final interpretation. The map of science in this field is thus organized as shown in Figure (14).

Here, as in the previous case, the map of science consists of a stack of main vocabulary and a number of peripheral keywords. The list of important keywords in this field of knowledge, based on the qualitative classification described in Section 2-3-1, is as follows:

1. Resilience; of course, Resilience in the field of energy seems to have a longer history than materials science. Also, the concept of Resilience in this field is slightly different from the field of materials science. In the latter, the mechanisms and structural components which may enhance resilience after an earthquake are studied. In contrast, in the field of energy, resilience is studied in a more general sense and in connection with keywords such as Hazard and Disaster (Figure 15).
2. Disaster, Vulnerability
   Hydraulic fracturing
3. Nuclear reactor, BWR (Boiling Water Reactor)
   Induced earthquake (studies in this area focus mainly on Hydraulic fracturing and Geothermals)
   Hazard, Risk, Safety, Fragility, Damage, Sustainability

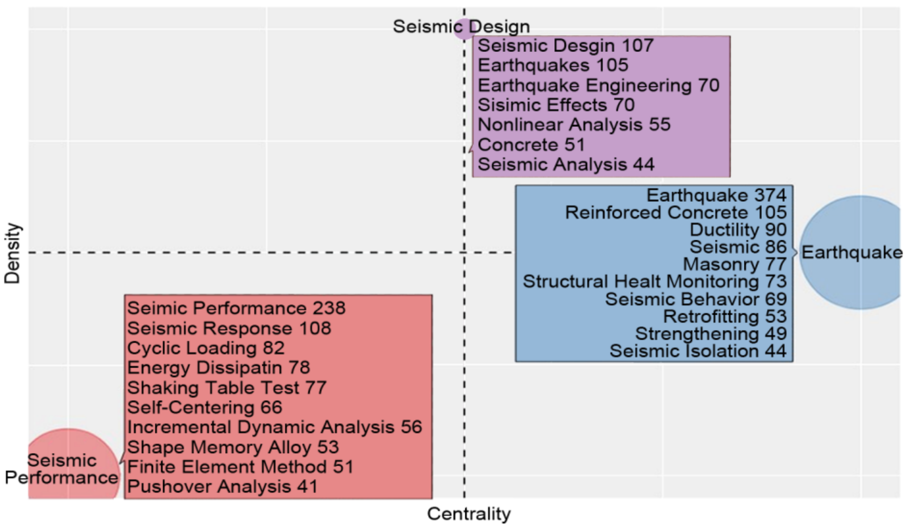

Figure 13. Thematic map for the domain of Earthquake studies in Materials Science.

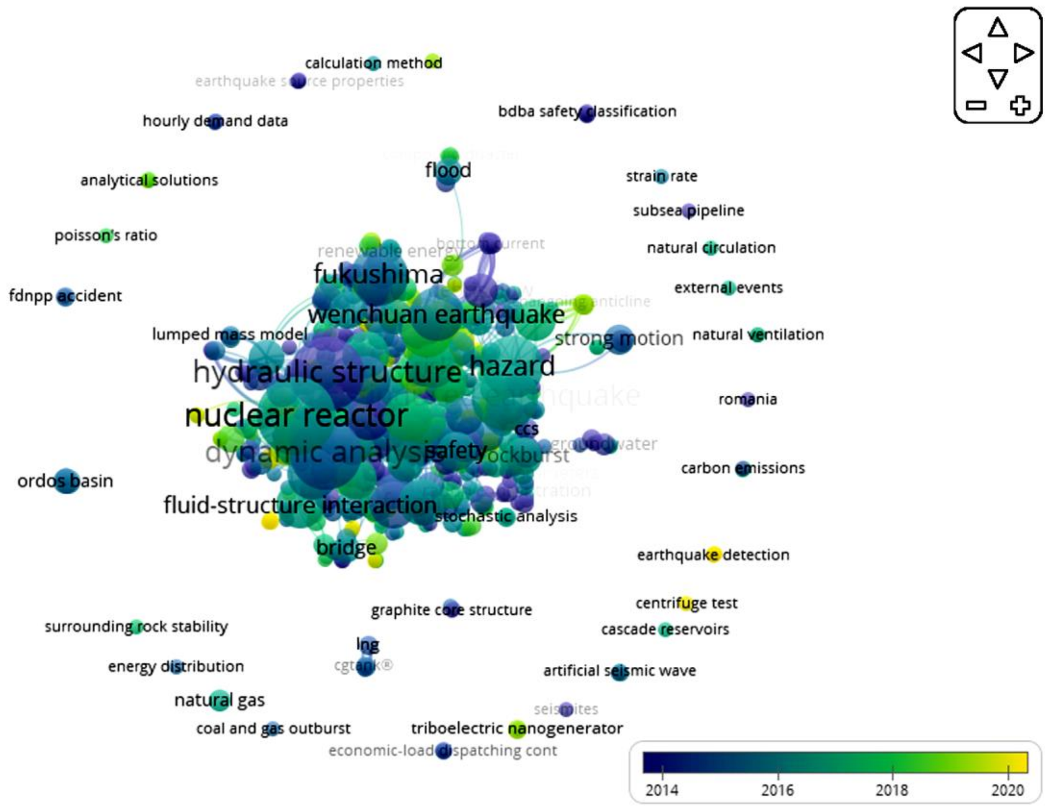

Figure 14. Keyword map for the domain of Earthquake studies in Energy Science (2010-2020).

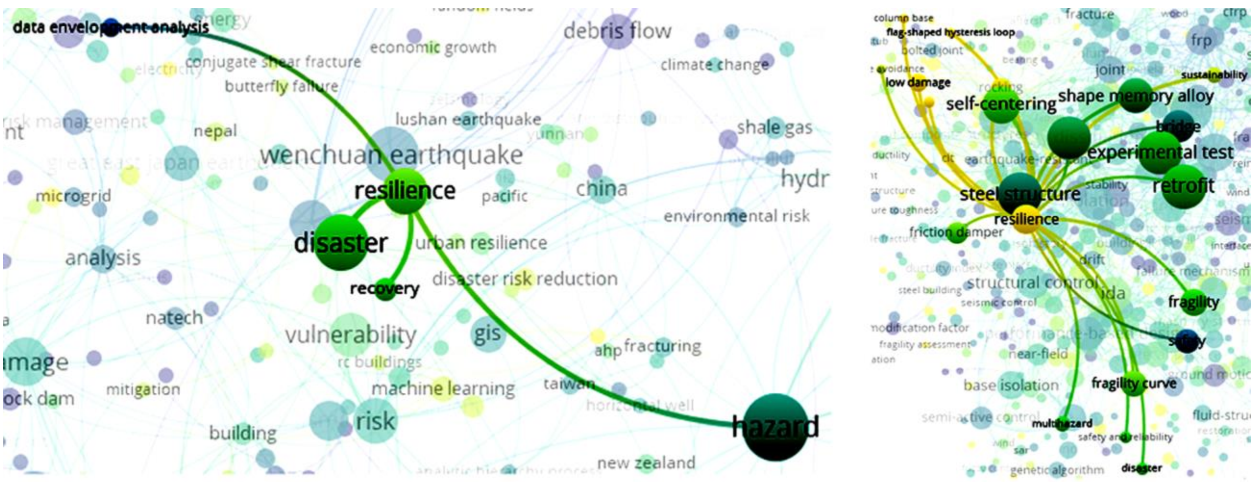

Figure 15. Comparison of keyword relationships for the research topic: Resilience for the two domain of Earthquake studies.

Wind turbine
Fluid-structure interaction
Isolation

4. Hydraulic structure
   Response spectrum
5. Retrofit (6): This research subject seems to be newer than its counterpart in materials science.
   Machine learning (5) with application in Damage and Vulnerability studies
6. Multi-hazard (4)
   Thermal structure (2)
   Radiation imaging (3)
7. Earthquake detection (2)
   Natural ventilation (2), Natural circulation (2)
   Triboelectric Nano-generator (3)
   Cascade reservoir (2)
   Centrifuge test (2)
   Prefabrication (2)

Post-disaster housing (2)

On this basis, research trends in this field can be identified as follows:

1. Analysis and evaluation: Just the same as the previous case, numerical methods, especially the finite element method and dynamic analysis are very practical in this field. Experimental methods are relatively employed by using Shake tables or newer methods such as Centrifuge test. It seems that various seismic assessments (Risk, Hazard, Vulnerability and Damage) have recently been widely used in estimating and predicting the behavior of both energy distribution networks and energy supply infrastructures such as dams, wind turbines, nuclear reactors and etc.
2. Design, Retrofit and Resilience: Studies in the field of design of energy supply and distribution infrastructures seem to have reached their maturity, and less research is done in this field. An interesting point is that the research on retrofitting of energy infrastructures (such as dams, power plants, reactors, etc.), in contrast to conventional buildings and structures (studied in the previous section), is by no means widespread. It seems that the design criteria for such structures have been conservative enough that have largely eliminated the need for retrofit and reinforcement. However, the resilience of energy infrastructures after severe accidents such as earthquakes and tsunamis is one of the current interesting topics in this field.
3. Induced Earthquakes: Another significant research topic is the subject of induced earthquakes. In particular, it seems that significant studies are being carried out by companies active in oil and gas industries for CO2 gas injection and storage.
4. As a general summary, the human expert divided the research themes of this science field into the following three categories:
   - Basic topics: Finite element analysis, dynamic analysis, design
   - Up-to-date Topics: Experimental methods, types of seismic assessments, seismic resilience
   - Special Topics: Induced Earthquakes

3.2.2. Quantitative Study

In this section, the three interpretive tasks are performed for the field of Earthquake studies in Energy sciences, using appropriate diagrams taken from Bibliometrix. In Figures (16a) and (16b), keyword frequencies in terms of their mean occurrence years are plotted for the two cases of with and without the use of the Thesaurus. In both graphs, the search keyword Earthquake has the highest frequency far from other keywords and is not displayed. Keyword arrangements for both graphs seem to be in good accordance with the pattern shown in Figure (2). The numbers shown on the clusters coincide with those shown in Figure (2).

Based on the graphs, it is clear that the general keyword Seismic Response is in the top middle part of the graph. Below it, commonly used keywords reside, which are mainly related to applied technologies in this field, such as numerical analysis (FEM, dynamic analysis, etc.), laboratory analysis (shake table), induced seismicity and nuclear reactors.

In Figure (10a), there are some other keywords that might be related to the above main keywords; e.g. Severe Accident that is related to nuclear power plant and risk assessment, or response spectrum that is related to seismic analysis.

It seems that the two diagrams a and b are well compatible with each other. However, in Figure (10b), clusters are better separated. In Figure (10a), some words (such as risk assessment) have a fuzzy behavior and might be attributed to both neighboring clusters. Such behavior seems to better reflect the functional reality of knowledge concepts. From this perspective, it can be said that for such analyzes, the use of the Thesaurus, in addition to the high cost of their construction, causes information lost and undesired distortion in keyword-map structure, and therefore are not recommended. However, an application of a necessary level of synonymization is inevitable; for example, terms such as finite element and finite element method are located in clusters 2 and 4 in Figure (10a). It is obvious that by equating the two, the term will shift completely into cluster 2, as has happened for FEM in Figure (10b).

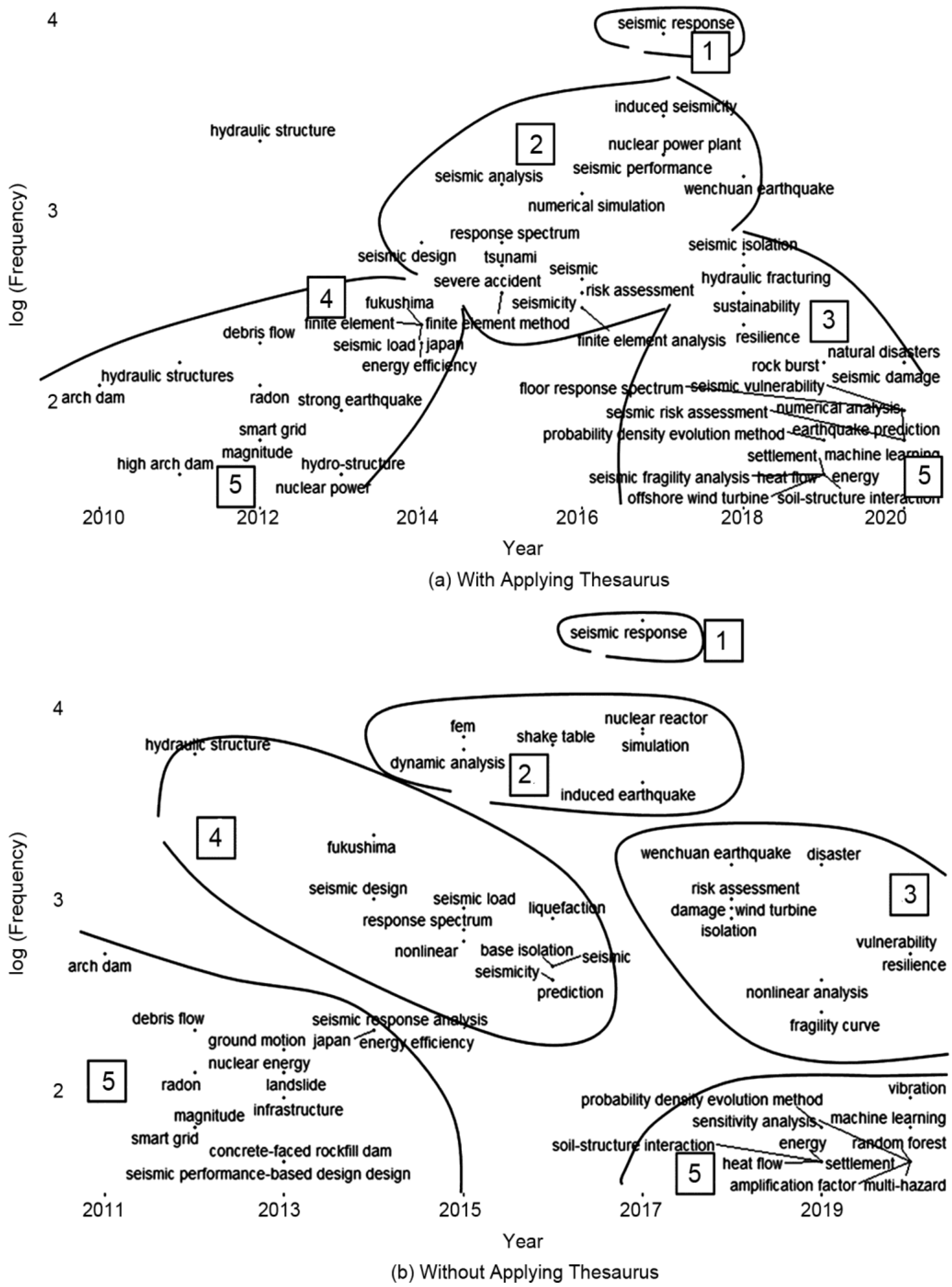

Figure 16. Keyword frequencies (Earthquake in Energy science) in terms of their mean years of occurrence.

Keywords in cluster 2 of the diagrams of Figure (16) (and especially Figure 16a) provide a clear view of the general research disciplines of this field, including: numerical and laboratory analysis, seismic assessment, seismic design, nuclear power plants and induced earthquakes. These keywords are well consistent with the main research trends suggested by the human expert.

Up to this point, research topics of the field, in the form of three: new, widely used and old vocabulary clusters, are identified from the diagrams in Figure (16).

In the next step, the position of research topics according to the nine groups described in Section 2-3-2, are determined. Here, we investigate, as samples, some research topics which were previously evaluated and accordingly positioned by the expert in Section 3.1.1.

Figure (17) shows a cumulative frequency chart of selected keywords for the years of the last decade. It is clear that the subject of Retrofit is at the embryoment stage of its research process.

The topics of Hydraulic Fracturing, Induced earthquake and Resilience are in the research development stage, albeit with slightly different growth rates. The general subject of Hydraulic structures is also at the end of the maturation stage and is beginning its aging phase.

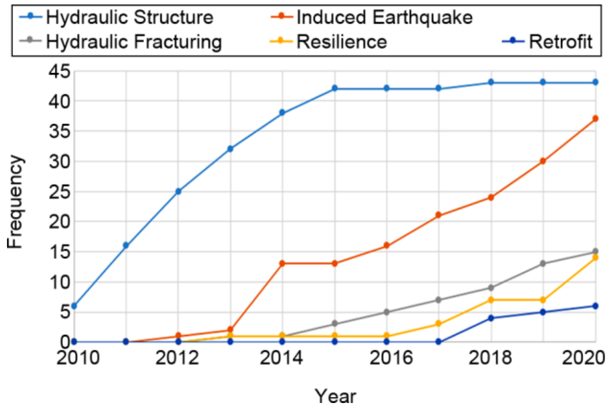

Figure 17. Cumulative frequency – year diagram for selected keywords.

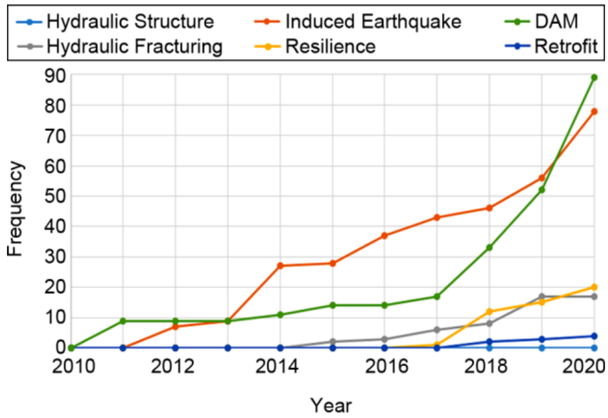

Figure 18. Cumulative number of sponsors - year diagram for selected keywords.

Figure (18) shows graphs of the number of sponsors by year for the five aforementioned research topics. Based on these charts, no financial support has been provided for the term Hydraulic structure. However, it should be noted that this keyword is general, and one must examine what specific meaning it has in the database. A general review shows that the keyword is mainly related to Seismic Analysis and Design of hydraulic structures. It is notable, however, that failure assessment of some hydraulic structures such as dams, as shown in Figure (18) (dam keyword diagram), has grown significantly in recent years. Thus, seismic analysis and design (but not assessment and resilience) of hydraulic structures are subjects that reside on commercial maturity stage and even seem to have entered the aging phase. The terms Hydraulic Fracturing and Induced Earthquake are at the end of their embryoment periods and are beginning their commercial growth stage. The other two topics are relatively in the commercial embryoment stage, although they experience different growth rates.

Based on the information obtained from Figures (12) and (13), the selected research topics are classified based on quantitative and qualitative classifications, as shown in Table (4).

Table 4. Qualitative and quantitative classifications for selected keywords.

Qualitative Category	Quantitative Category	Keyword
1	GE	Resilience
2	GG	Hydraulic Fracturing
5	EE	Retrofit
3	GG	Induced Earthquake
4	MM	Hydraulic Structure

We now turn to the third task of interpretation. Figure (19) shows the main research themes of this science field. Since the titles selected by Bibliometrix may not well represent the research themes, their most important keywords are specified with red markers. Based on this, research themes are classified as follows:

Basic Topics (Zone 3): Finite Element Analysis, Seismic Analysis and Computer Simulation, Design

Up-to-date Topics (Zone 1): Nuclear power plants, seismic assessment, hazard.

Special Topics (Zones 2 and 4): Induced Earthquakes, Fault, Hydraulic Fracturing, Sustainable Development, Water Supply, Landslide.

It can be seen that this classification for research themes is in good agreement with what the expert has suggested.

4. Conclusion

Exploring important and new scientific research topics, identifying research trends in each field of knowledge, evaluating research topics and their perspectives, and recognizing new

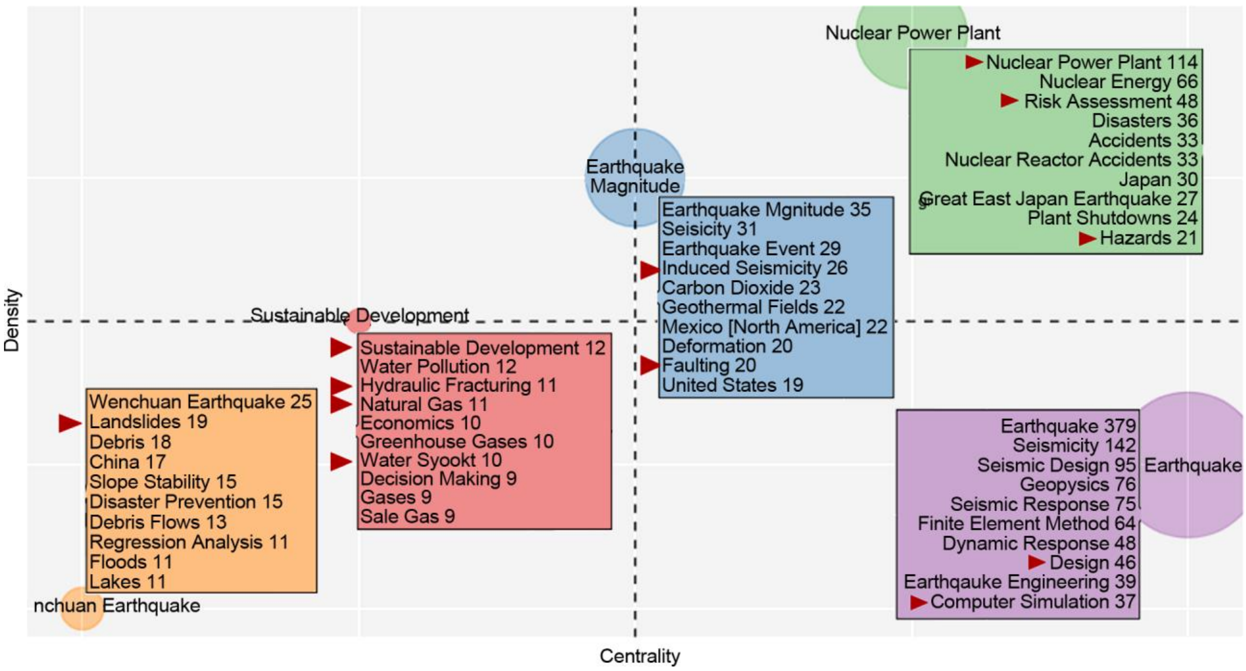

Figure 19. Thematic map for the domain of Earthquake studies in Energy Science.

technologies with commercial potential are among the requirements for growth and development of any field of knowledge. In fact, monitoring and observation of the global research ecosystem of a branch of knowledge is a prerequisite for future research activities and establishing scientific research policies, which are of great importance for researchers, research institutes, universities, scientific and professional communities and policy makers of a country.

With the development of citation databases of articles, as well as more advanced scientometrics tools and algorithms, and the increasing capabilities of computers, it has recently become possible to survey knowledge and research, based on keyword and collaboration networks. To the authors' knowledge, scientometric studies for Earthquake sciences are limited to reports on the performance of authors and research institutes, and no thematic analysis based on keyword co-occurrence or co-citation networks in this field is performed. Surely, the information obtained from such thematic analyses is very important for the policy-making of Iranian research institutes active in the field of earthquake sciences.

In this research, by using keyword co-occurrence maps and several other diagrams and indicators, the recent ten-year research trends in earthquake studies for the two applied fields of Materials and Energy sciences are investigated. According to the results of scientometric thematic analyses in this research, the main research trends in the subfields of Earthquake Studies (for Materials and Energy sciences) are found to be as follows:

1. Analysis: The study shows that in the subfield of seismic analysis, research trends have shifted towards simulating more complex nonlinear behaviors. This has given rise to increasing use of laboratory models such as shaking tables and centrifuge tests. Cyclic loading and hysteretic behavior of materials are noticeably under consideration. However, Finite Element Method, as a numerical modeling method, is still widely used in the literature. Numerical simulations are also mainly shifted towards nonlinear analysis, especially nonlinear dynamic analysis (IDA). Due to the complex nonlinearities of materials which are now under consideration and the over-complicated constitutive laws and hysteretic relations which have been presented, it seems that the traditional numerical methods of simulation may not go much further. There are hints in the literature and the corresponding keyword network that new tools such as Deep

Learning and Artificial Neural Networks are under consideration and development for the purpose of highly nonlinear simulations and forward modelings.

2. Assessment: Seismic assessment for various sophisticated nonlinear-based indices (such as Vulnerability, Fragility, and Damage) has become a main growing trend of the field. Such assessments are shifting from single buildings to more complex structures such as energy infrastructures (energy distribution networks and energy supply infrastructures such as dams, wind turbines, nuclear reactors), as well as wide blocks of urban structures.
3. Design and Retrofit: Seismic design subfield seems to approach its maturity (even for special structures such as energy supply and distribution infrastructures); yet interdisciplinary research is going on more sophisticated mechanical devices and mechanisms (e.g. Self-centering) to dissipate seismic vibrations. It is interesting to note that active control does not seem to be of much interest to researchers anymore, and passive or semi-active controls are more attractive. Retrofit studies, also approaching research maturity, are especially directed toward the field of energy infrastructures; such studies are, however, not very widespread.
4. Materials: Researchers are now less interested in concrete materials, and most research work is now directed toward steel, masonry and mortars. Advanced materials (such as high-strength steels and ECC) and geosynthetics can also be enumerated as two current and novel topics of the domain.
5. Special Topics: This study introduces Resilience as a main topic of the domain with high growing research potential and interest. Induced Earthquake is another special research topic of the field, which is mainly sponsored by U.S. oil companies for the purpose of CO_2 gas injection and storage.

This research, in addition to giving a perspective on the structure of earthquake studies in materials and energy sciences, proposes a method to quantitatively evaluate the current status of any research topic and its potential for further research and industrialization. The results obtained by the quantitative method are in good agreement with those obtained with the qualitative ones. This suggests use of the proposed method to automatically provide an overview of the growing research topics in the field, as well as research that has reached or is approaching its maturity and has begun the process of industrialization and commercialization. Such automation can surely compensate for Expert’s qualitative misclassification of research subjects and reconsiders those topics that might be overlooked by Expert’s navigation in the nested overwhelming network of the keywords. Based on this, the method introduced in this research can be extended to other areas of sciences, which can effectively provide an overview of research topics with industrial potential, for researchers in any field of knowledge.

The findings of this research can be useful for researchers and research institute administrators active in the field of Earthquake sciences. However, it seems that for a reliable research policymaking procedure, there needs more efforts to extend this research to other subject areas, specially the Earth and Planetary Sciences (as defined by SCOPUS categorization), which is the authors’ next research program. Detailed analysis of collaboration networks for both authors and sponsors is also of great significance, the most important of which is the relationships and interaction of the three keywords, authors and sponsors collaboration networks. Surely, a comprehensive scientometric study of the research field can significantly help to establish robust futurology studies and research policymaking procedures.

References

1. Li, J., Goerlandt, F., and Reniers, G. (2021) An overview of scientometric mapping for the safety science community: Methods, tools, and framework. *Safety Science*, **134**, 105093.

2. Kim, B.J., Jeong, S., and Chung, J.B. (2021) Research trends in vulnerability studies from

2000 to 2019: Findings from a bibliometric analysis. *International Journal of Disaster Risk Reduction*, **56**, 102141.

3. Liu, J., Chen, Y., and Chen, Y. (2021) Emergency and disaster management-crowd evacuation research. *Journal of Industrial Information Integration*, **21**, 100191.

4. Liu, H., Chen, H., Hong, R., Liu, H., and You, W. (2020) Mapping knowledge structure and research trends of emergency evacuation studies. *Safety Science*, **121**, 348-361.

5. Oh, N. and Lee, J. (2020) Changing landscape of emergency management research: A systematic review with bibliometric analysis. *International Journal of Disaster Risk Reduction*, **49**, 101658.

6. Cobo, M.J. and Gutiérrez-Salcedo, M.M. (2015) 25 years at knowledge-based systems: A bibliometric analysis. *Knowl.-Based Syst*., **80**, 3-13.

7. Li, J., Reniers, G., Cozzani, V., and Khan, F. (2017a) A bibliometric analysis of peer-reviewed publications on domino effects in the process industry. *J. Loss Prev. Process Ind.*, **49**, 103-110.

8. Li, Y., Jia, H., Li, J., Gong, J., and Sun, K. (2017b) Pedestrian evacuation behavior analysis and simulation in multi-exits case. *Int. J. Mod. Phys. C.*, 1750128.

9. Van Nunen, K., Li, J., Reniers, G., and Ponnet, K. (2018) Bibliometric analysis of safety culture research. *Saf. Sci.*, **108**, 248-258.

10. Liu, H., Yu, Z.H., Chen, C., Hong, R., Jin, K., and Yang, C. (2018) Visualization and bibliometric analysis of research trends on human fatigue assessment. *J. Med. Syst.*, **42**(10), 179.

11. Hong, R., Xiang, C.L., Liu, H., Glowacz, A., and Pan, W. (2019) Visualizing the knowledge structure and research evolution of infrared detection technology studies. *Information*, **10**(7), 227.

12. Ivanović, L. and Ho, Y.S. (2019) Highly cited articles in the education and educational research category in the social science citation Index: A bibliometric analysis. *Educational Rev.*, **71**, 277-286.

13. Chen, C. (2004) Searching for Intellectual Turning Points: Progressive Knowledge Domain Visualization. *Proc. Natl. Acad. Sci.*, USA, **101**, 5303.

14. Chen, C. and Song, M. (2019) *Visualizing a Field of Research: A Methodology of Systematic Scientometric Reviews*. PLoS ONE, **14**, e0223994.

15. Mahi, M., Ismail, I., Phoong, S.W. et al. (2021) Mapping trends and knowledge structure of energy efficiency research: what we know and where we are going. *Environmental Science and Pollution Research*, **28**, 35327-35345.

16. Van Eck, N. and Waltman, L. (2009) Software Survey: VOSviewer, a Computer Program for Bibliometric Mapping. *Scientometrics*, **84**, 523-538.

17. Van Eck, N. and Waltman, L. (2020) *VOSviewer Manual for VOSviewer Version 1.6.14*. Leiden University Press: EZ Leiden, Netherlands.

18. Cobo, M.J., Lopez-Herrera, A.G., Herrera-Viedma, E., and Herrera, F. (2011) An approach for detecting, quantifying, and visualizing the evolution of a research field: A practical application to the Fuzzy Sets Theory field. *Journal of Informetrics*, **5**, 146-166.