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PERSPECTIVE

Do civil engineering fronts emerge from interdisciplinary research?

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ABSTRACT Interdisciplinary research is considered a source of innovativeness and creativity, serving as a key mechanism for creating recombination necessary for the evolution of science systems. The aim of this study is to quantitatively establish the connection between interdisciplinary research and the research fronts that have recently emerged in civil engineering. The degree of interdisciplinarity of the research fronts was measured by developing metrics from bibliographic analyses. As indicated by the consistent increase in the metrics of interdisciplinarity over time, research fronts tend to emerge in studies with increasing diversity in the disciplines involved. The active disciplines involved in the fronts vary over time. The most active disciplines are no longer fundamental but those associated with energy, environment, and sustainable development, focusing on solutions to climate change and integrating intelligence technologies.

KEYWORDS interdisciplinary research, research front, bibliographic analysis

1 Introduction

Interdisciplinary approaches integrate separate disciplinary data, methods, tools, concepts, and theories to create a holistic view or common understanding of complex issues, questions, and problems [1]. We tend to consider interdisciplinary research as a source of innovation and creativity, serving as a critical mechanism for creating recombinations necessary for the evolution of science systems. Hence, interdisciplinary research has gradually held the center stage in many fields, including civil engineering [2–8]. The question that naturally arises is the extent to which interdisciplinary research plays a role in forming research fronts.

The Chinese Academy of Engineering (CAE) launched a project called “Global Engineering Fronts” in 2017. The project aims to assemble experts in engineering science and technology to identify engineering fronts each year by reviewing global papers, patents, and other data. In particular, this project identified 50 research fronts between 2017 and 2021 in civil, hydraulic, and architectural engineering. The data set collected in this project made it possible to quantify the role of interdisciplinary research in spawning research in civil engineering. This study aims to reveal this possible connection using a quantitative approach through bibliographic analysis.

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2 Data and methodology

2.1 Data and data structure

The “Global Engineering Fronts” has released five annual reports on global engineering fronts since 2017. Here, an engineering front refers to the main direction that is forward-looking, leading, and exploratory. It significantly influences and plays a leading role in the future development of engineering science and technology, and it serves as an essential guide for cultivating innovation capabilities in engineering science and technology [9]. Engineering fronts are divided into research and development fronts, which refer to theoretical research and application development, respectively.

Each year, engineering research fronts were obtained from a six-month search and screening. Domain, library, and information experts clarified the scope of data mining by underpinning the literature data consisting of Science Citation Index (SCI) journals and conference proceedings from the Web of Science (WoS) core collection of Clarivate Analytics. Next, the cocitation clustering method was used to cluster the literature topics that served as the basis for the expert review. Expert panel discussion and questionnaire surveys were organized to filter and revise the data mining results and, finally, generate a list of engineering research fronts in a specific field. For each front, a group of relevant papers was acquired from the WoS based on a set of carefully selected keywords. The papers were filtered to form a set of core papers published within five years before the nominating year and ranked in the top 10% of citation frequency among papers from the same year and discipline. As a significant outcome of the research fronts, the core papers provided a solid data set, of which the degree of interdisciplinarity could be assessed from a bibliographic perspective. Table 1 lists the 50 research fronts reported in the CAE project between 2017 and 2021 in civil, hydraulic, and architectural engineering. Along with the fronts, 4279 core papers were sorted. Figure 1 depicts the relationships among the research fronts, core papers, and papers cited by the core papers.

Table 1 Summary of 50 research fronts from 2017 to 2021 identified in CAE project

No.	research front	year	core paper	citation
1	High-performance civil, hydraulic, and building engineering structures	2017	377	42050
2	Ultrahigh-performance and multifunctional cement-based composite materials	2017	36	6196
3	Methods for analysis and simulation of complex structures	2017	135	14540
4	Built environment and occupant behavior	2017	34	3558
5	Removal of heavy metals and other high-risk pollutants	2017	29	3895
6	Reliability of civil engineering structures	2017	42	4685
7	Material biological remodeling	2017	34	3281
8	Mixed-pixel decomposition and spatiotemporal location big-data analysis	2017	95	12900
9	Structural defect analysis	2017	30	1103
10	Numerical simulation of fluid–structure interaction	2017	89	7900
11	Lifecycle reliability of civil engineering structures and systems	2018	215	12709
12	Ultrahigh-performance and smart cement-based composite materials	2018	64	8786
13	Highway pavement renewable materials and pavement material rejuvenation	2018	27	1643
14	Green vernacular architecture	2018	314	26136
15	Artificial-intelligence-based architectural design methodology	2018	107	11303
16	Intelligent control systems for building environment	2018	31	3809
17	Migration and transformation mechanisms of microplastics in wastewater treatment	2018	7	3513
18	Fusion and processing of multilevel space-air-ground remote-sensing data	2018	141	24019
19	Dynamic fusion of geographical spatiotemporal big data for smart cities	2018	52	7267
20	Lifecycle safety of water-related engineering	2018	49	2495
21	Mechanism and control of long-term performance evolution of structures	2019	72	4614
22	Green building design method based on whole life cycle	2019	33	2965
23	Nanomodification and fiber-reinforcement of cement-based materials	2019	75	5635
24	Urban design and planning for reducing urban heat island effect	2019	154	17538
25	Large-span bridge operational smart monitoring and inspection	2019	102	5070
26	Lifecycle deformation prediction and control for urban and undersea tunnels	2019	113	6736
27	Seismic analysis and safety evaluation of high dams under extreme earthquakes	2019	32	244
28	Spatial-temporal fusion of multisource satellite remote-sensing images based on deep learning	2019	40	6157
29	Refined prediction and rapid damage assessment of river basin floods	2019	36	3709

(*Continued*)

No.	research front	year	core paper	citation
30	Traffic-flow-modeling theory and methods for intelligent and connected vehicle (ICV) and humandriven vehicle (HDV) mixed traffic	2019	186	12498
31	Smart city and smart basin integrated sensing based on geo-spatiotemporal big data	2020	36	1857
32	Coupling response mechanisms of offshore engineering structures and seabed foundation systems under the actions of wind, waves, currents, and earthquakes	2020	40	2110
33	Urban spatial analysis and optimization methods based on big data	2020	58	4891
34	Ventilation theory for adaptive thermal comfort and indoor air quality	2020	544	29917
35	Multiscale prediction of dynamic hazard evolution for underground engineering	2020	93	4409
36	Nanoengineered concrete materials in civil engineering	2020	74	7700
37	Urban planning and design to reduce urban heat island effect	2020	188	15366
38	Performance evolution and durability design principles for materials and structures on highways and for track engineering	2020	56	3010
39	Formation mechanisms and changing trends of extreme hydrologic events	2020	238	16753
40	Catastrophic effects of deep energy exploitation and regulation of its mechanical behavior	2020	105	6509
41	Ecoenvironmental effects of interbasin water transfer	2021	26	1213
42	Resilience improvement of transportation infrastructure	2021	29	937
43	Low-carbon long-life cement-based materials	2021	84	12655
44	Development path of green building under background of carbon neutrality	2021	135	7601
45	Water pollution control and remediation in drinking-water source areas	2021	46	2271
46	Perception methods of spatiotemporal big data toward smart sustainable cities	2021	22	1472
47	Earthquake-resilient structural systems	2021	24	2034
48	Flow-induced vibration of flexible structures and antivibration measures	2021	22	801
49	Geographic big-data knowledge graph construction	2021	15	628
50	Disaster monitoring and mechanism analysis of bridge structure dynamic multiload coupled action	2021	71	2309

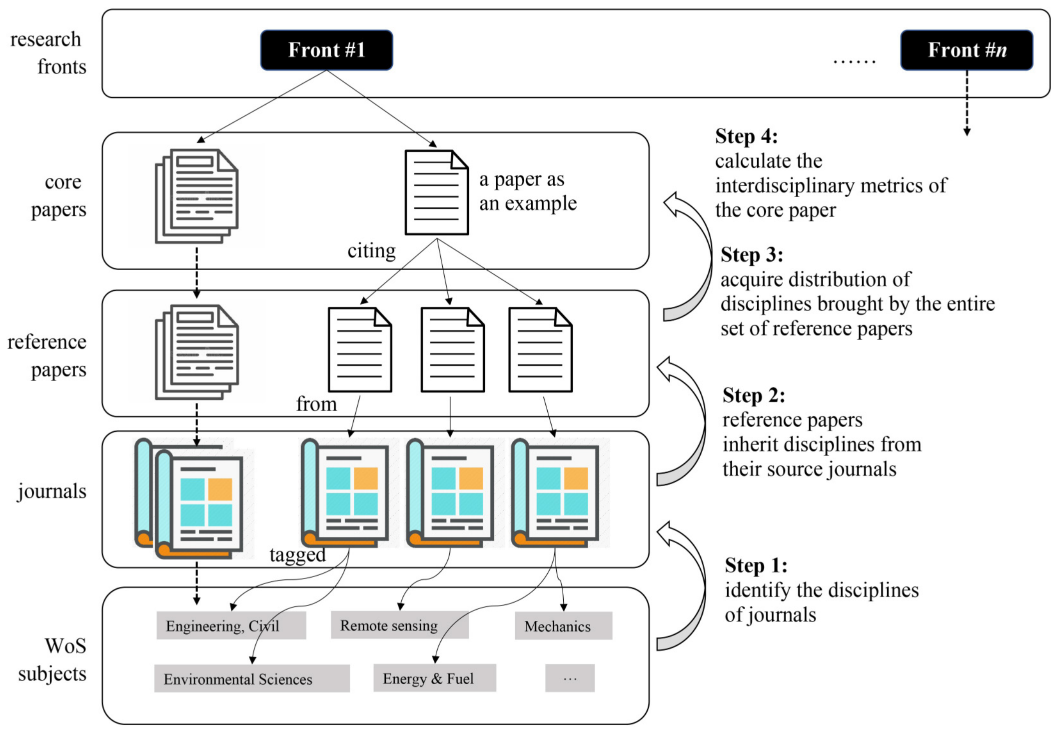

Fig. 1 Illustration for calculating interdisciplinary metrics of research front.

2.2 Bibliographic metrics for interdisciplinary research

The degree of interdisciplinarity of a paper can be evaluated based on its cited papers because a paper typically cites references based on relevance. Therefore, its interdisciplinarity positively correlates with the diversity of disciplines covered by the entire set of reference papers. In this evaluation process, the critical issue is to identify the discipline of each reference paper. For systematic recognition, we adopted the subject classification system of WoS provided by Clarivate Analytics [10,11]. The WoS system identifies more than 250 subjects and attributes a journal to at least one subject. We equated the subjects with disciplines and considered that a paper inherits discipline(s) from its source journal. Figure 1 shows a four-step workflow for assessing the interdisciplinarity of a core paper across the space of WoS subjects, journals, and reference papers based on the distribution of disciplines of the reference papers.

Interdisciplinarity metrics have been developed from bibliographic analyses, which provide quantitative tools for evaluating the involvement and outcomes of interdisciplinary research [12–17]. These metrics are formulated based on knowledge flow or keywords [18] or according to the cooperative relationships among countries, institutions, authors, and disciplines [19]. Because it is less dependent on expert judgment, cooperation-based metrics were selected in this study, such as variety, balance, disparity, and Rao–Stirling diversity [10,20].

The variety of a paper, denoted as v, is defined as the number of distinct disciplines in the reference papers. The more different disciplines are involved in the set of reference papers, the higher the variety and degree of interdisciplinarity of the paper citing the reference papers.

The balance describes the degree of discipline distribution of the reference papers [11] and is computed as follows.

$$\beta = -\frac{1}{\ln(v)} \sum\nolimits_{i=1}^{v} p_i \ln(p_i), \qquad (1)$$

where p_i is the percentage of the ith discipline in the entire set of disciplines involved in the reference papers. The discipline distribution was ideally balanced when the number of reference papers in each discipline remained identical. The more balanced the discipline distribution, the stronger the interdisciplinarity of the paper.

The disparity indicates the degree of difference between the citations of different disciplines [10,11] and is calculated as follows.

$$\delta = \frac{1}{v(v-1)} \sum\nolimits_{i,j} d_{i,j}, \qquad (2)$$

where $d_{i,j}$ is the distance (indicating the degree of difference) between disciplines i and j. It was calculated based on aggregated journal citation data in 2015 using the online tool from Leydesdorff website. A low disparity results from highly similar disciplines and thus indicates the low interdisciplinarity of the paper.

The Rao–Stirling diversity somewhat integrates these three metrics [11,21], and it is computed as follows.

$$\rho = \sum\nolimits_{i,j} p_i p_j d_{i,j}, \qquad (3)$$

where p_i and p_j are the percentages of the ith and jth disciplines, respectively.

It would also be meaningful to measure the impact of interdisciplinary research. The citation of a paper is often used as an indicator of its impact. However, directly comparing the citations of two papers from different disciplines can be misleading as one discipline could be prone to inducing more citations than the other. The category normalized citation impact (CNCI) was used in this study instead of the count of citations to eliminate the effects of the distinction in disciplines and the publishing year. The CNCI of a paper was calculated by dividing the number of citations by the expected citation rate of papers of the same document type, publication year, and discipline. The average ratio of the actual citation to the expected citation is used when a paper is attributed to more than one discipline.

3 Results and discussion

3.1 Are research fronts becoming more interdisciplinary?

The histograms of the different interdisciplinary metrics computed from 4279 core papers are presented in the diagonal cells of Fig. 2. All metrics were skewed. As shown in the scatter plots and the related coefficients below and above the diagonal cells, the four metrics do not necessarily positively correlate with each other. Negative correlation coefficients were observed for the variety–balance and balance–disparity pairs. However, the Rao–Stirling diversity was consistently correlated positively with the others. In particular, the Rao–Stirling diversity strongly correlated with the disparity, with a correlation coefficient of 0.76. This implies that the Rao–Stirling diversity is more comprehensive than the other metrics because it combines the factors considered in the others.

To measure the interdisciplinarity of the research fronts, we averaged the interdisciplinary metric values of the core papers for each front. Figure 3 shows the interdisciplinarity of the 50 research fronts obtained from different years. Each front is represented by a dot that varies in color according to the number of core papers and increases in size according to the average CNCI. The

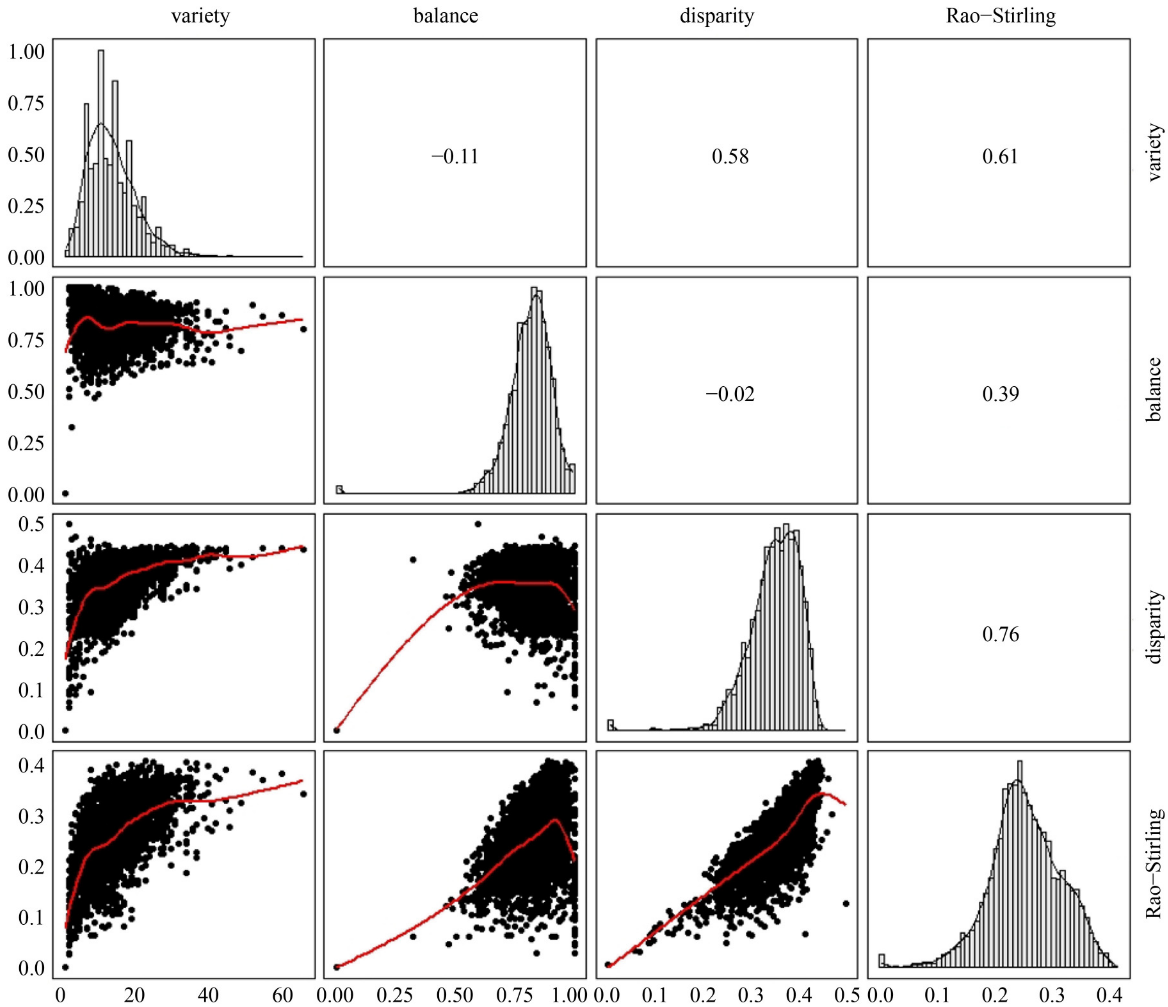

Fig. 2 Histograms and correlations between different interdisciplinary metrics.

mean interdisciplinarity of research fronts for each year is marked down and connected with lines to show the overall trend. Regardless of the selection of the metrics, the plots with different metrics show an upward trend, indicating increasingly interdisciplinary fronts, even though a slight decline in the balance is observed for 2021. Both the disparity and Rao–Stirling diversity consistently increased over time. These plots support the bibliographic perspective that the research fronts involve more disciplines and, thus, become more interdisciplinary over the years.

3.2 Which disciplines play critical roles?

The disciplines involved in the core papers were analyzed annually to identify the most active disciplines. Figure 4 shows a plot of the percentages of the top 15 disciplines with the highest frequency in the past five years. The percentage of the discipline, Engineering, Civil, was 14.2% in 2017 but consistently and gradually decreased to 12.1% in 2021, indicating that an increasing number of other disciplines are involved in the field of civil engineering. In 2021, Construction & Building Technology ranked second after Engineering, Civil, which is unsurprising as both disciplines are closely related. Interestingly, Energy & Fuels caught up and ranked third in 2021, probably because of the increasing demand for renewable energy to support sustainable development. Similarly, as green and sustainable development is increasingly valued, the disciplines associated with the environment (Engineering, Environmental; Environmental Sciences; Environmental Studies; Green & Sustainable Science & Technology) play increasingly significant roles in research. In contrast, the fundamental disciplines that support civil engineering, such as mathematics and material science, remained on the list of active players but with decreasing weight. As suggested by the change in discipline ranking, the energy crisis, climate change, environmental pollution, and natural resource depletion have raised global concerns, which also impact the research fronts in civil engineering in response to new challenges.

Figure 5 shows plots of the research fronts in a circular space enclosed by a ring formed with 15 disciplines

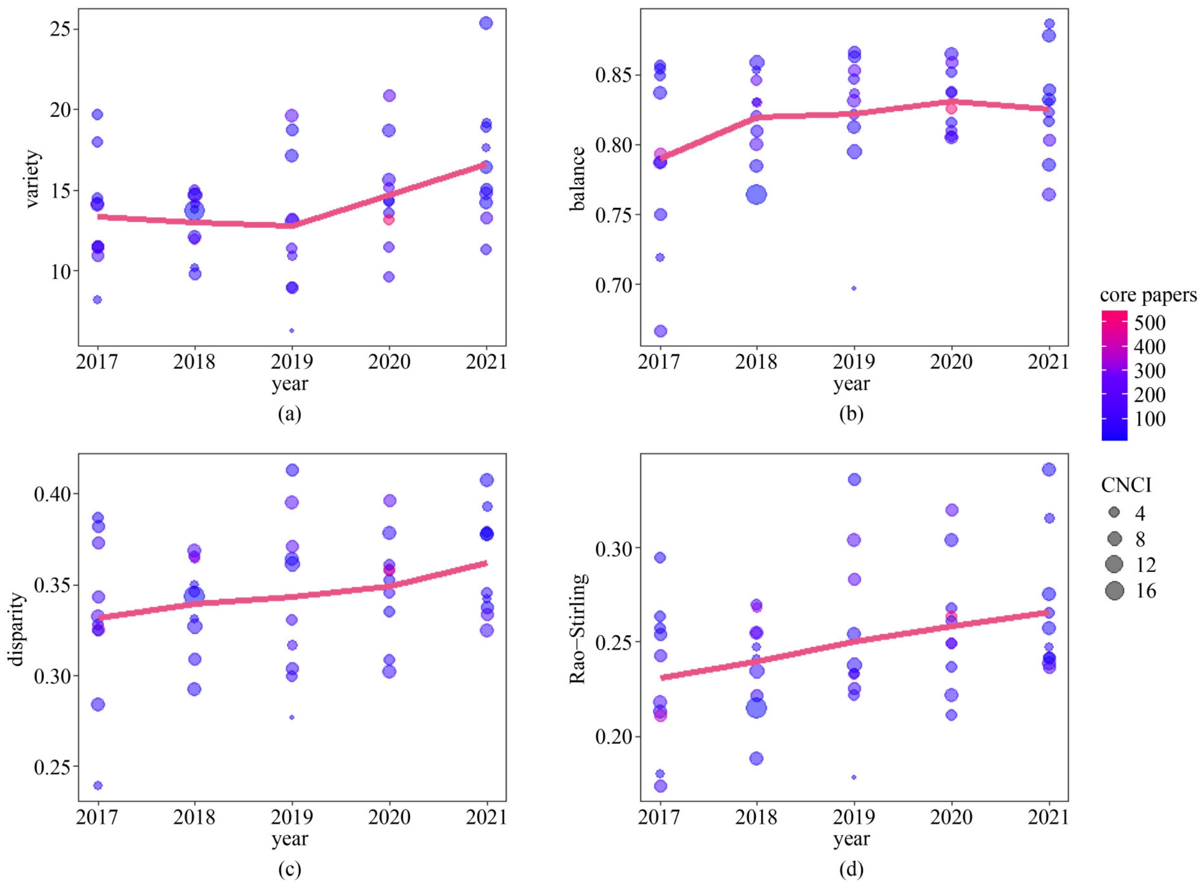

Fig. 3 Increasing trends in interdisciplinary metrics of research fronts: (a) variety; (b) balance; (c) disparity; (d) Rao–Stirling diversity.

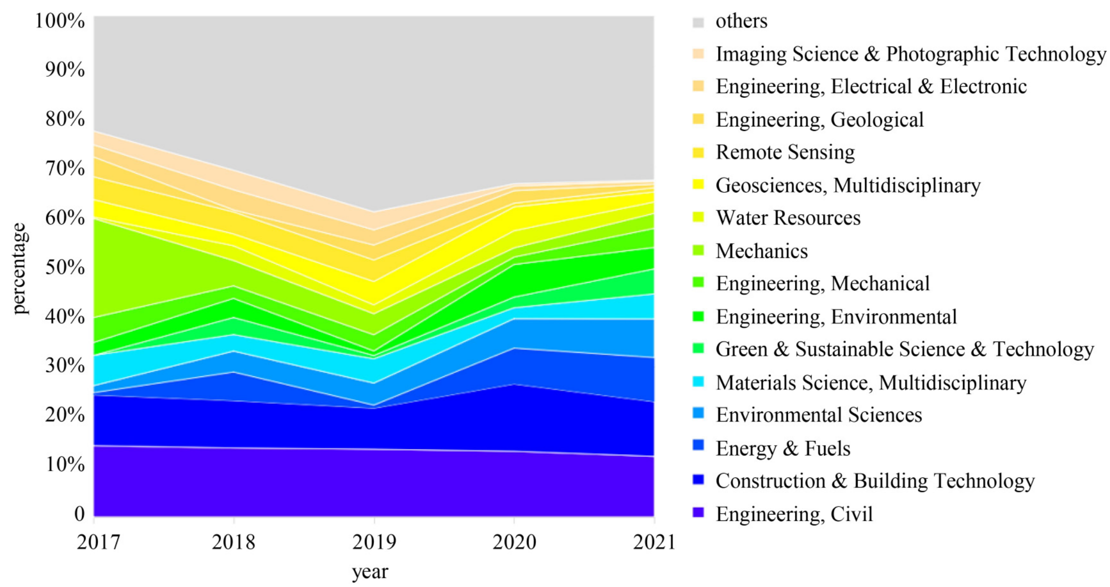

Fig. 4 Active disciplines involved in research fronts.

identified in Fig. 3 to analyze the involvement of different disciplines in every research front. Each front is represented by a bubble, which increases in size according to the averaged CNCI and color coding according to the most involved discipline. Generally, a near-center bubble indicates a highly interdisciplinary research front. As the bubble moves toward the edge of the ring, the degree of interdisciplinarity decreases, and the nearest discipline on the ring plays a dominant role in the research front. The research fronts reported between

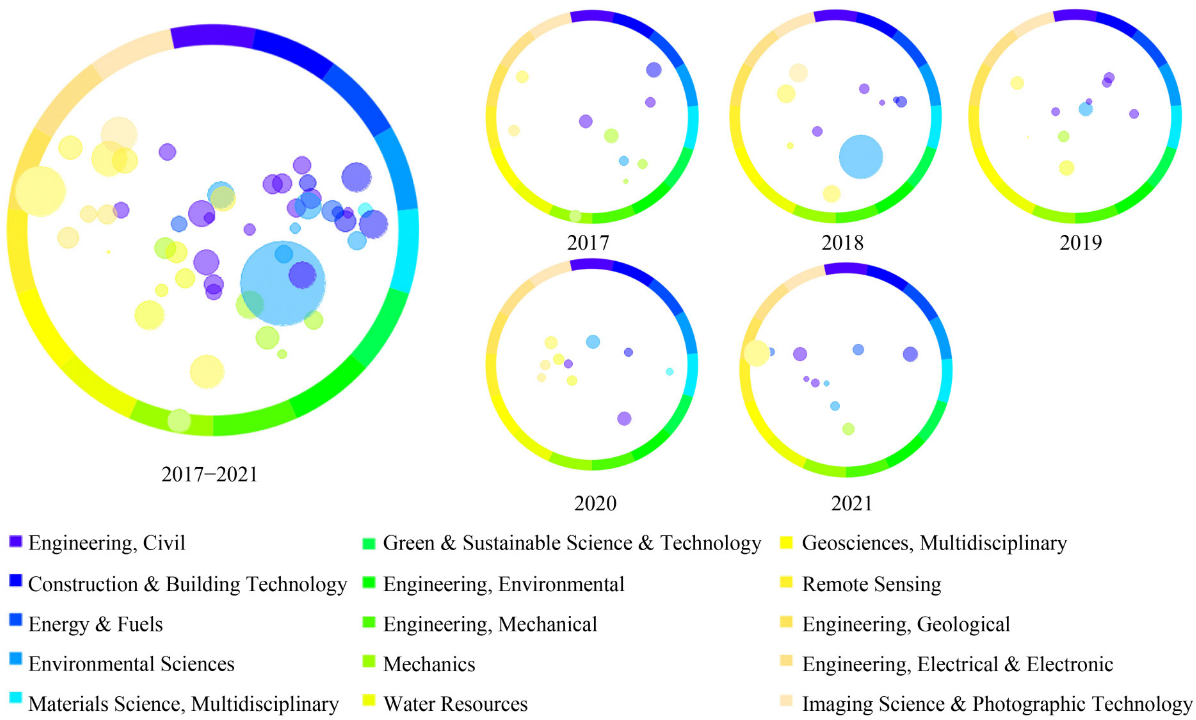

Fig. 5 Interdisciplinary rings of research fronts. The large ring combines all fronts reported between 2017 and 2021, and the small rings depict the fronts reported in different years.

2017 and 2021 spread over a broad area in the large ring, and few fronts remained on the edge of the ring, as most fronts involved multiple disciplines (Fig. 5). The bubbles gathered at a remote zone from the edge labeled Engineering, Civil, even though this discipline dominated some fronts, as indicated by the blue part. The fronts were grouped according to year and plotted in five small rings to trace the temporal variation. The fronts reported in 2017 were closer to the edge of the ring than those reported later, and a tendency of movement toward the center was observed from denser bubbles around the center of the rings, particularly in 2019 and 2020.

3.3 Where are the hot topics?

The keywords involved in the research fronts were used to develop a plot of keyword point clouds to identify the hot topics of the fronts. In this plot, every keyword is represented by a point underpinned according to the measures of interdisciplinarity and impact. Keywords were provided by the authors in the core papers. A keyword could be derived from multiple core papers, called the parent papers. The frequency of a keyword refers to the number of parent papers. The interdisciplinarity of a keyword is measured by the average Rao−Stirling diversity of the parent papers, while the impact of the keyword is measured by the average CNCI of the parent papers that contain the keyword.

Figure 6 shows the point clouds formed by 11255 distinct keywords obtained from the 4279 core papers. Each point was color-coded according to the frequency with which the keyword was represented. The red dotted lines represent the average Rao−Stirling diversity and the average CNCI of all keywords in the figure. As shown in the histogram above the keyword cloud plot, the CNCI of the keywords is log-normally distributed with a mean value of 4.11. The CNCI of most keywords exceeds the global average value (i.e., larger than 1), representing that the keywords of research fronts papers have high influence. No apparent trend was observed between the degree of interdisciplinarity and the impact of the keywords, as the points formed an almost circular cloud. To further examine the possible contribution of interdisciplinarity to the impact, we generated a subset of keywords with CNCI above the mean value and compared the histogram of the Rao–Stirling diversity of the subset with that of the entire data set, as shown in the right panel of the keyword cloud plot (Fig. 6). Less dispersion was observed in the distribution of the subset, even though its mean value was close to that of the entire data set. Figure 7 shows the keywords scaled in size with the occurrence frequency from two subsets, either with a high impact (indicated by a CNCI above the average value) or high interdisciplinarity (indicated by the Rao–Stirling diversity above the average value). Keywords such as “urban heat island,” “climate change,” “smart city,” “data fusion,” and “big data” frequently occurred in both subsets. These keywords indicate that the topics associated with solutions to climate change and the integration of intelligence technologies actively attract the most influential and interdisciplinary research.

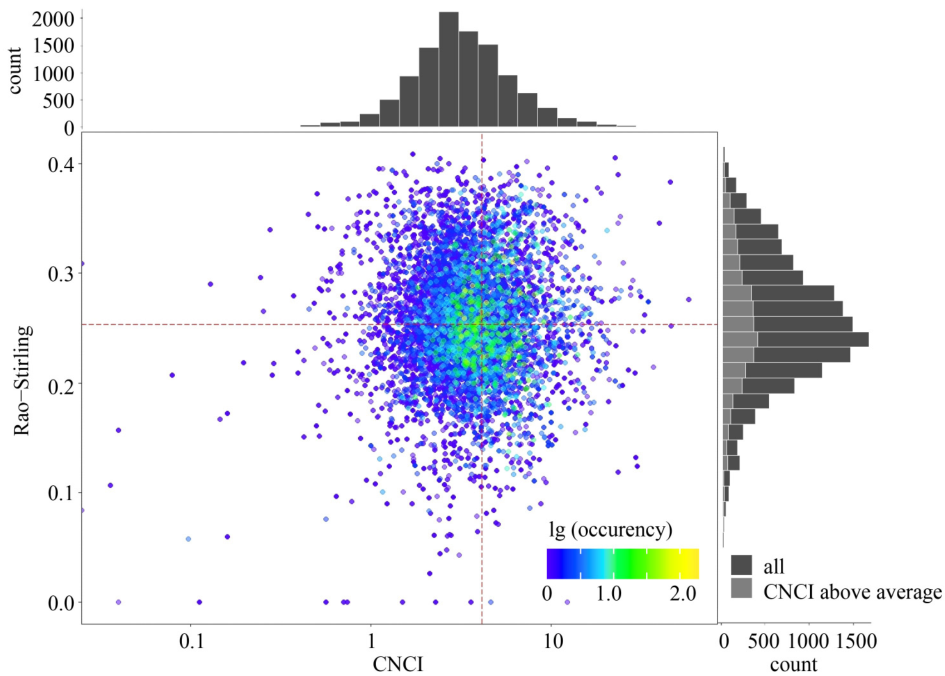

Fig. 6 Keyword cloud from core papers clustered at research fronts.

(a) (b)

Fig. 7 (a) Keyword cloud from subset with CNCI above average value; (b) subject with Rao–Stirling diversity above average value.

4 Concluding remarks

This paper quantitatively presents the significance of interdisciplinary research in giving birth to research fronts in civil, hydraulic, and architectural engineering from a bibliographic perspective. As indicated by the consistent increase in the interdisciplinarity metrics over time, research fronts tend to emerge in studies with increasing diversity in the disciplines involved. The active disciplines involved in the fronts vary over time. Currently, the most active disciplines, such as mathematics and materials science, are no longer fundamental. Instead, disciplines associated with energy, the environment, and sustainable development have gained increasing attention as climate change has become a global concern and intelligence technology has become a global wave. These emerging challenges call for scientific cooperation that breaks the boundaries between disciplines and nations.

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