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Fuzzy optimisation for business analytics: A bibliometric analysis

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Abstract. Business analytics refers to the application of sophisticated tools to obtain valuable information from a large dataset that is generated by a company. Among these tools, fuzzy optimisation stands out because it helps decision-makers to solve optimisation problems considering the uncertainty that commonly occurs in application domains. This paper presents a bibliometric analysis following the PRISMA statement on the Dimensions database to obtain publications related to fuzzy optimisation applied to business domains. The purpose of this analysis is to gather useful information that can help researchers in this area. A total of 2,983 publications were analysed using VOSviewer to identify the trend in the number of publications per year, relationships in terms in both the title and abstract of these publications, most influential publications, and relationships among journals, authors, and institutions.

Keywords: PRISMA statement, VOSviewer, bibliometric insights, scientific landscape, fuzzy optimisation, prescriptive analytics

1. Introduction

Data analytics has gained prominence in recent years as the number of available data sources has continued to grow [cf. 1]. However, the large amount of data generated by these sources can easily overwhelm traditional analytics methods. Consequently, several advances to exploit the potential of data analytics have emerged in the literature. A good example of this is the trans-disciplinary approach that was proposed by [2], which considers Augmented Analytics (AA) [3] that uses artificial intelligence methods for decision support.

Although AA has the potential to solve many problems, it struggles to model interpretability and explainability [4]. In particular, the lack of interpretability in an AA model limits its use in practical applications. This problem has been recognised and addressed by the literature [e.g. 5, 6]. Espin-Andrade et al. [2] discussed the relevance of using innovative fuzzy logic tools that favour the modelling of interpretability and explainability for the treatment of analytics-related problems. This issue has attracted increasing attention among researchers from the scientific community in the fields of business analytics and fuzzy logic.

Business analytics is one of the branches of data analytics, which refers to applying data analytics tools to solve business problems. This field has gained popularity because of the business needs, data availability, and recent technological and cultural changes [7]. The increasingly fierce competition in a globalised environment—where the customer has become more demanding because of the diversity of alternatives—has accentuated the importance of making the best decisions quickly and efficiently. As a consequence of the emergent technological advances, the quality and availability of data have increased

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without this translating into higher costs. More and more companies are finally adopting business analytics as a new way of getting the edge over their market competitors by making better strategic decisions.

According to Pedrycz et al. [1], the most representative types of analytics are: descriptive, predictive, and prescriptive. Descriptive analytics seeks to provide a vision of what is happening in the business, generally in the form of reports. Predictive analytics focuses on accurately determining the possible value of a variable in the future. Lastly, prescriptive analytics is about aiding decision-makers in taking future actions through simulation, optimisation, and decision-analysis methods.

Prescriptive analytics is where solutions have been proposed to address optimisation problems. These solutions answer the question "What should I do?" by offering decision-makers a helpful alternative to a large set of choices. Typically, even complex optimisation problems are tractable when dealing with a small amount of input data. However, their resource requirements are exponentially increased by the amount of input data [8]. Therefore, when a company has access to a large amount of data, it usually requires these cutting-edge solutions to address one or more real-world optimisation problems. Solving an optimisation problem involves finding an optimal solution within an ample search space, which is also subject to a set of constraints. To adequately reflect the uncertainty encountered in some application domains, optimisation models incorporating Fuzzy Logic (FL) have been proposed.

Zadeh [9] proposed FL as a multi-valued logic whose purpose is to model the imprecision and uncertainty inherent in real-world problems. For this purpose, fuzzy sets were introduced, which are represented by linguistic variables. Each linguistic variable has a membership function that determines the level of affinity that an object has to that variable. By incorporating FL, an optimisation algorithm can obtain solutions that more closely resemble the conditions of the application domain and, therefore, are more helpful to decision-makers.

The published studies are scattered in a wide range of scientific journals. The main motivation of this bibliometric analysis is to identify trends within the scientific literature on fuzzy optimisation for business analytics. Bibliometric analyses are methodologies that use statistics to analyse the literature in bibliographic terms, such as title, abstract, authors, affiliations, countries, sources, citations, among others. These analyses are helpful in presenting the scientific landscape in the literature, identifying trends, patterns, and relations. However, to our knowledge, there has not been an analysis of fuzzy optimisation applied to business analytics. To analyse this topic, we raised the following research questions:

1. What has been the trend in the number of publications addressing fuzzy optimisation in business analytics from 1977 to 2021?
2. Which have been the terms most used in the titles and abstracts of the publications?
3. Which have been the most influential scientific journals, research groups, research institutions, and articles?

The rest of this paper is structured as follows. Section 2 overviews the related bibliometric studies on fuzzy programming and business analytics that have been recently published. Section 3 presents the methodology used to conduct this analysis. Section 4 answers the research questions raised above, emphasising the publication trend, the most cited and productive journals, and the most influential authors, institutions, and publications. Lastly, Section 5 discusses some concluding remarks.

2. Related studies

Merigó et al. [10] performed a bibliometric analysis over fuzzy research from 1965 to 2015. During the search for publications, a set of 56,500 documents was found; journal articles made up this set. Publication analysis showed that most publications were from the last decade, with 45,700 publications from 2003 to 2012. For the journal analysis, the 30 most influential journals and 14 newer journals with a strong focus on fuzzy topics were analysed. Journal analysis showed that the most influential journals are *IEEE Transactions on Fuzzy Systems* and *Fuzzy Systems*; regarding newer journals, *Applied Soft Computing* and *Soft Computing* showed signs of becoming very popular. Concerning the most influential articles, Zadeh [18] was the most cited within the literature. This result correlates with the analysis of the most influential author, where Zadeh was also at the top of the list. About the most productive and influential institutions, they were ranked according to the h-index obtained in the 12 most influential journals. Here, the *University of Granada* obtained the top position at almost every criterion except for citations, whereas

Table 1
Related literature

Study	Subject	Period and Publications
Merigó et al. [10]	Fuzzy research	1965–2015 (56,500)
Yu et al. [11]	Fuzzy research in China	1966–2015 (12,936)
Arriola et al. [12]	Fuzzy optimisation applied to sustainable energy	2009–2018 (74)
Blanco-Mesa et al. [13]	Fuzzy decision making	1970–2014 (8,135)
Laengle et al. [14]	The journal *Fuzzy Sets and Systems*	1978–2016 (7,201)
Yu et al. [15]	The journal *Fuzzy Optimization and Decision Making*	2002–2017 (370)
Alfaro-García et al. [16]	22 journals on fuzzy sets	1975–2018 (62,000)
López-Guauque and Gil-Lafuente [17]	Fuzzy logic	1965–2017 (88,394)
This study	Fuzzy Optimisation applied to data and business analytics	1977–2021 (2,983)

the *University of California, Berkeley*, got the first position. In the analysis by country, each of them was ranked based on the h-index. This analysis showed that the USA were the most influential country, followed by China and the UK.

Yu et al. [11] presented a bibliometric analysis of fuzzy theory research done in China. The study focused on articles and review publications from 1986 to 2015, resulting in a set of 12,936 documents. The first analysis was performed on the regional production of publications over four periods of ten years. Here, the regions of Beijing, Jiangsu, Liaoning and Shanghai are shown to be the most productive over the years from a total of 31 regions. The study also presented which countries have worked with China over the same periods of years (as the former analysis). In this case, the most collaborative countries were the USA, Canada, the UK and Australia. Another analysis was performed over the citations included in Chinese publications, where the paper of Zadeh [18] was the most cited document. Afterwards, an analysis of the keywords used within six time periods of five years was performed to grasp the development of fuzzy research in China. The most used keywords were 'algorithm,' 'optimisation,' and 'information.' Journal analysis showed that *Fuzzy Sets and Systems*, *Information Sciences*, and *IEEE Transactions on Fuzzy Systems* were the most popular journals. Author citation analysis showed that Zadeh was the most cited author, and Xu Zeshui was the most cited Chinese author. The Harbin Institute of Technology, the Liaoning University of Technology, and the Southeast University were the most productive Chinese institutions.

A bibliometric analysis (with publications ranging from 2009 to 2018) on applications of fuzzy optimisation on problems connected to sustainable energies was performed by Arriola et al. [12]. During the search for publications, 96 publications were found, of which 74 were retained because of their relevance to the topic; 65 publications were identified as original research papers, and the other nine as literature reviews. The bibliometric analysis was performed on the data of the research papers (the reviews were described individually). The study identified the following aspects of the literature: trends, keywords, influential authors and their affiliations, organisations, journals, research areas, and most contributing countries (being China the largest contributor). In addition, optimisation methods, algorithms, and objective functions were also identified.

Blanco-Mesa et al. [13] presented a bibliometric analysis of the literature on Fuzzy Decision Making (FDM). Articles, reviews, and notes from 1970 to 2014 were considered, and 8,135 publications were obtained. The analysis considered the most influential journals, publications, authors, and universities. Besides statistical data, the authors also presented relation maps for all of the topics. To analyse the journals, a metric called H-FDM (which incorporates the h-index of the articles on FDM) was considered. As a result, the journals *Expert Systems with Applications*, *Fuzzy Sets and Systems*, *Information Sciences*, *Journal of Intelligent & Fuzzy Systems*, and *European Journal of Operational Research* were identified as being the most influential. The publication analysis revealed that the papers of Chen [19] and Herrera-Viedma [20] were the most cited. The analysis included the most productive and the most-cited authors in the literature, as well as the journals of their choosing. Finally, analysis of the universities showed that the Islamic Azad University, the University of Granada, and the University of Tehran were the most productive.

Laengle et al. [14] presented a bibliometric analysis of the journal *Fuzzy Sets and Systems*. This is an international journal of impact that was established in 1978. This study analysed the studies published from 1978 to 2016. During the search for publications, 7,201 documents were found. The institutions that were most cited in this journal include the Islamic Azad University, the University of Granada, and the Centre Nationale pour la Recherche Scientifique. In addition, China was the country that had the highest number of citations. The trend indicated that fuzzy theory has become more popular in Europe and Asia than in North America. The most cited articles in this journal were the seminal papers of Zadeh [21] (who introduced fuzzy logic) and Atanassov [22] (who introduced intuitionistic fuzzy sets). With regard to the institutions that have published in this journal, the participation of US institutions is low when compared to similar areas. When the countries that published in the journal were analysed, Asia and Europe were the main contributors, and both were well above North America. VOSviewer and SciMAT were used to analyse the relationships between other journals, institutions, and countries.

Yu et al. [15] presented a bibliometric analysis on the publications of the journal *Fuzzy Optimization and Decision Making* (FODM) over the period 2002 to 2017. To perform the analysis, 370 publications were obtained. The data of these publications were statistically analysed, and VOSviewer was used to create citation maps between authors, institutions, journals, and keywords. During the analysis, it was found that the countries that cite FODM publications were mostly China, Spain, and India. Following this trend, 14 of the 20 top institutions that cite the journal were Chinese. Another important aspect of the analysis was the identification of the most influential authors. The two most cited authors within the journal were Zeshui Xu (from Sichuan University) and Ronald R. Yager (from Iona College). The top institutions that were cited in FODM were Tsinghua University, Iona College, and North Carolina State University.

Alfaro-García et al. [16] analysed studies published from 1975 to 2018 and articles from 22 journals devoted to fuzzy logic were considered. About 62,000 publications were included in this analysis. For each journal, the topics covered by the publications were identified, as were the most productive and influential authors. In general, the authors with the highest number of citations were Zeshui Xu, Witold Pedrycz, and Francisco Herrera.

López-Guauque and Gil-Lafuente [17] presented a bibliometric analysis of the literature related to fuzzy logic published between 1965 and 2017. During the search, 88,394 publications were obtained. The study identified production growth, most influential journals, changes in the impact factors, and most influential articles and institutions. Growth analysis showed that there has been a noticeable increase since 2007, when the number of publications by year started to exceed 8,000. Journal analysis points at *Fuzzy Sets and Systems*, *Information Sciences*, *Expert Systems with Applications*, *Journal of Intelligent & Fuzzy Systems*, and *IEEE Transactions on Fuzzy Systems* as the most influential. For the impact indicators, the impact factor, h-index, average number of citations per document, among others, were analysed. The results showed an important growth over the years. The citation analysis revealed that the papers of Zadeh [18] and Takagi and Sugeno [23] were the most cited. In addition, a second analysis was performed with publications from 2007 to 2016 to identify those countries that have recently contributed to the literature on fuzzy logic. The review identified that the most influential and productive authors were Witold Pedrycz, Guohe Huang, and Ronald R. Yager. In the case of the institutions, the most influential and productive were the Islamic Azad University, the Indian Institution of Technology, and the University of Tehran. In addition, the period 2007 to 2016 was analysed to identify the latest trends regarding research areas and regional production. The most prevalent research areas were computer science, engineering, and mathematics. Regional analysis showed that the regions with the largest growth of production were the Middle East & North Africa, Sub-Saharan Africa, and South Asia.

This literature review has shown that several bibliometric analyses on fuzzy logic-related topics have been published. Table 1 compares this study with similar bibliometric analyses. To the best of our knowledge, this paper is the first bibliometric analysis of fuzzy optimisation applied to business analytics. We have considered the period between 1977 and 2021, which includes 2,983 articles. This paper discusses the publication tendency over the years, index terms, most influential publications, and most productive and cited journals, authors, and institutions.

3. Methodology

To perform a systematic review, the practices of the PRISMA statement[1] [24, 25] were adopted. The PRISMA statement (which is an acronym for Preferred Reporting Items for Systematic Reviews and Meta-Analyses) is a set of guidelines and recommen-

[1] http://www.prisma-statement.org/

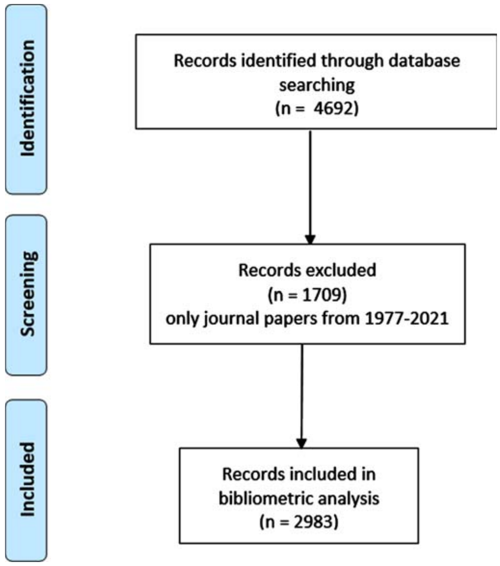

Fig. 1. PRISMA statement-based methodology to collect articles for the bibliometric analysis.

dations to improve reporting of systematic reviews or meta-analyses. Researchers interested in assessing or emulating literature analysis benefit greatly from the proper reporting of the search process by the authors. These guidelines include the specification of information sources, search strategy, data collection, eligibility criteria, and usage of flow diagrams, among other points. For these reasons, the PRISMA statement has been applied in the literature [e.g. 26]. However, it should be noted that other quality bibliometric analyses could use other means of reporting. For example, He et al. [27] and Yu et al. [28] described their searching process by indicating the search string, active filters, the date of the search, and the number of publications retrieved.

To begin our bibliometric analysis, we first searched for publications using the Dimensions database[2] (with more than 121 million publications) [29] using the following search string:

```
((("Optimization Problem" OR "Optimisation Problem") AND ("Fuzzy Optimization" OR "Fuzzy Optimisation")) AND "Business Analytics" OR "Data Analytics") NOT "Decision Maker".
```

The first part of the query, `(("Optimization Problem" OR "Optimisation Problem") AND ("Fuzzy Optimization" OR "Fuzzy Optimisation"))`, ensures that the topic of the publications refers to fuzzy optimisation regarding the solution of an optimisation problem, which is important because fuzzy optimisation is not always applied to solve optimisation problems (e.g., it may refer to fuzzy predicates or membership functions). The second part of the query, `AND "Business Analytics" OR "Data Analytics"`, is used to include those publications that consider either data or business analytics. It should be noted that the Dimensions search engine has a grammar that is slightly different to the regular programming languages; for example, the expression `("Optimization Problem" AND "Fuzzy Optimization") AND ("Business Analytics" OR "Data Analytics")` would be the equivalent expression following a regular operator hierarchy. The last part of the string, `NOT "Decision Maker"`, is used to exclude those publications that consider fuzzy optimisation regarding the treatment of a decision-making problem.

The search string returned 4,692 publications (13 April 2022). The publications categorised as articles were then selected, yielding 2,983 articles published between 1977 and 2021. Figure 1 shows a diagram of the use of the PRISMA statement to collect the studies considered in this analysis.

To analyse this dataset, we identified: (i) the growth trend in the number of publications addressing fuzzy optimisation in business analytics from 1977 to 2021; (ii) the most used terms in the titles and abstracts of the publications; (iii) the most influential scientific journals, (iv) research groups, (v) research institutions, and (vi) articles. VOSviewer [30, 31] was used to map the dataset. VOSviewer is a free-to-use software for bibliometric data mapping that has been widely used within the specialised literature [e.g. 28, 32]. Each mapping uses a graph to graphically represent the state of the data. The size of the nodes within the graph is proportional to the ‘total link strength.’ For example, in point (ii), the ‘total link strength’ is determined by the number of documents where a term appears. Additionally, VOSviewer can identify groups within the data maps that help to visualise better and interpret the data.

4. Results

This section presents the results that we obtained during the bibliometric review. The rest of this section is structured as follows. Section 4.1 describes

[2]https://app.dimensions.ai/details/publication/pub.1106289502

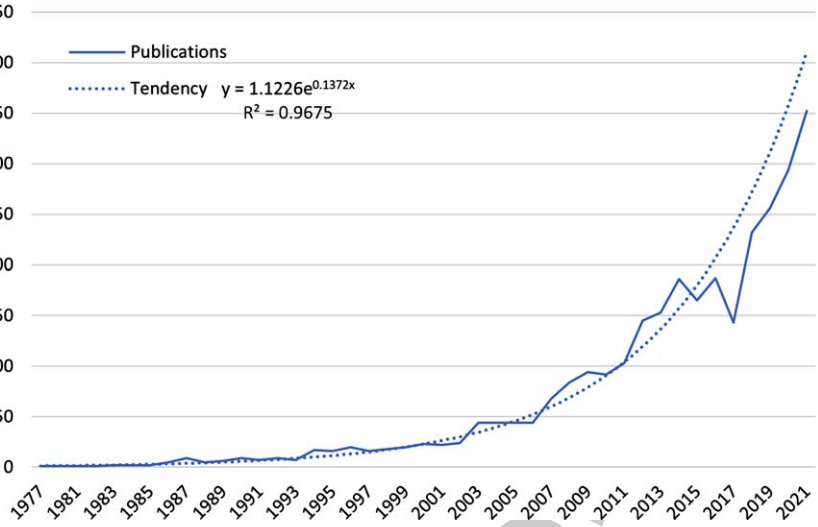

Fig. 2. Number of publications in the period 1977 to 2021.

the publication tendency during this period. Section 4.2 shows the usage of index terms in the publications. Section 4.3 describes the relationships between the journals. Section 4.4 presents the most influential authors and research groups. Section 4.5 analyses the research institutions and their relationships. Finally, 4.6 describes the most cited publications within the dataset.

4.1. Publication per year

As shown in Fig. 2, the first publication was made in 1977. However, it was not until 2007 that the literature reached 50 publications per year. This factor is usually attributed to various technological advances that have facilitated the availability and quantity of data for analytical processes [cf. 7]. Figure 2 also shows the publication tendency, in this case $y = 1.1226e^{0.1372x}$, which implies that there has been an exponential growth in this topic. The R^2 value indicates the fit ratio of the equation with the publication data ($0 \leq R^2 \leq 1$). The higher the R^2 values, the higher the correlation between the equation and the data. According to the prevailing trend, an exponential growth in the number of publications on fuzzy optimisation with analytics-oriented applications is expected.

4.2. Identifying the most used index terms

This analysis took into account the words that the authors chose to compose the title and abstract of their papers. Figure 3 shows how the terms that appear in at least ten publications are related:

- Blue: The main index term of this group is the word ‘function,’ which is the most used term on the map and refers to the membership function in FL models. Other terms in this group are ‘set,’ ‘fuzzy optimization,’ ‘concept,’ and ‘numerical example’. Therefore, it can be said that this group is related to the fuzzy and mathematical modelling of the problem.
- Green: The terms that are presented in this group are related to the problems addressed in the literature. Some of the most used terms are ‘power system,’ ‘energy,’ ‘scheduling,’ ‘capacity,’ ‘load,’ ‘market,’ ‘profit,’ and ‘distribution network’.
- Red: The terms that are presented in this group are related to the algorithm chosen to solve the optimisation problem. In this case, Particle Swarm Optimisation (PSO) is the most used algorithm. Some of the most used terms are: ‘population,’ ‘convergence,’ ‘dataset,’ ‘differential evolution,’ ‘prediction,’ and ‘classification’. The terms ‘prediction’ and ‘classification’ suggest a mixture of optimisation and machine learning approaches.
- Yellow: In this set, the terms related to the literature (e.g., ‘review,’ ‘researcher,’ ‘survey,’ ‘overview,’ and ‘trend’) stand out. There are also some terms that refer to prescriptive analytics, such as ‘product,’ ‘total cost,’ ‘customer,’ ‘supply chain,’ and ‘enterprise’.

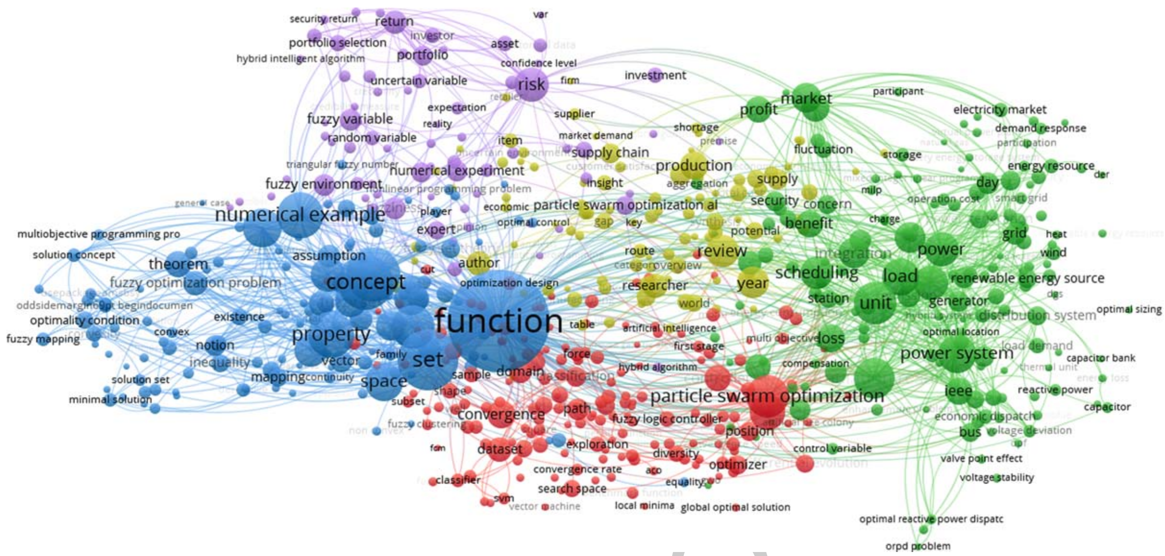

Fig. 3. A map relating the index terms.

Table 2
Most used index terms

Index term	Frequency
Function	779
Set	336
Concept	291
Example	283
Property	218

– Purple: Finally, the purple set includes terms related to the portfolio and investment problems, such as ‘risk,’ ‘return,’ ‘investment,’ ‘portfolio,’ ‘investor,’ and ‘variance’.

Table 2 shows the terms that are the most recurrent in the literature.

4.3. Sources

This analysis considers those sources with at least five documents that are cited. Although we have only considered journal articles, some conferences can be seen in this analysis. This situation is caused by the citation from journal articles to conference papers. This analysis considers scientific journals and conferences with at least five citations.

Figure 4 shows a map of the relationships between these sources, in which the connectivity of the groups is based on the number of times that they cite each other. Comprehensive information about the groups (considering the 111 sources) may be consulted in the supplementary materials[3]. Figure 4 only presents the five most productive journals of each group to favour readability. Several groups of journals and conferences within this research area are visible on the map, as follows:

– Yellow: This group has 13 sources with 345 publications, which represents 19.3% of the total number of publications. This group has the most relationships with other groups, having relatedness with all the groups except one. This means that papers published by journals of this group are cited in several areas in the literature. The most productive journals of this group are *Information Sciences*, *IEEE Transactions on Fuzzy Systems*, *Expert Systems with Applications*, and *Journal of Intelligent & Fuzzy Systems*. Among these journals, two are devoted to fuzzy research (*IEEE Transactions on Fuzzy Systems* and *Journal of Intelligent & Fuzzy Systems*), while the others are more focused on soft computing theory and applications.
– Green: This group has 20 sources with 368 publications, which represents 20.6% of the total number of publications. Among the most productive journals in this group are *Fuzzy Sets and Systems* and *Fuzzy Optimization and Decision Making*. Both journals focus on fuzzy topics and applications. This group is related to the yellow and purple groups.

[3]https://github.com/luis-cis/Biblio_Review

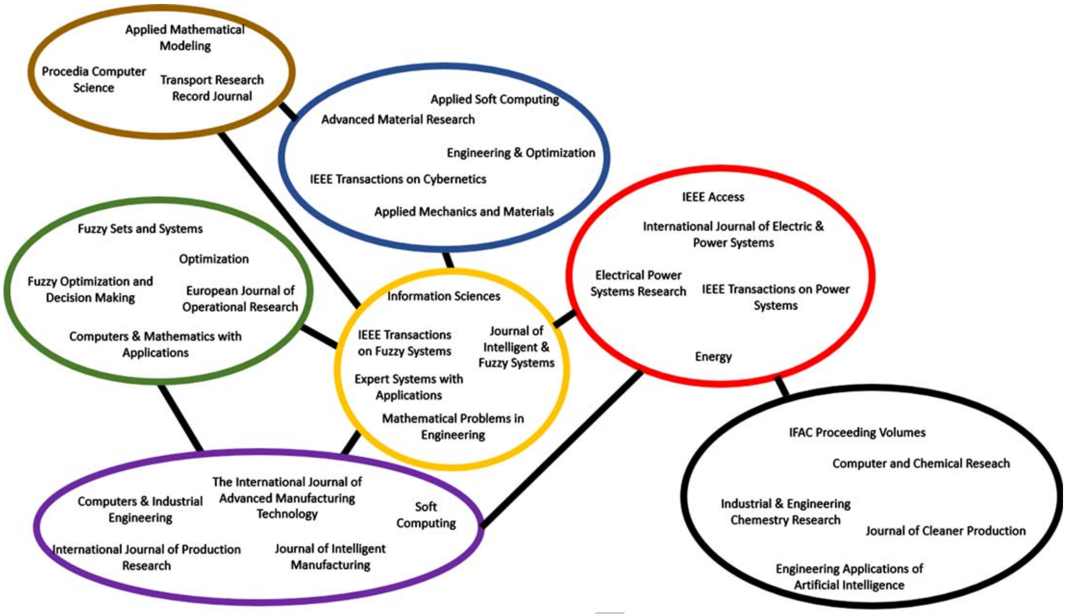

Fig. 4. Most influential sources of citation of each group.

– Purple: This group has 14 sources with 192 publications, which represents 10.7% of the total number of publications. In this group, the journals *Computer & Industrial Engineering* and *Soft Computing* are the most productive. Computer and industrial engineering is an area that has seen many uses of soft computing over the decades. The other journals in this group are dedicated to publishing papers that solve manufacturing or industrial problems. This group is related to the yellow, green and red groups.
– Red: This group has 28 sources with 399 publications, which represents 22.3% of the total number of publications. Most journals in this group are devoted to the energy sector (e.g., *International Journal of Electrical Power and Energy Systems*, *Applied Energy*, *Energy Conversion and Management*, and *Energy*). This group is the second regarding the number of relations with the other groups, and is connected with the yellow, purple, and black groups.
– Black: This group has 11 sources with 154 publications, which represents 8.6% of the total number of publications. The journals with the highest number of publications in this group are *Industrial & Engineering Chemistry*, *Journal of Cleaner Production*, and *Computer and Chemical Engineering*, which are dedicated to applied uses of chemistry and chemical engineering. Some of these solutions have been motivated by reducing the environmental impact (see the production of *Journal of Cleaner Production*). Fuzzy theory can be used to model the imprecise nature that emissions often have, as remarked by Arriola et al. [12]. It is worth noting that this group is only related to the red group.
– Blue: This group has 22 sources with 304 publications, which represents 17% of the total number of publications. Among the most productive journals in this group are *Applied Soft Computing*, *Advance Material Research*, and *Engineering & Optimization*. Two of these journals focus on optimisation problems and their application in real-life scenarios, which often require a consideration of uncertainty. This group is connected with the yellow and brown groups.
– Brown: This group has three sources with 27 publications, which represents 1.5% of the total number of publications. Two of these sources are the journals *Transportation Research Record* and *Applied Mathematical Modelling*. The first is dedicated to transportation topics, while the second focuses on solving problems through the use of mathematical models. Meanwhile, *Procedia Computer Science* publishes conference proceedings across many topics of computer sci-

Table 3
Top five sources of each group

Group	Noteworthy Sources	Publications
Yellow	Information Sciences	75 (4.2%)
	IEEE Transactions on Fuzzy Systems	52 (2.9%)
	Expert Systems with Applications	41 (2.3%)
	Journal of Intelligent & Fuzzy Systems	39 (2.2%)
	Mathematical Problems in Engineering	32 (1.8%)
Red	Fuzzy Sets and Systems	109 (6.1%)
	Fuzzy Optimization and Decision Making	92 (5.1%)
	European Journal of Operational Research	26 (1.5%)
	Optimization	16 (0.9%)
	Computers & Mathematics with Application	14 (0.8%)
Purple	Computers & Industrial Engineering	40 (2.2%)
	Soft Computing	38 (2.1%)
	International Journal of Production Research	16 (0.9%)
	The International Journal of Advanced Manufacturing Technology	16 (0.9%)
	Journal of Intelligent Manufacturing	14 (0.8%)
Green	IEEE Access	64 (3.6%)
	International Journal of Electric & Power Systems	57 (3.2%)
	IEEE Transaction on Power Systems	32 (1.8%)
	Energy	28 (1.6%)
	Electrical Power Systems Research	23 (1.3%)
Black	Industrial & Engineering Chemistry Research	27 (1.5%)
	Journal of Cleaner Production	23 (1.3%)
	Computer and Chemical Engineering	22 (1.2%)
	IFAC Proceeding Volumes	19 (1.1%)
	Engineering Applications of Artificial Intelligence	16 (0.9%)
Blue	Applied Soft Computing	50 (2.8%)
	Advanced Material Research	27 (1.5%)
	Engineering & Optimization	22 (1.2%)
	Applied Mechanics and Materials	21 (1.2%)
	IEEE Transactions on Cybernetics	17 (0.9%)
Brown	Applied Mathematical Modelling	15 (0.8%)
	Procedia Computer Science	7 (0.4%)
	Transportation Research Record Journal of the Transportation Research Board	5 (0.3%)

Table 4
The ten most cited sources

Source	Citations	Publishing house
Fuzzy Sets and Systems	3120	Elsevier
Information Sciences	2653	Elsevier
International Journal of Electrical Power and Energy Systems	2329	Elsevier
Fuzzy Optimization and Decision Making	2102	Springer
IEEE Transactions on Fuzzy Systems	2017	IEEE
Applied Soft Computing	1935	Elsevier
IEEE Transactions on Smart Grid	1792	IEEE
European Journal of Operational Research	1578	Elsevier
Renewable and Sustainable Energy Review	1302	Elsevier
Computer methods in Applied Mechanics and Engineering	1226	Elsevier

Table 5
The ten most productive sources

Source	Publications	Publishing house
Fuzzy Sets and Systems	91	Elsevier
Fuzzy Optimization and Decision Making	71	Springer
Information Sciences	71	Elsevier
IEEE Access	58	IEEE
International Journal of Electrical Power and Energy Systems	57	Elsevier
IEEE Transactions on Fuzzy Systems	91	IEEE
Applied Soft Computing	71	Elsevier
Expert Systems with Applications	71	Elsevier
Computers & Industrial Engineering	58	Elsevier
Journal of Intelligent & Fuzzy Systems	57	IOS Press

ence. This group is most related to the yellow and blue groups.

Table 3 presents the top five sources of each group (with the evident exception of the brown group). As a complement, Tables 4 and 5 show the sources that are most cited and those with the highest production regardless of these groups. These tables show that the sources with the highest number of citations and articles correspond to research journals published by Elsevier, Springer, IEEE, and IOS Press.

4.4. Authors

The following is an analysis of research groups within the literature. Authors are considered if they

Table 6
Authors with the highest production

Author	Publications	Affiliation
Junzo Watada	26	Waseda University
Hsien-Chung Wu	23	National Kaohsiung Normal University
Huiling Chen	19	Wenzhou University
Dingwei Wang	18	Northeastern University
Shu-Chenrng Fang	17	North Carolina State University
Ali Asghar Heidari	15	National University of Singapore
Yan-Kuen Wu	15	Vanung University
Geng-Sheng Wu	15	Wayne State University
Jie Lu	14	Australian AI Institute
Guangquan Zhang	14	University of Technology Sydney

Table 7
Most cited authors

Author	Citations	Affiliation
Taher Niknam	1118	Shiraz University
Didier Dubois	677	Centre National de la Reserche Scientifique
Dingwei Wang	629	Northeastern University
Junzo Watada	587	Waseda University
Harish Garg	562	Deemed University
Oscar Castillo	549	Tijuana Institute of Technology
Jie Lu	529	Australian AI Institute
Guangquan Zhang	529	University of Technology Sydney
Ali Asghar Heidari	521	National University of Singapore
Hsien-Chung Wu	505	National Kaohsiung Normal University

participated in at least five publications. The relationships among these authors are based on the number of times that they co-authored a publication. Figure 5 shows the map of the research groups.

According to Fig. 5, we can identify four research groups, as follows:

– Green: This group is composed of three Indian authors (Mukesh Mehlawat, Pankaj Gupta, and Arun Kumar) and two Chinese authors (Wei Chen and Lifen Jia). The main areas of interest are the development of decision-making solutions with fuzzy optimisation modules [33–35], and fuzzy machine learning with optimisation [36, 37]. Among the problems addressed by this group are portfolio selection and flood mapping. Portfolio selection is solved by using decision-making solutions, whereas flood mapping is solved using the fuzzy machine learning methods that were proposed by the authors. It should be noted that some of these studies used real-world data during experimentation.
– Red: This group is composed of three Chinese authors (Xiang Li, Qin Zhongfeng Qin, and Sini Guo) and two Indian authors (Samarjit Kar and Manoranjan Maiti). The studies of this group include fuzzy optimisation problems using heuristics [e.g. 38–40]. Among the problems addressed are supply chain, path planning, portfolio selection, travelling salesperson, and stock pricing. It should be noted that only triangular and trapezoidal membership functions are used in this group of publications.
– Blue: This group includes Yanfei Lan, Yankui Liu, and Ruiqing Zhao, who are all Chinese authors. This group has the particularity that in their publications the authors handle real-world case studies [e.g. 41–43]. In addition, they have used a type of membership function that is called Generalised Parametric Interval-Valued (PIV), which is characterised by representing type-2 fuzzy variables. As parametric functions, it is possible for a PIV to alter the range of the membership function, which allows it to express a larger number of application domains, while employing a single membership function. The problems that this group has worked with are the green closed-loop supply chain, four-dimension transportation problem, resource allocation, sus-

Fig. 5. Map of relationships between authors.

tainable development, and the single-period inventory problem.
– Yellow: This group includes Bo Li and Yuanguo Zhu, who are both Chinese. Unlike the other research groups, this group uses a variety of the fuzzy theory that is called the Uncertainty Theory [e.g. 44–46]. Unlike the classic fuzzy theory, uncertainty theory only defines increasing functions to determine the measure of uncertainty (the equivalent of the degree of membership of a fuzzy variable), and differentiates between dependent and independent variables.

Regardless of these research groups, Table 6 lists the authors with the highest scientific production and Table 7 lists those with the highest number of citations. The top three most productive authors are Junzo Watada, Hsien-Chung Wu and Huiling Chen. Watada is know for contributing to possibilistic regression and fuzzy portfolio selection [e.g. 47–49], Wu is known for contributing to interval-valued problems and applying FL to finance analytics [e.g. 50, 51], and Chen is known for introducing two optimisation algorithms [52, 53] and applying support vector machines [e.g. 54]. The top three most-cited authors are Taher Niknam, Didier Dubois, and Dingwei Wang. Niknam is known for contributing to micro-grid optimisation [e.g. 55, 56], and cluster analysis [e.g. 57]. Dubois's research revolves around the basis for fuzzy and possibility theory [e.g. 58, 59]. Finally, Wang is known for researching fuzzy production planning [e.g. 60] and fuzzy genetic algorithms applied to partner selection problems in the context of manufacturing environments [e.g. 61].

4.5. Institutions

This section analyses the institutions that have appeared in at least five publications. The relationships between the institutions are based on the number of publications with affiliated co-authors. Figure 6 shows the map of relations between these affiliations. Comprehensive information about the groups of institutions (considering the 188 institutions) may be found in the supplementary material[4]. Figure 6 only presents the five most productive institutions of each group to favour readability. Here, we can identify that the affiliations are mainly distributed among the following six groups:

[4]https://github.com/luis-cis/BiblioReview

Table 8
Highest contributing institutions for each group

Group	Noteworthy Institution	Publications
Blue	Tsingjua University	33 (1.6%)
	Beihuang University	31 (1.5%)
	Waseda University	30 (1.5%)
	Northeastern University	27 (1.3%)
	University of Technology Sydney	26 (1.3%)
Red	University of Tehran	30 (1.7%)
	Iran University of Science and Technology	28 (1.4%)
	Amirkabir University of Technology	27 (1.3%)
	National University of Singapore	26 (1.3%)
	Shiraz University of Technology	24 (1.2%)
Yellow	University of Nottingham Malaysia	30 (1.5%)
	Texas A&M University	18 (0.9%)
	University of Granda	17 (0.8%)
	University of Technology Malaysia	16 (0.8%)
	University of Malaysia	12 (0.6%)
Green	Indian Institute of Technology, Delhi	18 (0.9%)
	University of Seville	17 (0.8%)
	University of Delhi	15 (0.7%)
	Indian Institute of Technology, Kharagpur	15 (0.7%)
	Jadavpur University	13 (0.6%)
Purple	National Institute of Technology	13 (0.6%)
	Vidyasagar University	9 (0.4%)
	West Bengal University of Technology	8 (0.4%)
	University of Burdwan	7 (0.3%)
	Indian Institute of Engineering	6 (0.3%)
Black	Hanshan Normal University	16 (0.8%)
	Guangzhou University	9 (0.4%)
	Guangdong University of Finance	7 (0.3%)

Table 9
Institutions with the highest production

Institution	Publications	Nationality
University of Tehran	34	Iranian
Tsinghua University	33	Chinese
Beihang University	31	Chinese
University of Nottingham, Malaysia	30	Malaysian
Waseda University	30	Japanese
Iran University of Science and Technology	28	Iranian
Northeastern University	27	Chinese
Amirkabir University of Technology	27	Iranian
Anna University	27	Indian
National University of Singapore	26	Singaporean

– Blue: This is the largest group and is composed of 108 institutions (which represents 60.2% of the total). As a group, they have contributed

Table 10
Institutions with the highest number of citations

Institution	Citations	Nationality
Shiraz University of Technology	1424	Iranian
Iran University of Science and Technology	1252	Iranian
Tsinghua University	1242	Chinese
Sharif University of Technology	1142	Iranian
Hong Kong Polytechnic University	1141	Chinese
Texas A&M University	963	USA
Anna University, Chennai	952	Indian
Nanyang Technological University	941	Singaporean
University of Nottingham, Malaysia	869	Malaysian
University of Technology, Sydney	842	Australian

1,219 publications (which is 57.5% of the total). This group is related to the red, black, yellow and purple groups, and is the group with the highest number of connections.

– Red: This groups is composed of 30 institutions (15.7%) and has contributed 318 publications (16%). This group is related to the blue and purple groups.
– Purple: This group is composed of six institutions (2.4%) and has contributed 48 publications (3.2%). This group is related to the red, blue, yellow, and green groups.
– Green: This group is composed of 20 institutions (9.9%) and has contributed 201 publications (10.6%). This group is related to the yellow and purple groups.
– Yellow: This group is composed of 21 institutions (10.2%) and has contributed 206 publications (11.2%). This group is related to the blue. purple, and green groups
– Black: This group is composed of three institutions (1.2%) and has contributed 32 publications (1.6%). This group is only related to the blue group.

Table 8 presents the five most productive institutions of each group. Additionally, Tables 9 and 10 list the ten institutions with the highest number of both published articles and citations, regardless of their group.

As shown in Table 9, the Chinese institutions are the largest producers of the related literature, followed by Iranian institutions. These results are consistent with other analyses where China has been identified as the largest producer of literature on fuzzy logic-related topics. In contrast, although China produces more articles, Iranian institutions have the highest number of citations (as shown in Table 10). In addition, the inclusion of US, Indian, Singaporean, Malaysian, and Australian institutions stands out—although these institutions do not produce articles in the same numbers as the others, they are among the most cited.

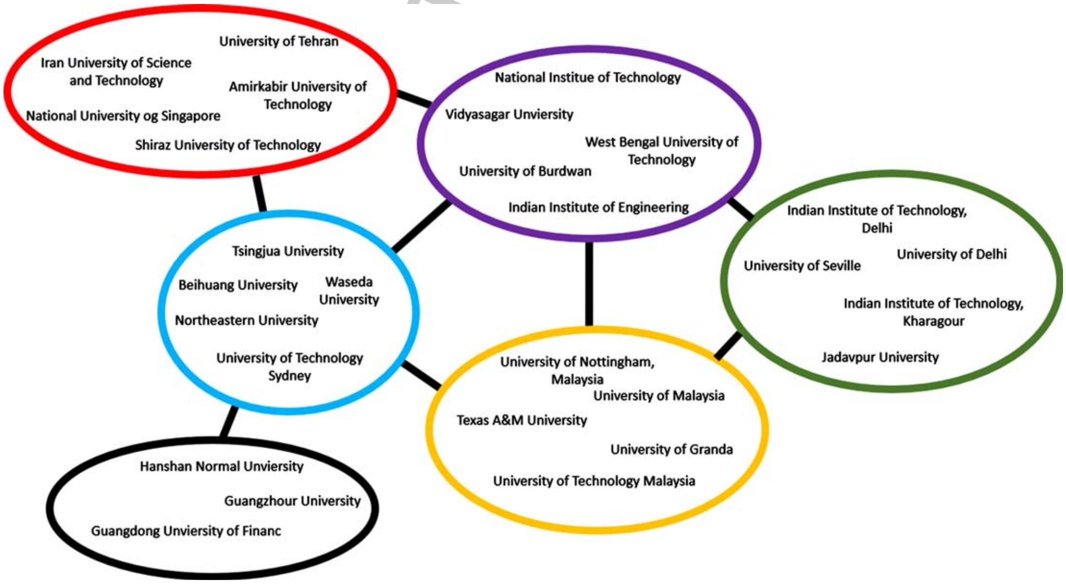

Fig. 6. A map of the institutions.

Table 11
Publications with the highest number of citations

Title	Authors	Year	Cites
Robust optimization: A comprehensive survey	Beyer and Sendhoff [62]	2007	1003
Optimal power flow management for grid connected PV systems with batteries	Riffonneau et al. [63]	2011	678
Sizing of energy storage for microgrids	Chen et al. [64]	2011	622
An annotated overview of system-reliability optimization	Kuo and Prasad [65]	2000	470
A hybrid PSO-GA algorithm for constrained optimization problems	Garg [66]	2016	373
The three semantics of fuzzy sets	Dubois and Prade [67]	1997	367
Fuzzy neural networks: A survey	Buckley and Hayashi [68]	1994	333
A survey of credibility theory	Liu [69]	2006	329
Particle swarm optimizer, ant colony strategy and harmony search scheme hybridized for optimization of buss structures	Kaveh and Talatahari [70]	2009	304
A fuzzy-optimization approach for generation scheduling with wind and solar energy systems	Liang and Liao [71]	2007	261

4.6. Publications

This section analyses those publications that have the largest number of citations. Table 11 list the ten most-cited publications. It should be noted that four of these publications are surveys. Regarding those works that consider domain applications, we observe energy and transportation cases. Among the three most cited studies, we have:

– Beyer and Sendhoff [62]: This study presents a survey of robust optimisation. Robust optimisation refers to a methodology that accounts for uncertainty within the application domain. This is achieved by defining a series of parameters that accurately describe the application domain. This survey described several robust design techniques. Then, several methods for the application of the designs are mentioned. Finally, performance measures are discussed.
– Riffonneau et al. [63]: This study presents a power management mechanism for grid systems with photovoltaic storage for the optimal scheduling of energy (uncertainty presents itself in energy generation and consumption, as well as battery performance). Dynamic programming was used to deal with this uncertainty. Using real data, a simulation was carried out to measure the performance of the system with satisfactory results.
– Chen et al. [64]: This study presents a method for the optimal sizing of power storage in a microgrid. Some measurements were employed to account for the error between forecast, and actual wind and solar behaviours. Two case studies were proposed to test the methodology.

5. Conclusions

In this paper, a bibliometric analysis was carried out to identify several trends in the application of fuzzy optimisation to business analytics problems from 1977 to 2021. In total, 2,983 publications were gathered using the Dimensions database. Our analysis included: (i) publication trend; (ii) most used terms; (iii) sources: groups, production, and citation; (iv) authors: groups, production, and citation; (v) institutions: groups, production, and citation; and (vi) publications. In conclusion, we would like to emphasise the following points:

– Publication trend: An exponential increase in the number of publications related to the subject was identified from 2010 onward.
– Terms: After analysing the most frequently used index terms in these publications, it was possible to observe the preference for PSO to solve fuzzy optimisation problems. In addition, the two most popular applications were the energy sector and the investment-oriented problems.
– Sources: A total of 111 sources were analysed. We identified seven groups within the literature based on citation. The most productive sources were *Fuzzy Sets and Systems*, *Fuzzy Optimization and Decision Making*, and *Information Sciences*, while the most cited were *Fuzzy Sets and Systems*, *Information Sciences*, and the *International Journal of Electrical Power and Energy Systems*.
– Authors: Based on co-authorship, a total of four research groups were identified, with a total of 15 authors. Two of these groups have proposed novel approaches to treat uncertainty in optimisation problems. Another group has focused on applying fuzzy optimisation to real-world prob-

lems. The last has addressed decision-making problems and fuzzy machine learning with fuzzy or crisp optimisation.
- Institutions: A total of 188 institutions were identified and clustered into six groups that were based on co-authorship. The most productive institutions were the University of Tehran, Tsinghua University, and Beihang University. The most cited institutions were the Shiraz University of Technology, the Iran University of Science and Technology, and Tsinghua University.
- Publications: During the publication analysis, the studies of Beyer and Sendhoff [62], Riffonneau et al. [63], and Chen et al. [64] were identified as the most cited publications.

Overall, both experienced and in-training researchers will find the insights from this bibliometric analysis valuable because they help depict the scientific landscape of fuzzy optimisation in business analytics-oriented problems. The analysis shows that interest in this topic has increased over the years. This trend evidences an increasing interest in coping with uncertainties in real-world applications. Research in this area is meaningful because it enhances the ability of the business sector to tackle modern problems in an effective manner. During the bibliometric analysis, we found several examples of these problems, such as portfolio selection, supply chain management, power system optimisation, and scheduling.

In future research, this study could be extended by considering other databases, such as Web of Science, to search for publications that are not present in Dimensions. Another promising direction for future research is the analysis of the VOSviewer networks created when other counting techniques are applied (for instance, fractional counting). Also, other mapping software (e.g., CiteSpace [72]) could obtain relevant and different information about this dataset. Furthermore, future research could consider dividing the dataset among different periods to study the evolution over time of institutions, authors, countries' production and citation, keywords, research groups, and so on.

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