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Research Article

A Scientometric Analysis of Multiobjective Optimization Research

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ABSTRACT
Multiobjective optimization (MOO) has been adopted in many areas of research where optimal decisions must be made in the presence of trade-offs between two or more conflicting objectives. MOO assists researchers and practitioners to optimize multiobjective simultaneously. Despite the volume amplification of the MOO research in many scientific and engineering fields, there is not a single analytical study addressing the evolution and impact of this topic. Thus, the present study conducts a scientometric analysis to anatomize the publications on MOO research, and their intellectual structure and networking. The study offers a comprehensive analysis of the research by analyzing and identifying the advancement, growth, active contributors, influential journals, and seminal documents. It also visualizes the intellectual network through mapping publications' co-citation analysis. Through an in-depth analysis of MOO research evolution and pathways, this study provides researchers and practitioners with a better understanding of the development trends that have emerged in this field over the past three decades, which can also be a guidance for future research. As the first scientometric investigation of MOO research, the present study offers several implications for future research.

Keywords: Multiobjective optimization, Scientometric analysis, Bibliometrics, Research impact, Research trend.

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INTRODUCTION

Multiobjective optimization (MOO), also known as multi-objective programming or Pareto optimization, is an area that deals with optimization problems with more than one objective function to be optimized simultaneously. In various research areas, the application of MOO techniques has a great interest in finding optimal solutions in the presence of conflicting objectives.[1,2] The demand to optimize more than objective simultaneously has recently been increased. Therefore, the field of MOO research has acquired more attention and global popularity in recent years. The applications of MOO are receiving greater attention and many studies have been conducted.[3,4] MOO is also an interdisciplinary research field, covering disciplines such as computer science, engineering, management, mathematics, and decision science. Some review articles offered an overview of MOO research; however, they focused on reviewing its applications in certain domains such as petroleum refinery,[5] engineering,[6] economics and finance,[7] wireless sensor networks,[8] and energy-saving,[9] and other disciplines.[10,11] None of the conducted studies provides an analysis study screening the previous reviews and assessing the bibliometric indicators.

Nevertheless, no study has attempted to answer the following questions: (i) When did research begin in the field, how did it grow over the past decades, and what is the annual growth rate? (ii) What are the existing authorship patterns and author productivity in the field? (iii) Which research areas have widely applied MOO for the optimization purpose and how have they developed? (iv) Which countries, institutions, and authors are active contributors in this research topic? What is the difference in research progress between countries? (v) What is the degree of collaboration among scholars, institutions, and countries? (vi) Which journals are most represented in the MOO field? (vii) Which documents played a vital role in the evolution of knowledge about MOO?

We believe that answering the above questions will provide a comprehensive picture for researchers in the field, which in turn will help them direct their research and identify potential collaboration opportunities. The analysis of scientific literature is referred to as *scientometric,* which is a powerful tool for discovery and information management to provide beneficial analytical results in different fields.[12] It adopts statistical methods to mine the data of publication quantities, citation frequencies, and collaborations involved in retrieved publications. Scientometric analysis has been increasingly used for research evaluation in different aspects.[13-15] It facilitates effective understanding of the magnitude of publications and citation growth, the trends and patterns in growth, the contribution of authors, institutions, or countries, recognition of major research areas, and the collaboration pattern in certain disciplines.

To the best of our knowledge, no single scientometric analysis has been conducted to analyze the evolution, advancement, and major contributors in the MOO research. Thus, this study aims to offer a comprehensive analysis of the MOO research by identifying and analyzing the advancement, growth, active contributors, influential journals, and seminal documents. This study would help researchers and practitioners to identify research trends, potential funders, and collaborators. The primary objectives of this study can be summarized as follows: (i) presenting a quantitative assessment of different aspects of MOO research for the period from 1990 to 2019; (ii) identifying the basic characteristics of the literature, such as research growth in terms of quantity of publications and citations, and expected trends; (iii) identifying the influential contributors in this research topic; (iv) evaluating the authorship and collaboration pattern in research productivity; (v) constructing collaboration analysis at different levels (vi) identifying the focal journals and documents which have played a key role in the knowledge evolution in the field; (vii) uncovering the research areas and changing trends over time, and (viii) investigating funding support.

MATERIALS AND METHODS

Data Source

There is no unified term used for multiobjective optimization. Scholars often used terms such as multiobjective optimization, multi-objective optimization, or multiobjective optimization, etc. Therefore, this study takes different possible expressions to refer to MOO as search terms. Data in this study were extracted from the Web of Science (WoS) database core collections.

The following retrieval strings are used to capture the MOO research publications on WoS: TS=("Multiobjective optimization" OR "Multi-objective optimization" OR "multiobjective optimisation" OR "multi-objective optimisation" OR "multiobjective evolutionary" OR "multi-objective evolutionary"* OR "multiobjective genetic*" OR "multi-objective genetic*" OR "multi-objective programming" OR "multiobjective programming" OR "Pareto optimization" OR "multi-objective optimal*"). We looked at the complete horizon by setting up the period from 1900 to 2019.. The bibliographic data were collected from the Web of Science on November 20, 2020 (Appendix Table A1). Accordingly, a total of 29,228 publications were downloaded. Each publication contains detailed bibliographic information, e.g., publication's title, abstract, keywords, citations, authors, authors' affiliation, year, and country.

Table A1: Search results (WOS).

Number	Research Query	Results
#1	TS=("Multiobjective optimization" OR "Multi-objective optimization" OR "multiobjective optimisation" OR "multi-objective optimisation" OR "multiobjective evolutionary" OR "multi-objective evolutionary"* OR "multiobjective genetic*" OR "multi-objective genetic*" OR "multi-objective programming" OR "multiobjective programming" OR "Pareto optimization" OR "multi-objective optimal*")	49,321
#2	#1 Refined by: [excluding] PUBLICATION YEARS: (2020)	44,358
#3	#2 Refined by: [excluding] DOCUMENT TYPES: (Book Review, Poetry, Art Exhibit Review, Proceedings Paper, Note, Biographical Item, Correction Addition, Letter, News Item, Excerpt, Early Access, Book Chapter, Discussion, Film Review, Meeting Abstract, Data Paper, Record Review, Reprint, Editorial Material, Retracted Publication, Retraction, Software Review)	29,231
#4	#3 Refined by: [excluding] PUBLICATION YEARS: (1960-1989)	29,032

Although the first MOO-related publication was in 1960, for the next 30 years only 196 publications (less than 0.7% of total) were recorded, as depicted in Figure 1. The results reveal significant growth in MOO research during the last three decades. As the number of publications reached 29,032, MOO research accounted for 99.33% of the total publications. The evolution rate of the MOO-related publications was gradually increasing; however, it demonstrated an exceptional growth during 2010-2019. Therefore, in this study, we will focus on the last thirty years as it includes most of the research activity in this field. Furthermore, to guarantee the quality of the paper, only article and review search types are adopted. In the sequel of this paper, we will refer to them as publications.

Methodology

The pool of retrieved publications was analyzed to uncover the evolution of MOO research, influential journals, citation patterns, potential research areas and trends, contributors, and funding agencies. After the data extraction, further analysis was conducted to identify the basic characteristics of the literature. We first looked at the growth of the field over the years from 1990 to 2019, and we calculated the annual growth rate of the total publications, year-wise, using the following formula.

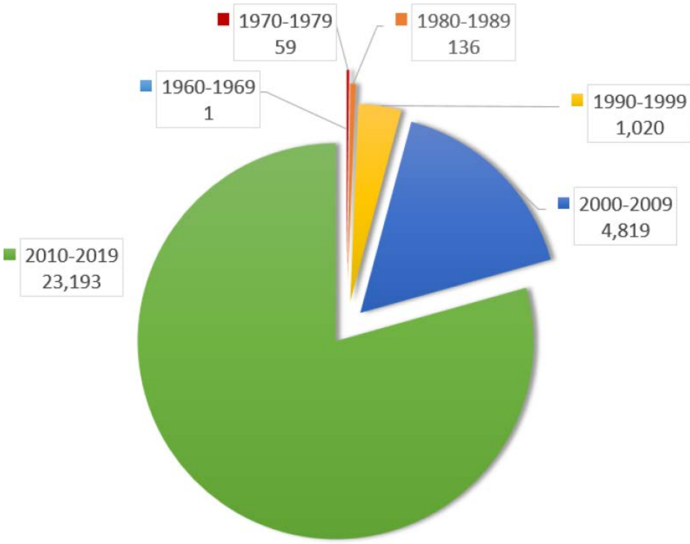


Figure 1: The evolutionary growth in number of publications covering MOO research.

$$AGR = \frac{\text{end value} - \text{first value}}{\text{first value}} \times 100 \quad (1)$$

In addition to analyzing the growth in MOO research, we have sought through this research to analyze the contributions at different levels and assess their collaboration. We used different research indicators to investigate the most influential scholars, institutions, and countries. These metrics include the total number of publications (TP), the share of the total number of publications (TP%), total number of citations received by a set of publications (TC), an average of citation per publication (ACPP), average citations per year (ACY), and 5-year impact factor according to Clarivate Analytics (IF).

Collaboration has become one of the important focus areas in scientometric analyses.[16] In this context, we used the degree of collaboration (DC) and collaborative coefficient (CC) metrics to evaluate the extent of collaboration in the MOO research field. DC, given in Equ. 2, is defined as the ratio of collaborative publications to the total publications during a certain period.[17] It is easily interpretable as a degree of collaboration that lies between zero and one, where zero indicates that the publication has only a single author and a higher value represents how often multiple-authored publications are produced. However, DC does not differentiate among the multiple authorship levels.

$$DC = \frac{N_m}{N_m + N_s} \quad (2)$$

where N_m is the multi-authored publications count and N_s is the single-authored publications count.

On the other hand, the CC metric arrives at its value by considering the proportion of multi-authored papers. It reflects both the average number of authors per publication and the proportion of multi-authored publications.[18] CC is a numerical value that lies between zero and one. When its value is close to zero, it indicates a weak collaboration rate. The following formula shows the CC calculation.

$$CC = 1 - \frac{\sum_{j=1}^{k} (1/j) f_j}{N} \quad (3)$$

where N is the publications count, k is the highest number of authors per publication, and fj is the number of j-authored publications.

The conducted analysis covers six dimensions:

(i) Geographical distribution of publications: Statistical analyses to measure a country performance and collaboration can not only help finding the most productive country in a research field but also provide a clear understanding of the output capacity of that country under study and how are the differences compared to other countries. The contribution of major countries to the global output was assessed based on the number of authors from each country. Different indicators such as the total of produced publications, received citations, the average citation per paper, and *h*-index have been considered. *h*-index is calculated according to the definition given by Hirsch.[19] In addition, we calculated the activity index (AI) and attractive index (AT) for determining the dynamic developments in a country. AI indicates the relative research effort of a country to a research field based on publications, and AT characterizes the relative impact of a country on a research field based on citations.[20] The two indicators can be calculated using the following formulas:

$$AI_y^r = \frac{P_y^r / \Sigma^P}{TP^y / \Sigma^{TP}} \quad (4)$$

$$AT_y^r = \frac{C_y^r / \Sigma^C}{TC^y / \Sigma^{TC}} \quad (5)$$

Activity index and Attractive index of country r in the year y, respectively. and are the number of publications and citations on MOO research of country in the year y; and are the total number of publications and the sum of citations about MOO in-country during the investigated period. Similarly, and represent the global number of publications and their citations in the year y; and represent globally the total number of publications and the sum of citations during the same period as that of and , respectively. A quadrant diagram has been used to compare the productivity and impact of the topmost productive countries.

*(ii). **Influential Research Institutions:*** analysis of research at the institutional level assist the funding agencies and dictions-makers to get detailed insights about the institutions' productivity in a particular field, impact, and relevance to industry. A list of the top ten most productive institutions worldwide has been presented with a set of indicators including the total of produced publications, received citations, the average citation per paper, and *h*-index.

*(iii) **Authorship analysis:*** This dimension focuses on analyzing the authorship pattern, identifying the most productive authors, and uncovering the author collaboration. Different metrics have been considered such as the rate of single and multiple authors, average author per paper, and productivity per author.[21] The formulas to calculate the two metrics are mathematically represented as below:

$$\text{Average author per paper} = \frac{\text{No. of authors}}{\text{No. of papers}} \quad (6)$$

$$\text{Productivity per author} = \frac{\text{No. of papers}}{\text{No. of authors}} \quad (7)$$

*(iv) **Co-citations analysis*** – Citations analysis is used to assess the publication's quality and influence via its received citations,[22] while Co-citation analysis is used to measure publications similarity to cluster them by narrative patterns.[23] In this study, the two analysis types are adopted to identify the most influential articles and sources titles.

*(v) **Research areas and trends:*** The field of MOO is an interdisciplinary research area, and it deals with tremendous research areas. In this study, we investigated the research areas associated with the retrieved data from WoS and their evolvements over the last three decades.

*(vi) **Funding support:*** The funding support analysis of MOO research can reflect the areas of concern to governments, private enterprises, and other funding institutions. Thus, according to the available data, we identified potential funding agencies with the highest research yield in terms of publications.

The data analysis and visualization were performed using MS Excel, VOSviewer,[24] and Biblioshiny[25] software.

RESULTS AND DISCUSSION

Research Output Trend

The growth in the volume and pattern of scientific knowledge is closely related to the evolution and pattern of publications. In this section, we analyzed the general evolutionary trend of MOO research via numerical analysis of the publications and their received citations. The data shows a significant growth of publications as this field has attracted many researchers' attention. Figure 2. Reveals that before 2000, scientists published relatively few studies in the field of MOO. However, this number has augmented in an approximately linear fashion since then. It can be perceived that a surge in MOO research happened after 2000, which is consistent with the scientists' comprehension of the capability of MOO algorithms to resolve real-world problems in different fields that require optimizations of conflicting objectives simultaneously. Looking at the study period, in 2019, the number of publications reached a peak level of 4,668 compared to 24 papers in 1990. The productivity in this area increased by 195 times and the average annual publication volume reached 967.7 articles, with an average annual growth rate of 24.5% (Appendix Table A2). This indicates that MOO research is in a "growth phase" and has great potential for evolution, which implies its critical importance for the academic and industry communities.

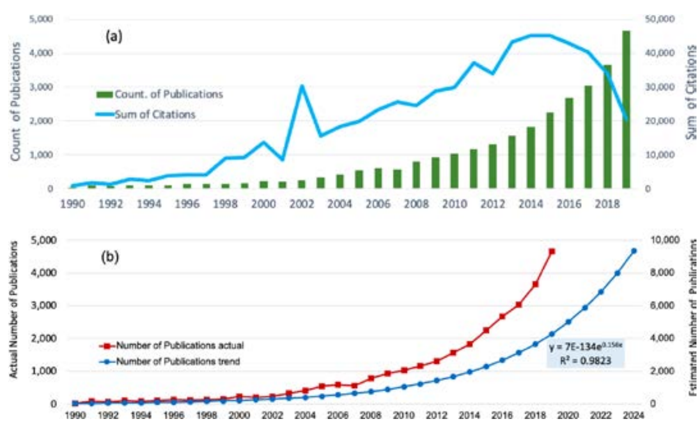


Figure 2: (a) Trends in the number of MOO related publications and their citations, (b) Trend of the MOO research growth (1990-2019), and forecast of the next five years.

Our analysis shows that not only the count of publications alone has noticeably increased over the investigated period, but the citations received by the publications have also increased significantly as well, Figure 2a. The Figure reflects the rapid increase in the number of citations to MOO-related publications. The metrics showed that TC was 619,107 during the period (1990-2019), while ACPP was 21.3. The volume of citations from articles on MOO research before the twenty-first century grew slowly, while the total volume of citations after 2001 increased steadily after 2003. This trend also reflects

Table A2: Growth of MOO research publications.

Publication Years	Count of Documents	Percentage of Total	Cumulative total	Annual growth rate
1990	24	0.00	24	
1991	84	0.00	108	2.50
1992	73	0.00	181	−0.13
1993	101	0.00	282	0.38
1994	89	0.00	371	−0.12
1995	99	0.00	470	0.11
1996	128	0.00	598	0.29
1997	126	0.00	724	−0.02
1998	141	0.00	865	0.12
1999	155	0.01	1020	0.10
2000	226	0.01	1246	0.46
2001	204	0.01	1450	−0.10
2002	237	0.01	1687	0.16
2003	329	0.01	2016	0.39
2004	409	0.01	2425	0.24
2005	540	0.02	2965	0.32
2006	595	0.02	3560	0.10
2007	559	0.02	4119	−0.06
2008	791	0.03	4910	0.42
2009	929	0.03	5839	0.17
2010	1035	0.04	6874	0.11
2011	1154	0.04	8028	0.11
2012	1306	0.04	9334	0.13
2013	1574	0.05	10908	0.21
2014	1831	0.06	12739	0.16
2015	2253	0.08	14992	0.23
2016	2681	0.09	17673	0.19
2017	3032	0.10	20705	0.13
2018	3659	0.13	24364	0.21
2019	4668	0.16	29032	0.28
Total	**29032**	**1.0**		
Average annual	**967.7**			**24.5%**

the increased attention that has been devoted to this field during the past two decades. The jump that happened in 2002 was due to the most cited article entitled "A Fast and Elitist Multiobjective Genetic Algorithm: NSGA-II" which was authored by Deb. K. *et al.*[26] The article proposed the NSGA II algorithm that has been widely employed in various fields for optimizing multiobjective. Up to the time of collecting the data, the article has been cited a total of 18,748 times and can be considered as the basis for the MOO studies. As the growth was not linear through the investigated period, an exponential regression is used to show the trend of the retrieved data and to predict the trend of growth for years after. Figure 2b shows the trend value for total publications, calculated on an annual basis, which is shown to be on an increasing trend. Moreover, forecasting the trend to 2024 also indicates an upward trend. As the trend is not linear, we used an exponential regression to show the trend of the data. We used the illustrated equation to forecast the number of publications for the next five years (2020 – 2024). The prediction results show that scholars will publish more than nine thousand publications in the MOO filed in 2024.

Geographical distribution of publications

Identification of most productive Countries

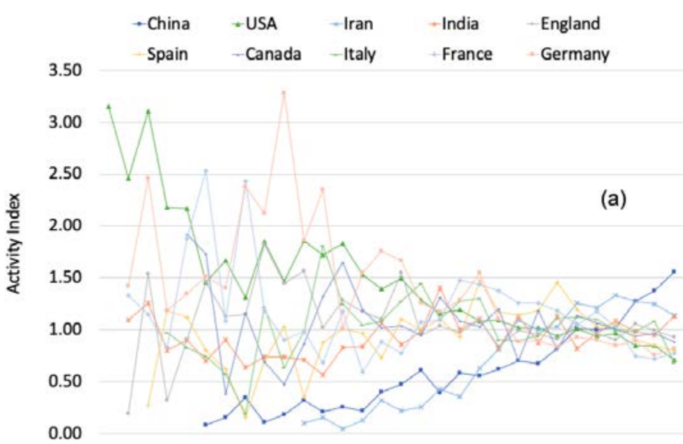
Based on the authors' addresses, the retrieved publications originate from around 127 countries. However, it can be seen that the largest share of publications came from a few countries. Based on the publications count, the research output of different countries is depicted in Figure 3, while the most productive countries are listed in Table 1. Full counting is considered to assign collaborative publications to countries or institutions. MOO publications mainly come from China, the USA, Iran, India, Canada, and some European countries. Developing nations showed significant contributions to this research topic as they captured around 51% of publications when looking at the top-ten list. China is the leading country accounting for 25.2% of MOO publications during the investigated period. The publications count alone does not imply the contribution; thus, we consider other indicators in this analysis. Among these indicators, TC, the share of TP, ACPP, and *h*-index. The analysis shows that, although China is ranked as 1st in terms of publications count, it secured the lowest ACPP compared with the top ten countries. England occupied the first position when considering ACPP, while its rank is the fifth one in terms of productivity. The USA research in this area showed a significant impact as reflected by the largest number of citations and the highest *h*-index as well. Further investigation shows that Saudi Arabia is the most

Figure 3: Geographic distribution of country in MOO research.

Table 1: The most productive countries in terms of relevant articles.

Rank	Country	TP	TP (%)	TC	ACPP	*h*-index	AI	AT
1	China	7,316	25.2	114,727	15.68	111	0.60	0.84
2	USA	4,222	14.54	116,424	27.58	127	1.49	0.72
3	Iran	2,677	9.22	52,598	19.65	86	0.70	0.99
4	India	2,525	8.7	77,016	30.51	93	0.93	0.69
5	England	1,806	6.22	62,864	34.81	103	1.08	0.72
6	Spain	1,459	5.03	28,068	19.24	69	0.94	0.69
7	Canada	1,185	4.08	27,693	23.37	72	1.07	0.78
8	Italy	1,179	4.06	25,898	21.97	70	1.02	0.74
9	France	1,043	3.59	19,197	18.41	61	1.17	0.73
10	Germany	970	3.34	22,336	23.03	70	1.43	0.76

Note: TC: Total Citations, TP: Total Publications, ACPP: Average Citations per Paper, AI: Activity Index and AT: Attractive Index



productive country in the Arab world with 333 publications, while Egypt is ranked as the second in the Arabs world and as the first one in Africa.

To assess the relative effort devoted by a country to MOO research, we adopted the activity index (AI). In addition, we used the attractive index (AT) to evaluate the impact made by a particular country.[20,27] When the value of AI equals 1, that means the research effort of a country in a particular year is equal to the global average, while the higher or lower value refers that the research effort of a country is higher or lower than the global average, respectively. Similarly, for the AT matric which assesses the research impact. The last two columns in Table 1 show the average of AI and AT for each country. More details about the values over years, the starting and ending years of AI and AT indexes for each country are presented in Figure 4.

International Collaboration

Research collaborations are an essential means of exchanging knowledge and ideas, diversifying sources of research funding, and increasing opportunities for emerging researchers.[28,29] The analysis of international cooperation in the field of MOO

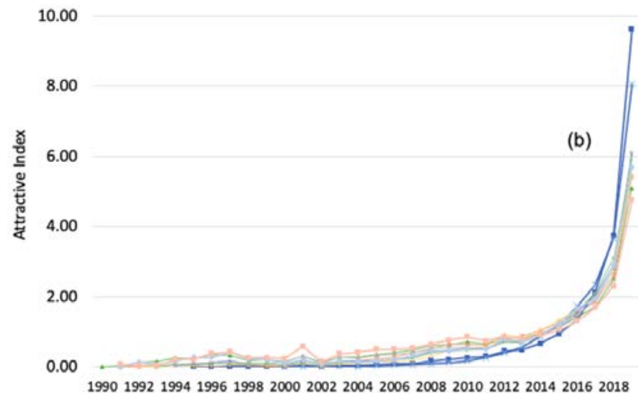


Figure 4: (a) The active index over years; and (b) the attractive index over years for the top ten most productive countries.

research revealed important insights about the countries, scientific institutions, and scientists actively collaborating in this field. Such findings are of interest to researchers to find potential partners for further research collaboration or funding opportunities in this field. Figure 5 illustrates the network of countries collaborating on MOO research. The nodes sizes refer to the publications produced by a country, and the width of connected lines denotes the count of publications jointly published by two countries in MOO research. We looked at the collaborations between countries that produce at least 100 publications, with 42 countries have met the threshold. The total link strength points out the total strength of the links of a country with other countries. The top countries' collaboration is grouped into three clusters, represented by different colors. Cluster 1 has 19 countries led by England, Spain, and Italy, while Cluster 2 consists of 15 countries led by China, the USA, and Iran. Cluster 3 includes eight countries

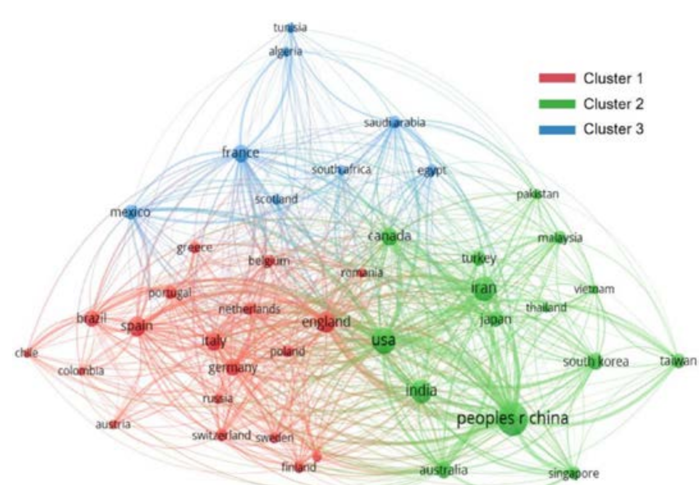


Figure 5: The collaboration of the most productive countries in MOO-related research.

led by France, Mexico, and Saudi Arabia. The network reveals a significant collaboration between the developing countries and the developed countries.

Influential research institutions

The analysis of the research output of the institutions helps in obtaining useful insights about their impact. It also shows the extent of the existing collaboration in the field of study between research institutions with each other and between research institutions and industry as well. In this study, the results showed that 5,962 research institutions around the world contribute to the field of MOO. The most productive research institutions are listed in Table 2 in descending order of the publications count. It is not surprising that eight of the ten listed institutions are from developing countries.

Table 2: Top ten most productive institutions in terms of relevant articles.

Rank	Institution	TP	TC	ACPP	*h*-index
1	Indian Institute of Technology System IIT, India	819	44,313	54.11	72
2	Islamic Azad University, Iran	528	9,560	18.11	50
3	University of Tehran, Iran	494	11,384	23.04	53
4	Chinese Academy of Sciences, China	423	8,107	19.17	44
5	Center National De La Recherche Scientifique CNRS, Franch	421	7,588	18.02	40
6	Huazhong University of Science Technology, China	299	6,028	20.16	41
7	University Science Technology, Iran	294	6,727	22.88	42
8	National University of Singapore, Singapore	286	9,289	32.48	51
9	Tsinghua University, China	266	5,618	21.12	41
10	Xidian University, China	264	5,143	19.48	36

The Indian Institute of Technology System (IIT) is the most productive institution with 819 publications, followed by Islamic Azad University with 529 publications, and the University of Tehran with 494 publications. IIT occupies the first position in all different aspects, i.e., number of publications, citations, average citations per publication, and *h*-index as well. The National University of Singapore ranks third in the total number of citations, but second in the average number of citations. The results indicate that the most-active MOO research institutions are concentrated in Asia. Nine of the top 10 research institutions are located in India, Iran, China, and Singapore. Only one among the top ten is located in France. Most of the institutions are from China, hence, it can be interpreted that the MOO research has been dominated by Chinese researchers. Surprisingly, although the USA occupied the second position at the top of the most productive countries, none of its institutions appears in the top ten productive list.

Figure 6 presents the co-authorship network of institutions with at least 100 international collaboration papers on MOO research. Only 51 institutions have met the threshold and presented in the network. In the Figure, the sizes of the nodes and fonts refer to volume size, while the nodes' colors designate the clusters to which the institutions fit. A line between two nodes implies the existence of collaborative publications produced by the connected institutions. The thickness of the line signifies the count of jointly authored publications between the two connected components. The fifty-one units are clustered into six clusters. Three of these clusters are occupied by Chinese institutions. Cluster 1, Cluster 3, and Cluster 5 consist of 20, 8, and 4 institutions, led by the Chinese Academy of Sciences, Hunan University, and Huazhong University of Science and Technology, respectively. Cluster 2 is led by the Indian Institute of Technology System and consists of 20 institutions. Cluster 4 includes seven institutions led by Islamic Azad University. The last cluster has only two institutions located in Spain.

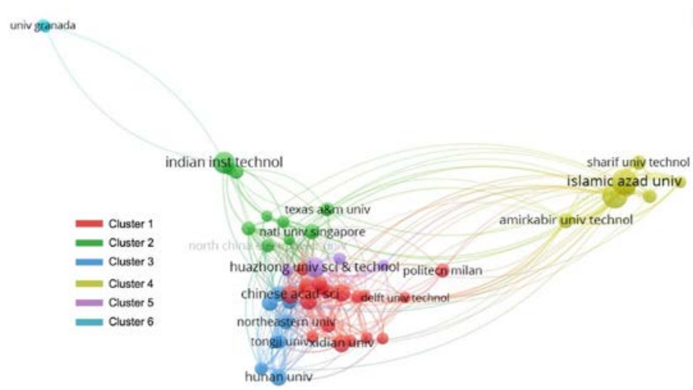


Figure 6: Collaboration network of institutions jointly authoring publications on MOO research.

Authorship Analysis

Authorship pattern

The authorship pattern analysis is concerned with the percentage of single and multiple authors. Figure 7a presents the productivity pattern of single and multiple authors yearly. Our analysis reveals that multi-authored publications are more than single-authored contributions. A total of 1,552 (5.35%) documents were single-authored publications, while the remaining documents (27,480; 94.65%) were multi-authored publications. Further analysis shows that most publications have been contributed by three authors 8,272 (28.5%), followed by two authors 7,062 (24.3%), and four authors

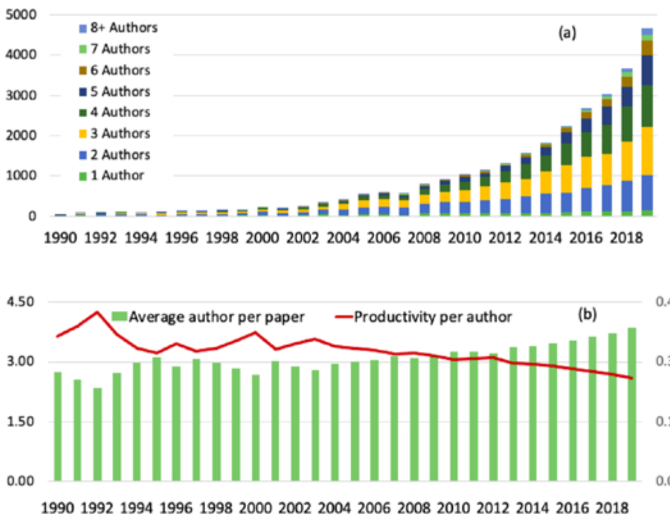


Figure 7: (a) Authorship pattern and (b) Authorship trend analysis in the field of MOO publications from 1990-2019.

6,106 (21%), respectively. Even among multiple authorships, publications involving more than seven authors have also helped to extend the literature growth on the subject. For instance, during the past four years 2017, 2018, and 2019, the number of publications co-authored by eight authors, or more are 60, 90, and 158, respectively. Interestingly, the productivity patterns on the MOO contributed by the multiple authors have increased steadily over years. The obtained observation revealed the MOO research is dominated by multiple authors, which is consistent with the interdisciplinary nature of the MOO applications.

Figure 7b depicts the data about the average author per paper and author productivity. The analysis exposes the average number of authors per publication is 3.1 for 29,032 papers published during the last three decades. A careful examination of the findings reveals that over the years there is a continuous increase in average author per paper in proportion to the growth in the field and the increase in the number of publications. In addition, the average productivity per author for the investigated period is 0.33. The obtained average productivity of the author ranges between 0.26 and 0.42 (Appendix Table A3). The highest productivity per author was recorded in 1992. The lowest percentage was in 2019, although it has the highest number of publications. This is an expected result due to the increase in collaborative work between scholars.

Identification of most influential authors

Co-authorship can be used as an indicator of scientific collaboration.[30] As shown above, 94.65% of the publications had multiple authorship and 5.35% of contributions had single authors. The calculations of the degree of collaboration (~0.95) and collaboration coefficient (= 0.64) show the strength of collaboration in the MOO research field.

Author collaboration analysis can reflect the contribution of an author, as well as the degree of collaboration, but it cannot reflect the influence of a given author on MOO research. We use a collaboration network map to provide further analysis and to show the cooperative relationships between various authors. Figure 8 demonstrates the collaboration network map of the authors of MOO research. In the network, each node represents an author. The size of a node is proportional to the number of publications co-authored by the author, while

Table A3: Authorship trend analysis.

Year	Count of publications	Number of authors	Publications authored by a single author	Publications authored by multiple authors	Average authors per paper	Productivity per author
1990	24	66	3	21	2.75	0.36
1991	84	215	21	63	2.56	0.39
1992	73	172	12	61	2.36	0.42
1993	101	274	12	89	2.71	0.37
1994	89	266	10	79	2.99	0.33
1995	99	308	12	87	3.11	0.32
1996	128	370	15	113	2.89	0.35
1997	126	386	16	110	3.06	0.33
1998	141	421	16	125	2.99	0.33
1999	155	439	19	136	2.83	0.35
2000	226	606	31	195	2.68	0.37
2001	204	617	18	186	3.02	0.33
2002	237	686	22	215	2.89	0.35
2003	329	918	51	278	2.79	0.36
2004	409	1,207	38	371	2.95	0.34
2005	540	1,615	42	498	2.99	0.33
2006	595	1,807	44	551	3.04	0.33
2007	559	1,750	36	523	3.13	0.32
2008	791	2,448	68	723	3.09	0.32
2009	929	2,939	87	842	3.16	0.32
2010	1,035	3,372	72	963	3.26	0.31
2011	1,154	3,749	73	1081	3.25	0.31
2012	1,306	4,194	71	1235	3.21	0.31
2013	1,574	5,304	83	1491	3.37	0.30
2014	1,831	6,215	75	1756	3.39	0.29
2015	2,253	7,798	98	2155	3.46	0.29
2016	2,681	9,472	118	2563	3.53	0.28
2017	3,032	11,017	126	2906	3.63	0.28
2018	3,659	13,591	120	3541	3.71	0.27
2019	4,668	18,008	143	4523	3.86	0.26

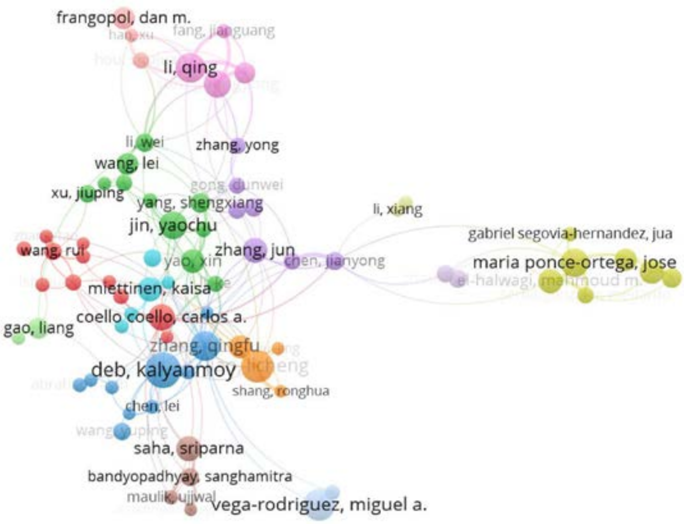


Figure 8: Collaboration network of authors.

the distance between two nodes is inversely proportional to the number of collaborative publications. The strength of collaboration is represented by the thickness of the connected lines. In this analysis, researchers were selected if he has co-authored at least 20 publications. Out of 54,498 authors, only 122 authors have met the threshold. Because some of the 122 items are not connected, the largest set of connected items consists of 74 authors grouped into 14 clusters, as shown in Figure 8. The impact of authors has been examined based on TP, TC, ACPP, and *h*-index. The 10 most productive authors in the MOO field are listed in descending order of the publications count in Table 3. The analysis exposes that Kalyanmoy Deb has the highest number of total citations, 30,499 from 124 publications, and the highest *h*-index.

Table 3: Top 10 authors in the MOO field during 1990-2019.

Lead Author	Institute	TP	TC	ACPP	*h*-index
Deb, Kalyanmoy	Michigan State University, USA	124	30,499	249.99	42
Jiao, Licheng	Xidian University, China	92	2,468	26.83	26
Li, Qing	Univ Sci and Technol Beijing, China	88	3,951	50.01	40
Vega-Rodriguez, Miguel A.	University of Extremadura, Spain	70	512	7.31	14
Zhang, QingFu	City University of Hong Kong, Hong Kong	66	9,152	138.67	32
Kim, Kwang-Yong	Inha University, South Korea	62	938	15.13	19
Coello Coello, Carlos A.	Metropolitan Autonomous University, Mexico	62	3,292	53.1	28
Maria ponce-Ortega, Jose	Michoacan University of Saint Nicholas of Hidalgo, Mexico	61	1,327	21.75	20
Marechal, Francois	Swiss Federal Institute of Technology Lausanne. Switzerland	60	2,023	33.72	28
Jin, Yaochu	Southern University of Science and Technology, China	59	3,590	60.85	27

Citations Analysis

Analysis of Publications

Citation analysis is a way to measure the publication impact by looking at the number of times that publication is cited.[31] The publication's analysis offers insights that help researchers explore the overall evolution and identify new topics for further research. Therefore, in this section, we identify the most influential articles based on citations received in MOO research from 1990 to 2019. Although the retrieved publications were cited 619,107 times, 2,323 (nearly 8%) publications have never been cited by other publications.

Co-citation is defined as the frequency of citation from two publications together in other publications, and co-citation analysis is an effective method for assessing publication similarity and identifying narrative patterns in research by grouping publications into different groups.[32] Figure 9 depicts the citations and co-citation network of MOO publications that have been cited by scholars more than 300 times. A total

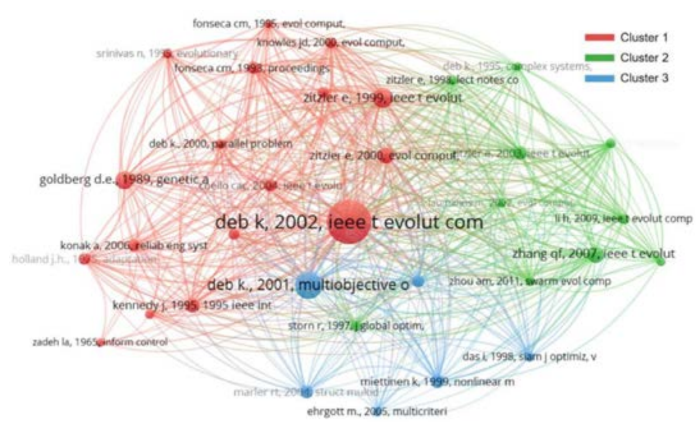


Figure 9: Co-citation network of publications cited more than 100 times by WoS.

of 33 references meeting the threshold are divided into four clusters. The node size is associated with the number of times a publication was cited. The different clusters, signified by different colors, are associated with broad narrative patterns in MOO research. Cluster 1 is about the evolutionary algorithms and it contains seventeen papers led by the seminal paper of Deb K. Cluster 2 includes ten papers that uses the decomposition as a strategy in multiobjective optimization, while cluster 3 contains only six papers introducing the concept of multi-criteria to this field of research.

Table 4 illustrates the top 10 most highly cited papers published in the context of MOO research. The paper "A fast and elitist multiobjective genetic algorithm: NSGA-II" by Deb, K *et al.*[26] is the most cited article. This is clearly indicated by the citation-analysis conducted using Vosviewer and depicted in Figure 9. Also, the analysis identifies its high quality through receiving the highest average of citations per year. This focal paper of Deb[26] had been further analyzed by Zitzler in[32] where the strengths of the method described in the focal paper has been highlighted further. That analysis has made the Deb's technique (NSGA-II) became an essentail tool for MOO research studies. It is worth mentioning that the citation window we considered for each article started from its publication year and continued until the end of 2019.

Table 4: List of topmost cited MOO related citations.

Article	Title	TC	ACY
(26)	A fast and elitist multiobjective genetic algorithm: NSGA-II	16,956	942.0
(32)	Multiobjective evolutionary algorithms: A comparative case study and the Strength Pareto approach	3,855	183.6
(33)	MOEA/D: A multiobjective evolutionary algorithm based on decomposition	2,624	201.8
(34)	Comparison of Multiobjective Evolutionary Algorithms: Empirical Results	2,671	133.6
(35)	Differential Evolution: A Survey of the State-of-the-Art	2,207	245.2
(6)	Survey of multi-objective optimization methods for engineering	1,954	122.1
(36)	Performance assessment of multiobjective optimizers: An analysis and review	1,869	109.9
(37)	Handling multiple objectives with particle swarm optimization	1,761	110.1
(38)	Multi-objective optimization using genetic algorithms: A tutorial	1,437	102.6
(39)	An Evolutionary Many-Objective Optimization Algorithm Using Reference-Point-Based Non-dominated Sorting Approach, Part I: Solving Problems with Box Constraints	1,047	174.5

Note: ACY: Average Citations per Year

Co-citation is defined as the frequency of citation from two publications together in other publications, and co-citation analysis is an effective method for assessing publication similarity and identifying narrative patterns in research by grouping publications into different groups.[32] Figure 9 depicts the citations and co-citation network of MOO publications that have been cited by scholars more than 300 times. A total of 33 references meeting the threshold are divided into four clusters. The node size is associated with the number of times a publication was cited. The different clusters, signified by different colors, are associated with broad narrative patterns in MOO research. Cluster 1 is about the evolutionary algorithms and it contains seventeen papers led by the seminal paper of Deb K. Cluster 2 includes ten papers that uses the decomposition as a strategy in multiobjective optimization, while cluster 3 contains only six papers introducing the concept of multi-criteria to this field of research.

Analysis of publication sources

The journals are essential resources for any research field that provides significant, high-impact research, which encourages further research and study in research communities. It is, therefore, worthwhile to assess the journal's impact on the area of research under study. In this regard, the journals were analyzed to identify the journals with the largest share of MOO publications. The retrieved articles were published in 3,448 unique publication sources. However, more than 50% of publications appear in the top 150 sources.

Table 5 lists the top 10 most significant journals on MOO research to which scholars in the field are contributing. It ranks the most productive journals related to MOO research during the period 1990–2019 concerning the number of publications. In addition, the table depicts publication to share, citation

Table 5: Top ten productive journals in MOO research.

R	Journal	TP	TC	AC	IF	*h*-index	Initial Year	AAGR
1	Applied Soft Computing	529	11,338	21.44	5.39	49	2005	62.7
2	Energy	513	14,642	28.59	6.046	57	1990	65.7
3	Energy Conversion and Management	444	13,235	29.84	7.447	61	2007	54.3
4	Applied Energy	380	13,085	34.47	9.086	57	2006	24.1
5	International Journal of Advanced Manufacturing Technology	375	7,059	18.85	2.925	42	2000	47.6
6	European Journal of Operational Research	372	15,658	42.1	4.729	65	1990	45.2
7	Expert Systems With Applications	311	8,802	28.32	5.448	51	1996	30.9
8	Journal of Cleaner Production	305	8,040	26.48	7.491	43	2005	6.4
9	Applied Thermal Engineering	286	6,718	23.52	4.514	39	1997	39.1
10	IEEE Transactions on Evolutionary Computation	280	56,945	205.35	11.17	91	1999	48.4

frequency, citations per publication, the impact factor for five years, and *h*-index (according to the retrieved data). A higher *h*-index implies better impact. In Table 5, we also considered the year in which each journal published its first relevant article and the AAGR (the average annual growth rate) of the volume size of each journal in the MOO research field. In Table 5, we also considered the year in which each journal published its first relevant article. Applied Soft Computing tops the list of the most productive journals, although it contributed only to half of the investigated period. It has the maximum number of publications (529), the impact factor (5.39), and the ratio of citation per publication (21.44). These indicators expose the high impact of the Applied Soft Computing journal in the MOO research field, although it published the first article in this field in 2005. It has a much better attraction to MOO scholars than many journals. The journals Energy and Energy Conversion and Management are ranked second and third in terms of publications count. Although IEEE Transactions on Evolutionary Computation journal occupy the tenth position in the list in terms of the number of publications, it has the maximum of citations (56,945) and highest *h*-index (91). The *h*-index here is calculated by considering the retrieved MOO-related Publications. That means that more than 90 articles and reviews published by IEEE Transactions on Evolutionary Computation journal have been cited at least 91 citations each. It is worth mentioning that around 30% of citations received by IEEE Transactions on Evolutionary Computation journal were for the most cited paper presented in the previous section. More details are given in the Appendix (Table A5).

Generally, the top ten productive journals cover related publications in various fields such as soft computing, energy manufacturing, computer science, expert systems applications, and thermal engineering. It is worth mentioning that the papers published in the listed journals represent only 13.26% of the total, while the remaining 86.74% are distributed over 3,438 source titles. This indicates that research on MOO is inter-sectional and diverse and reflects the complex development of MOO research.

Figure 10 illustrates the co-citation network of journals. The network represents with large nodes the journals that have substantial impact in MOO research. The network comprises 125 journals that met a threshold of having at least one thousand citations. The node's color denotes the journal topic, while its size indicates the received citations. The total link strength is associated with the closeness to other journals. IEEE Transactions on Evolutionary Computation is the most-cited journal (total link strength 538,343, citations 25,883). The NSGA-II technique that is showed in Figure 9 was published in this journal, which increased the research interest on MOO applications. This is followed by the European Journal of Operational Research (total link strength 386,156, citations

Table A5: The publication output of the top ten publication sources of MOO research.

Year	Applied Soft Computing	Energy	Energy Conversion and Management	Applied Energy	International Journal of Advanced Manufacturing Technology	European Journal of Operational Research	Expert Systems with Applications	Journal of Cleaner Production	Applied Thermal Engineering	IEEE Transactions on Evolutionary Computation
1990										
1991		-100				-50				
1992						300				
1993						-50				
1994						-50				
1995						600				
1996						-57				
1997						67	-100			
1998						-20			-100	
1999		-100				175				
2000						-45	-100			0
2001					-100	17				0
2002						0	-100			100
2003		-100				-43				500
2004					200	100				-50
2005					-33	50				-50
2006	100				500	33	0	-50		267
2007	350	0		0	-33	100	0	-100	0	-45
2008	33	0	0	-100	13	-41	300		100	83
2009	-25	0	100		144	26	400	-100	50	27
2010	-11	1100	150	-17	-14	25	25		133	14
2011	338	17	-10	40	16	-67	76	-100	0	-38
2012	-14	79	-33	0	-32	30	-30		-29	40
2013	27	4	183	57	100	-54	-26	100	140	-7
2014	11	50	88	109	17	250	-30	38	-17	62
2015	29	28	53	0	-17	67	88	109	180	5
2016	-6	38	-22	143	28	-46	10	43	71	18
2017	57	17	58	21	22	37	-21	42	15	-15
2018	9	15	57	15	-16	-19	-19	66	-9	45
2019	-18	4	29	21	16	-24	52	22	12	13
	62.70	65.75	54.35	24.14	47.62	45.21	30.86	6.39	39.07	48.43

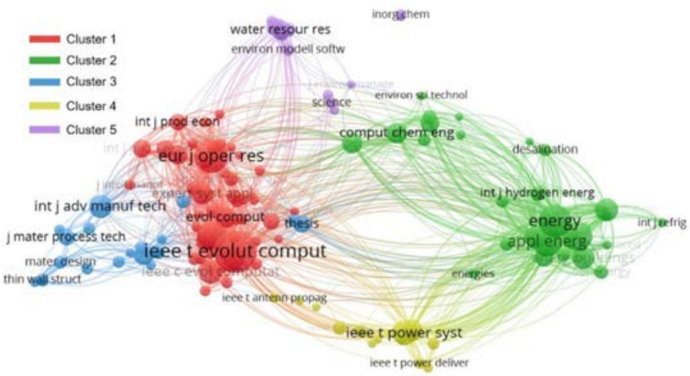


Figure 10: Co-citation network of journals cited more than 1000 times.

16,188) and Energy (total link strength 511,802, citations 15,199). In Figure 10, five clusters are depicted. Cluster 1 contains fifty-one journals, and their topics focus on MOO algorithm and computational details. Cluster 2 includes 27 journals focusing on energy, fuel, and chemical engineering. Cluster 3 which contains twenty journals, focuses on manufacturing processes and multidisciplinary optimization. Cluster 4 contains fourteen journals and concentrates on the optimization of power systems, while Cluster 5 covers 13 journals concentrating on water and environmental research.

Analysis

Research Areas

The field of MOO is interdisciplinary, and it has been dealing with various research areas, but the major subject contributors remain unidentified. Our analysis revealed that the publications are distributed among 137 research areas. The analysis reveals that engineering (14,177 publications, accounting for 48.8% of the total) and computer sciences (7,726 articles, 26.6%) are the major contributors to research areas. These are followed by energy fuels (10.7%); operations research management science (10.6%); mathematics (8.2%); mechanics (6.6%); chemistry (6.1%); thermodynamics (5.9%); materials science and science technology occupy the ninth and tenth positions with an identical share of publications (4.8.%). More details are provided in the Appendix (Table A4). The aggregate of the proportions of the research directions exceeds 100% due to the overlapping of research areas of the publications. The frequency of publications in different areas of research reveals two important aspects, the first being the direction of MOO research, and the second the extent to which this topic is considered interdisciplinary.

Figure 11 presents the top 10 research areas of MOO-related publications based on the analysis. To see the evolvement of the top research areas over time, the investigated period is divided into three panels: 1990-1999, 2000-2009, and 2010-2019. The number of publications in each area reflects the trends of MOO research in that area. A careful investigation

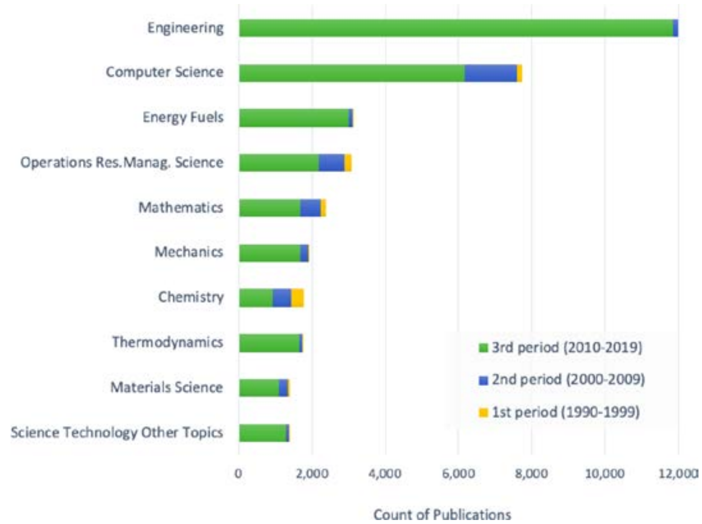


Figure 11: The evolvement of the top 10 research areas over the past three decades.

shows that from the first period to the second period, the publication volume of most research areas grew slowly. Then, it increased significantly in the third period. The areas of engineering, computer science, and energy fuels had a clear jump during the past decade. Although areas such as energy fuels and thermodynamics had no significant volume during the first period, the third period witnessed a sharp increase in productivity. In contrast, other areas, such as chemistry and business economics, had a considerable number of publications (compared to others) during the first period, but the growth was slightly slow in the subsequent periods.

It is found that research articles in areas such as energy fuels, mechanics, and thermodynamics are increasing rapidly. For example, in the energy fuels area, the number of publications jumped from 104 in the second period to 3,000 in the third period. This shows that researchers are now more focused on the adaptation of MOO to optimize real-world problems that encompass conflicting objectives.

Thematic map

The thematic map was constructed on the basis of density and centrality, and it has been divided into four quadrants in a two-dimensional graph as shown in Figure 12. The intensity and centrality are represented by x-axis and y-axis, respectively. The Figure shows multiple search streams in the MOO literature by analyzing the authors' keywords.

The upper-right quadrant includes the topics achieving high and central intensity. In our context, it contains well-structured and well-developed research themes: 'optimisation' and partially its variant 'optimization'. The quadrant at the top-left shows highly specialized subjects, as designated by a high density but low centrality. These topics include

Table A4: The publication output of the top ten research areas of MOO research.

Rank	Research Areas	1990-1999	2000-2009	2010-2019	Total (1990-2019)	%TP
1	Engineering	294	2,042	11,845	14,216	48.8
2	Computer Science	133	1,429	6,171	7,750	26.6
3	Energy Fuels	13	104	3,000	3,117	10.7
4	Operations Research Management Science	178	709	2,190	3,111	10.6
5	Mathematics	152	552	1,678	2,419	8.2
6	Mechanics	18	197	1,692	1,911	6.6
7	Chemistry	331	522	927	1,838	6.1
8	Thermodynamics	6	58	1,662	1,727	5.9
9	Materials Science	43	248	1,098	1,393	4.8
10	Science Technology Other Topics	13	71	1,301	1,393	4.777
11	Environmental Sciences Ecology	27	172	1,181	1,392	4.756
12	Automation Control Systems	37	241	1,064	1,352	4.622
13	Physics	70	234	782	1,097	3.74
14	Water Resources	17	139	877	1,041	3.561
15	Telecommunications	8	79	897	984	3.365
16	Business Economics	80	217	611	931	3.127
17	Construction Building Technology	4	51	525	580	1.997
18	Transportation	7	73	455	537	1.842
19	Instruments Instrumentation	15	62	346	424	1.457
20	Geology	6	28	260	294	1.013

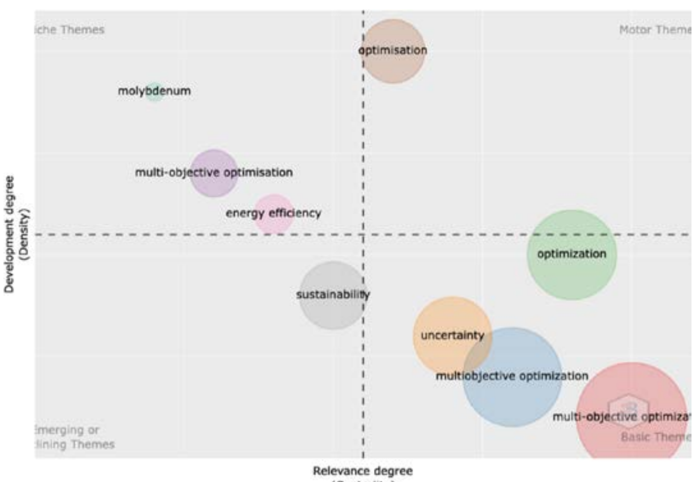


Figure 12: Thematic map of research streams in MOO research.

"molybdenum" and "energy efficiency". The lower-left quadrant includes emerging or disappearing topics. This quarter indicates that the topics are in their infancy with marginal importance. It should be noted that "sustainability" has taken over this area. Finally, the lower-right quadrant contains core subjects, indicated by high centrality but low intensity. They are important for research as general topics, and include 'uncertainty', 'multi-objective optimization' and 'multi-objective optimization'.

Word-cloud of the authors' keywords

The word cloud in Figure 13 demonstrates a visualization of the words that appeared most frequently in the section of authors' keywords in the investigated publications. The Figure comprises the frequent keywords. The obtained results are consistent with the major research themes. Clearly, the words related to the investigated topic have been frequently appeared in the authors' keywords. These include optimization, multi, objective, algorithms, multiobjective, evolutionary, programming, etc. However, it is likely to note that the field of MOO encompasses frequent keywords from sciences areas such as molybdenum, electron, and others. This observation

Figure 13: Word-cloud of authors' keywords.

Table 6: Top 10 productive funding agencies supporting the MOO research.

Funding Agencies	Country	TFP	PTP	PTF
National Natural Science Foundation of China (NSFC)	China	4,624	15.9%	31.5%
Fundamental Research Funds for the Central Universities	China	729	2.5%	5.0%
National Science Foundation (NSF)	USA	562	1.9%	3.8%
European Union EU	EU	546	1.9%	3.7%
National Basic Research Program of China	China	458	1.6%	3.1%
Engineering Physical Sciences Research Council (EPSRC)	UK	429	1.5%	2.9%
Spanish Government	Spain	386	1.3%	2.6%
National Council for Scientific and Technological Development (CNPQ)	Brazil	351	1.2%	2.4%
Natural Sciences and Engineering Research Council of Canada	Canada	293	1.0%	2.0%
China Postdoctoral Science Foundation	China	291	1.0%	2.0%

Notes: TFP=Total number of funded publications; PTP= % total number of retrieved publications; PFT= % total number of funded publications.

reveals to which extent the MOO algorithms can be applied in different fields to solve real-world optimization problems.

Funding for MOO Research

For the retrieved data, 14,656 publications (accounting for 50.5% of the total) contained funding information. Table 6 lists the top 10 funding agencies with the highest number of publications. The fund from the National Natural Science Foundation of China (NSFC) supported the highest number of publications, with 4,620 funded publications (31.5% of the total number of funded publications). It is followed by the Fundamental Research Funds for the Central Universities with 729 publications (5% of funded publications) and the National Science Foundation with 562 publications (3.8% of funded publications). Four of the top 10 funding agencies are from China (with 41.6% of total), which justifies the first position occupied by China when analyzing countries' productivity. The other six agencies are in the USA, EU, UK, Spain, Brazil, and Canada.

DISCUSSION AND CONCLUSION

This study, to our knowledge, performed the first analysis of MOO research. It aims to advance the insights and convergence of a variety of knowledge needed to analyze the relevant literature. The analysis also indicated significant growth in the number of publications. During the past three decades, a high annual growth rate has been recorded, averaging about 24.5%. The trend analysis, we conducted to predict the direction of MOO research, shows that more literature will be published in the coming years. This means the topic becomes more interesting to the research community especially with clear evidence of climate change's negative implications. Usually, the clean environmental objectives contradict the industry productivity objectives, and hence, MOO methods may be borrowed to optimize such obstacles. Therefore, we expect a large number of scientists are going to continue their research in the field.

The present study has implications for both academic and industrial aspects. The study contributes to the current body of knowledge by analyzing the evolution of MOO research and its impact. It provided researchers and practitioners with new knowledge of the evolution and impact of MOO. In different areas of research, many real-world problems require identifying the optimal solution considering conflicting objectives. As a result, there has been very significant inflation in the number of research published in this area, which was revealed in this study.

The findings offer a clearer picture of the MOO research by identifying and analyzing the leading countries, institutions, authors, journals, and influential documents. Through citation and co-citation analysis, it derives insights on influential authors, affiliated institutions, contributing journals, and the author's geographical networks. Furthermore, the study explores the research areas in which MOO algorithms are applied. The evolution of MOO research in some areas would arouse the scholars' attention to apply MOO algorithms to solve real optimization problems. This will help domain experts to think of more applications of MOO algorithms to solve problems in different domains. This research also helps in identifying research networks that may have the potential to create new, and interdisciplinary collaborations.

Nevertheless, there are some limitations related to this study that can be mentioned here. The first limitation relates to the coverage of publications. This review of thirty years of MOO research is limited to papers published in WoS-indexed journals, and conclusions drawn are based on these articles. The type of documents included in the study was also limited to journal publications. This may have fundamental flaws in the coverage of publications. Similarly, the extracted articles were based on specific keywords presented in the Appendix, Table A1 There might be more keywords related to the MOO algorithms descriptions. Accordingly, there can be different results with varying search databases or keywords. In addition, the citation analysis is based on quantity it does not emphasize quality. Other scientometrics techniques, like Google's PageRank analysis, Zipf's law, and bibliographic coupling were not used in this research.

In addition to the knowledge value that this study will add to those interested in the field of research, the gaps in this study can be exploited as indicators of potential research directions.

One such trend is to increase coverage of the MOO literature by using different citation databases and keyword-related algorithms. There is a possibility that other suitable keywords will appear in the future. Another direction also could look at other document types and add more indicators to assess impact, correlations, and quality in the literature. Furthermore, emerging scientific techniques can be used to produce detailed insights to address the limitations of this study.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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