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Review

A Comprehensive Bibliometric Analysis of Fractional Programming (1965–2020)

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Abstract: Fractional programming (FP) refers to a family of optimization problems whose objective function is a ratio of two functions. FP has been studied extensively in economics, management science, information theory, optic and graph theory, communication, and computer science, etc. This paper presents a bibliometric review of the FP-related publications over the past five decades in order to track research outputs and scholarly trends in the field. The reviews are conducted through the Science Citation Index Expanded (SCI-EXPANDED) database of the Web of Science Core Collection (Clarivate Analytics). Based on the bibliometric analysis of 1811 documents, various theme-related research indicators were described, such as the most prominent authors, the most commonly cited papers, journals, institutions, and countries. Three research directions emerged, including Electrical and Electronic Engineering, Telecommunications, and Applied Mathematics.

Keywords: fractional programming; literature review; bibliometric analysis; visualization; mapping network

MSC: 90C32

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1. Introduction

A constrained optimization problem aims at selecting the best (optimal) solution from all feasible (possible) solutions via the optimization (maximization/minimization) of an objective function in the presence of a set of constraints. If the objective function involves a ratio of two functions, the problem is called fractional programming (FP). The earliest known FP is probably the equilibrium model of Von Neumann [1], where the objective function was the maximization of the growth rate (Frenk and Schaible) [2]. Charnes and Cooper [3] had the merit to pioneer a methodical study on FP, in which a linear FP is converted into a linear program through a variable transformation. The first collection of results pertaining to FP with a single ratio can be found in Schlette [4]. Over two consecutive decades, two books, authored by Craven [5] and Stancu-Minasian [6] were published, each including a chapter on multi-ratio FP. The most recent bibliography on FP is by Stancu-Minasian [7]. Studies on FP span many fields of economics, management science, information theory, optic and graph theory, communication, and computer science, etc. Recent applications include bank asset and liability management (Chuluunbaatar, Rentsen [8]), cyber-security (Zheng et al. [9]), power allocation (Dao and Kim, [10]; He et al. [11]), device-to-device communication (Hamdi et al. [12], wireless communication (Ammar et al. [13]; Sboui et al. [14]), mobile edge computing (Ma et al. [15]), optimization of resources for satellites (Ding et al. [16]), oil refinery waste management

(Zhumadillayeva et al. [17], optimization of the operating modes of catalytic reforming units (Orazbayev et al. [18]), data envelopment analysis (Toloo [19]), and consequential life cycle optimization (Zhao and You, [20]), to mention just a few studies. Per se, the spectrum of real-world applications of FP is significantly expanding, which renders it crucial that a review of related literature is conducted for a better understanding of the state-of-the-art, besides more informed identification of future research directions. From this perspective, a literature review provides scholars with the evidence to pursue prospective research venues (Grant, Booth [21]).

The bibliometric approach is adopted for conducting the proposed literature review on FP. Such an option lies in the superior features of the bibliometric review, which (i) provides a quantitative analysis of written publications (ii) includes geographical and institutional aspects in the analysis, and (iii) examines the indicators of performance, including developments over time periods, subject domains or disciplines, and types of literature and authorship. For an in-depth discussion on the advantages of a bibliometric review, we refer the reader to Ellegaard and Wallin [22].

Depending on the review's purpose and approach, the most common types of literature reviews include the critical review, systematic (mapping) review, rapid review, narrative (traditional) review, scoping review, bibliography review, and the bibliometric review (Grant, Booth [21]).

A systematic review uses repeatable analytical methods to collect, analyze, and synthesize secondary data to inform practice (Munn et al. [23]). Systematic reviews formulate research questions that are broad or narrow in scope, and identify the data that are directly related to these questions. Very often, these reviews provide an exhaustive summary of current evidence that is relevant to a research question. In some cases, such reviews appraise research studies from a more critical perspective, and synthesize the findings qualitatively or quantitatively. Our initial search reveals that there are 216,274 systematic review records in the Web of Science (WoS), where the first paper is published by Alm [24], and the top-cited paper is due to Stroup et al. [25], with 12,610 citations.

A critical review is much more than a simple summary, as it involves an analysis, as well as an evaluation of the extant studies. It requires researchers to question the literature and to present their evaluation of the paper. Williams [26] highlights that reading critically and analyzing all elements of a research paper are essential for a high-quality critical review. Indeed, all aspects of the text should be considered, including the structure, the methods, the reasons and evidence, and the conclusions. According to our preliminary investigation, there are currently 29,873 critical review records in the WoS databases; Whiteside, Walton [27] and Podsakoff et al. [28] are the first and the top-cited (29,448 citations) critical review papers, respectively.

A narrative review has been considered as an objective, critical, and comprehensive analysis of information in a particular field. Using this method provides some opportunities for researchers to establish a theoretical framework for their research. However, the latter review type is criticized for its lack of explicit intent to maximize the scope of the data collection or its analysis. Our cursory analysis points out that there are 14,691 narrative review papers in the WoS databases., the first one being published by Buell [29]. Warburton et al. [30] is the top-cited systematic review paper, with 3686 citations.

A rapid review is a form of literature synthesis that systematically reviews a part of the literature. It uses several design decisions and practical steps to reduce the time needed to identify, aggregate, and answer the research question. This type of review assesses what is already known for research, and critically evaluates the existing studies (Thomas et al. [31]). Time limitation is the main weakness of a rapid review, which may lead to lower quality of the assessment, compared to other types of literature reviews. Our brief examination reveals that 1114 rapid review papers exist in the WoS. The first research is published by Settlage et al. [32], whereas Brooks et al. [33] is the top-cited paper, with 2869 citations.

A scoping review aims to search for the key concepts underpinning a field of study by mapping the language and data that surround these concepts, and by synthesizing the available evidence (Mays et al. [34] and Arksey, O'Malley [35]). A scoping review may often be a preliminary stage for a systematic review to determine the scope of coverage of a body of literature (Munn et al. [23]) Our preliminary investigations show that 9932 scoping review papers are recorded in the WoS; Arksey [36] and Peters et al. [37] are, respectively, the first and the top-cited (1099 citations) papers.

A bibliographical review involves the analysis and explanation of all concepts, definitions, hypotheses, theoretical approaches, studies, and antecedents of a particular topic (Esquirol-Caussa et al. [38]). A bibliographical review can support high-quality research by enabling the elaboration of the most appropriate research protocols, the integration of the best scientific evidence, and the best insights into the field of study (Eckert et al. [39]). Our preparatory research demonstrates that there exist 873 bibliographic review papers. Geddes, James [40] is the first paper under this category, whereas Zhang, Jiang [41] is the top-cited paper, with 1374 citations.

A bibliometric review provides an overall structure of a particular research field by using quantitative (statistical) analysis and distributed architecture research/literature production (Persson et al. [42]). In addition to a comprehensive review of the literature, it also considers other elements of the paper, such as the keywords, affiliation, title, and abstract, etc. Historically, the bibliometric review can be traced back to the 1920s (Hulme [43]). In our initial search, we found 14,717 records on bibliometric review in the WoS databases, with Fairthorne [44] as the first paper and Van Eck, Waltman [45] holding a top number, with 2205 citations.

Figure 1 compares the aforementioned types of literature reviews from four different standpoints: speed, methodological details, risk of bias, and comprehensiveness.

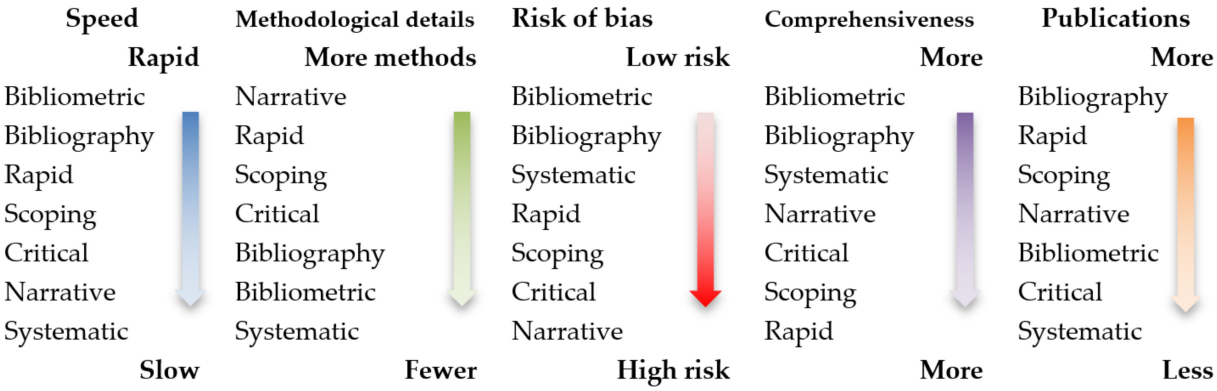

Figure 1. Schematic of the main differences between the types of literature review.

As can be seen, bibliometric reviews can be conducted faster than the other types of reviews, especially systematic reviews, which are the most time demanding, which is certainly due to the advanced level of the methodological details that they may require. Moreover, bibliometric studies are the most comprehensive but the least likely to be biased, as opposed to narrative reviews, where fewer methods are generally covered.

For an in-depth discussion regarding the types of literature reviews, we refer the reader to Grant and Booth [21].

Writing a literature review requires not only a good level of organization of the previous research (Shuttleworth [46] and Rowley, Slack [47]), but also an adequate choice of citation database. The proposed review of FP was conducted on the WoS. The choice for the WoS data source was due to the fact that (i) WoS is the largest and most trusted global citation database in the world, (ii) WoS is the most powerful research engine, providing the best-in-class publication and citation data for access and evaluation, and (iii) WoS collects and indexes high-quality research and creates the most comprehensive and complete

citation network for every single record. The WoS data source is widely used for bibliometric reviews in many areas, including supply chain management (Govindan et al. [48]), blockchain (Guo et al. [49]), data envelopment analysis (Liu et al. [50]), sustainable business models (Rosato at al. [51]), energy metabolism (Tang et al. [52]), Fenton oxidation (Usman, Ho [53]), and uncertain group decision making (Wang et al. [54]). The WoS website provides a navigation environment for a broad search across disparate resources, and enables the graphical representation of publication trends.

Among the data sources that are available for researchers to find, cite, link, access, and reuse academic publications, MathSciNet, CrossRef, Google Scholar, Scopus, and WoS are the most commonly used.

(i) **MathSciNet** is the most reliable source in the field of mathematics, and it originated in 1940 as the journal *Mathematical Reviews*. It is a bibliographic database created by the American Mathematical Society in 1996. MathSciNet encompasses almost 3.6 million items and over 2.3 million direct links to original articles from approximately 650 journals.

(ii) **CrossRef**, as the first data source, was established in 2000 by 12 publishers to simplify the process of linking to research on other publishers' platforms. In recent years, CrossRef has also been used for citation analysis, digital object identification (DOI), and metadata search (Harzing [55]).

(iii) **Google Scholar** is one of the academic projects by Google, founded in November 2004 as an index for academic literature full text or metadata search. The objective of Google Scholar was to bring Google search simplicity to the academic environment, but it has crawled the whole web by indexing any record with seemingly academic structure (Martín-Martín et al. [56]). By using this inclusive approach, Google Scholar provides comprehensive coverage of scientific/academic documents without following the selective journal-based inclusion policies (Orduña-Malea et al. [57]; Van Noorden [58]; and Martín-Martín et al. [59]). Google Scholar covers over 300 million records (Delgado López-Cózar et al. [60]).

(iv) **Scopus** was launched in 2004 as Elsevier's abstract and citation data source. It is one of the largest abstract and citation databases of publications (with over 1.7 billion cited references), covering nearly 41,462 titles from approximately 11,678 publishers. It covers over 76 million records with 3 million new items added every year (Baas et al. [61]). Scopus is used by more than 3000 academic, government, and corporate institutions.

(v) **WoS** was established by the Institute for Scientific Information (ISI). Later, it transferred to Thomson Reuters, and is currently a part of Clarivate Analytics. WoS contains the following six main citation databases: (i) Science Citation Index (SCI), (ii) Social Sciences Citation Index (SSCI), (iii) Arts & Humanities Citation Index (AHCI), (iv) Emerging Sources Citation Index (ESCI), (v) Book Citation Index (BCI), and (vi) Conference Proceedings Citation Index (CPCI). It is the world's first citation database, with over 1.9 billion cited references from over 171 million records, including 34,358 titles such as journals, books, and conference proceedings).

Under the WoS website, the wealth of data extracted for the bibliometric review leads indubitably to data processing and interpretation challenges (Solomon [62]). To address these issues, visualization and mapping tools are the best suited for creating graphical representations of the data and enhancing users' understanding. In this study, we employ the well-known VOSviewer software (Van Eck, Waltman [63–65]), which allows for a comprehensive bibliometric analysis, including the co-citation of cited references, cited authors, and cited journals. VOSviewer is a Java-based program that is able to construct, visualize, and explore node-link maps based on bibliographic data (see Van Eck, Waltman [63]). It focuses entirely on the visualization of bibliometric networks and provides distance-based visualizations rather than graph-based ones. Moreover, VOSviewer (i) possesses functionalities for zooming, scrolling, and searching, (ii) uses the "visualization of similarities" technique to construct a map, and (iii) provides bibliometric mapping and

co-occurrence analysis on the title, abstract, and keywords. Furthermore, VOSviewer is an easy-to-use software and it is freely available to the bibliometric research community. Yet, VOSviewer cannot perform citation burst analysis. Such a deficiency has been tackled by using the application CiteSpace (Chen [66,67]), which enables us to show a temporal perspective on the publication and present citation burst.

There are other tools for creating bibliometric networks, but they cannot comprehensively cover all aspects of a bibliometric analysis, such as 'bibliometric coupling', 'text mining', and 'co-occurrence analysis'. For instance, CitNetExplorer (van Eck and Waltman, [65,68]) and HistCite (Garfield [69]) only focus on citation analysis.

The rest of this study is organized as follows. Section 2 succinctly discusses the procedures employed for conducting the current study. In Section 3, the extracted information is analyzed from multiple perspectives, and appropriate conclusions are drawn. Finally, Section 4 concludes the paper.

2. Methodology

This section presents the procedures that are adopted for gathering, visualizing, and mapping data toward an efficient synthesis of the current literature on FP and its applications. We employ the WoS website as a data source, and VOSviewer software for constructing and visualizing bibliometric networks.

2.1. Data Source (WoS)

In order to search the relevant literature records, we proceeded as follows.

(i) We select the "Web of Science Core Collection" database, which includes all of the mentioned indexes.
(ii) We select "Topic" from the search field list box and use "Fractional Programming", "Fractional Optimization", and "Ratio Optimization" as a suitable "Basic Search".
(iii) We select "Custom Year Range" from the "Timespan" list box, and we set 1965–2020 to cover 55 years.

The search returns 1811 published documents.

The collected data is used for a trend analysis (via WoS) and citation analysis (via VOSviewer) of publications.

A trend analysis of publications aims to collect data on published articles from multiple resources, to comprehensively evaluate the visibility and impact of the publications. It includes time trends, research direction, document types, prolific authors, institutions, and countries. As illustrated in Figure 2, the trend analysis is performed as follows.

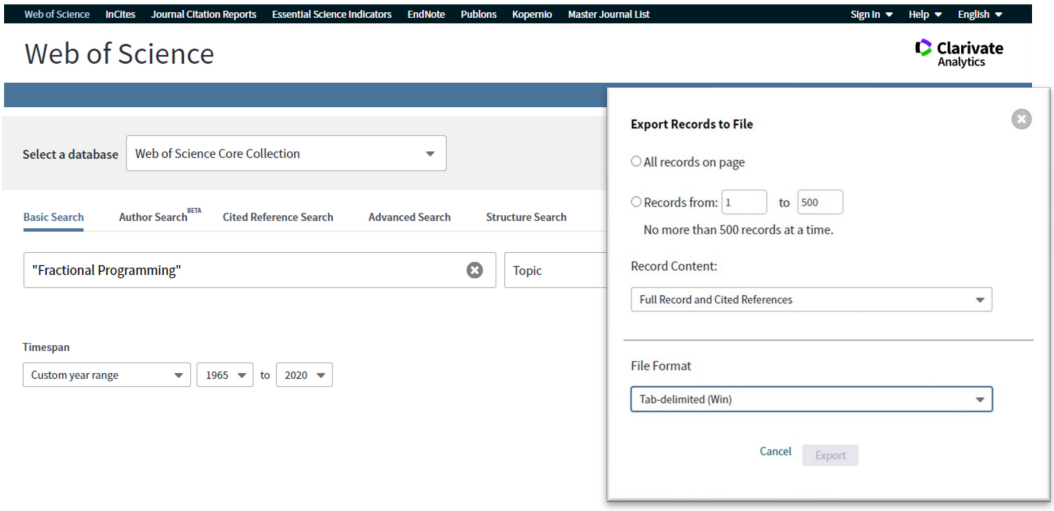

Figure 2. Search settings in WoS.

(i) Export the obtained records to a file by picking "Other File Format" from the "Export Records to File" list box.
(ii) Select "Full Record and Cited References" from the "Record Content" list box.
(ii) Choose "Tab-delimited (Win)" option from the "File Format" (the VOSviewer accepts this type of file format) list box.

Citation analysis is a common bibliometric method that has been successful in enhancing the retrieval of academic information. The importance of citation analysis has been highlighted in a large number of studies (see Shotton [70] for references).

Note that for the citation analysis via WoS, we select the "Comma-Separated Values" (CSV) option from the "File Format" list box.

2.2. Visualization and Mapping Networks

The VOSviewer software is employed for visualizing bibliometric networks using the data imported from the WoS data source. Our initial search for "VOSviewer" in the "Title, Abstract, Keywords" field of the WoS data source (done on 22 April 2021) reveals that this software has been used as an analysis tool in over 1195 papers.

As illustrated in Figure 3, all the default settings of VOSviewer are kept unchanged. Any non-meaningful term (such as "upper level", "phi", "objective", and "research") can be excluded from the analysis by unchecking the corresponding case in the "Verify selected terms" dialog box displayed in VOSviewer.

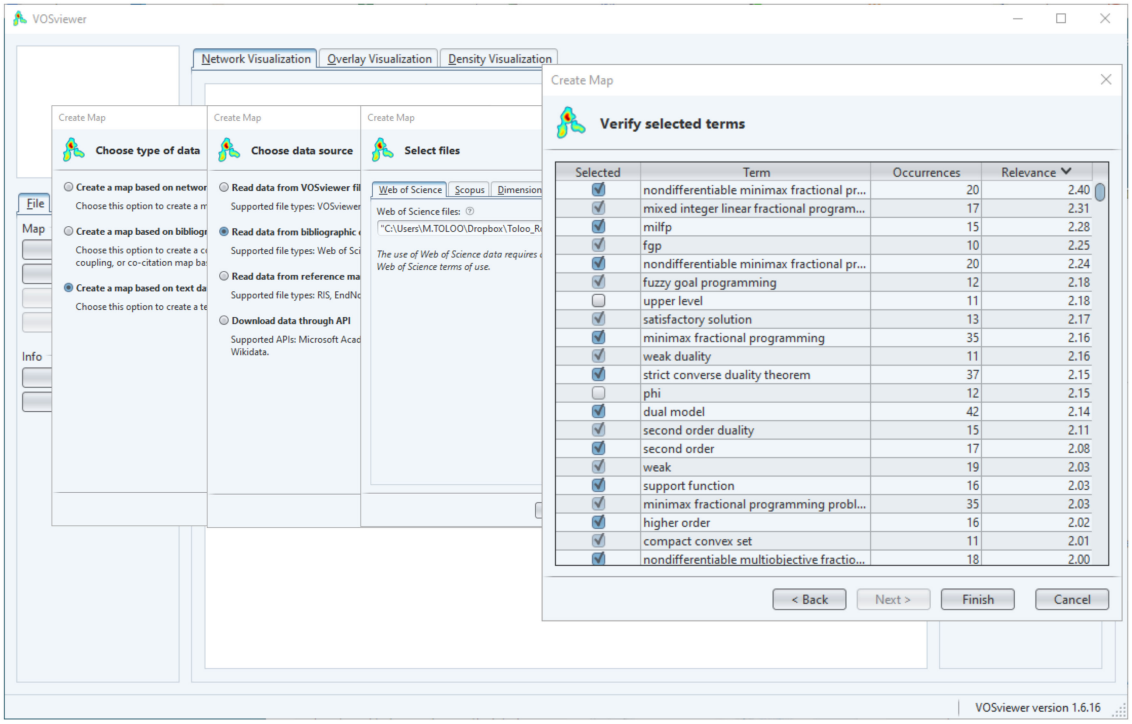

Figure 3. VOSviewer analysis process.

3. Analysis

In this section, the results of the study are analyzed. The analysis starts with a descriptive bibliometric analysis, which includes the research direction, document type, prolific researchers, productive institutions, journals, and countries. Next, the visualization and mapping networks of the FP research landscape are presented by using the VOSviewer software, along with the associated cooperation networks. In addition, a thematic analysis of author keywords is performed to examine the co-occurrences network of FP research. The analysis section ends with burst citation analyses (BCA) of FP research from three different perspectives, comprising Keywords, Cited Authors, and Cited Journals. Burst

detection finds the articles that receive particular attention from related scholars over a certain period (see Zhou et al. [71]).

3.1. Descriptive Bibliometric Analysis

The "Analyze Results" feature in WoS helps us to extract data from the selected field and produce a report of ranked values. We use this feature with the selected records to conduct a descriptive bibliometric analysis, which involves the distribution of types of documents, the most prolific articles, the authors, the institutions, and the countries.

3.1.1. Research Direction

The first research trend consists of identifying "Web of Science categories" where FP-related documents are produced. There are 1811 published documents in the FP field from 1965 to 2020, falling under 25 categories. Figure 4 illustrates that the top three categories are Engineering Electrical Electronic, with 565 records, Telecommunications, with 482 records, and Applied Mathematics, with 465 records. In the meantime, fewer papers on FP have been found in Multidisciplinary Sciences, with only 22 records, with the same occurring in Water Resources, with 21 records, and Energy Fuels, with 18 records.

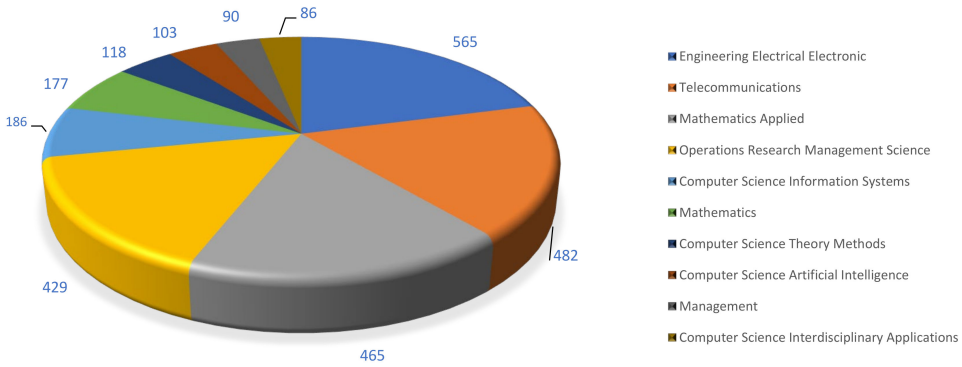

Figure 4. Top 10 FP categories.

The analysis of the WoS's outputs reveals that the majority of the publications that are related to FP appeared between 1990 and 2020, i.e., 1706 out of 1811 publications. As shown in Figure 5, the highest and the lowest numbers of publications are recorded in 2017 and 1990, respectively.

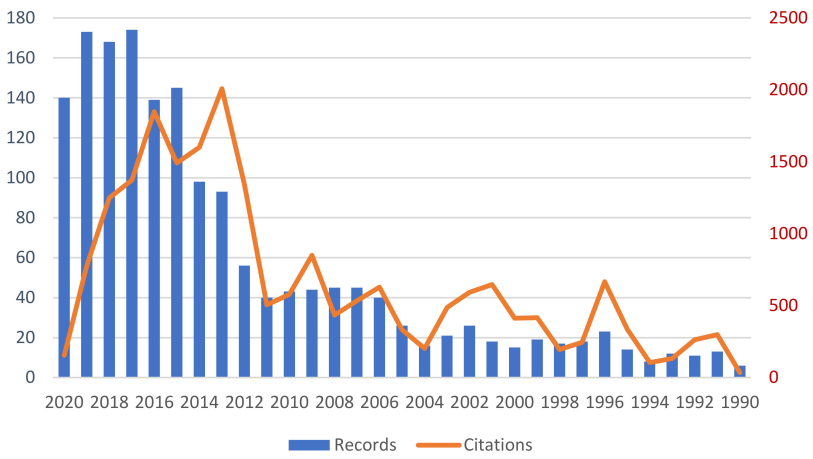

Figure 5. Number of publications and citations (1990–2020).

3.1.2. Document Types

Among 1811 publications in the FP field between 1965 and 2020, there are 11 document types. We employ a treemap chart to visualize various document types in this study. On

a treemap, each item is represented by a rectangular shape, where smaller rectangles represent the sub-groups. As shown in Figure 6, articles and proceeding papers are the main choices for researchers in the FP field.

Figure 6. Types of publications related to FP.

The most frequent types consist of 1303 (71.95%) original articles. Meanwhile, there are 439 (24.24%) proceedings papers, 24 (1.32%) book chapters, 13 (0.71%) notes, 8 (0.44%) Early Access, 6 (0.33%) reviews, and only 3 (0.16%) bibliographies. Additionally, in our dataset, out of 1811 records, 643 of them are open access.

3.1.3. Prolific Scholars

With regard to the authors' factor, researchers evaluate the records by using seven indicators, including the total number of publications (TP), the percentage of TP accounting for total publications (%TP), the top three affiliated countries, the total number of citations (TC), the average number of citations per publication (TC/TP), the H index, and the number of publications that are cited more than 10 times (>10). These indicators are widely used in bibliometric analyses to reflect the general situation of the publications. Based on our dataset, there are 3036 authors in total, and the top 9 prolific authors are listed in Table 1.

Table 1. Most prolific scholars of Fractional Programming.

Authors	TP	TP%	TC	TC/TP	H index		Top	>10	Active Years
					Total	FP	Citation		
You, FQ	38	2.09	1114	29.32	52	16	133	19	2005–2021
Lai, HC	25	1.38	284	11.36	13	11	59	13	1999–2018
Zappone, A	25	1.38	557	22.28	22	9	230	9	2009–2021
Huang, GH	22	1.21	321	14.59	72	11	61	11	1996–2021
Schaible, S	22	1.21	837	38.05	31	11	131	13	1977–2012
Sakawa, M	21	1.16	404	19.24	37	10	61	10	1978–2011
Zalmai, GJ	18	0.99	98	5.44	11	7	13	3	1985–2018
Ahmad, I	17	0.93	167	9.47	15	7	28	6	2004–2021
Ng, DWK	17	0.93	1452	85.41	41	11	355	11	2009–2021

TP = Total Publication; TC = Total Citation; TC/TP = Citation Per Item; >20 = more than 20 citations; C/Y = Cites/Year; C/P = Cites/Paper; FP= Fractional Programming.

Accordingly, You, FQ has been indicated as being the most productive scholar, with 38 (2.09%) publications. This author is also ranked at the top of the list in terms of the H index, and according to >10 indicators. However, this researcher ranks second with respect

to the TC indicator, where Ng, DWK takes the lead. A similar pattern is detected for the TC/TP ratio with You, FQ ranked third, following Ng, DWK and Schaible, S. Among the top nine authors, Zalmai GJ seems to be the least cited, with a TC = 98 and a >10 indicator of only 3.

3.1.4. Prolific Journals

Table 2 exhibits the most prolific journals, evaluated based on six indicators.

Table 2. Top 10 most productive journals in Fractional Programming.

						H Index					
Source Titles	**TP**	**TP%**	**TC**	**TC/TP**	**G Index**	**Total**	**FP**	**>20**	**Active**	**C/Y**	**C/P**
Eur. J. Oper. Res.	55	3.03	1290	23.45	698	406	20	20	1978	12,550.84	552
J. Optim. Theory. Appl.	55	3.03	886	16.11	295	169	16	15	1968	2504.47	132.74
IEEE. Access.	50	2.76	494	9.88	278	165	13	9	2013	16,068.88	128.58
J. Glob. Optim.	47	2.59	964	20.51	304	127	16	13	1991	3850.20	115.51
J. Math. Anal. Appl.	40	2.21	603	15.08	400	241	15	11	1960	3776.61	230.60
IEEE. Trans. Wirel.	39	2.15	2368	60.72	461	266	22	22	2002	14,532.26	276.11
IEEE. Trans. Veh.	33	1.82	897	27.18	415	258	15	11	1972	4988.33	244.43
IEEE Int. Conf. Commun.	31	1.71	127	4.1	97	60	7	1	1989	575.66	18.42
IEEE. GLOBECOM	29	1.60	98	3.38	116	76	5	2	1984	1009.68	37.36
IEEE Trans. Commun.	28	1.54	885	31.61	631	348	13	11	1972	9097.76	445.79

TP = Total Publication; TC = Total Citation; TC/TP = Citation Per Item; >20 = more than 20 citations; C/Y = Cites/Year; C/P = Cites/Paper; FP= Fractional Programming.

It is clear that the majority of the papers have been published by *The European Journal of Operational Research* and the *Journal of Optimization Theory and Applications*, with 55 (3.03%) documents for each journal. However, these two journals exhibit different trends for other indicators. For instance, *The European Journal of Operational Research* ranked second for TC and >20 indicators, while the *Journal of Optimization Theory and Applications* ranked third for the H index, fifth for both TC and >20, and sixth for the ratio TC/TP indicators. Interestingly, *IEEE Transactions on Wireless Communications* stands at the top of the list for the indicator TC. Such a result corroborates the outcomes of the research direction, which indicate that 1047 published documents, i.e., 57.8% of the reviewed records, fall under the categories of Engineering Electrical Electronic, as well as Telecommunications.

3.1.5. Prolific Institutions

The same indicators used to analyze the prolific authors are adopted to evaluate the institutional affiliations of the authors for the publications analyzed. Among 1097 institutions, the top 10 prolific institutions are listed in Table 3.

Table 3. Most productive universities in Fractional Programming.

Organizations	**Country**	**TP**	**TC**	**TP%**	**TC/TP**	**H Index**	**>20**
Indian Institute of Technology	India	75	694	3.99	9.25	15	11
Southeast University	China	62	797	3.30	12.85	13	10
University of Delhi	India	52	192	2.76	3.69	7	2
Beijing University Posts Telecommun	China	46	403	2.45	8.76	9	4
Xidian University	China	43	784	2.29	18.23	16	12

Table 3. *Cont.*

Organizations	Country	TP	TC	TP%	TC/TP	H Index	>20
North China Electric Power University	China	38	820	2.02	21.85	15	13
Tsinghua University	China	29	449	1.54	15.48	11	8
University of Electronic Science and Technology	China	29	160	1.54	5.52	6	3
Chinese Academy of Sciences	China	28	247	1.49	8.82	10	2
Dresden University of Technology	Germany	27	598	1.44	22.15	9	6

TP = Total Publication; TC = Total Citation; TC/TP = Citation Per Item; >20 = more than 20 citations; FP= Fractional Programming.

Interestingly, 7 out of the top 10 universities are located in China. Nonetheless, the Indian Institute of Technology System (IIT System, India) ranks first for the TP and TP% indicators. Based on the TC/TP indicator, Dresden University of Technology leads the list, which may reveal the in-depth research and wide recognition of FP in this institution.

3.1.6. Prolific Countries

Regarding the countries of affiliation, the publications are evaluated through the six indicators, as presented in Table 4.

Table 4. Most productive countries for Fractional Programming.

Countries	TP	TP %	TC	TC/TP	H Index	>50
China	626	34.56	8005	12.79	40	35
USA	286	15.79	5180	18.11	40	32
India	271	14.96	1659	6.12	21	4
Canada	129	7.12	2713	21.03	27	10
Taiwan	100	5.52	1319	13.19	20	7
Japan	96	5.30	1962	20.44	25	13
England	77	4.25	1075	13.96	17	5
Germany	72	3.97	1921	26.68	17	10
Iran	67	3.70	448	6.69	11	3
South Korea	55	3.03	334	6.07	11	0
Italy	53	2.92	661	12.47	12	3
Australia	51	2.81	823	16.14	14	3

TP = Total Publication; TC = Total Citation; TC/TP = Citation Per Item; >50 = more than 50 citations; FP= Fractional Programming.

According to both the total number and the percentage of publications, China is the most prolific country, with 626 (34.56%) publications, followed by USA, with 286 (15.79%) and India, with 271 (14.96). With six Asian countries/regions (China, India, Taiwan, Japan, Iran, and South Korea) listed among the top 10 most prolific countries, these results suggest that Asian universities are the most high-performing, according to the FP-related research.

3.2. Visualization and Mapping Network

This section is dedicated to visualizing the networks of scientific research that are related to FP, which include bibliometric networks such as collaboration networks, semantic networks, and publication citation networks. Collaboration and publication citation networks are used to create a comprehensive overview of the FP research landscape. The author's keyword co-occurrence network is also analyzed to track the research themes in the FP field.

Cooperation Networks of FP

In order to examine the scope of collaboration among researchers in different countries from 1965 to 2020, VOSviewer is used to construct the country collaboration network shown in Figure 7.

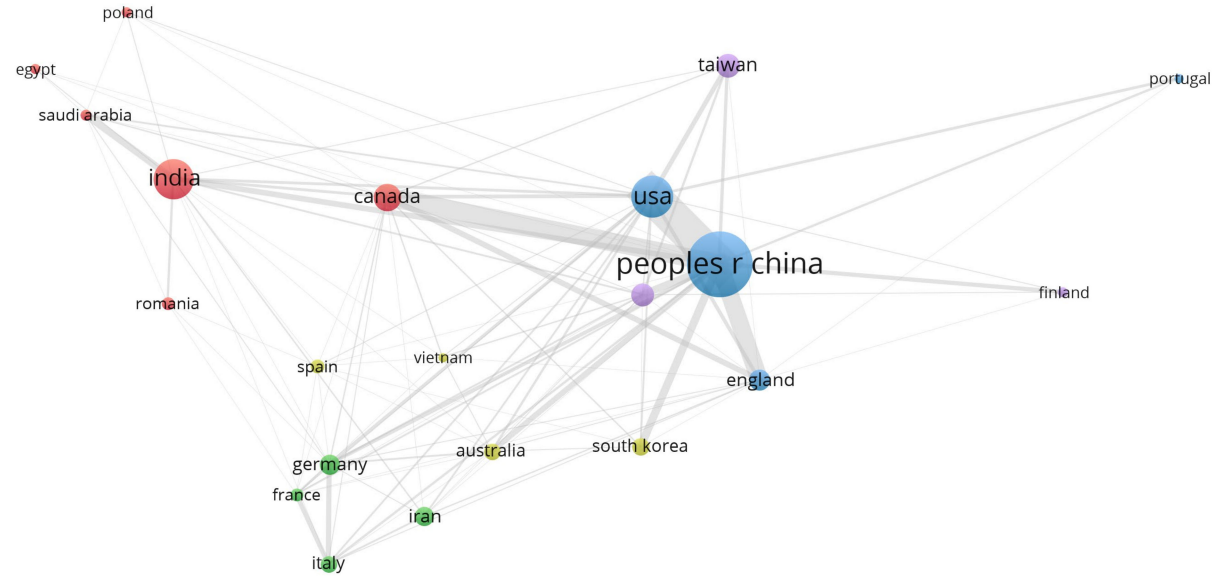

Figure 7. Co-authorship collaboration between the 20 most collaboration-intensive countries.

Each color represents one category. The size of the node depicts the number of publications. The links between the nodes show the presence of authorship collaboration, while the thickness of the link reflects the strength of the collaboration. In view of the latter criterion, China's collaboration with USA, Canada, and England seems to be the strongest. China's research ties with India, South Korea, Australia, and Taiwan are relatively weaker.

With respect to institutional collaboration, Figure 8 presents the relationships between the top 15 connected institutions from 1965 to 2020.

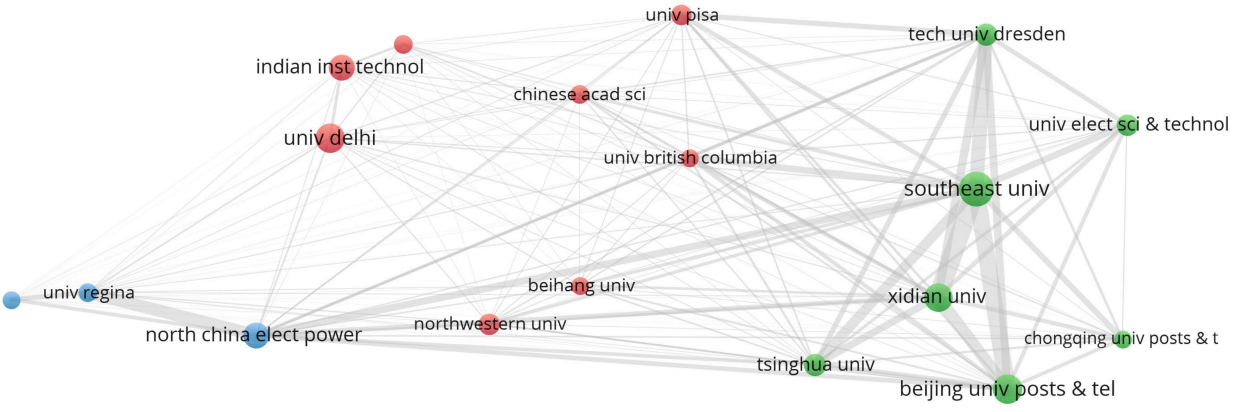

Figure 8. Co-authorship collaboration of the 15 most collaboration-intensive institutions.

Over a total of 1097 institutions that contributed to the FP literature, 54 institutions produced more than 10 research publications. Southeast University, Beijing University of Posts & Telecommunications, Tsinghua University, and Xidian University, all from China, and the German university Technische Universität Dresden are the most collaboration-intensive institutions.

The ten most-cited articles published in FP and identified within our study are listed below. We should underline here that no theoretical article can be found in this list, because

the publishers of such conceptual papers are not usually indexed in WoS. For instance, the prominent Charnes–Cooper transformation approach (Charnes, Cooper [3]), which plays a chief role in applying FP in various disciplines, has been published in the *Naval Research Logistics Quarterly* journal, which is not indexed by WoS.

1. Ng, D.W.K., Lo, E.S., and Schober, R. [72]. Wireless information and power transfer: Energy efficiency optimization in OFDMA systems. *IEEE Transactions on Wireless Communications*, 12(12), 6352–6370, 2013. Total citations: 354 Average per-year citation: 39.33.
2. Ng, D.W.K., Lo, E.S., and Schober, R. [73]. Energy-efficient resource allocation in OFDMA systems with large numbers of base station antennas. *IEEE Transactions on Wireless Communications*, 11(9), 3292–3304, 2012. Total Citations: 353; Average per-year citations: 35.30.
3. Carlsson, C. and Fullér, R. [74]. Fuzzy multiple criteria decision making: Recent developments. *Fuzzy sets and systems*, 78(2), 139–153, 1996. Total citations: 287; Average per-year citations: 11.04.
4. Isheden, C., Chong, Z., Jorswieck, E., and Fettweis, G. [75]. Framework for link-level energy efficiency optimization with informed transmitter. *IEEE Transactions on Wireless Communications*, 11(8), 2946–2957, 2012. Total citations: 254; Average per-year citations: 25.5.
5. Pastor, J. T., Ruiz, J. L., and Sirvent, I. [76]. An enhanced DEA Russell graph efficiency measure. *European Journal of Operational Research*, 115(3), 596–607, 1999. Total citations: 214; Average per-year citations: 9.30.
6. Huang, C., Zappone, A., Alexandropoulos, G. C., Debbah, M., and Yuen, C. [77]. Reconfigurable intelligent surfaces for energy efficiency in wireless communication. *IEEE Transactions on Wireless Communications*, 18(8), 4157–4170, 2019. Total citations: 209; Average per-year citations: 69.67.
7. Wu, Q., Tao, M., Ng, D.W.K., Chen, W., and Schober, R. [78]. Energy-efficient resource allocation for wireless powered communication networks. *IEEE Transactions on Wireless Communications*, 15(3), 2312–2327, 2015. Total citations: 201; Average per-year citations: 33.50
8. Cozman, F.G. [79]. Credal networks. *Artificial intelligence*, 120(2), 199–233, 2000. Total citations: 186 Average per-year citations: 8.45.
9. Zhou, Z., Dong, M., Ota, K., Wang, G., and Yang, L.T. [80]. Energy-efficient resource allocation for D2D communications underlaying cloud-RAN-based LTE-A networks. *IEEE Internet of Things Journal*, 3(3), 428–438, 2015. Total citations: 179; Average per-year citations: 29.83.
10. Ng, D.W.K., Lo, E.S., and Schober, R. [81]. Energy-efficient resource allocation for secure OFDMA systems. *IEEE Transactions on Vehicular Technology*, 61(6), 2572–2585, 2012. Total citations: 171; Average per-year citations: 17.01.

The most highly cited article was published by Ng, Lo, and Schober in 2013, and reached 354 citations. Among the 10 most highly cited articles, the majority were published after 2010, with only two papers published before 2000. The most prolific author, Ng D.W.K., has four papers in the list of the top-cited papers, ranked 1st, 2nd, 7th, and 10th, and published in 2013, 2012, 2015, and 2012, respectively. This researcher's papers reached 1079 citations. None of the other most prolific authors were ranked on the same scale. The smallest difference in the number of citations was between the first and the second articles.

In order to carry out a comprehensive bibliometric analysis, the authors' keywords within the published articles were examined. These keywords reflect the main ideas and concepts of the papers, and, hence, they represent an important way for connecting authors with readers. In this study, VOSviewer is used to visualize the authors' keywords co-occurrences network, and to identify the themes of the papers published in FP (see Figure 9).

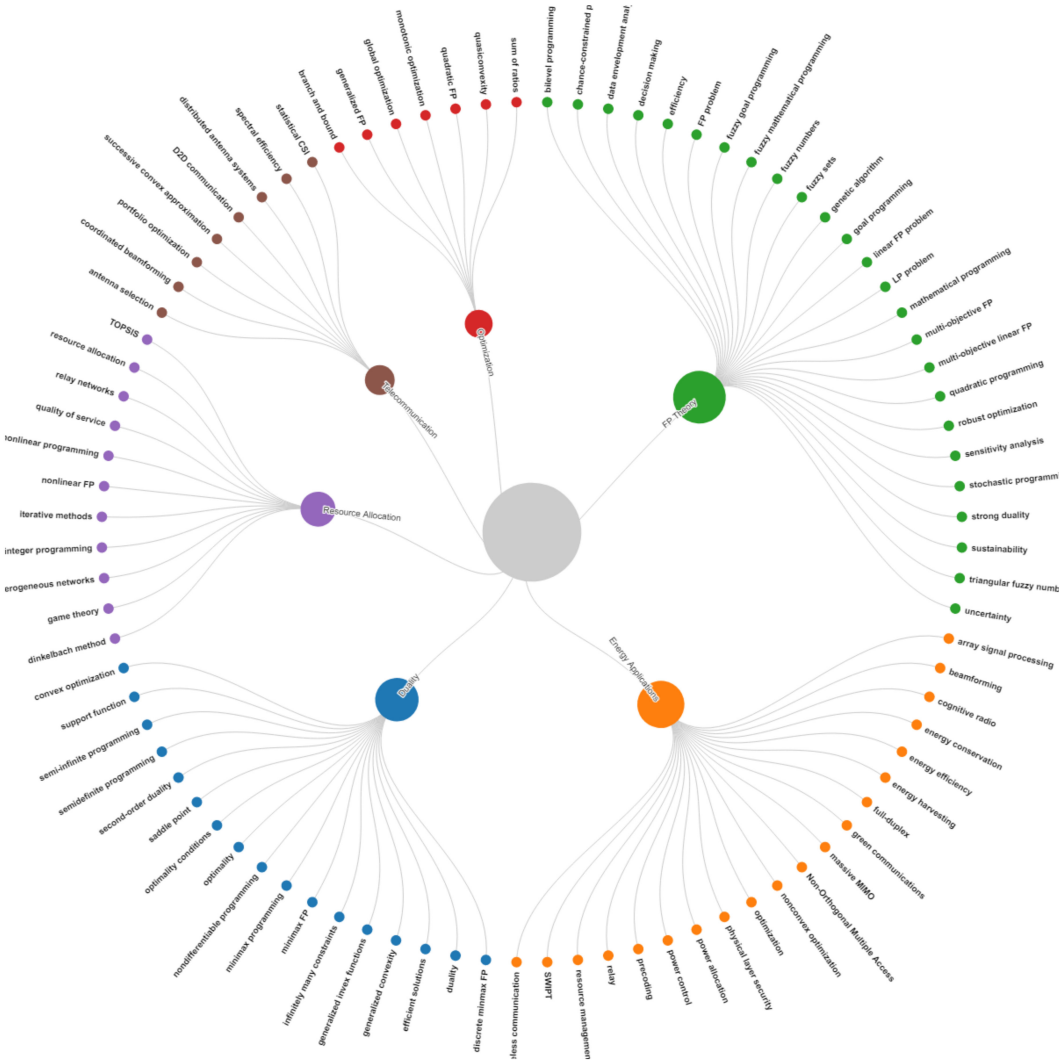

Figure 9. Author keywords co-occurrences network, $n > 10$.

The results indicate that the authors used 3386 different keywords. The keywords that were used more than 10 times include "energy efficiency" and "resource allocation", which are by far the most frequent, followed by "quality", "power allocation", "linear fractional programming" and "global optimization". The keywords occur within six different clusters of different colors, representing the following themes:

- **FP Theory** (green color) contains author keywords such as: "bilevel programming", "chance-constructed programming", "data envelopment analysis", "decision making", "efficiency", "FP problem", "fuzzy goal programming", fuzzy mathematical programming", "fuzzy numbers", "fuzzy sets", "genetic algorithm", "goal programming", "linear FP problem", "LP problem", "mathematical programming", "multi-objective FP", "multi-objective linear FP", "quadratic programming", "robust optimization", "sensitivity analysis", "stochastic programming", "strong duality", "sustainability", and "under", etc.
- **Energy Application** (orange color) is characterized by author keywords such as: "array signal processing", "beamforming", "cognitive ratio", "energy conservation", "energy efficiency", "energy harvesting", "full-duplex", "green communication", "massive MIMO", "Non-Orthogonal multiple access", "nonconvex optimization", "optimization", "physical layer security", "power allocation", "power control", "precoding", "relay", "resource management", and "SWIPT", etc.

- **Duality** (blue color) is represented by author keywords such as: "discrete minimax FP", "duality", "efficient solution", "generalized convexity", "generalized invex function", "infinitely many construct", "minimax FP", "minimax programming", "non-differentiable programming", "optimality", "optimality conditions", "saddle point", "second-order duality", "semidefinite programming", semi-infinite programming", "support function", and "convex optimization", etc.
- **Resource Allocation** (violet color) is represented by author keywords such as: "dinkelbach method", "heterogeneous network", "resource allocation", "integer programming", "interactive methods", "non-linear FP", "non-linear programming", "quality of service", "relay networks", and "TOPSIS", etc.
- **Telecommunication** (brown color) contains author keywords such as: "antenna selection", "coordinated beamforming", "portfolio optimization", "successive convex approximation", "D2D communication", "distributed antenna systems", and "statistical CSI", etc.
- **Optimization** (red color) contains keywords connected to optimization, such as: "sum of ratios", "quasiconvexity", "quadratic FP", "monotonic optimization", "global optimization", "generalized FP", and "branch and bound", etc.

3.3. Citation Burst Analysis

The burst detection technique is used to identify sharp increases of interest or particular attention in FP from 1965 to 2020. Table 5 exhibits the chronological evolution of authors' keywords during the period of time. The second column shows burst strength which represents the intensity of the burst, that is, how great the change is in the word frequency that triggered the burst. In addition, the last column includes blue and red lines where the blue line portrays the beginning and end of a keyword through the years and the red line illustrates the period of keyword burst. To be more specific, CiteSpace (Chen [66,67]) is used to show the degree of attraction of scholars to different FP research fields, and to explicitly capture the active areas. Technically, CiteSpace uses the burst detection algorithm Kleinberg [82] to detect burst-terms with high-frequency change rates. In this research, the CiteSpace function unveils that 1991 was the year of mutation for the field of FP. Table 5 demonstrates that scientific production in FP includes duality, optimality condition, global optimization, optimality, sufficient conditions, fractional programming criteria, generalized convexity, multi-objective FP, invexity, duality theorem, convexity, energy efficiency, generalized FP, efficiency, resource allocation, goal programming, massive MIMO, fuzzy programming, minimax FP, SWIPT, sufficient optimality condition, nonlinear sum, downlink, and bound algorithm.

In order to enhance the comprehensive overview of FP, burst detection was further applied to analyze the most strongly cited authors. Table 6 illustrates the top 15 cited authors with the strongest citation bursts.

Bector appears at the top of the list, with a maximum burst strength of 28.35. Additionally, Mangasarian records the longest burst duration, spanning 1972 to 2007. Zappone exhibits the most recent citation burst, starting from 2017, which may suggest that this author's work is likely to be a hot and leading topic in FP.

Table 7 presents the top 10 cited journals with the strongest citation bursts from 1965 to 2020.

The listed journals received frequent citations in FP-related papers over a certain period of time. The citation bursts of the *Journal of Mathematical Analysis and Applications* were the strongest (54.73). Among the top 10 cited journals, *Operational Research* and *Naval Research Logistics* present the longest burst durations of 44 years (1968–2011) and 41 years (1965–2005), respectively. The latter result suggests that FP-related publications cited these journals earlier and explosively. More recently, the citation burst of *IEEE Access* was the closest to 2020, the date of the present study, which means that this journal still has a substantial influence on the FP area, and thus, it can have impacts upon future research directions.

Table 5. Top 25 keywords with the strongest citation bursts.

Author Keywords	Strength	Begin-End	1965–2020
Duality	28.23	1990–2014	
Optimality Condition	14.55	1995–2014	
Global Optimization	14.03	2000–2014	
Optimality	10.46	2005–2014	
Sufficient Condition	9.38	2000–2014	
Fractional Programming	8.37	2005–2014	
Criteria	8.27	1995–2014	
Generalized Convexity	7.39	1990–2014	
Multi-Objective FP	6.86	2000–2019	
Invexity	6.56	1990–2014	
Duality Theorem	6.3	2000–2014	
Convexity	6.17	1995–2014	
Energy Efficiency	6.13	2015–2020	
Generalized FP	6.04	1990–2009	
Efficiency	5.97	1995–2014	
Resource Allocation	5.9	2015–2020	
Goal Programming	5.58	1995–2009	
Massive MIMO	5.55	2015–2020	
Fuzzy Programming	4.99	2000–2014	
Minimax FP	4.77	2010–2014	
SWIPT	4.76	2015–2020	
Sufficient Optimality Condition	4.72	2005–2009	
Nonlinear Sum	4.59	2005–2014	
Downlink	4.52	2015–2020	
Bound Algorithm	4.39	2005–2014	

Table 6. Top 15 cited authors with the strongest citation bursts. The last column includes blue and red lines where the blue line portrays the beginning and end of a cited author through the years and the red line illustrates the period of a cited authors burst.

Cited Authors	Strength	Begin -End	1965–2020
Bector	28.35	1990–2011	
Chandra	28.16	1988–2012	
Weir	24.44	1990–2008	
Zappone	23.61	2017–2020	
Jagannathan	21.53	1968–1996	
Ng	21.13	2015–2018	
Vandenberghe	20.51	2016–2018	
Miao	19.71	2012–2016	
Mangasarian	19.52	1972–2007	
Craven	19.4	1975–2008	
Lai	19.18	1999–2014	
Mishra	18.82	2006–2013	
Liu	18.25	1998–2014	
Mond	18.21	1978–2013	
Hanson	17.33	1989–2013	

Table 7. Top 10 cited journals with the strongest citation bursts. The last column includes blue and red lines where the blue line portrays the beginning and end of a cited journal through the years and the red line illustrates the period of a cited authors burst.

Cited Journals	Strength	Begin-End	1965–2020
J Math Anal Appl	54.73	1984–2012	
Ieee Access	47.23	2018–2020	
J Optimiz Theory App	39.05	1984–2012	
Optimization	37.88	1995–2011	
Nonlinear Programmin	35.00	1972–2009	
J Global Optim	32.44	2002–2013	
J Aust Math Soc B	32.28	1988–2013	
Nav Res Log	29.13	1965–2005	
Oper Res	27.13	1968–2011	
J Info & Optimiz Sci	27.12	1990–2012	

4. Discussion

One of the most striking results is undoubtedly the fact that 94.2% of the publications related to FP appeared after 1990, corresponding with the upsurge of the digital revolution, and characterized by the adoption and proliferation of digital computing and communication technologies.

The synchrony of these events is better perceived through the disciplines where FP has been duly applied, with the top categories being Engineering Electrical Electronic (31.19%), Telecommunications (26.61%), and Applied Mathematics (25.67%). Regardless of the disparities noted among the proportions of publications within the different categories, these results reflect without a doubt the practical scope of FP as a sharp tool for modeling problems across several disciplines. As such, it is perhaps essential to disseminate these facts to the broader scientific community with the intention of opening new research horizons.

These results do not corroborate with the profile of the most productive scholar, You, FQ, who is indicated as being the most productive scholar, with 2.09% of the total publications and a ranking at the top of the list for the H index and >10 indicators, while originating from energy systems engineering. Although the category of "energy" has the least number of publication records (0.99%), it is very likely that such a ranking is due to the term "engineering", which falls into the first position, along with Electrical and Electronic, along with 31.49% of the records. Nevertheless, the ranking patterns of the TC indicators, as well as the ratio TC/TP, seem to be more consistent with the overall results, revealing Ng, DWK, who belongs to the wireless communication field, as the lead.

No conflict can be found regarding the journals ranking for the TC indicators. Here, *IEEE Transactions on Wireless Communications* stands at the top of the list, emphasizing the outcomes of the research direction, which indicate that 57.8% of the reviewed records fall under the categories Engineering Electrical Electronic and Telecommunications.

In terms of the affiliations of the scholars who are actively working on FP, 7 out of the top 10 higher education institutions are universities that are located in China, though the Indian Institute of Technology System (IIT System, India) ranks first for the TP and TP% indicators, whereas the Dresden University of Technology leads the list based on the TC/TP indicator, which may suggest a wide degree of recognition for FP in this institution.

With regard to both the total number and the percentage of publications, China is the most prolific country, with 626 (34.56%) publications, followed by USA, with 286 (15.79%), and India with 271 (14.96). With six Asian countries/regions (China, India, Taiwan, Japan, Iran, and South Korea) listed among the top 10 most prolific countries, these results suggest that Asian universities are the most high performing within FP-related research.

The collaboration of FP Chinese scholars appears to be the strongest, with peers in USA, Canada, and England, but it is somehow weaker compared to other scholars from India, South Korea, Australia, and Taiwan. It is worth noting that the majority of the top scholars who have been identified as working on FP in USA, Canada, England, and Australia, are presumably from a Chinese background. Accordingly, the aforementioned collaborative pattern can be partly viewed from the migration perspectives of mainland Chinese students and scholars, besides the flow of migrants that followed the Hong Kong handover in 1997 (Gürüz [83]).

5. Conclusions

This paper presented the first comprehensive review of the literature pertaining to FP. This review is unique, not only because it spans 55 years of FP-related research (1965–2020), but also because it was conducted through the bibliometric approach, a state-of-the-art methodology with proven superior features. Moreover, the importance of such a study stems from the emergence of FP as a piercing tool to model real-life problems that are likely to occur over a wide range of industries where the potential of FP still needs to be further explored. With 1811 records extracted from WoS data sources, we constructed a series of scientific maps of the publication numbers, countries, institutions, prolific authors, and

journals. We also performed papers co-citation analysis, keywords co-occurrence analysis, and burst citation analysis on FP studies to provide a general overview of the field.

Our findings showed that China's universities are leading the research in FP, as not only the most productive, but also the most superior in terms of the prolific universities that have been identified in the field, which counted 7 Chinese universities out of 10. Additionally, the strongest citation bursts place China at the top of the list from the high quality of the research perspective. Overall, universities from the USA and India succeed in the ranking, rendering the three countries as the main players in the FP research field.

With respect to the scientific journals, *The European Journal of Operational Research* (*Eur. J. Oper. Res*) has the most significant influence among the academic journals publishing FP research, followed by the the *Journal of Optimization Theory and Applications* (*J. Optim. Theory. Appl.*). Through thematic analysis, the extracted knowledge bases revealed that the research hotspots of FP studies focus on the FP Theory, Energy Application, Duality, Resource Allocation, Telecommunication, and Optimization. Finally, burst detection analysis revealed that more burst keywords emerged and changed more frequently during the period spanning 1990–2014, compared with the early stages of the research, suggesting that there were no steady research directions. However, the recent upsurge of keywords, such as "Multi-Objective FP", "Energy Efficiency", "Resource Allocation", "Massive MIMO" (multiple-input and multiple-output), "SWIPT" (simultaneous wireless information and power transfer), and "Downlink" in FP studies undoubtedly unveils that there is a real proliferation of FP in applications pertaining to telecommunication and electrical engineering.

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