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Bibliometric survey and network analysis of biomimetics and nature inspiration in engineering science

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ABSTRACT

The field encompassing biomimetics, bioinspiration and nature inspiration in engineering science is growing steadily, pushed by exogene factors like the search for potentially sustainable engineering solutions that might exist already in Nature. With help of information provided by bibliometric database and further processed with dynamic network and semantic analysis tool, we provide insight at two scales on the corpus of nature inspired engineering field and its dynamics. At macroscale, the web of science (WoS) categories, countries and institutions are ranked and ordered by thematic clusters and country networks, highlighting leading countries and institutions and how they focus on specific topics. Such an insight provides an overview at a macro scale that can be valuable to orient scientific strategy at the country level. At mesoscale where science is incarnated by collaborative networks of authors and institutions that run across countries, we identify six semantic clusters and subclusters within them, and their dynamics. We also pinpoint leading academic collaborative networks and their activity in relation with the six semantic clusters. Trends and prospective are also discussed. Typically one observe that the field is becoming mature since, starting by merely copying Nature, it proceeded with mimicking more complex natural structures and functions and now it investigates strategies used in Nature in response to changes in the environment and implements them in innovative and adaptive artefacts. The sophistication of devices, methods and tools has been increasing over the years as well as their functionalities and adaptability whereas the size of devices has decreased at the same time.

KEYWORDS

Biomimetics, bioinspiration, nature inspiration, engineering, bibliometrics

1 Introduction

Nature-inspired achievements are becoming increasingly common in many areas of research and innovation. Evidently, a lot of current scientific knowledge and engineered artefacts were produced without any reference to Nature and many technological achievements have no equivalent in nature (Bensaude-Vincent 2011). Indeed the route of technology copying nature is paved of failures, such as early aeronautics mimicking birds, when the understanding of mechanisms and laws is not mastered. This establishes the ambivalence of nature inspiration design between the natural world and the anthropic world on the ridge of a combination of science and usage (Vogel, 1998). Nowadays, awareness of global changes that human world is facing pushes also research towards nature inspiration in the hope of potentially sustainable solutions for a healthier planet. In addition to descriptive technological issues, this also raises philosophical issues, that some authors call normative issues, such as human relation to nature (Speck *et al* 2017, Bensaude-Vincent 2019, Dicks and Blok 2019, Biomimicry institute 2021). These descriptive and normative issues are also supplemented with emotional issues about the way one perceives nature-inspired achievements (Speck *et al* 2017). In this paper, we will restrict to descriptive - technological issues based on a bibliometric survey.

Conscious of early mention of biomimetics (Speck *et al* 2017), the conceptualisation of biomimicry is usually attached to Janine Benyus' book *Biomimicry: innovation inspired by nature* first published in 1997 (Benyus JM 2002). The field has since spread largely in engineering science. In 2015, the ISO1848 and ISO1849 norms further distinguished biomimetics and biomimetism, but one also speaks of bioimitation, bioinspiration, and nature-inpiration as they all refer to the imitation of structures, properties, processes and interactions that are expressed in biological and non-living natural entities. Nature is an evident source of inspiration, with its diversity of entities, context and strategies for addressing the global challenges that society and science is facing for developing artefacts that are more adaptable, resilient, energy-lean, etc…

Janine Benyus defined biomimicry as the aim "to take inspiration from natural selection solutions adopted by nature and translate the principles to human engineering". The ISO standards differentiate biomimetics (ISO1848) and biomimicry (ISO1849). Biomimetics is established as the "Interdisciplinary cooperation of biology and technology or other fields of innovation with the goal of solving practical problems through the function analysis of biological systems, their abstraction into models, and the transfer into and application of these models to the solution". Biomimicry is restricted to "philosophy and interdisciplinary design approaches taking nature as a model to meet the challenges of sustainable development (social, environmental, and economic)". In reality, this principle of imitation can be extended to Nature as a whole in a process called inspiration by nature to take also into account the non-biological processes/structures/properties implemented in nature. More specifically, inspiration by nature corresponds to the exploitation for engineering purposes of concepts present in nature.

It can be done in different ways and to different extents. Following a bottom-up approach from Nature to engineering, one can gradually imitate natural structures, or structure/function relations, structure/property relations and process, or reproduce only the function, property or process without reproducing the structure, or mimic interactions and inter-individual organizations or even copy natural being strategies for coping with changes in their environment. The opposite approach, top-down from engineering issue to solutions inspired from Nature is also used, initiated by an identified and formalized scientific and/or technological problem for which one wishes to find an engineering solution. It is usually more effective in terms of breakthrough innovation since it calls for an understanding of phenomena and mechanisms so as to seek in nature models that can constitute a factor of inspiration (Coppens 2005, 2019, 2021, Gerbaud *et al* 2020).

As research grows in this challenging semantic, it is of major interest to map worldwide academic stakeholders and their preferred topics, identify the different networks and their dynamics versus time. This the aim of this survey. The availability of innovative bibliometric tools allowed us to build a corpus of 21858 scientific documents issued in the 2005-2019 period, source in the Web of science Clarivate database. The publication field encompassing biomimetics, bioinspiration and nature inspiration swarms with reviews. Indeed, extending our query to include all periods, proceedings and meeting abstracts one recovers more than 66 056 documents among which a noticeable number of 5637 documents tare agged as reviews by Clarivate. Citation figures are also high with the top two documents over 3200 citations each. But such a database gives a limited picture of the reach of nature inspiration. Neither referenced by Clarivate nor by Scopus, the number of citation of the pioneering book by Janine Benyus, is estimated over 1500 by semantic scholar (SemanticScholar 2021) and over 4000 by google scholar (GoogleScholar 2021).

With such a huge amount of scientific production, exhaustivity is illusory. Hence, most of the review papers on biomimetic, bioinspiration or nature inspiration are domain specific. Some are concerned with materials

(Fratzl and Weinkamer 2007, Wegst *et al* 2015, Yang *et al* 2017, Nikolova and Chavali 2019), computing (Bongard 2009), sensors (Fratzl and Barth 2009, Scognamiglio *et al* 2015), self-healing materials (Diesendruck *et al* 2015, Hager *et al* 2010), surfaces (Sun *et al* 2005, Liu *et al* 2017, Sun and Gao 2019), biological nanotechnologies (Sarikaya *et al* 2003), energy absorption (Ha and Lu 2020), organ-on-chip (Wu *et al* 2020), on green processes for nature inspired nanoparticles (Rana *et al* 2020), soft robotics (Zeng *et al* 2021), etc. Many of these domain specific works also address processes, techniques and artefacts not inspired by Nature. General reviews are more focussed on nature inspiration as they seek to unravel the law and mechanisms underlying research in the field (Coppens 2005, Bar-Cohen 2006, Vincent *et al* 2006, Fratzl, 2007, Bhushan 2009, Vincent 2009, Knippers and Speck 2012, Coppens 2019, Gerbaud *et al* 2020, Yu *et al* 2020). Other focus on classification of processes, practice, tools and technological achievements for rationalizing future developments and implementation of biomimetics approaches (Fayemi *et al* 2017, Wanieck *et al* 2017, Speck *et al* 2017). Finally a few papers also deal with bibliometric indicators of the field and attempt to decipher subjects and research communities either in the whole field (Lepora *et al* 2013) or in specific domains like soft-robotics (Bao *et al* 2018), biomimetic air-vehicle (Ward *et al* 2015) or water filtration bioinspired membranes (Goel *et al* 2021).

Our contribution is also a bibliometric survey aiming at covering the whole field of biomimetics, bioinspiration and nature inspiration over the period 2005-2019. We do not provide detail information on processes, techniques and artefacts and they can be found in other reviews, like those aforementionned. By using recent text data analysis using the CorTexT Manager tool, we were able to identify the prominent WoS categories, top countries and top institutions in the corpus and their interrelations, including institution networks. We were also able to classify the documents in six clusters based on scientific semantics and analyse how they split in subclusters and how they evolved over time.

Besides, we could reveal research contributions by geographical area and country, top institutions for each WoS category and countries, highlighting leading academic groups and networks working on this challenging scientific field. Furthermore, the occurrence of keywords from 2005-2019 reveals the shifts in the topics and scientific bottlenecks addressed by the research teams in the world.

After presenting the methodology followed in this survey, the key results of our contributions are presented below, split into an analysis of the nature inspired engineering corpus as a whole and into a deeper investigation of thematic clusters, semantic clusters and institutions networks. A supplementary material provides extra tables, lists and figures.

2 Bibliometric Methodology

2.1 Constitution of the corpus from the Web of Science® database

We performed the bibliometric study using the web of science® (WoS®) produced by clarivate (WoS 2020). Wos® is a leading bibliographic database for scientific community around the world, indexing more than 10,000 peer-reviewed journals selected for the international scope of their articles. The WoS® also has the advantage of listing all the addresses of authors, which allows a complete analysis of collaborative networks between countries and institutions.

The parameters selected in the WoS are:

- SCIE (Science Citation Index Expanded) and Conference Proceedings Citation Index - Science (CPCI-S) databases,
- Types of documents: articles, letters, reviews and proceeding papers,
- Time span: 2005-2019,
- the Topic (TS) field which includes the title (TI), abstract (AB), author keywords (DE) and Keywords Plus (ID)[1]

The term query is the following:

[1] The labels of the fields Authors keywords (DE) and Keywords Plus (ID) were changed by Clarivate® mid-2020 as author keywords (AK) and Keywords Plus (KP).

TS = (("bio-inspir *" or "bioinspir *" or biomimeti *) or (("nature inspir *") or ("nature" near / 1 "inspir *")))

The query is applied to the TS field, which includes the TI, DE, AB and ID fields (see also footnote 1). A corpus of 46,500 references is obtained. The 46,500 references are filtered in Cortext on TI and DE (Keywords) in order to constitute the corpus of analysis comprising only documents containing the query terms in TI and/or DE. Besides, documents containing these query terms exclusively in AB and/or DE fields are excluded through Cortext because they are considered too far from the subject. A corpus containing 21,858 documents is the obtained.

2.2 Text analysis in Cortext

CorTexT (Cortext, 2020) is a platform for methodological development, software engineering and support for the analysis of textual corpora for the Humanities and Social Sciences. In particular, it allows data mining and information extraction through a panel of dedicated scripts.

The functionalities (scripts) used for the different steps of the analysis are:

- Lexical extraction and reindexing of terms from TI and DE fields: Terms extraction / terms indexer
  - These scripts are used to extract and reindex text data from open text fields of type “Title” and “Descriptors”.
  - Harmonization of terms
- Lexical extraction and reindexing of countries and institutions from the fields of the Countries and Research institutions fields: list builder / index
  - These scripts are used to extract and reindex text data from the Countries and Research Institutions fields
- Temporal analyzes: Demography
  - This script is used to represent the temporal evolution of the selected data.
- Mapping (networks): Network mapping
  - For all networks, the nodes represent the modalities of the analyzed variables (WoS category, keyword, country, institution) with a size proportional to their total number of occurrences. The links between two nodes have a thickness proportional to the number of co-occurrences between two modalities.
  - Homogeneous networks (crossing of two identical variables) use a “distributionnal” type proximity measurement algorithm while heterogeneous networks are based on a “chi2” type algorithm.
  - When the network clusters are annotated, it is done with the terms sorted in descending order according to a chi2 test.
  - The dynamic maps were generated by adding the option "regular" to the settings in order to create uniform intervals of time.
- Contingency matrix
  - Contingency matrices are heterogeneous cross tables (two different variables) based on a chi2 test. The boxes at the intersections have a colour corresponding to an area of the spectrum associated with the matrix. A red shift indicates a stronger association (very significant chi2) while a blue shift indicates a weak association, the white area indicating an equidistribution.
- Data filtering: Query
  - the “Query” script made it possible to constitute the final corpus by excluding the references containing the keywords of the query only in the Keyword plus (KP) and the summaries.

Finally, terms displayed in the temporal map of each cluster based on their average age in the corpus, which is computed as Sum (Ni x PYi) /Sum Ni, with Ni the number of occurrences of term i and PYi the publishing year of the article containing term i.

3 Nature inspired engineering corpus analysis

Usual bibliometric databases give easily access to information about the most prolific journals in the NIE field, or the top authors and they are not discussed in this document.

3.1 Documents distribution by query terms

The Nature inspired engineering (NIE) corpus, formed from the WoS after the filtering described in the methodology section, combines 21,858 documents over the period 2005-2019.

This large volume of articles allows for a reliable comparative analysis of trends and dynamics by topic by geographic area and network. The complete corpus is then analyzed by using the CorTexT Manager platform, with help of the various scripts described earlier. The 21,858 documents split according to the original query terms as displayed in table 1.

Table 1. Number of documents extracted from WoS by web query term over the period 2005-2019.

Query Terms	Number of documents
biomimet*	14,601
bioinspir* or bio-inspir*	6,493
nature inspir* or "nature" near / 1 "inspir *"	820

The greatest number of documents is obtained with the "biomimet" query with 14,601 hits, far ahead of the other two query terms. The sum is marginally greater than 21,858 by less than 1%, meaning that few documents answer at least two of the queries displayed in Table 1 and that these terms are selectively used independently by their authors.

3.2 Corpus splitting by WoS categories

The 21,858 referenced split into 195 WoS categories, which relative weights are very contrasted. Indeed, the top 20 WoS categories represent 83% of the 21,858 documents, while the top 40 represents only 92% of the corpus. Table 2 shows the 20 most important WoS categories, based on the number of associated documents over the period 2005-2019. 'Materials Science. Multidisciplinary' is the largest with 3,695 documents, followed by 'Chemistry. Multidisciplinary 'with 3,062 references. The WoS category at rank 10 is "Robotics" with 1,654 documents. The labels of these WoS categories span different semantics, which suggests that an extra clustering might be needed. This will be analysed in section 4.

Table 2. Top 20 WoS Categories in terms of documents over the period 2005-2019.

Top 10 WoS categories	Number of documents (2005-2019)	The 11th to 20th WoS Categories	Number of documents (2005-2019)
Materials Science. Multidisciplinary	3,695	Polymer Science	1,114
Chemistry. Multidisciplinary	3,062	Computer Science. Theory & Methods	1037
Materials Science. Biomaterials	2,612	Chemistry. Organic	885
Engineering. Electrical & Electronic	2,292	Physics. Condensed Matter	862
Nanoscience & Nanotechnology	2,226	Engineering. Multidisciplinary	788
Chemistry. Physical	2,148	Automation & Control Systems	786
Engineering. Biomedical	1,993	Biochemistry & Molecular Biology	721
Computer Science. Artificial Intelligence	1,968	Engineering. Mechanical	710
Physics. Applied	1,805	Multidisciplinary Sciences	634
Robotics	1,654	Computer Science. Information Systems	620

Extra information is provided in supplementary materials (annex 1) regarding the evolution rates of the number of documents of each WoS categories in the NIE corpus, in the full WoS database and the ratio of these evolutions. It shows that 18 of the top 20 WoS Categories of the NIE corpus grows much faster than the full WoS database. Biomimetics, bioinspiration and nature inspiration is definitely a hot topic in engineering sciences.

3.3 Publishing countries

An analysis by geographic area and by country reveals the locations of contributors that are listed in Table 3. Beforehand, it should be noted that some documents co-signed by authors from different areas are counted for each areas. Hence, the total number of documents used for computing percentages is 27,903 and is greater than the total of 21,858 independent documents in the NIE corpus.

Bearing this in mind, one notices that 88.4% of the total number of documents in the NIE corpus result from the work of researchers located in Asia and Europe, with 45.8% (10,006 documents) and 42.6% (9,318 documents) respectively. The North American zone occupies the third position with 26.7% (5,843 documents). The other four regions of the world (Middle East, Oceania, South America, Africa) amount for 2,726 documents only.

Table 3 display the contributions of individual countries in the NIE corpus publishing in the top 20 WoS categories. It shows total number of documents per country, the evolution rate between periods 2005-2011 and 2012-2019, without (ER_country) or with (ER_country_weighted) weighting the average number of documents by the average number of researchers per 1000 workers (source OECD). The weighted value translates the evolution of scientific production in the NIE semantic in relation to the overall research effort made by a country. The time evolution per country is detailed in supplementary materials (annex 2).

Table 3. Top 20 countries in terms of NIE corpus documents over the period 2005-2019, and evolution rates (ER) between periods 2005-2011 and 2012-2019. (*) weighted by the number of researchers per 1000 active people.

	NIE Corpus		**ER_country**		**ER_country weighted (*)**	
Country	Number of Document	Rank	Rate of increase	Rank	Rate of increase	Rank
Popular Republic of China	5408	1	1.5	13	1.7	11
USA	5030	2	2.6	4	2.3	8
Germany	1539	3	1.5	14	1.5	13
United Kingdom	1518	4	2.0	8	2.1	10
India	1207	5	2.4	5	-	-
Italy	1110	6	1.1	17	1.4	15
South Korea	1047	7	2.0	7	3.6	5
Japan	1015	8	4.2	2	3.9	3
France	1005	9	1.9	10	3.7	4
Spain	718	10	1.7	12	2.3	7
Australia	603	11	1.9	9	-	-
Canada	564	12	3.1	3	3.1	6
Singapore	450	13	2.1	6	2.19	9
Brazil	442	14	0.4	20	-	-
Switzerland	399	15	1.0	19	1.6	12
Iran	369	16	1.1	18	-	-
Netherlands	336	17	1.9	11	7.7	2
Republic of China	320	18	5.1	1	39.5	1
Portugal	292	19	1.1	16	1.2	16
Turkey	270	20	1.4	15	1.5	13

The top 10 publishing countries account for 84.7% of the total number of documents. The largest publishing countries in the corpus are the Popular Republic of China (23.1%) and USA (21.5%), followed much farther by European and Asian countries like Germany, UK and India. Although the evolution rate favors small publishing countries, it shows that publishing dynamics is very diverse, led by Republic of China, Japan, Canada, USA and India and ended by Brazil, whereas among the two biggest publishing countries, Popular Republic of China and USA, only USA is in the top 5. Besides, when one weights the production of documents by the number of researchers per 1000 active workers (source OECD[2], no data for India,

[2] https://data.oecd.org/rd/researchers.htm

Australia, Iran and Brazil), the evolution ranking amplifies the leadership of Republic of China whereas France and Netherland enter the club of the top 5 dynamic contributors completed by Japan and south Korea.

3.4 Country and institution thematic clustering

As science involves collaborations, we display in figure 1 a map of interconnections between the top 40 publishing countries and WoS Categories. This network analysis leads to five thematic clusters. In addition, the figure proposes for each thematic cluster the ten most publishing institutions (in bold characters and capital letters). The proximity of the thematic clusters reflects the proximity of the terms analyzed in the documents associated with these clusters. The size of each cluster and of each country is proportional to the number of associated documents.

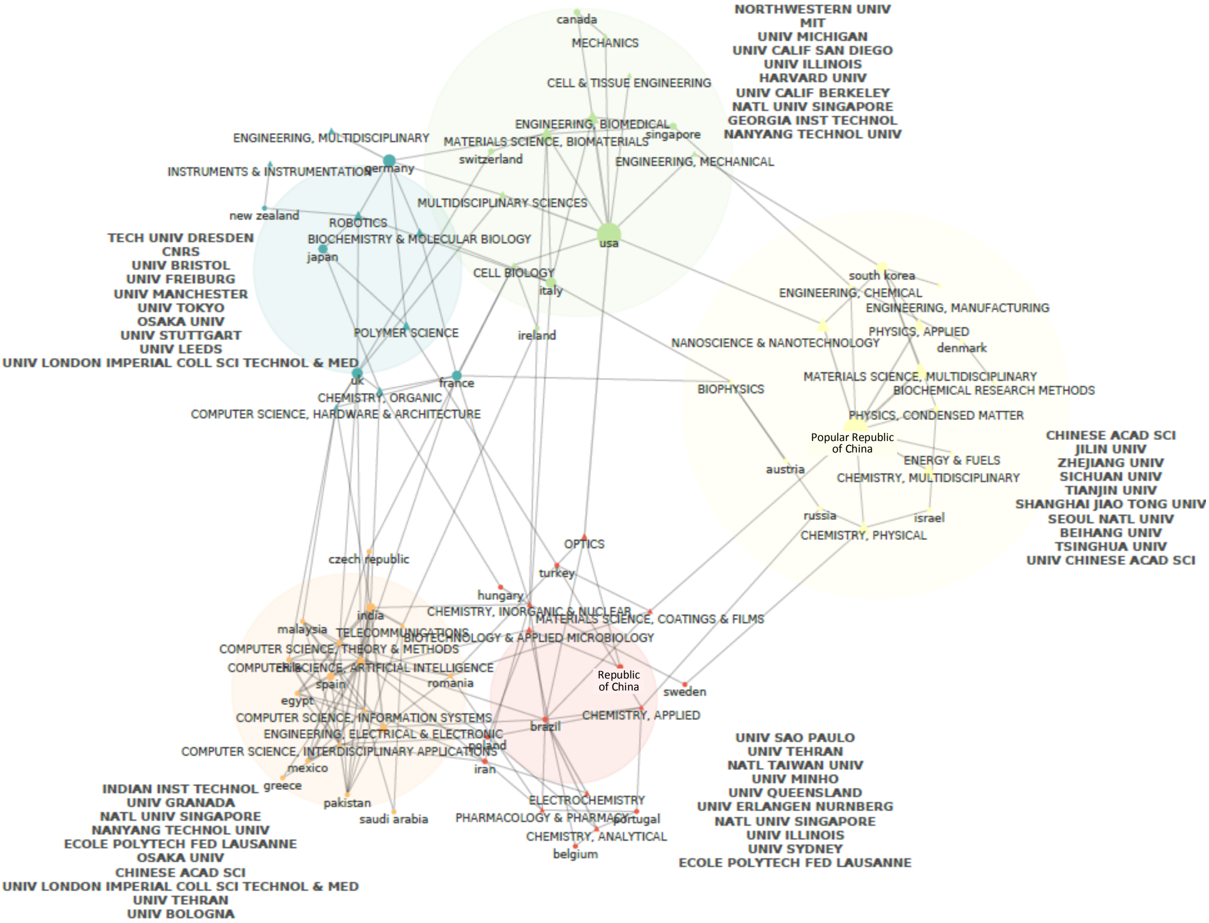

Figure 1. Map of interconnections between countries, WoS categories and key institutions with thematic clusters.

If one looks at the main publishing institutions, the interconnection map confirms what has been observed above. Indeed these institutions are mainly located in the USA or in Popular Republic of China, the top 2 publishing countries, supplemented by a few other countries.

For example, for the cluster located at the top left of Figure 1 and encompassing WoS categories such as “Polymer science”, "Biochemistry & molecular biology" and "robotics", one can identify Tech Univ Dresden ranked first, the CNRS being the second followed by the Univ of Bristol. This podium gathers European institutions, whereas for example the third cluster, in the centre right, has an exclusively Chinese podium with the Chinese Acad of Sci. Jilin Univ and Zhejiang Univ.

The thematic cluster map also displays the expertise of each country related to WoS categories. However, this is even better illustrated by means of a contingency matrix shown in Figure 2. The contingency matrix represents a coloured cross ranking of countries and WoS categories with respect to the average (white colour) based on a Chi2 test. The blocks have sizes, widths and heights, proportional to the number of documents. A red shift shows a stronger association, while a blue shift hints at a milder association.

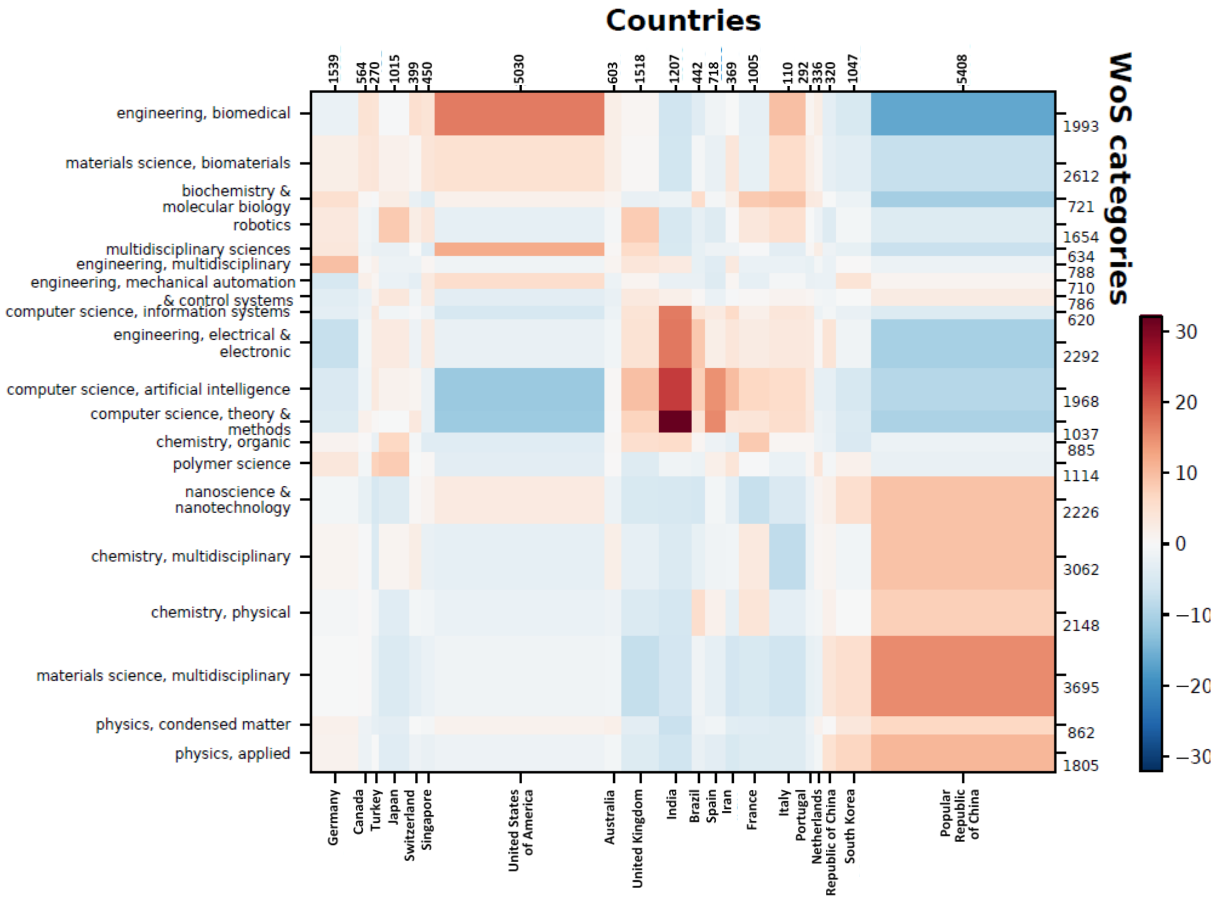

Fig 2. Contingency matrix indicating the interconnections between the first 20 countries and the first 20 WoS categories of the NIE corpus.

The contingency map exhibits striking features about the leadership of countries in WoS categories. For example, USA contributes to WoS categories 'Engineering Biomedical' 'Biomaterials' and 'Multidisciplinary Sciences'. They animate a cluster with Italy, Canada, Switzerland and Singapore (see Figure 1). Chinese scientists are leaders in chemical and physical sciences, nanosciences and materials sciences (excluding medical application). They lead a cluster in these semantics with Russia, Denmark, Israel, South Korea (see Figure 1). India is the world leader in 'Computer Science, theory & methods ' and it aggregates a cluster with a great number of less publishing countries around the topics related to computers and electronics (see Figure 1). The fourth cluster is focused on 'polymer science', 'robotics' and 'biochemistry and molecular biology' WoS categories with Japan and several European countries and New Zealand. The last cluster is less specialized and it revolves around Brazil and Republic of China with Belgium, Turkey and Portugal on the borders.

In addition to the top 10 institutions for each of the five thematic clusters, supplementary materials (annex 3) give a list of the top 100 publishing institutions. In summary, the top 3 publishing institutions are from Popular Republic of China, led by the Chinese Academy of Science with 869 documents while the second has only 279 (Jilin Univ). MIT (USA) ranks 4th and the first 2 institutions outside PRC and USA are respectively the Seoul Nat Univ. (South Korea) and the CNRS (France) at rank 14 and 19 respectively. Tohoku university ranks 100th with 59 documents over the period 2005-2019.

3.5 Top institutions per WoS categories

Studied jointly, the interconnection map (figure 1) and the contingency matrix (figure 2) provide extra information about the most prominent WoS categories. Table 4 display the top 15 WoS categories with the top five institutions in each. The number of documents is also displayed. Notice that documents are often assigned to more than one WoS category. Amounting to more than half of all NIE corpus documents, the top 6 WoS categories are 'Materials science, multidisciplinary', 'Chemistry, multidisciplinary', 'Materials science biomaterials', 'Engineering. electrical & electronics', 'Nanoscience & nanotechnologies' and 'Chemistry Physical'.

Table 4. Contributions of academic institutions to WoS categories. focus on the 5 main WoS categories for the 15 WoS Categories of the NIE corpus.

WoS Categories (nb. documents)	Institutions (nb. of documents)
Materials Science Multidisciplinary (3695)	chinese acad sci (280) jilin univ (95) univ chinese acad sci (83) beihang univ (78) shanghai jiao tong univ (61)
Chemistry Multidisciplinary (3062)	chinese acad sci (288) univ chinese acad sci (85) zhejiang univ (56) beihang univ (51) korea adv inst sci technol (48)
Materials Science Biomaterials (2612)	chinese acad sci (58) natl univ singapore (49) sichuan univ (42) jilin univ (41) nanyang technol univ (41)
Engineering Electrical & Electronic (2292)	chinese acad sci (61) nanyang technol univ (42) natl univ singapore (25) MIT (25) korea adv inst sci & technol (22)
Nanoscience & Nanotechnology (2226)	chinese acad sci (192) univ chinese acad sci (62) beihang univ (50) jilin univ (47) zhejiang univ (42)
Chemistry Physical (2148)	chinese acad sci (198) univ chinese acad sci (59) jilin univ (54) beihang univ (43) zhejiang univ (39)
Engineering Biomedical (1993)	natl univ singapore (36) chinese acad sci (29) nanyang technol univ (27) univ connecticut (26) MIT (25)
Computer Science Artificial Intelligence (1968)	chinese acad sci (43) cairo univ (33) nanyang technol univ (23) univ guadalajara (23) ecole polyt. fed lausanne (21)
Physics Applied (1805)	chinese acad sci (141) jilin univ (66) univ chinese acad sci (39) beihang univ (36) tsinghua univ (29)
Robotics (1654)	chinese acad sci (66) nanyang technol univ (40) scuola super sant anna (33) univ bristol (32) ecole polyt. fed lausanne (32)
Polymer Science (1114)	chinese acad sci (30) zhejiang univ (27) sichuan univ (20) max planck inst col. Interf. (20) tianjin univ (19)
Computer Science Theory & Methods (1037)	cairo univ (18) huazhong univ sci technol (14) agh univ sci technol (14) ecole polyt. fed lausanne (12) osaka univ (11)
Chemistry Organic (885)	chinese acad sci (42) lanzhou univ (19) univ nottingham (18) univ oxford (16) cnrs (15)
Physics Condensed Matter (862)	chinese acad sci (79) jilin univ (31) beihang univ (24) univ chinese acad sci (23) korea adv inst sci technol (20)
Engineering Multidisciplinary (788)	jilin univ (34) konkuk univ (19) beihang univ (18) chinese acad sci (16) univ bonn (16)

The Chinese academy of science is leader in 12 of the top 15 WoS categories. Two other WoS categories are led by other Chinese academic institutions, and only 1 out of 15 WoS "Computer Science Theory & Methods", is led by a non-Chinese academic institution, with Cairo University. It is interesting to note that this institution has "only" 18 documents as the first institution in this WoS category, which represents 1037 documents in total, therefore less than 2% of the total number of documents.

Apart from Chinese institutions, Singaporean institutions, like Nanyang Technology University and National University of Singapore, and Korean institutions, like the Korea adv inst sci & technol or Konkuk University are often listed in the top five.

It is quite surprising that there is a limited number of American institutions, only three in Table 4, with MIT present in the WoS categories 'Engineering Electrical & Electronic' and 'Engineering Biomedical' and the University of Connecticut in the WoS category 'Engineering Biomedical', and the Mexican University of Guadalajara.

Cairo University and its related institutes is the only African institution found in Table 4, and its work is concentrated in specific WoS categories: it ranks first in 'Computer Science theory and methods' and second in "Computer Science Artificial Intelligence".

Among European institutions, the Ecole Polytechnique of Lausanne is present in three WoS categories, all related to computers and robotics, but other European academic institutions are nevertheless visible, like CNRS, University of Oxford, University of Nottingham, University of Bonn University of Bristol, the Scuola Superior Sant'Anna or the Max Planck Institute.

Supplementary materials provide the top five publishing institutions per country (annex 4).

4 Semantic classification of the corpus

In section 3, the bibliometric analysis was carried out based on WoS Categories, countries and institutions. However, the information extracted is quite general. In section 4, the NIE corpus is further analysed based on significant terms so as to identify more detailed clusters and their relationship. To achieve this, the first 1000 occurring terms in the Title (TI) and Keywords (AK) fields were collected in all the documents in the NIE corpus, without paying attention to their WoS categories classification. They are further screened to removed irrelevant terms (articles, abbreviation, acronym, etc.) and aggregate similar variant terms (e.g. model|&|models|&|modeling|&|modelling -> model). Table 5 displays the top 25 terms. A list of the top 100 terms is provided as supplementary material (annex 5).

Table 5. Most frequent top 25 terms from the Title and Keyword fields in the NIE Corpus.

Terms	variants	occurrences	nb. distinct documents
model	model|&|models|&|modeling|&|modelling	1690	1397
materials	materials|&|material	1230	1074
surface	surface|&|surfaces	1163	976
biomimetic synthesis	biomimetic synthesis|&|synthesis of biomimetic	1159	1034
nature	nature	1146	1026
design	design|&|designs|&|designer	1049	923
robot	robot|&|robotics|&|robots	924	721
control	control|&|controller|&|controllers|&|controls	886	701
scaffold	scaffold|&|scaffolds	839	664
synthesis	synthesis	813	744
hydroxyapatite	hydroxyapatite|&|hydroxyapatites	780	597
optimization	optimization|&|optimizer|&|optimized|&|optimality|&|optimizers	767	625
polymer	polymer|&|polymers	764	627
complexes	complexes|&|complex|&|complexity|&|complexation	751	629
algorithm	algorithm|&|algorithms	739	581
tissue engineering	tissue engineering|&|tissue engineered	714	603
nanoparticles	nanoparticles|&|nanoparticle	705	566
membrane	membrane|&|membranes	703	538
hydrogel	hydrogel|&|hydrogels	701	513
coatings	coatings|&|coat|&|coating	693	559
protein	protein|&|proteins	680	522
networks	networks|&|network	676	506
sensor	sensor|&|sensors	650	506
inspired algorithms	inspired algorithms|&|inspired algorithm	616	554
Human	human	606	495

4.1 Overview of semantic clusters

The analysis of the terms is carried out using a network mapping script, enabling to identify 6 semantic clusters which are described below. These semantic clusters based on a semantic analysis are different from the thematic clusters displayed in Figure 1 that were based on the analysis of documents published by countries crossed with WoS category assigned to each documents by Clarivate.

4.1.1 Description of semantic clusters

- **Semantic cluster A/Materials sciences and engineering/ top two WoS categories: [engineering.manufacturing] and [engineering.mechanical]**

Semantic cluster A is about materials science and related engineering. 51% of the related documents have been issued by authors affiliated to PRC and USA institutions. The contribution of authors from other countries is much smaller, like 6% each for South Korea or Japan. In Europe, which amounts for 16% of the total documents; in slight growth since 2015; UK is the largest contributor.

- **Semantic cluster B/Computer sciences and robotics/ top two WoS categories: [computer science.information systems] and [computer science.artificial intelligence].**

Semantic cluster B deals with computer science and robotics, control systems and automatic. The leading publishing country is by far India, followed by Europe (led by Spain, Italy, France and UK). On the other hand, USA, PRC and Germany are contributors below average.

- **Semantic cluster C/Sciences and technologies for health and biology/ top two WoS categories: [Materials Science.biomaterials] and [Engineering.biomedical].**

Semantic cluster C spans topics related to sciences and technologies for health and biology, and nearly half (46%) of the total document are assigned to two WoS categories: [materials science]. [biomaterials and engineering.biomedical]. Recently, one notices the rise of the WoS category [chemistry.analyticals], hinting that new analytical methods are emerging. Among publishing countries, USA, Italy and Germany are above average.

- **Semantic cluster D/Applied physics/ top two WoS categories: [Materials Science.multidisciplinary] and [chemistry.multidisciplinary]**

Semantic cluster D covers topics related to applied physics, nanoscience and nanotechnologies. A limited set of WOS categories are associated to this semantic cluster, led by [materials science.multidisciplinary] and [chemistry.multidisciplinary] that sum up to 46% of the documents. Notice that they are also the biggest WoS categories represented in the whole corpus. Another 42% of the documents in semantic cluster D are covered by [chemistry & physical], [nanoscience & nanotechnology] and [physics.applied] WoS categories. [physics.condensed matter] is the sixth WoS category. PRC is the undisputed leading publishing country. South Korea comes next, followed by USA and Europe countries. In Europe, Germany leads the documents.

- **Semantic cluster E/Chemistry/ top two WoS categories: [chemistry.applied] & [chemistry.organic]**

Semantic cluster E is about chemistry in general and 55% of the documents refer to organic chemistry, polymer science and pharmacology. PRC is the world leading publishing country. In Europe, Germany and France are leaders.

- **Semantic cluster F/Environmental sciences and technologies/ top two WoS categories: [green & sustainable science & technology] & [engineering.environmental]**

Semantic cluster F is a smaller semantic cluster that covers various topics related to environmental sciences and technologies. No leadership is evidenced among contributors.

4.1.2 Size and time coverage of semantic clusters

The six semantic clusters do not have the same importance and representativeness in the corpus in terms of number of documents as shown in table 6. The highest number of document is the one attached to the semantic cluster D (applied physics) followed by semantic clusters B (computational sciences and robotics) and C (sciences and technologies for health and biology). Semantic cluster F (environmental sciences and technologies) is clearly smaller in the NIE corpus.

Table 6. Importance of the six semantic clusters established from the WoS categories in the NIE corpus.

Semantic cluster name	main WoS categories	Number of documents
D Applied physics	[materials Science.multidisciplinary] & [chemistry.multidisciplinary]	6137
B Computational sciences and robotics	[computer science. information systems] & [computer science. artificial intelligence]	4841
C Sciences and technologies for health and biology	[cell biology] & [biophysics]	4345
E Chemistry	[chemistry. applied] & [chemistry. organic]	2644
A Materials Science and engineering	[engineering. manufacturing] & [engineering. mechanical]	1275
F Environmental sciences and technologies	[green & sustainable science] & [technology & engineering. Environmental]	820

Recalling that the NIE corpus covers the 2005-2019 period, the six semantic cluster do not span this period integrally. Semantic cluster A/Materials sciences and engineering/ spans the 2005-2019 period, semantic cluster B/Computer sciences and robotics/ spans the 2010-2019 period, semantic cluster C/Sciences and technologies for health and biology/ spans the 2011-2019 period. Semantic cluster D/Applied physics/ spans the 2009-2019 period, semantic cluster E/Chemistry/ spans the period 2010-2019 and finally semantic cluster F/Environmental sciences and technologies/ spans the 2006-2019 period. The reason is related to the relevancy of terms over the years. Indeed, by means of Cortext tool, terms are displayed in the temporal map of each semantic cluster based on their average age in the corpus, which is related to the number of document per year containing the term (title, abstract, author's keywords). For example as will be displayed later in Figure 7 and despite its large number of documents, the nearly absence of terms in the semantic cluster D/Applied physics/ map after 2019 hints that no new terms but 3D-printing have emerged compared to previous years and that the documents are building on already existing terms. Another example is the one shown in Figure 9 later about the semantic cluster F. It spans the period 2006-2019 in the corpus because the Cortext tool analysis did not find significant terms before 2006, although there are several documents and associated terms that belong to this cluster many years earlier. An illustration of term relevancy is provided as supplementary material (annex 6).

Many terms are common to several semantic clusters where they reveal different dynamics. For instance, the term '*robot'* is present in the semantic cluster A/Materials sciences and technologies/ and the semantic cluster B/Computer sciences and robotics/. In the semantic cluster A/Materials sciences and technologies/ the focus is clearly on the design manufacturing and operation of robots based on active artificial organ; while in the semantic cluster B/Computer sciences and robotics/ the focus is on robotics related to environmental perception and sensors'. Another example is related to the term *'surface'*. In the semantic cluster E/Chemistry/, *'surface'* is linked with chemical structures and molecules; while in the semantic cluster A/Materials sciences and technologies/ the surface refers to the manufactured object.

4.1.3 Sub-clusters and maturity assessment of semantic clusters

Within each of the six main semantic clusters which time evolution will be displayed below, sub-clusters indicated by different colours can be differentiated and a variety of behaviours is observed. For instance, the semantic cluster F/Environmental sciences and technologies/ shows an obvious interweaving of its sub-clusters, as does the semantic cluster A/Materials sciences and technologies/ to a lesser extent. Conversely, the other four main semantic clusters B/Computational sciences and robotics/, C/Sciences and technologies for health and biology/, D/Applied Physics/, and E/Chemistry/ display distinct sub-clusters that have evolved almost independently over the years. For these four semantic clusters, this can be interpreted as a degree of maturity of research work in the fields associated with the WoS categories of each of these four semantic clusters. Schematically, the WoS categories concerned have been in place for almost a century in the case of chemistry and physics, and since 1945 in the case of the computational sciences. However, manufacturing engineering, the most important category of semantic cluster A/Materials sciences and technologies/, is also very old. But, since engineering overlaps with many disciplines this may explain the interconnections of the sub-clusters in the semantic cluster A/Materials sciences and technologies/. On the other hand, the main WoS category of semantic cluster F/Environmental sciences and technologies/, namely [green & sustainable science & technology] emerged only in 1994 in the WoS and WoS category [environmental engineering] was launched in 1967. The interconnections between sub-clusters of the semantic cluster 'Environmental science and technology' are strong and are growing with time. They thus evidence a field in emergence, which provokes a very dense network of interrelations, swarming as years pass.

4.2 Time evolution of semantic clusters

The time evolution of each of the six semantic clusters is displayed on Figure 3.

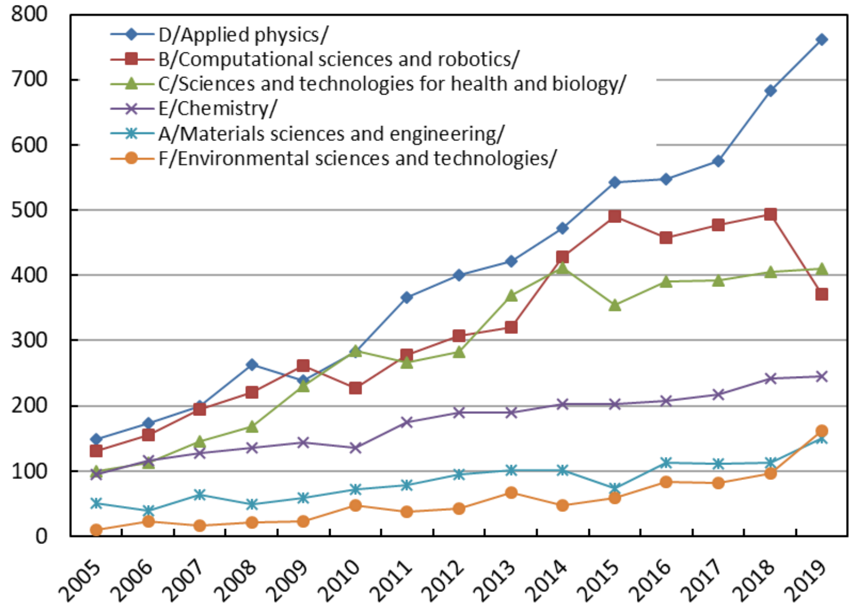

Figure 3: Time evolution of the number of documents of the six semantic clusters. Period 2005 – 2019

The global trend is a growth as the number of documents increased 46x fold between 2005 and 2019. The top three semantic clusters are D/Applied physics/, B/Computanional sciences and robotics/ and C/Sciences and technologies for health and biology/, followed by E/Chemistry/ and well below by semantic clusters A/Materials sciences and engineering/ and F/Environmental sciences and technologies/. Over the years, semantic cluster D/Applied physics/ is the undisputed leader. Semantic cluster C/Sciences and technologies for health and biology/ grew fast for the first 10 years but has steadily slowed after 2014. On its own, semantic cluster B/Computational sciences and robotics/ has stagnated after 2015, with a sudden decrease in 2019 that continued in 2020 (not shown). On the other hand, semantic cluster F/Environmental sciences and technologies/ is gaining momentum in the recent years, being fifth in 2019, after being the sixth and last one for all previous years.

4.2.1 Semantic cluster A/Materials sciences and engineering/

Figure 4 displays the time evolution of semantic cluster A about materials science and related engineering.

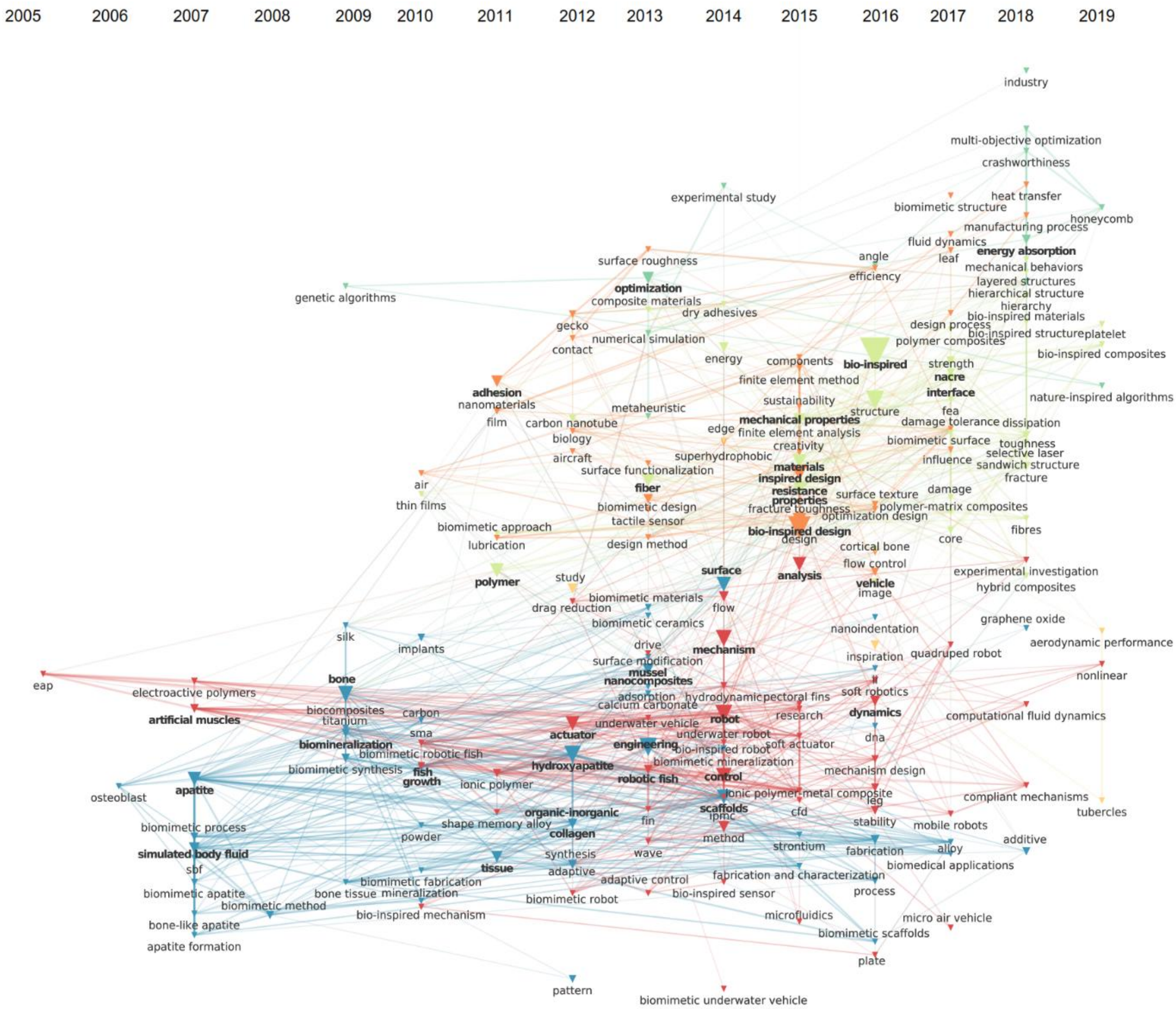

Figure 4: Time evolution of the occurrence of meaningful terms and their interconnections for the semantic cluster A/Materials sciences and engineering/

For semantic cluster A, the first significant keywords emerged in 2005 related to electro active polymers on one hand (red sub-cluster) and to apatite and simulated body fluid (blue sub-cluster). These keywords are also the initiators of the semantic cluster C/Sciences and technologies for health and biology/. In 2011, a new topic (orange sub-cluster) rose, related to surface engineering. Two other sub-clusters are also ascribed to semantic cluster A: one (deep green sub-cluster) is about optimization and simulation and is very diffuse but is getting a new interest since 2018; one (light green sub-cluster) refers to structure (polymer, fiber, hierarchical structure) and bio-inspired properties. The term ‘structure’ is also present to a lesser extent in semantic cluster D/Applied physics/ (hierarchical structures) and concerning specific application in the semantic cluster F/Environmental sciences and technologies/.

The initiators of the blue sub-cluster propagate over the years with explicit terms, bones, hydroxyapatite (also found in the semantic cluster D/Applied physics/), engineering on one hand and tissue, collagen on the other hand, that indicate what this semantic cluster is about: engineering artificial bones and simulated body fluids. A specific mention is the aim is at mimicking human or animal organ and material. On the contrary, for the red sub-cluster, the focus is on copying the organs and function using non-animal and non-human devices for developing robots and vehicles.

Both red (active polymers) and blue (bone-like structures) sub-clusters interlink strongly since artificial muscles, bones or body fluids are essential together for developing artificial underwater, ground and more recently air-borne vehicles.

Regarding the other three sub-clusters, orange, deep green and light green, they are interconnected primarily with the ‘surface’ term to the blue sub-cluster and via ‘mechanism’ and ‘analysis’ term to the red sub-cluster. These three smaller sub-clusters exhibit a majority of conceptual and abstracted terms, dominated by adhesion and bio-inspired design (orange) and resistance properties, structure, materials and bio-inspired (light green). More explicit terms rarely emerge, like ‘gecko’ connected to ‘adhesion’ or ‘nacre’ connected to ‘surface’. ‘surface’ and ‘structure haves already been cited as significant terms. They also appear in many composed terms especially in the orange and light green sub-clusters. Here in two sub-clusters, ‘surface’ and ‘adhesion’ terms are also displayed in a single major sub-cluster of the main semantic cluster E – chemistry that is connected in semantic cluster E to specific chemical structures and molecules.

All over the semantic cluster A, secondary terms refer to mechanism, characterisation, fabrication, control, etc. The fact that there are also connections between the red and blue sub-clusters on one hand and the deep green sub-cluster about optimization, evidence that the field encompassing the material scienes and engineering semantic cluster A is now getting mature: the initial phase of designing devices and parts has shifted towards their assembling into larger devices, like vehicles and robots. The proof of concept is undisputed and its transfer to industry seems on the verge to happen, as industry keyword appears in 2018 in the deep green sub-cluster.

4.2.2 Semantic cluster B/Computer sciences and robotics/

Figure 5 displays the time evolution of semantic cluster B that deals with computer science and robotics, control systems and automatic. Despite remaining among the top three semantic clusters in terms of documents, with semantic cluster D/applied physics/ and semantic cluster C/Sciences and technologies for health and biology/, its importance is decreasing in the corpus since 2015, being the only semantic cluster with no increase in documents.

The time span of Semantic cluster B covers the period 2010 – 2019. It is symptomatic that four distinct sub-clusters are displayed, evolving quasi-autonomously over the years.

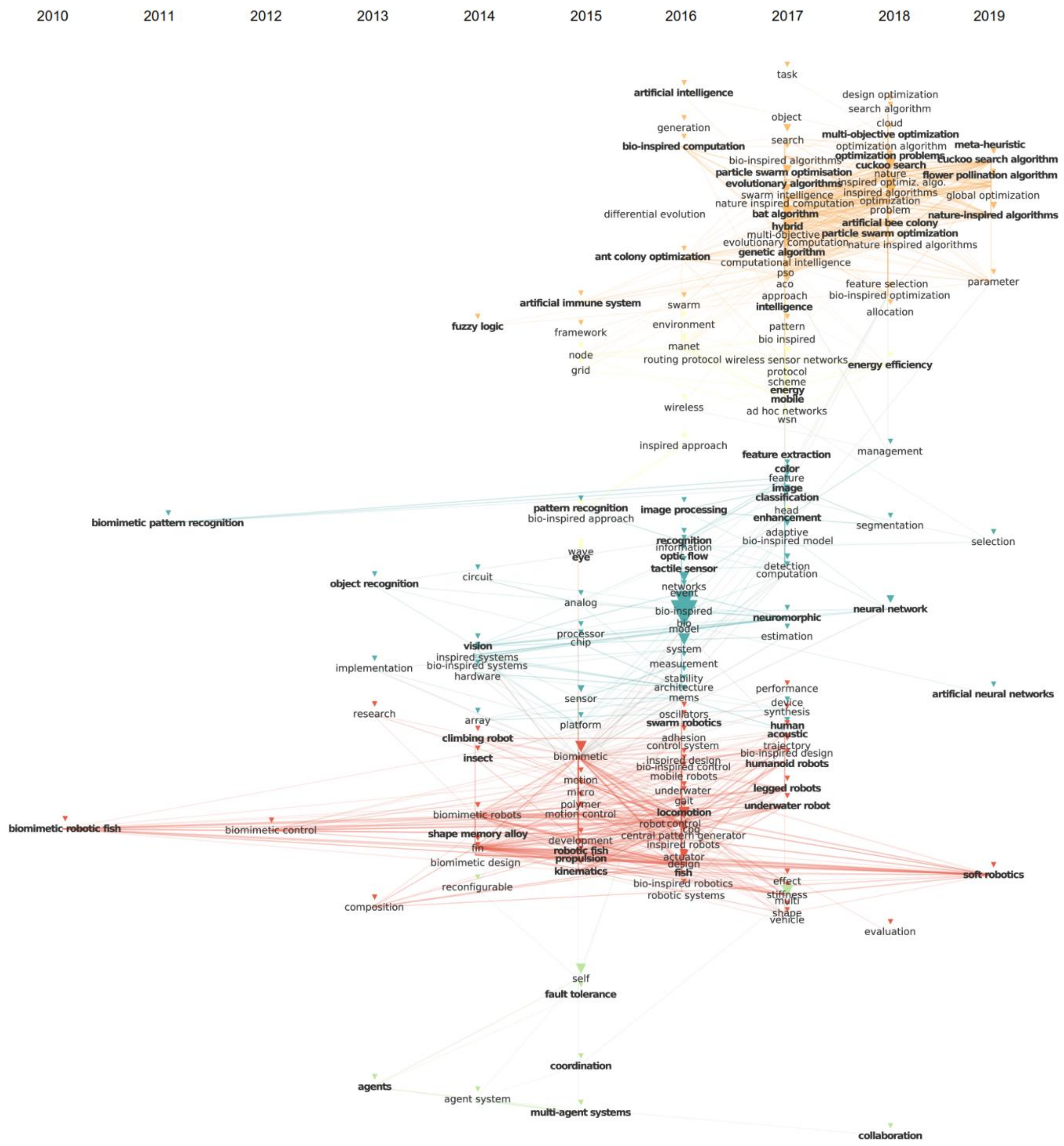

Figure 5. Time evolution of the occurrence of meaningful terms and their interconnections for the semantic cluster B/Computational science and robotics/

The earliest sub-cluster, the red one, is about robots and robotics. Robots is also a popular keyword in semantic cluster A /Engineering and materials sciences/. In the semantic cluster /Computational Sciences and Robotics/, the focus is on robot science, robotics and associated applications. This sub-cluster thus concerns the mobility of robots and the design of actuators to activate the elements making up the robots. The sources of inspiration and the targeted functions are numerous: human, fish, insects, climbing robots. etc. Animal mimicry appears first, providing inspiration for a wide variety of propulsion-movement types and actuators. Human inspiration does not become significant until 2017, which might indicate that this is a late self-classification of roboticists in this field. It is probably related to the opportunity to develop humanoid robots that we already see commercialized or developed in relation with cognitive science.

After a sudden decrease in 2017 and 2018 in the number of new terms, the soft-robotics topic appears in 2019. This keyword encompasses both science (soft-robotics) and applications (soft-robots). It is an interesting concept: initially in the field of nature-inspiration and biomimetism, one started to copy devices, structures and functions. Soft robotics goes a step further by getting inspiration in the way living organisms move and adapt to their surroundings.

The second turquoise sub-cluster focuses on the perception issue, which is deployed on the five senses: vision, tactile perception, hearing and visual recognition. There are strong and natural links with the red sub-clusters as robots need to be equipped with sensors to interact with their surroundings. Again, the approach is refined over the years. For example, the initial study of functions ('object recognition' and 'shape recognition') evolves towards more anthropomorphic concepts like 'sight sensor' and 'contact sensor' and then a deepening of the way signals are exploited ('neural network'. 'classification').

The smallest yellow sub-cluster is about energy and energy network and seems ephemeral over the year 2015-2018. In science in general, energy and energy network is an important semantic, but it does not make a lasting mark in the field of nature-inspiration and biomimetics that we analyse.

In a very interesting way, we can observe that the positioning in the red and turquoise sub-clusters has evolved from the concept of biomimicking to that of bio-inspiration.

The orange sub-cluster is about computation, algorithms and optimization. Although the field of computational science has been studied for decades around the world. it has emerged quite recently into the field of nature-inspired engineering (since 2014). It is very dense and active, with a strong focus on optimization. On one hand, its recent occurrence in the field of nature-inspiration and biomimetic could be seen as an opportunistic assignation of existing research activity. Indeed, many stochastic algorithms have been inspired by nature since their creation several decades ago and have kept the name: genetic algorithm, cuckoo search, 'tree-forest' algorithm, 'flower pollination' algorithm, 'bee colony' algorithm, 'bat' algorithm... However, the emergence of approaches inspired from collective behavioural (swarm intelligence. artificial bee colony. …) is a new trend that also exists in other fields and that may represent a significant evolution.

The green sub-cluster is about multi-agent systems. It is marginal and fully independent from the other but for some links with other sub-clusters through concepts like stiffness, reconfigurable and fault-tolerance, related to conferring some kind of resilience to artificial devices. Two interesting keywords are also displayed in this sub-cluster, namely coordination in 2015 and collaboration in 2018. These are important characteristics of human and non-human societies but they seem to be not fully exploited yet in the field of nature-inspiration and biomimetics although there exist recent documents aiming at analysing the collective behaviour of a group of robot-like devices.

4.2.3 Semantic cluster C/Sciences and technologies for health and biology/

Figure 6 displays the time evolution of semantic cluster C that spans topics related to sciences and technologies for health and biology. Semantic cluster C displays a set of five distinct sub-clusters that develop nearly independently from each other, unlike what is observed in other semantic clusters, like ‘D’ (Applied physics). Three of them are almost homogenous, while the two remaining are rather an application field semantic cluster, focusing on medical repairing and engineering. Albeit that the corpus study starts in 2005, the first terms deemed significant by the Cortext tool analysis appear in 2011.

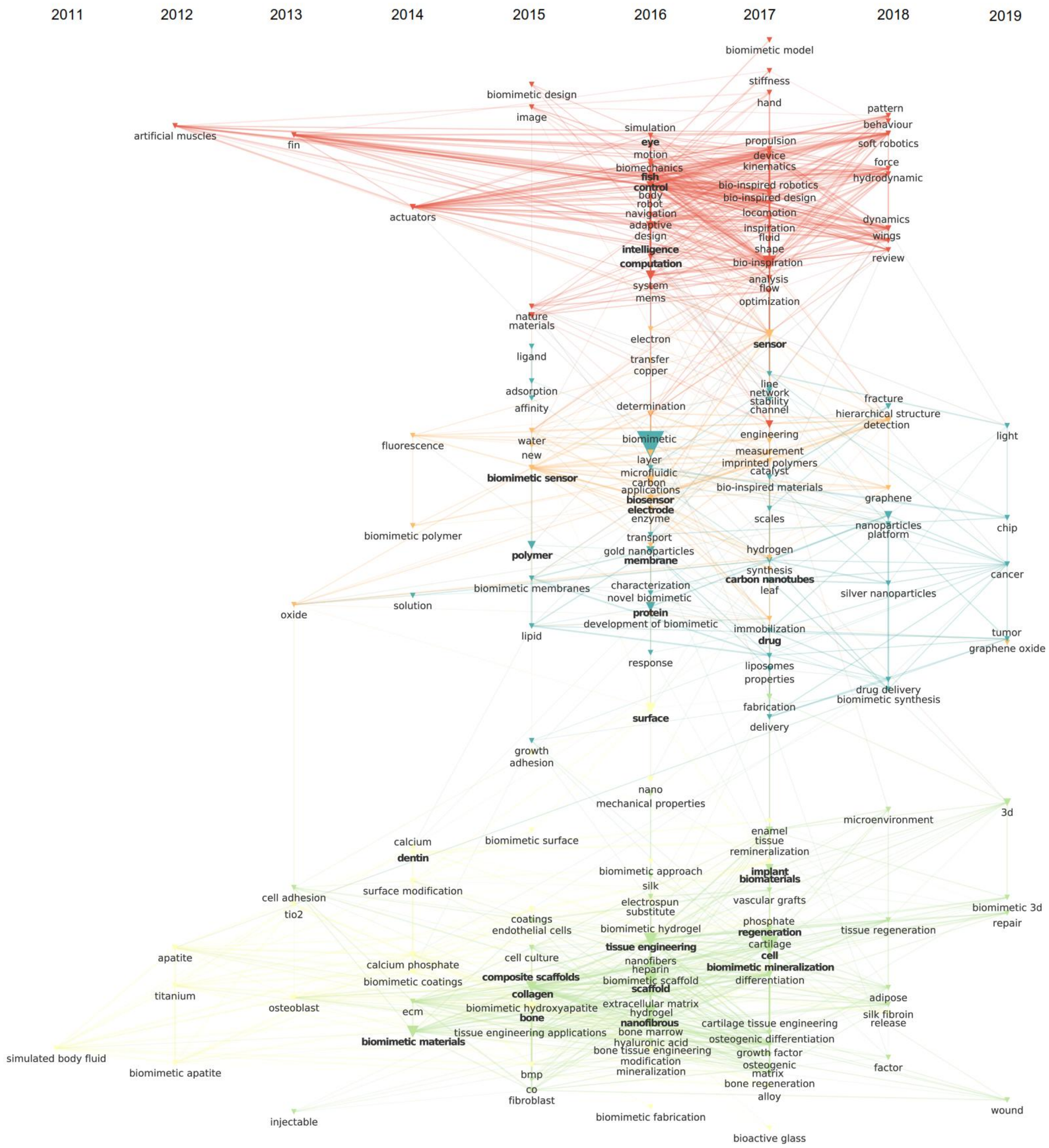

Figure 6. Time evolution of the occurrence of meaningful terms and their interconnections for the semantic cluster C/Science and technologies for health and biology/

The first sub-cluster in red colour gathers terms belonging to the locomotion and movements under robotic control. Starting from the ‘artificial muscles’ term in 2012, the global evolution of this sub-cluster gradually expands over the years towards a strong interconnected set of terms, illustrated by thick lines connecting ‘fish control’, or ‘bio inspiration’ terms for instances. The occurrence of papers using terms related to locomotion and robotic control seems at its maximum in a time spam of 3-4 years around 2015-2018; in a similar way to what is observed in the semantic cluster B/Computational science and robotics/ in the sub-cluster about robots and robotics. Recalling that only significant new terms are displayed, this means that the red sub-cluster topics are still active but with no new emergence.

A vertical connection with the second orange sub-cluster, which is more related to biological inspiration sensors, can be observed thanks to the terms ‘nature materials’ or ‘sensor’. This connexion with the locomotion subssemantic cluster via the ‘sensor’ keyword is indeed an obvious link since robotic movements needs sensors to be reliable. This biologic inspiration sensors sub-cluster starts from terms like ‘oxide’ or ‘biomimetic polymer’ to evolve toward ‘cancer’ or ‘tumor’, ‘chip’ in the recent year, meaning a gain in maturity to embrace applications, that once again concern the medical field.

The third blue sub-cluster is strongly linked to the orange one, with terms related to small artefacts like ‘membrane’, ‘nanotubes’ in connection to biology. Then it evolves gradually towards ‘cancer’, ‘tumor’ and ‘chips’, which we interpret as a maturation shift towards global health issues.

The last two yellow and green sub-clusters run independently of the first three, and gathered keywords more related to the nature of materials and their applications in health and biology. Keywords revealing the properties of materials as a single material seem dominate, for instance with ‘dentin’ in 2014. It moves to dynamic system in recent years, with terms ‘microenvironment’, ‘3D’ emerging in 2019.

The yellow sub-cluster is not so dense, unlike the green one and there are both intertwined. Tissue engineering, medical repairing, which is the core of the green sub-cluster, are logical application fields of the yellow sub-cluster. Some terms emerged like ‘collagen’, ‘bone’, ‘scaffold’ or ‘cell’ over a limited period of about 4 years, from 2013 to 2016, then the green sub-cluster density decreases. In 2019, only ‘wound’ and biomimetic 3d repair’ terms does exist in the field of bioinspiration. This evolution hints at limited innovation but it also show a maturation from simple building material (dentin, collagen for instance) towards approaches with a biological functionality (bone regeneration, biomimetic 3D repair for instance). These concepts are recent, and cover many semantics, whch may explain the limited number of emerging terms.

4.2.4 Semantic cluster D/Applied physics /

Figure 7 displays the time evolution of semantic cluster D that gathers terms related to applied physics, nanoscience and nanotechnologies. It is the semantic cluster with the largest number of documents and is still growing but the time evolution of terms shows that the number of emerging terms is gradually dwindling over the years, hinting that innovation in the field of bioinspiration is declining. Indeed, as the time span of the whole bibliography corpus ranges from 2005 to 2019, emerging terms appear only in 2009 and nearly end after 2017. In 2019, on the term ‘3D-printing’ is displayed.

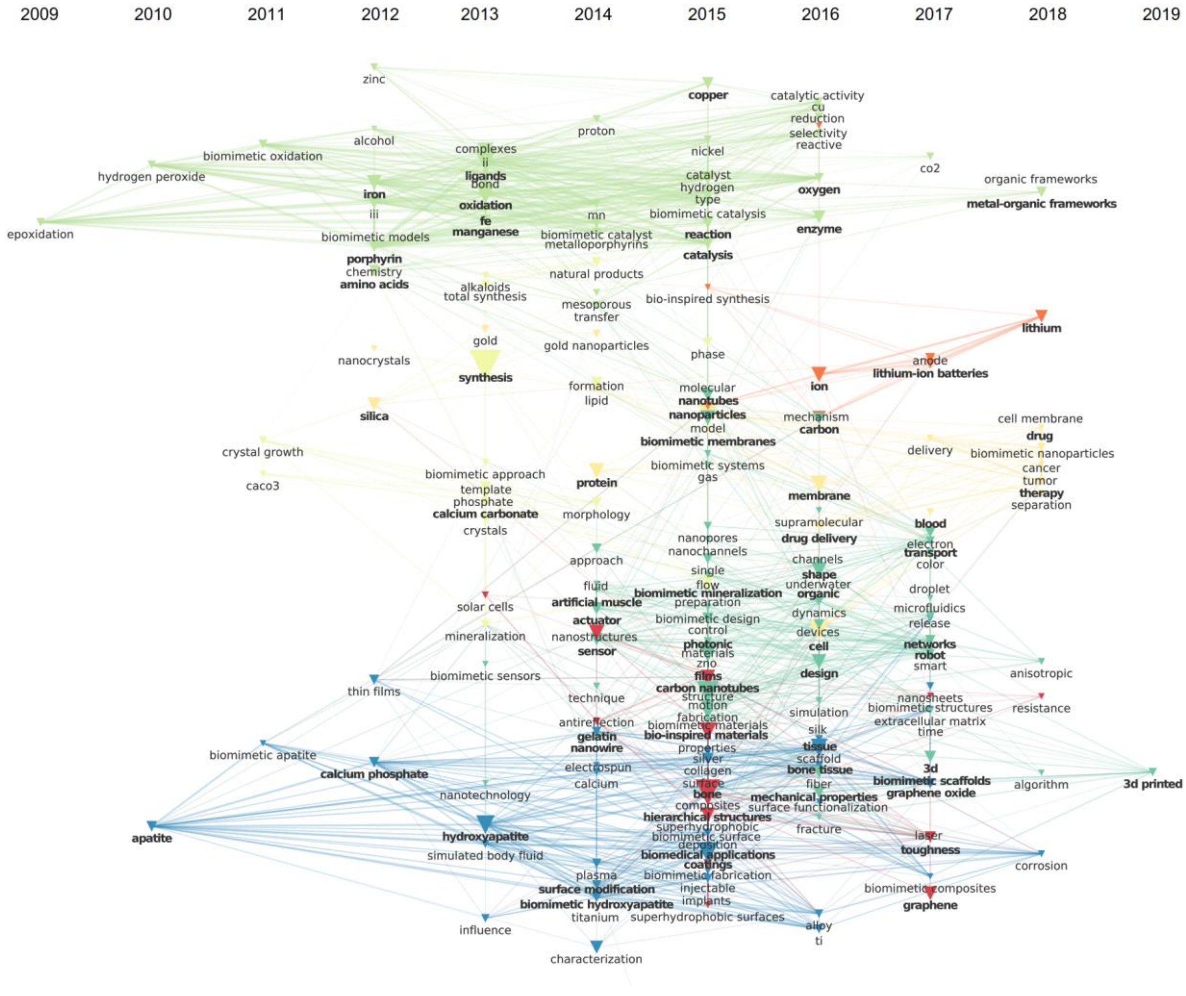

Figure 7. Time evolution of the occurrence of meaningful terms and their interconnections for the semantic cluster D/Applied physics/

The semantic cluster is composed of two nearly independent entities connected to each other through the terms about nanotubes, nanoparticles and biomimetic membranes, although one does not perceive the meaning of this link. The first entity is composed of only one homogeneous sub-cluster while the second one encompasses four sub-clusters strongly interconnected.

The first entity that corresponds to the light green sub-cluster is clearly related to catalysis and catalyst since terms describing chemical reaction (epoxidation, oxidation) are combined with chemical reactants (alcohol, amino acids, hydrogen peroxide) and metal or catalysts (Fe, Manganese, zinc, porphyryn, nickel, copper). The light green sub-cluster is rather homogeneous and only a slight shift can be identified from terms related to a single reaction or compounds (epoxidation, pophyrin) to more complex and global concepts such as biomimetic catalysis, catalytic activity. Some terms, like 'manganese' or 'oxidation' are also shared with the red sub-cluster of semantic cluster F/Environmental sciences and technologies/ where they will be discussed. After 2016, the sub-cluster is declining with no new term but the "metal-organic framework" one that appears in 2018.

The second entity is composed of four entangled sub-clusters. The oldest one (blue semantic cluster) starts in 2009 and is about biomedical application and more specifically bone regeneration or implants, as indicated by the frequent related terms (apatite, hydroxyapatite, implants). The blue sub-cluster is also related to elaboration, fabrication as a transverse research question as indicated by keywords such as nanotechnology, biomimetic fabrication or 3d printed, that later being also a term present in the dark green sub-cluster. The blue and dark green sub-cluster link terms related to general topics (bio-inspired materials, tissue, bone tissue, biomimetic scaffold), with a focus in the blue one on elaboration and characterization of structure, and in the dark green one on more complex systems or strategy. One also note that the blue one appears first and the dark green is second, in agreement with the general trend observed in bioinspiration to move from structure description/fabrication to mechanism investigation.

The three remaining red, yellow and orange sub-clusters are interconnected with the blue and dark green. Their terms are related to specific topics, namely photonic/optical (red), drug delivery/biomedical devices (yellow) and battery/energy (orange).

In conclusion, semantic cluster D does not display a very strong identity and is in fact highly heterogeneous suggesting that bioinspiration is not really a key issue in the corresponding WoS categories but more likely a side effect.

4.2.5 Semantic cluster E/Chemistry/

Figure 8 displays the time evolution of semantic cluster E that is about chemistry in general. 55% of the documents refer to organic chemistry, polymer science and pharmacology.

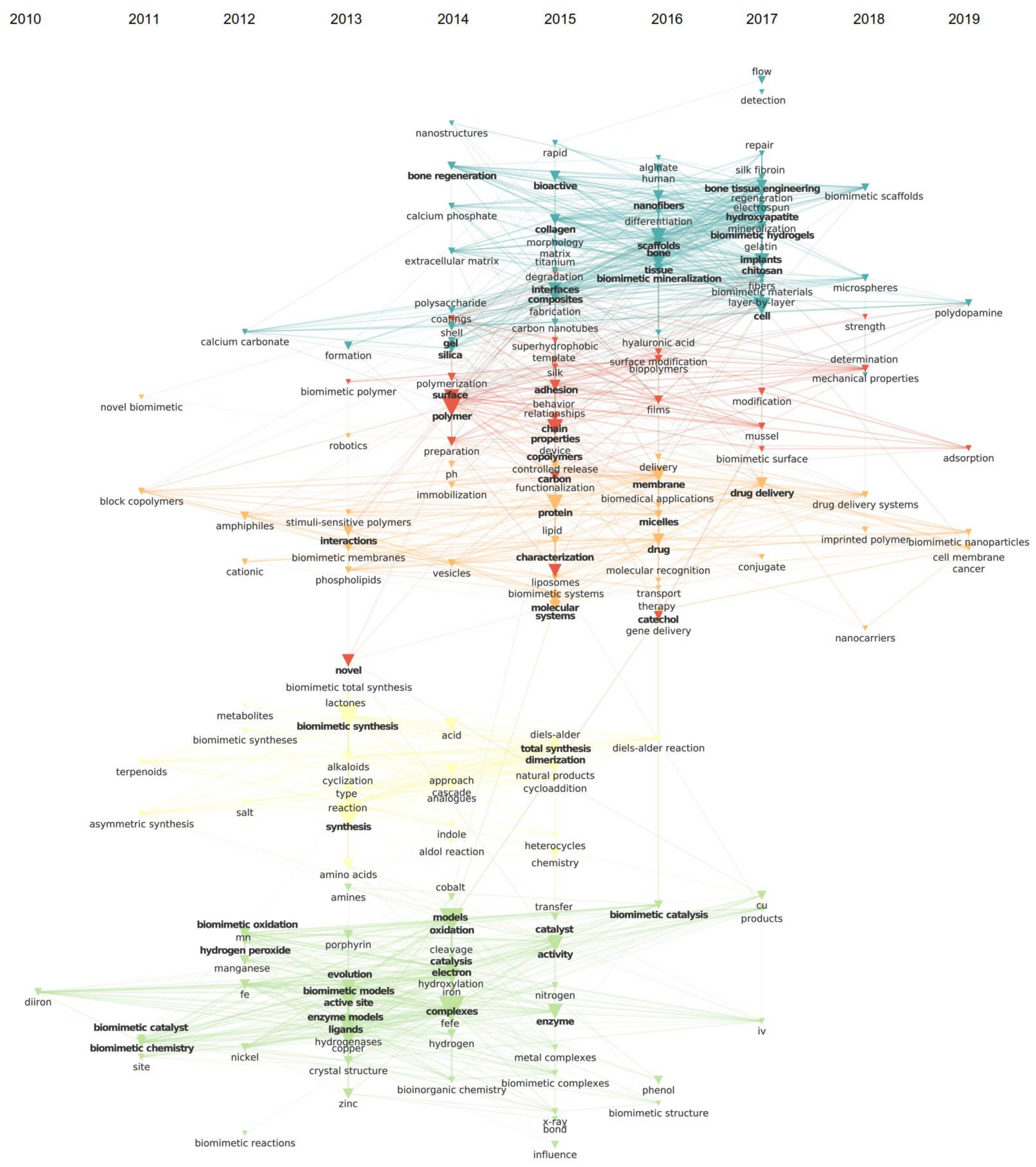

Figure 8. Time evolution of the occurrence of meaningful terms and their interconnections for the semantic cluster E/Chemistry/

The earliest significant terms emerged in 2010 for the semantic cluster E. Five sub-clusters are highlighted by this data treatment and define clearly two entities.

One entity of three sub-clusters (blue, red and orange) gathers terms related to health applications. Starting in 2012, the first blue sub-cluster focuses on regenerative medicine. A hot spot is identified by the link between terms "bone and tissue, regeneration and engineering" and polymers or analogs as "collagen, hydrogels, chitosan". This blue sub-cluster exhibits a strong diversification of terms and links in 2017 and later a new focus on 'biomimetics scaffolds' and 'microspheres', which are terms shared with three of the main semantic clusters, semantic cluster A/Materials sciences and engineering/, semantic cluster D/Applied physics/ and at a later date semantic cluster C/Sciences and technologies for health and biology/. The blue sub-cluster is connected to another red sub-cluster, describing physical phenomena involving polymers as adhesion, films, chain properties; and via the term "membranes", to a third orange sub-cluster, that focuses on drug delivery and therapy.

Starting in 2010, the second entity associates a yellow sub-cluster on organic synthesis with a green sub-cluster on chemical catalyst and biocatalyst. Biomimetic chemistry and catalyst were first investigated and modeling approach started to explore more and more complex phenomena. The evolution of this entity reveals a maximum activity from 2013-2015 with a sudden stop whose cause is unclear.

As a whole, the semantic cluster E/Chemistry/ is significantly about chemistry related to biology and health issues.

4.2.6 Semantic cluster F/Environmental sciences and technologies/

Figure 9 displays the time evolution of semantic cluster F. It has the smallest number of documents and covers various topics related to environmental sciences and technologies.

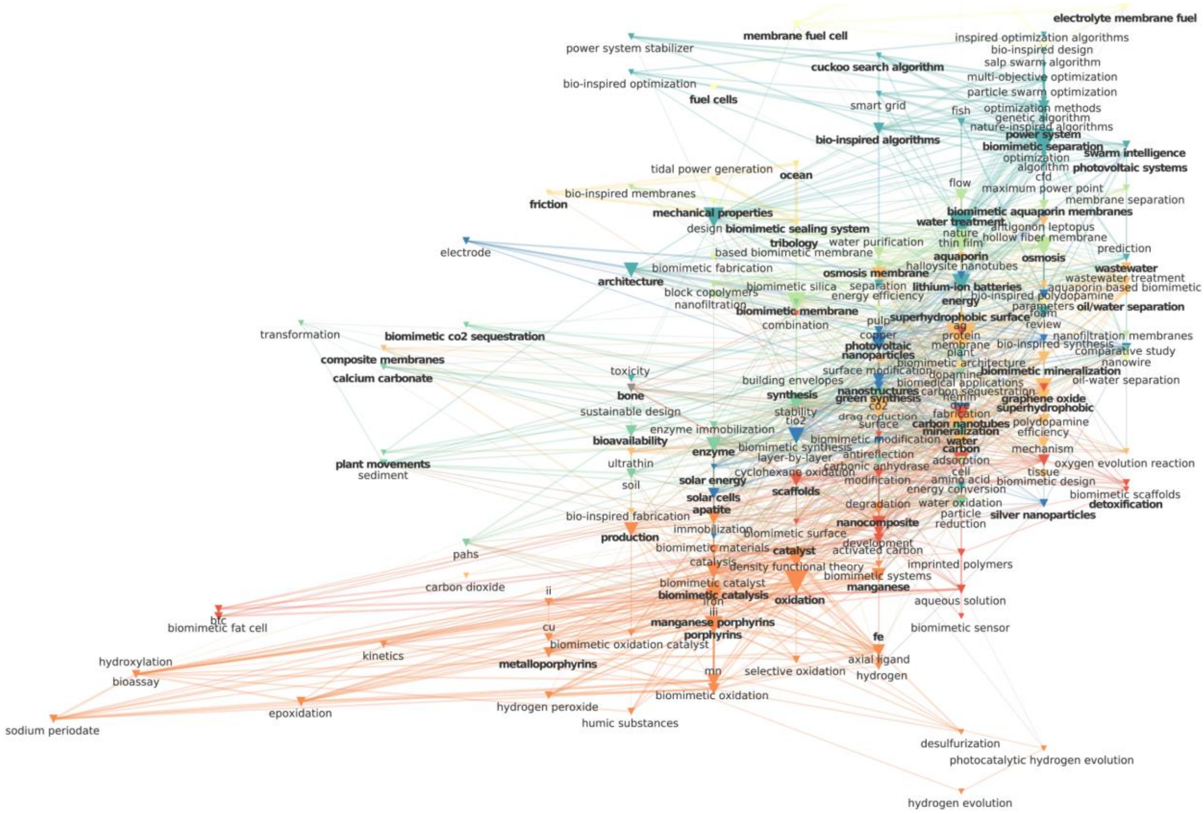

Figure 9. Time evolution of the occurrence of meaningful terms and their interconnections for the semantic cluster F/Environmental sciences and technologies/

Semantic cluster F is what we could call an emerging science. Indeed, the associated WOS categories, namely green, sustainable science & technology and environmental engineering were created in 1994 and 1967 respectively. A similar comment hold for the scientific journals assigned to these categories. The display of the semantic cluster F is also atypical compared to the five other main semantic clusters. In semantic cluster F, one can identify seven sub-clusters but they are highly intermingled, exhibiting a very dense network of interrelations, that swarm as years pass. A first comment is that science behind semantic cluster F is not stabilized and is growing rapidly. A second comment is that the subtopics are strongly interdisciplinary since no specific disciplines are evidenced.

As before, semantic cluster F shares several terms with other main semantic clusters, in particular those related to algorithms and optimization (also in semantic cluster B/Computational science and robotics/) and those related to catalysts are common also to semantic cluster D/Applied physics/ and to semantic cluster E/Chemistry/. In semantic cluster D the metal-based catalyst are explicited; in semantic cluster E, the chemical molecules, the active sites of catalysts are discussed, whereas in semantic cluster F, the application, like selective oxidation, is pointed out.

Compared to the other five main semantic clusters, semantic cluster F has also a specific set of terms, typically those related on nanoscale objects, environment-related topics and green processes.

Nanoscale related terms are indeed a strong cement in the semantic cluster F dense network: they appear as ‘nanocomposite of catalysts’, ‘nanostructures’ and ‘nanoparticles’ for developing solar cells, ‘superhydrophobic nanostructures’, ‘nanoscale aquaporin’ and ‘carbon nanotube membranes’ for water treatment.

Environment-related topics are typically water treatment, solar energy, ocean and fuel cells. Solar energy builds on electrodes, battery and the use of metallic nanoparticles. Water treatment concerns membrane processes inspired from aquaporins, using osmosis process and superhydrophobic surfaces. Ocean related topic interest like tidal power generation was ephemeral and lasted over the years 2012 – 2015. Fuel cells topic is self-standing since 2014. Since fuel cell science is far more anterior to 2014, this can be interpreted as an opportunist display within the field of nature-inspiration and biomimetics. In semantic cluster F, terms are related to energy production devices but not to energy networks, that emerged in semantic cluster B/Computational sciences and robotics/.

Green processes topics are for example green synthesis and share the enzyme keyword with the main semantic cluster C/Sciences and technologies for health and biology/ but none with semantic cluster E/Chemistry/ where there is yet a sub-cluster about biomimetic synthesis, excluding enzymes.

4.3 Matrix of junction of the six semantic clusters

Figure 10 below displays the network and interactions between the six semantic clusters. The size of each semantic cluster is proportional to the number of documents and their closeness depicts how close documents from different semantic clusters are with respect to the analysis of their terms. One can also notice that some WoS categories bridge several semantic clusters:

- Semantic clusters A/Materials sciences and engineering/ and B/ Computer sciences and robotics/ are connected through the [engineering. mechanical] WoS category and are close to each other.
- Semantic clusters C/Sciences and technologies for health and biology/, D/Applied physics/, F/Environmental sciences and technologies/ are also close to each other.
- Semantic clusters A/Materials sciences and engineering/ and C/Sciences and technologies for health and biology/ are connected through the [materials science. composites] and [materials science. biomaterials] WoS categories.
- Semantic clusters D/Applied physics/ and C/Sciences and technologies for health and biology/ are connected through the [nantechnology], [chemistry.analytical] and [biochemical research methods] WoS categories.
- The semantic cluster E/Chemistry/ is connected to semantic clusters D/Applied physics/ and C/Sciences and technologies for health and biology/ through [biochemistry & molecular biology] [pharmacology pharmacy], [biochemical research methods], [biophysics] and [nanosciences. Nanotechnologies].
- The semantic cluster F/Environmental sciences and technologies/ is connected to C/Sciences and technologies for health and biology / through the [energy fuel] WoS category and to semantic cluster D/Applied physics/ through [engineering.chemical] and [environmental science].

Besides, figure 10 shows the ten most frequent terms of each semantic cluster, on the basis of their number (blue list) and on the basis of their relevancy in the semantic evaluated using a Chi2 test (black list).

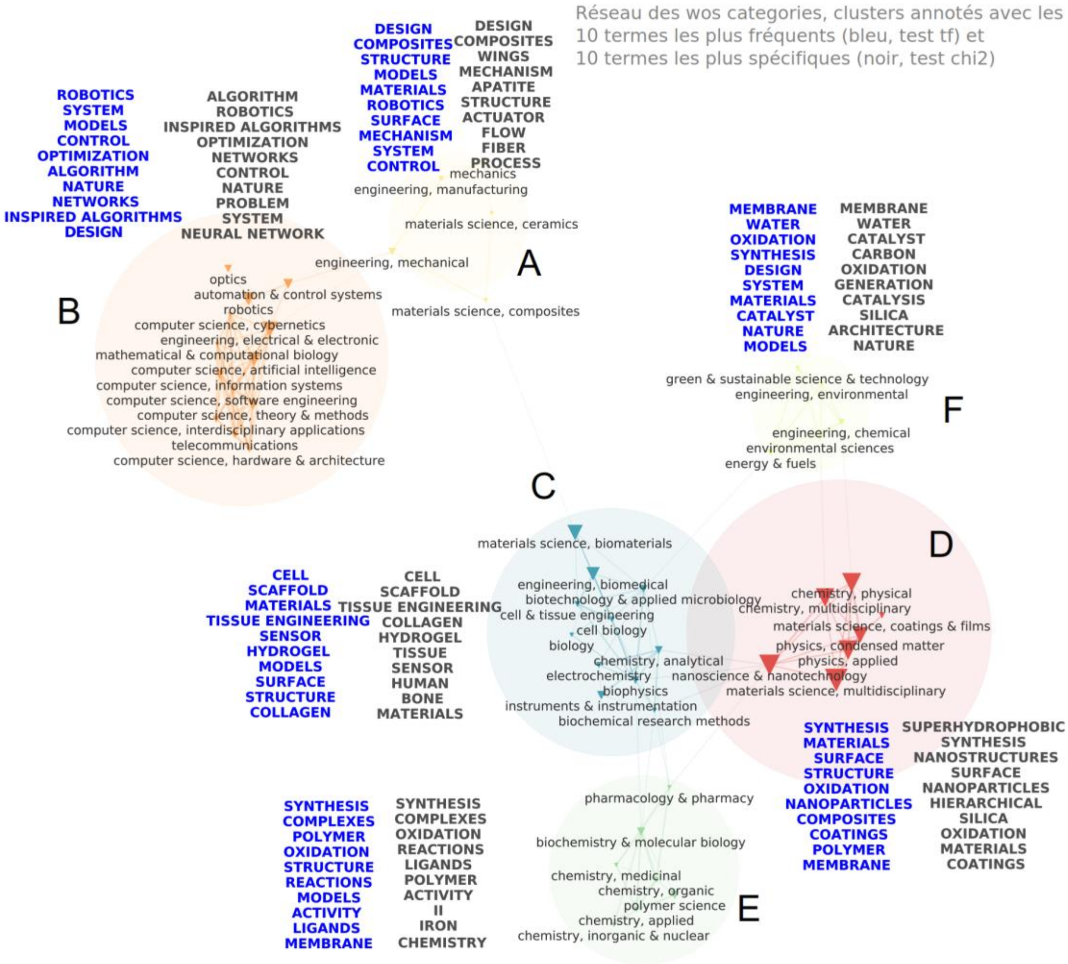

Figure 10. Network of the six semantic clusters with key WoS categories and key related terms

5 Academic collaborative networks and semantic clusters

The six semantic clusters aforementioned are further cross-referenced with ten academic collaboration networks identified from the first 200 academic institutions. These networks detailed in the supplementary materials (annex 7) are labelled by Cortext based on the first two contributing institutions. The nationalities of the 10 most active academic collaborative networks is given in Table 7.

The percentage of the document split among the 6 semantic clusters sum up to less than 100% because only document assignations statistically significant based on a “chi2” type are shown. The percentage of the top contributing countries sum up to more than 100% because co-authors sometimes belong to different countries.

Table 7. Top 10 international collaborative networks in the NIE Corpus.

Documents	Academic network name	Split of documents in the 6 semantic clusters *	Top 6 contributing countries in the academic network
4,284	Tianjin Univ & Chinese Acad Sci	cluster D (1,717 ; 40.1%)	Popular Republic of China (86.4%)
		cluster C (816 ; 19.1%)	USA (11.1%)
		cluster B (614 ; 14.3%)	Singapore (7.6%)
		cluster E (436 ; 10.2%)	Republic of China (3.5%)
		cluster A (269 ; 6.3%)	Australia (2.1%)
		cluster F (191 ; 4.5%)	Canada (2.1%)
1,835	Tech Univ Dresden & Aix Marseille Univ	cluster D (508 ; 27.7%)	Germany (28.9%)
		cluster C (440 ; 24.0%)	USA (19.6%)
		cluster B (331 ; 18.0%)	France (16.9%)
		cluster E (221 ; 12.0%)	Switzerland (16.7%)
		cluster A (91 ; 5.0%)	Netherlands (7.2%)
		cluster F (65 ; 3.5%)	Iran (7.1%)
1,382	Harvard Univ & MIT	cluster D (376 ; 27.2%)	USA (85.2%)
		cluster C (367 ; 26.6%)	India (10.2%)
		cluster B (217 ; 15.7%)	Popular Republic of China (7.0%)
		cluster E (132 ; 9.6%)	South Korea (5.9%)
		cluster A (91 ; 6.6%)	Singapore (2.8%)
		cluster F (31 ; 2.2%)	UK (2.5%
965	Penn State Univ & Univ Maryland	cluster D (282 ; 29.2%)	USA (87.9%)
		cluster C (257 ; 26.6%)	Popular Republic of China (9.8%)
		cluster B (158 ; 16.4%)	Egypt (6.9%)
		cluster E (88 ; 9.1%)	Japan (3.9%)
		cluster A (78 ; 8.1%)	Germany (1.6%)
		cluster F (32 ; 3.3%)	Romania (1.5%)
874	Univ Bologna & CNR	cluster C (232 ; 26.5%)	Italy (50.9%)
		cluster B (217 ; 24.8%)	Spain (26.1%)
		cluster D (173 ; 19.8%)	UK (24.3%)
		cluster E (110 ; 12.6%)	Belgium (8.1%)
		cluster A (44 ; 5.0%)	Sweden (6.3%)
		cluster F (27 ; 3.1%)	USA (5.4%)
663	Sungkyunkwan Univ & Pusan Natl Univ	cluster D (249 ; 37.6%)	South Korea (68.0%)
		cluster C (128 ; 19.3%)	USA (39.1%)
		cluster B (107 ; 16.1%)	Popular Republic of China (3.2%)
		cluster E (69 ; 10.4%)	Australia (1.8%)
		cluster A (46 ; 6.9%)	UK (1.5%)
		cluster F (17 ; 2.6%)	Japan (1.5)
579	Southwest Univ & Osaka Univ	cluster D (173 ; 29.9%)	Japan (63.7%)
		cluster B (125 ; 21.6%)	Popular Republic of China (26.9%)
		cluster C (114 ; 19.7%)	USA (10.7%)
		cluster E (78 ; 13.5%)	Australia (10.0%)
		cluster A (33 ; 5.7%)	UK (2.9%)
		cluster F (12 ; 2.1%)	Singapore (2.3%)
540	Univ Coll London & Inha Univ	cluster D (134 ; 24.8%)	UK (74.8%)
		cluster C (117 ; 21.7%)	USA (15.6%)
		cluster B (104 ; 19.3%)	Australia (10.6%)
		cluster E (75 ; 13.9%)	South Korea (9.6%)
		cluster A (37 ; 6.9%)	Popular Republic of China (7.8%)
		cluster F (9 ; 1.7%)	Germany (3.7%)
239	Univ Sao Paulo & Univ Porto	cluster C (64 ; 26.8%)	Portugal (61.9%)
		cluster D (61 ; 25.5%)	Brazil (46.0%)
		cluster E (56 ; 23.4%)	Spain (8.8%)
		cluster B (24 ; 10.0%)	USA (7.5%)
		cluster F (11 ; 4.6%)	UK (3.8%)
		cluster A (10 ; 4.2%)	India (2.9%)
80	Univ Waterloo & New York Univ	cluster D (18 ; 22.5%)	USA (58.8%)
		cluster B (15 ; 18.8%)	Canada (47.5%)
		cluster E (11 ; 13.8%)	Popular Republic of China (10.0%)
		cluster A (10 ; 12.5%)	Germany (7.5%)
		cluster C (9 ; 11.3%)	Italy (3.8%)
		cluster F (5 ; 6.3%)	France (3.8%)

* Semantic clusters: A/Materials sciences and engineering/ B/Computational sciences and robotics/ C/Sciences and technologies for health and biology D/Applied physics/ E/Chemistry/ F/Environmental sciences and technologies/

The academic collaborative networks are related to geographical areas (e.g. European countries, Asian countries), cultural relations (eg. Portugese language network). Nevertheless, one notices the presence of the USA and China in almost all the networks. This is an evidence of the scientific influence of both countries around the world.

The size of the academic collaborative networks is disparate, evaluated in terms of number of distinct documents. Besides, the top 10 networks displayed in Table 7 only amount for less than half the documents in the NIE corpus, showing that many other collaborations exist. Examination of the split of documents among semantic cluster, we find that 8/10 clusters exhibit a top connection with semantic cluster D/Applied physics/ and 2/10 with semantic cluter C/Sciences and technologies for health and biology/. This is not surprising since these are the first and third largest semantic clusters (see Table 6). For the same reason, the smallest semantic cluster F/Environmental sciences and technologies/ is last for all collaborative networks.

Other particularities are evidenced: Regarding the number of documents, the first network, labelled *'Tianjin Univ & Chinese Acad Sci'* is mainly composed of other Chinese institutions and specializes in applied physics. It is also implicated above average in the semantic cluster F/Environmental Sciences and Technologies/. The second network has a size one-third from the first one. It is a network mostly European, labelled *'Tech Univ Dresden & Aix Marseille Univ'*, much as the fifth network labelled *'Univ Bologna & CNR'*. Both show an above average implication in semantic cluster B/Computational Sciences and Robotics/. The third network in size labelled *'Harvard Univ & MIT'* and the fourth one labelled *'Penn State Univ & Univ Maryland'* are networks composed of for 8/10 by American institutions collaborating with a few Asian countries and some European countries. They are both focused on Engineering and Materials Science (semantic cluster A) and Science and Technology for Biology and Health (semantic cluster C). The sixth academic network labelled '*Sungkyunkwan Univ & Pusan Natl Univ'* is led by South Korean universities collaborating with Asian and Oceanian countries, USA and UK. The seventh network labelled '*Southwest Univ & Osaka Univ*', revolves around Japan and USA. The eighth network labelled '*Univ Coll London & Inha Univ'* is led by UK and South Korean universities. The ninth one labelled '*Univ Sao Paulo & Univ Porto*' is a network of institutions with Portuguese language countries. The tenth network labelled, '*Univ Waterloo & New York Univ'* revolves around Canadian and American institutions.

6 Discussion

With help of information provided by Clarivate's Web of Science® database further processed with Cortext® dynamic network and semantic analysis tool, results in section 3 to 5 bring out comprehension at both macroscale and mesoscale about the corpus of biomimetics, bioinspiration and nature inspiration engineering field and its dynamics. At the macroscale, knowledge about thematic clusters and country networks (section 3) provides valuable insight to orient scientific strategy at the country level, for example for orienting subsidies. At the mesoscale where science is performed, identification of collaborative networks of authors and institutions that run across countries adds detailed insight useful for direct contributors to the NIE field (section 4 and 5).

At the macroscale, information is processed from the published documents' metadata: significant terms in title, abstract and keywords; author affiliation and years. The evident information is that the NIE field is growing fast and faster every year, at a pace larger than the Web of Science's growth (section 3). Being a hot topic, it has also seen some opportunistic tagging by some research subdomains, as exemplified in the semantic cluster analysis (section 4) by the research on algorithms. This research emerged decades ago, often labelling at that time algorithms in reference to nature ('cuckoo search', 'tree-forest', 'flower pollination', 'bee colony', 'bat') but it only appears in the NIE field after 2015. Other research activities like those about robots have taken their autonomy over the years within the NIE field itself, starting from the development of sensors, followed by organs, then assembled in human or animal-like robots and ultimately emerging as robots adaptable to their environment as soft-robots (section 4.2.1 and 4.2.2).

Regarding the subjects investigated, the size of the WoS categories is unequal and the largest WoS category in the corpus is the one named [materials science, multidisciplinary]. Its growth rate is remarkable and similar to other WoS categories [nanoscience & nanotechnology], [physics applied], [engineering multidisciplinary] and [multidisciplinary sciences]. Inversely, other WoS categories are decreasing in number since 2016, namely [computer science, theory & methods] and [automation & control system]. The largest publishing countries in the corpus are the Popular Republic of China (23.1%) and USA (21.5%), followed much farther by European and Asian countries like Germany, UK and India. However, when one weights the document production by the number of researchers per 1000 active workers provided by OECD, the ranking is drastically altered, led by Republic of China (Taiwan), Japan and Canada. In terms of growth rate between the periods 2005-2011 and 2012-2019, Republic of China is an uncontested leader followed by Netherland, and a group of countries like France, Japan, Canada and South Korea.

A cross ranking of countries and WoS categories exhibits striking features about the leadership of countries in WoS categories. For example, USA contributes to WoS categories [engineering biomedical] [biomaterials] and [multidisciplinary sciences]. Chinese scientists are leaders in chemical and physical sciences, nanosciences and materials sciences (excluding medical application). India is a world leader in [computer science, theory & methods]. The world top three institutions are from PRC, led by the Chinese Academy of Science with 869 documents. MIT (USA) is at rank 4. The first two institutions outside PRC and USA are the Seoul Nat Univ. (Corée du Sud) and the CNRS (France) at rank 14 and 19 respectively.

At the mesoscale relevant for performing daily science, we bring to light the dynamics of six semantic clusters and subclusters within them, (section 4) and pinpoint leading academic collaborative networks and their activity in relation with the six semantic clusters (section 5). The semantic clusters exhibit different size and dynamics. Regarding their prevalence among documents in the NIE field, cluster D/Applied physics/ (30,7%) is leading, followed by cluster B/Computer sciences and robotics/ (24%), cluster C/Sciences and technologies for health and biology/ (21,7%), cluster E/Chemistry/ (13,2%), cluster A/Materials sciences and engineering / (6,3%), cluster F/Environmental sciences and technologies/ (4,1%). Their history is contrasting, since WoS categories related to physics, biology or chemistry (clusters D, C, E respectively) have been created decades earlier than the WoS categories that are concerned with environmental sciences and technologies (cluster F). The dynamics of each cluster is different: cluster F/environmental sciences and technologies/ is the most recent, but also the most active with a burst of new terms in the recent years and a growing density of interrelations. Inversely, older, and often bigger, clusters like cluster D/Applied physics/ and cluster C/Sciences and technologies for health and biology/ are still active but with less new terms and a more diffuse network density of relations.

All six semantic clusters are interlinked, in particular cluster A/Materials sciences and engineering/ and cluster B/computational sciences and robotics/ on one hand, and cluster C/sciences and technologies for health and biology/, cluster D/Applied physics/ and cluster E/Chemistry/ on the other hand. Links are evidenced by terms like robot or surface, occurring in several semantic clusters. This multiple assignation is meaningful as connections to other terms within each semantic cluster tell different stories. For example, the 'robot' term appears in the cluster A/Materials sciences and engineering/ in relation with design, fabrication and operation of robots built from active artificial organs, while in the cluster B/Computational sciences and robotics/ 'robot' is related to robotics with sensors about a robot's environment. Similarly, the 'surface' term refers to chemical structures and molecules in the cluster E/Chemistry/ but refers to a manufactured artefact in the cluster A/Materials sciences and engineering.

Our work also highlights ten academic networks that, once crossed with the six semantic clusters, show a strong specialisation, both scientific and geographic between the institutions,. Typically, Chinese collaborate preferably with Chinese, American with American, European with European, Portuguese language countries with themselves, etc. Chinese institutions are leaders in the Cluster D/Applied physics/ while the cluster B/Computational sciences and robotics/ is dominated by two European institutions networks, one Japanese network and one UK institutions networks. American networks are present in every network, and are dominant in cluster A/Materials sciences and engineering/ and cluster C/Sciences and technologies for health and biology/. European networks are marginal in clusters D/Applied physics/, A/Materials sciences and engineering/ and F/environmental sciences and technologies/ but are present in the other three semantic clusters. However, a deeper the geographical and thematic specializations of these academic networks would need further investigation, for example in terms of details about co-authored works and whether they are supported by international collaboration agreements, research funding policy and intellectual property rights.

Regarding trends in the NIE field, we first address the global vision, which is that since all cluster share a rather important number of terms with other clusters, we can postulate that NIE field can be considered as a scientific field by itself involving multidisciplinary approaches and connected to fields that are more traditional. Another trend is illustrated by the research activities on robots. Starting with a merely copy of natural objects (e.g. artificial organs), it proceeded with a mimicking of more complex natural structures and natural functions (e.g. assembly of devices with sensor, like robots). Recently, the emerging trend is to study strategies used in Nature in response to changes in the environment (e.g. soft-robotics, collaborative algorithms). In the same vein, engineering activity is inherent in many terms among several clusters but with different meaning, from classical engineering of manufactured artefacts of significant size for specific usages (vehicles) in cluster A/Materials science and engineering/ to engineering of more complex systems related to nanoscale objects, environment-related topics and green processes in cluster F/environmental sciences and technologies/. One can also observe that, although they are the two smallest clusters, they are both growing in size. They are also both displaying a network of term connections that is more intermingled than in the other four semantic clusters, where distinct sub-clusters are easier to perceive. The density of the A and F cluster semantic network shows that engineering blossoms at the crossing of multidisciplinary approaches with a large spectrum of applications. One notices a particular connection between nanoscale items and environmental sciences and technologies.

On the other hand, the other four semantic clusters, B C D and E, evidence that topics investigations, again with a shift from simple objects to complex systems, are heading towards technologies of higher maturity and specific applications, like constitutive substances (e.g. dentin, collagen) (cluster C), biology related and targets health applications or the catalysis and associated chemistry (cluster E). Within these specialties, the tendency is to move towards complexity as well, like systems integrating biological functionality (e.g. bone regeneration, biomimetic 3D repair) or advances and adaptive modes of locomotion exploring collaboration and coordination between multiple bioinspired artefacts (cluster B). Regarding semantic cluster D, we observed that it does not display a very strong identity and it is in fact highly heterogeneous, suggesting that bioinspiration is not really a key issue in the corresponding WoS categories but more likely a side effect.

Finally, we recognize some limits to our work. Firstly, our results provide mostly insight about the bottom-up approach from copying Nature to engineering. The opposite approach, a top-down one from engineering issue to solutions inspired from Nature that rely upon deciphering mechanisms at work in Nature, is likely present but remains hidden in our results. Only a deeper investigation of documents might reveal it, such as those listed in introduction (Coppens 2005, Bar-Cohen 2006, Vincent *et al* 2006, Fratzl, 2007, Bhushan 2009, Vincent 2009, Knippers and Speck 2012, Coppens 2019, Gerbaud *et al* 2020, Yu *et al* 2020). The cross analysis of them remains to be done.

Secondly, we remind that our survey has barely touch some aspects of nature and bio inspiration in science by addressing mostly descriptive issues. But, other issues are equally important for scientists, like normative issues about the philosophical and metaphysical aspects and emotional issues about the way one perceives nature-inspired achievements should be included as well to better grasp (Speck *et al* 2017, Bensaude-Vincent 2019, Dicks and Blok 2019, Biomimicry institute 2021)

7 Conclusion

The field encompassing biomimetics, bioinspiration and nature inspiration in engineering science is growing steadily, pushed by exogene factors like the search in Nature of potentially sustainable engineering solutions for a healthy planet. With help of information provided by Clarivate's Web Of Science database and further processed with Cortext dynamic network and semantic analysis tool, we provide insight at two scales on the corpus of nature inspired engineering field and its dynamics. At macroscale, the WoS Categories, countries and institutions have been ranked and ordered by thematic clusters and country networks. Such an insight provides an overview at a macro scale that can be valuable to orient scientific strategy at the country level and evaluating parties involved. At mesoscale where science is incarnated by collaborative networks of authors and institutions that run across countries, we have been able to identify six semantic clusters and subclusters within them, and their dynamics (section 4) and pinpointed leading academic collaborative networks and their activity in relation with the six semantic clusters (section 5).

At first, China and USA are seen as undisputed leaders but the picture is more subtle since they do not cover all topics and in parallel other countries animate academic networks that are specialized in specific themes. Notice that US institutions are present in all ten top academic network. Thematic clusters are lightened by the analysis of six semantic clusters. Dynamics show that traditional domains of importance by the number of documents assigned, such as applied physics and sciences and technologies for health and biology are still active but with less new terms and a more diffuse network density of relations than a younger semantic cluster about environmental sciences and technologies. This cluster is the most active with a burst of new terms in the recent years and a growing density of interrelations.

Further information is extracted such as trends and prospective. Typically, one observed that the field is becoming mature since, starting by merely copying Nature, it proceeded with mimicking more complex natural structures and functions and now it investigates strategies used in Nature in response to changes in the environment and implements them in innovative artefacts. Similarly, the sophistication of devices, methods and tools has been increasing over the years as well as their functionalities and adaptability whereas the size of devices has decreased at the same time.

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