



Four decades of fuzzy sets theory in operations management: application of life-cycle, bibliometrics and content analysis

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Abstract

The development of a scientific discipline is partly determined by the growth of its literature. Bibliometrics constitute a set of mathematical and statistical techniques employed to explore, organize, and quantitatively analyze large pools of scientific literature. In this study, 11,433 papers published between 1974 and 2015 are collected and analyzed by applying life-cycle analysis, bibliometrics and text mining in order to provide a full thematic overview of the application of fuzzy theory in operations management. Top countries (i.e. the most productive, influential and collaborative countries), most frequently cited journals, and key research topics are identified by employing bibliometric techniques. Finally, the articles' common research themes and methodologies are determined by combining text mining with experts' input. Results show that the application of fuzzy theory in operations management is still in its infancy, and hence suitable for future research. This study serves as a guide for researchers to identify the hidden patterns, key actors, topics, and methods in this area.

Keywords Fuzzy sets theory · Operations management · Bibliometrics · Text mining · Life-cycle analysis

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Introduction

The world has become increasingly complex due to the frequency of unpredictable incidents that partly constitute its environment. Our limited knowledge of nature, the continuously changing financial, social and economic determinants of organizations, and the vast diversity of opinions make it very difficult to prognosticate, make decisions and accordingly take actions (Gil-Aluja 2004; Mardani et al. 2015). This is while a lack of ample accurate information impede the formulation of precise quantitative mathematical models (Papageorgiou et al. 2017). In the 1960s, fuzzy set theory was introduced as a powerful response to this issue to mathematically represent the uncertainty and vagueness (Zadeh 1965). Regarding the importance of decision making in managerial tasks and processes, fuzzy set theory has been used to develop a wide variety of managerial processes, particularly in production and operations management. As a result, the number of published research in this area has increased significantly since the late 1980s (Wang et al. 2016).

The sheer abundance of research in this area can overwhelm decision-makers in the science policy process, especially those new to the field. The failure to digest the bulk of available literature might lead to false recommendations and suggestions, hence suboptimal priorities in research and development agendas. This issue manifests itself at different levels and scales in private companies, the public sector and academia (Rezaeian et al. 2017). For instance, individual scientists and research departments are keen to spend their time and financial resources in areas with high promises of impact. Lots of studies have been carried out to find the emerging areas in science and technology and track the areas of strategic importance (Kajikawa et al. 2008; Kostoff 1995, 2008; Leydesdorff et al. 1994; Ogawa and Kajikawa 2015). Likewise, (inter)national governmental institutions seek to make policies that give priority to development and innovative solutions with optimal social/economic consequences (Coccia 2009; Kidwell 2013). A clear picture of scientific research productivity in this field can give assistance to above-mentioned authorities to have a clear pathway about the research directions which should be built in the future, or the specific research activities which should be supported to have the most positive impact in different scientific, economic or political sectors as a long term strategic plan (Matcharashvili et al. 2014).

In order to provide a panoramic view of this massive literature and to keep up with its developments, a comprehensive systematic review and bibliometrics assessment is required. Bibliometrics can be employed for a variety of purposes, most importantly in making decisions about research funding. Bibliometrics is defined as a quantitative study of scholarly literature and publications to analyze developments within a research area (Ghadimi et al. 2019). Also, it provides insights into the intellectual structure, current status, research topics and key factors within a scientific discipline (Stelzer et al. 2015). It helps to visualize past academic research activities and identify current research gaps intuitively (Fergnani 2019). Bibliometrics has gained popularity in recent years and has been used in many researches such as Ghadimi et al. (2019), Han and Shin (2014), Mardani et al. (2017, 2018), Mund and Neuhäusler (2015) and Wang et al. (2016) etc.

According to the importance of bibliometric analysis for expanding knowledge boundaries and developing multidisciplinary studies, fuzzy set theory has been analyzed with bibliometric techniques in different studies (Blanco-Mesa et al. 2017; Liu and Liao 2017; Merigó et al. 2015; Yu and Liao 2016). Despite the strong points of these articles, there are some critical analyses (e.g. trend analysis, content analysis, extracting thematic scientific fields, and analyzing international collaboration between countries, etc.) that haven't been

considered in previous studies. For covering this gap, this paper aims to present a clear overview about the past and current status of fuzzy sets theory in operations management and highlight main streams and potential developments and discuss research gaps and fragmentations in this area. To do so, a bibliometric analysis is used alongside with text mining and publication life-cycle analysis to present a comprehensive visualization of the past and current status of scholarly activities in the field of application of fuzzy sets theory in operation management over a 40-year period at national and international levels. Furthermore, the abstract, title and keywords of relevant articles are analyzed through text mining and classification techniques to supplement the bibliometric analysis. This methodological framework allowed us to (i) describe the historical development of the field, forecast the future trend and estimate its potential for further development, (ii) find top countries (in terms of productivity, influence and international collaboration), and journals which made the most contribution in this field, (iii) identify the relevant studies based on the most common research areas or clusters, and (iv) analyze the content of the articles by text mining and classification techniques to classify most frequent and common methods and key research streams applied in this field.

Complementing quantitative automated analysis (bibliometrics and life-cycle analysis) with qualitative methods (expert judgment and text mining), this paper aims to provide a convenient and useful platform which could assist researchers in identifying the hidden patterns, hot topics, and methods in this area. Note that the most apparent advantage of this systematic review as compared to traditional narrative reviews is that it minimizes the bias frequently observed in expressing expert judgments.

Literature review

Fuzzy sets theory

Fuzzy set theory was introduced in 1965 for the mathematical representation of uncertainty and vagueness (Zadeh 1965). It includes fuzzy logic, mathematical models and linguistic variables and attempts to explain two capabilities: the capability of rational decision-making in a contingent situation, and the ability to analyze a wide range of physical and psychological activities that cannot be easily calculated and measured. Fuzzy logic goes beyond a simple rational system and extends to cognitive and relational dimensions (Zadeh 2008). Its main objective is to capture the vagueness of the thinking process and to express it through appropriate mathematical instruments (Werro 2015). In other words, the theory of fuzzy sets constitutes an aspect of mathematics as adapted to treat the subjective and the uncertain (Gil-Aluja 2004). It also deals with subjective uncertainty problems arising from employing linguistic variables to represent a problem or an event. As a methodology, therefore, fuzzy set theory combines ambiguity, impression, and subjectivity into model formulations and solution processes (Guiffrida and Nagi 1998).

In the beginning, the theory of fuzzy sets failed to attract much attention, but the number of researchers studying fuzzy sets theory was increased in the 1970s. In an attempt to review preceding studies on the theory of fuzzy sets, *Fuzzy Sets and Systems*, the pioneering journal in the field, was launched in 1978 (Merigó et al. 2015). An article discussing the application of fuzzy linear programming approaches to the linear vector maximum problem was among the first papers published in this journal. It explored the consequences of using different ways of combining individual objective functions in order to determine

an “optimal” compromise solution (Zimmermann 1978). Following American scholars, many more European and Asian researchers were attracted to fuzzy logic which led to the establishment of the International Fuzzy Sets and Systems Association (Merigó et al. 2015). The aim of this international venue is to develop fuzzy sciences and examine its applications in the fields of system modeling, system analysis, forecasting, decision support in management control systems, and administrative sciences as well as electromechanical systems and construction industries.

The increasing popularity of this theory led to the publication of several books on possibility theory, control, behavioral and social sciences in fuzzy environments as well as thousands of articles in fuzzy journals during the 1980s (Atanasov 1986; Gorzalczyk 1987; Klir and Folger 1988; Takagi and Sugeno 1993; van Laarhoven and Pedrycz 1983). The application of fuzzy expert systems, fuzzy control, computer science and fuzzy decision support systems also increased considerably. The 1990s witnessed the development of the theory of fuzzy sets into fuzzy technology. This shift caused the emergence of hardware and software instruments that significantly improved the design of fuzzy systems and their practical applications. Since 1994, the theories of fuzzy sets, neural networks, and genetic algorithms have been increasingly intertwined. These have led to the emergence of computational intelligence.

Fuzzy set theory has influenced human reasoning by facilitating the process of decision making in uncertain and unstable situations. It has been employed in developing formalized tools to deal with the imprecisions intrinsic to a wide variety of problems (Naeni et al. 2014). Being recognized as an important problem modeling and solution technique, fuzzy set theory is now applied in engineering, business, medical sciences, healthcare, finance, and natural sciences. In addition, there have been successful applications and implementations of fuzzy set theory in operations and production management (Chen et al. 2006; Haq and Boddu 2017; Kumar et al. 2017).

Application of fuzzy sets theory in operation management

Operations management is a function that enables organizations to achieve their goals by efficient acquisition and utilization of resources (Bayraktar et al. 2007). Since 1980, the discipline of operations management has witnessed an increasing expansion of empirical research to promote issues such as manufacturing strategy, flexibility, quality and inventory management (Rungtusanatham et al. 2003). In the past, operations management was considered to be a regular knowledge as obtained from a rational and systematic point of view, and the term primarily referred to manufacturing production. The business definition for operations management, however, consists of attempts to maintain, control and improve organizational activities that are necessary for producing goods or services for customers (Arias-Aranda et al. 2010). Since operations management includes every functional area of an organization ranging from marketing, accounting, purchasing/logistics, and information management to engineering and human resources, the field has also expanded to include service systems (Bayraktar et al. 2007). Today, operations management refers to organizational knowledge that involves both technical and social structures, hence, besides production issues, it also includes both behavioral and organizational concerns (Voss et al. 2002).

Fuzzy set theory has vast applications in different disciplines of operations management. In project management, the limited resources have made the managers to prioritize the projects with the highest productivity and profitability. Jafarzadeh et al. tried to combine quality function deployment and data envelopment analysis approach in fuzzy space

to present the best project priorities with considering all dependencies between them. Using the introduced combined approach, managers can make efficient decisions in uncertain conditions (Jafarzadeh et al. 2018). In another study, considering the critical role of scheduling in project management, an optimized schedule was presented by Khalilzadeh et al. using heuristics algorithm with fuzzy parameters in their research. The suggested algorithm calculates the least activities time in fuzzy space and uses parallel time scheduling (Khalilzadeh et al. 2017).

In the field of inventory management and control, Bean et al. designed a fuzzy model to manage army organizations inventory in uncertain conditions. In this research, the fuzzy-probabilistic multi-objective model has been designed and applied for determining inventory level for required items under three different scenarios. The findings showed that the presented model has a high reliability in inventory management issues (Bean et al. 2016). In another study, it is stated that although application of fuzzy set theory has expanded in inventory management, the determinants of the decision-making process and its impact on the decision makers have not been addressed in modeling so far (Kazemi et al. 2015). Therefore, human learning is considered in the planning horizon by presenting a new model of the economic order quantity with a backorder. The model presented in the above-mentioned paper was the expansion of the EOQ inventory model with backorder, in which both the time of demand and delivery were fuzzy. The findings indicated that the EOQ inventory model with backorders and human learning could have a great impact on the effectiveness of solving stock problems.

In new product development management, Yuen used the F-AHP method to choose the best new product development strategy. It is revealed that the proposed F-CNP, with the mathematical definition of the fuzzy pair distance scale, provides a better understanding of the difference between the couple (Yuen 2014). Given the importance of demand forecasting for new products, Aydin et al. presented a new methodology for developing a fuzzy market demand forecasting model, considering the uncertain demand for new products. The presented model was a combination of fuzzy regression and discrete selective analysis. To evaluate the effectiveness of the model, the authors used the proposed model to predict the demand for a new tablet (Aydin et al. 2014).

As industries seek to increase reliability and safety of production systems by paying reasonable costs, the selection of the most appropriate repair strategy has been considered by the researchers in the field of operation management. Considering the importance of the issue, Kirubakaran & Ilankumaran applied a multi-criteria decision-making method to select the optimal strategy for repairs in the paper production industry. The presented approach was a combination of a fuzzy analytical hierarchy process, gray relations analysis, and TOPSIS method that evaluated four repair strategies (corrective repair strategy, preventive maintenance strategy, time-based preventive maintenance strategy, and conditional-driven strategy) with focusing on four criteria of safety, cost, value-added, and feasibility (Kirubakaran and Ilankumaran 2016).

The estimated cost for quality control has a significant impact on the development of the quality management system. Due to this fact, a cost-effective quality estimation method was undertaken in a study, by focusing on the hidden quality costs. The study identified the position of business in the Crosby quality management maturity network and determined the degree of membership of each stage of the management maturity network. In addition, the Crosby correlation coefficient was used to determine the weight and fuzzy quality cost (Martínez and Selles 2015).

Closed loop supply chain management is one of the most important managerial issues in supply chain management that attract the attention of customers, organizations,

and government. Ghahremani-Nahr et al. designed a closed-loop supply chain network and provided a mathematical fuzzy model. The results showed that the proposed algorithm is powerful to find the nearest optimized solution effectively (Ghahremani-Nahr et al. 2019). Sustainable supply chain production systems is another important field of supply chain management which enable companies with resource constraints to contribute to the improvement of social conditions and the growth of economic indicators. Tseng et al. analyzed the existing relationships in the service innovation hierarchy of the service delivery system in the sustainable supply chain. They applied a combination of Fuzzy Delphi, important-performance analysis (IPA) and the analytical network process (ANP). The results of their study showed that sustainable consumption, participatory advantage, innovative activities, and service innovation capabilities are the characteristics of the sustainable service supply chain (Tseng et al. 2018). In another study, Jindal and Sangwan, provided a mathematical model of closed loop supply chain focusing on environmental and economic factors by using a fuzzy multi-objective decision-making approach. The proposed fuzzy multi-objective integer linear programming model considers the client area, assembly centers, disassembly sites, external suppliers, and various product recovery processes, such as purchase costs, shipping costs, processing costs, costs setting up and capacity constraints (Jindal and Sangwan 2017).

Methodology

This research is based on a Four-step methodological framework that is executed, under the supervision of a panel of experts which are academics in the field of operation management and have sufficient knowledge and expertise in fuzzy sets theory. Figure 1 demonstrates the overall methodological framework which is used in this study.

Database

Establishing a database is the first step in the bibliometric analysis. The search is performed in 2015 and included all the papers published by April 2015. The search is performed in the title, abstract and keywords of papers in the Scopus database. Scopus is selected because it offers high quality and reliability in terms of coverage and includes complete bibliographical data. As the aim of this study is to conduct a bibliometric analysis of scientific articles, different keywords (e.g. operations management) are selected as the search strategy to locate relevant articles. Because the term “operations management” does not cover all relevant areas including production management and supply chain management, a more general term, “management”, is substituted for it. Although this made the filtering task more difficult and time-consuming, it eliminated the possibility of losses. 11,433 papers were retrieved by combining “Fuzzy” and “Management” as two keywords. Afterward, the general pool is filtered twice. First, papers published in journals with Impact Factors lower than one were excluded. At this stage, the delimited pool did not include papers only dealing with the use of fuzzy methods in the field of management, so papers were scanned according to the scope of the journals to make sure that only relevant papers were included. Eventually, 6075 papers on the topic were selected and archived for further analysis.

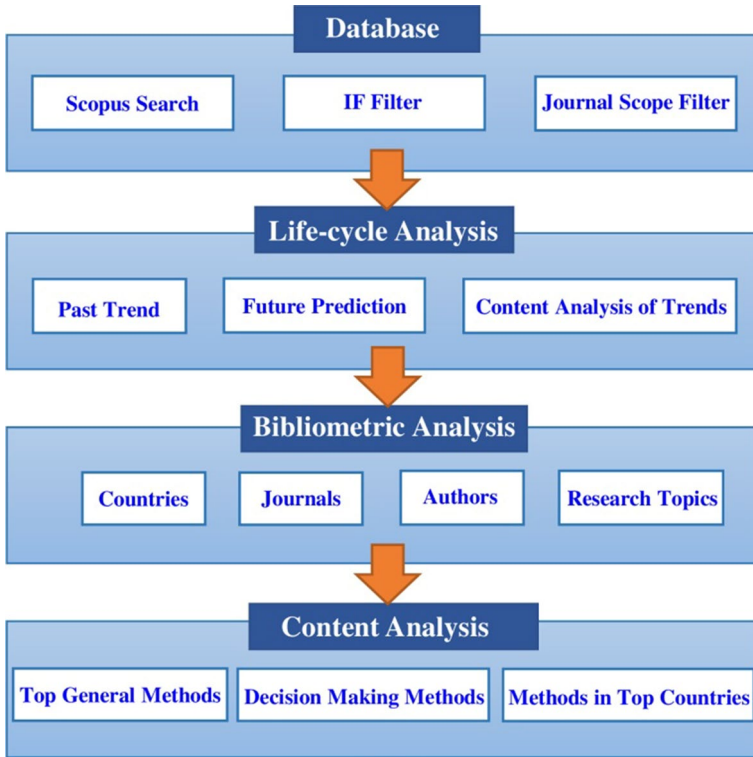


Fig. 1 The general framework of methodology

Life-cycle analysis

Life-cycle analysis is a widely-used data analysis technique that can be applied to describe the historical developments of a research domain or technology, and, subsequently, to predict its future trends. According to Ernst (1997), scientific evolution over time can be sketched as an S-shaped curve representing scientific trends and life-cycle. If the current stage of a scientific field or technology is already known, it would be possible to forecast its future trends, predict its saturation level and, therefore, estimate its potentials for further development. In addition, the evolution of the field and the factors that enhance or hinder its growth can be determined by analyzing the growth trend (Rezaeian et al. 2017). Discovering the maturity and future potentials of scientific innovations helps researchers decide whether they should continue researching the field or should alter their field of interest (Campani and Vaglio 2014; Trappey et al. 2010, 2011).

This study employs cumulative publications for determining developmental trends and predicting the future of the field by using Loglet analysis. LogletLab 4 is used to perform the analysis. It refers to the decomposition of growth and diffusion into S-shaped logistic components, roughly analogous to wavelet analysis, popular for signal processing and compression (Meyer et al. 1999). Equation (1) is used to calculate logistic growth.

$$N(t) = \frac{K}{1 + \exp \left[-\frac{\ln(81)}{\Delta t} (t - t_m) \right]} \tag{1}$$

where K is the asymptotic limit that the growth curve approaches and shows the saturation level of growth, Δt is the characteristic duration that specifies the time required for a trajectory to grow from 10 to 90% of the limit K , and t_m is the midpoint of the growth trajectory. Further information is presented by Meyer et al. (1999).

Bibliometrics

The term “bibliometrics” was originally coined by Pritchard (1969) to replace “statistical bibliography” (Stelzer et al. 2015). In 1995, this method was introduced by Kostoff as a measure to assess research impact and then as a scanning tool to identify innovation opportunities (Kostoff 1995). It denotes a set of mathematical and statistical techniques to quantitatively analyze, explore and organize large amounts of scientific and technological literature including journal articles and patents. It seeks to facilitate the examination of literature’s properties including countries of origin, affiliations, venues, and citations (Mao et al. 2015; Zyoud and Fuchs-Hanusch 2017). Considering its potential to eliminate subjective and local biases as frequently observed in expert judgments, bibliometrics has been widely adopted in various domains including emerging sciences and technologies (Bildosola et al. 2017; Mund and Neuhäusler 2015), energy (Li et al. 2015; Liao et al. 2016; Mao et al. 2015; Wang et al. 2016; Zhang et al. 2015), operations management (Shang et al. 2015), technology forecast (Han and Shin 2014; Stelzer et al. 2015), social science (van der Have and Rubalcaba 2016; Verleysen and Weeren 2016), environment (Daughton 2016), water management (Fu et al. 2013; Zheng et al. 2015) and computer sciences (Fu et al. 2013; Garousi and Mäntylä 2016; Garousi and Varma 2010). Presenting the bibliographic data graphically with different network maps is a useful technique for knowledge transfer (Gibson et al. 2018; Liao et al. 2018). Various software tools are also developed for this purpose. They enable the visualization and exploration of different maps that help researchers identify research fronts and knowledge bases despite the plethora of records. In this paper, VOS viewer, a free Java application, is used for constructing and visualizing bibliometric networks. These networks may include journals, countries, or individual publications, and they can be constructed based on co-citation, bibliographic coupling, or co-authorship relations (van Eck and Waltman 2007).

This technique, however, has its limitations: (1) lack of access to the entire scientific developments as they are not all publically released in the form of publications; (2) inability to measure the real worth of records as citation frequency does not necessarily indicate the quality; and (3) the lead time that temporarily separates research and its appearance. We employed bibliometrics alongside with other qualitative methods, such as expert judgment and content analysis, to partly defeat these limitations. In addition, we applied the text mining function of VOS viewer along with other content analysis techniques (e.g. word frequency) to construct and visualize the coincidence of networks of common terms as extracted from a body of scientific literature.

Content analysis

Content analysis of title, abstract and keywords is conducted based on a text mining technique to identify relations, patterns or trends of the papers. Text mining is defined as the process of identifying valuable information such as relations, patterns or trends in textual data (Choudhary et al. 2009; Delen and Crossland 2008; Ghazinoory et al. 2013). It has been administered to explore complex relationships in scientific documents (de Miranda

Santo et al. 2006; Singh et al. 2007). Transformation of text into numerical data is among the main themes supporting text mining (Rezaeian et al. 2017). This transformation, which has proved remarkably successful, uses statistical methods to convert text mining into a classical data mining encoding (Weiss et al. 2010). Text mining is used to (i) identify the most common methods and top countries in applying each method, (ii) classify the papers into most important operation management research themes based on experts’ opinion and (iii) classify the papers based on their methodology. First, the title, abstract and keywords of articles were broken into meaningful words and phrases. Then, the extracted words and phrases were filtered by experts to develop a dictionary of keywords as related to methodologies and the research themes of papers. Next, the frequency of keywords in papers is calculated and the research theme/methodology of each paper is identified by comparing the frequency of these keywords using Eq. (2).

$$T_{ij} = \sum_{m=1}^{T(KP_i)} KPF_m \tag{2}$$

where T_{ij} is the frequency of research methodology i in paper j , $T(KP_i)$ is the number of methodology keywords (related to research methodology i) in paper j , and KPF_m is the frequency of keyword m (related to research methodology i) in paper j .

Results

Life-cycle analysis

Figure 2 presents the results of the life cycle analysis on operations management articles featuring an application of fuzzy theory. First, the logistic growth is visualized by simply plotting data on an absolute and linear scale. The Fisher-Pry transform is used to transform the logistic curve into a linear one. By doing so, Δt , t_m , and K can be determined. The Fisher-Pry transform of the publication growth is illustrated in Fig. 2a. The time in which the value is between 10^{-1} and 10^1 is equal to Δt , and the time at 10^0 is the point of inflection (van Eck and Waltman 2007).

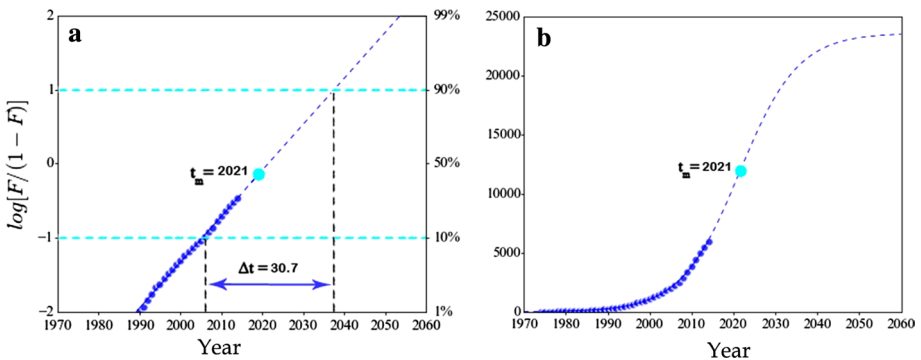


Fig. 2 a Determining Δt and t_m of the logistic growth using Fisher-Pry transform that renders the logistic linear. b Growth of publications fitted to a logistic curve

Figure 2b depicts the growth over a 40-year period and the growth predictions by 2060. The first articles on applications of fuzzy method in operations management date back to the 1970s. “A concept of compromise solutions and the method of the displaced ideal”, the pioneering article, was published in *Computers & Operations Research* journal by Zelany (1974). It aimed to help decision makers reduce the set of non-dominated solutions by eliminating some “obviously bad” solutions through fuzzy weight assessment.

After a slight fluctuation in 2000, the growth stage commenced at an exponential rate. It has grown since 2000 and the growth is estimated to continue for about 30 more years. Content analysis is administered to compare the articles published before and after 2000 to explain the rapid growth. The most significant developments were identified through comparing the words that frequently appear in each span. Terms “intuitionistic fuzzy” and “fuzzy AHP” were first applied in operations management in 2001 and have grown into the most popular methods in this field since then. This exponential growth can be explained by the increasing occurrence of terms “supply chain,” “fuzzy type 2,” “fuzzy AHP” and “data mining” in operations management articles employing a fuzzy methodology. These concepts were not common in operations management before 2000 and have gained momentum since then. Another reason can be the increasing number of journals where related articles were published. The scope of only 64 journals allowed the publications of such articles before 2000, while this number increases to 165, afterward.

The publication count is predicted to maximize in 2037 at 23,615 papers. This extrapolation, therefore, indicates a clear potential for further developments in this field. This saturation level does not mark an end but rather advancements into a new level; that is to say, the growth period can still be extended, if there are new breakthrough innovations in this area.

To have an overview of the accuracy of the predictions, a sensitivity analysis has been done to compare the actual numbers of publications with the predicted numbers by life-cycle analysis by 2018. The results of the sensitivity analysis are shown in Fig. 3. As it is shown, the accuracy of the predictions is considerably high.

Bibliometrics analysis

Visualization

The bibliometrics analysis of 6075 revealed the top-rated countries, journals, and institutions. Moreover, the networks were identified and visualized by using VOS viewer through exporting the papers’ bibliometric data from the Scopus database.

Countries Table 1 presents the statistical records of the most influential, productive and collaborative countries in the field of fuzzy approaches to operations management. Top three countries are Taiwan, the United States, and China. Such analyses are necessary to understand different countries’ position relative to global and domestic standards of research quality and production.

Figure 4 illustrates publication growth in the top five countries according to their publication counts. China and Iran has witnessed significant growth in this field since 2004 and 2006 respectively. While the growth rates are much lower in the case of the United States and Spain. The highest growth rate among other countries by 2009 belongs to Taiwan, but it has considerably decreased afterward and reached 52 in 2014.

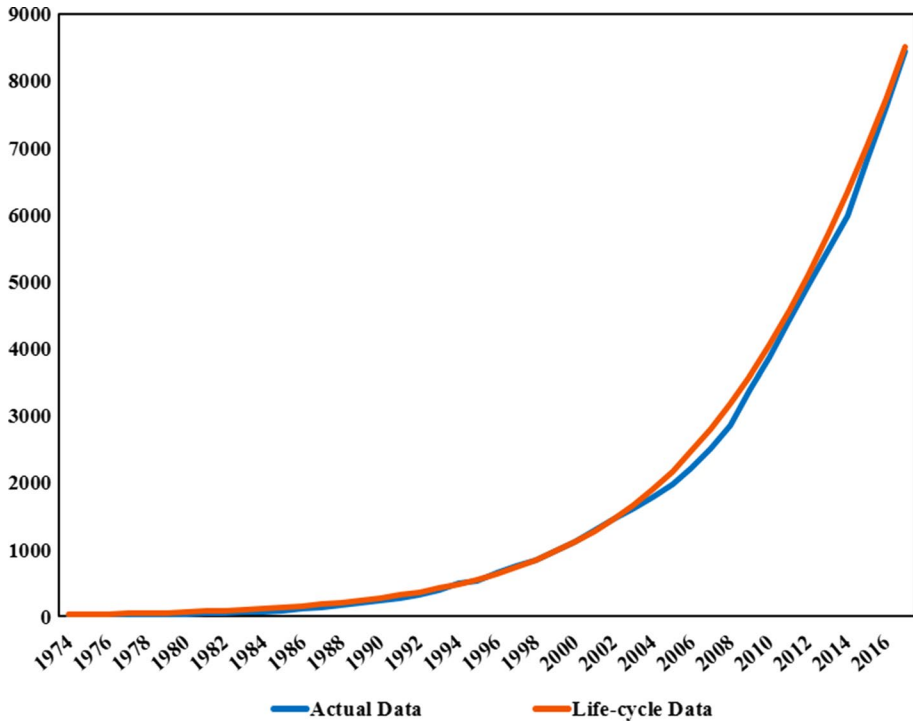


Fig. 3 The comparison of actual and predicted data

Journals The number of articles in different journals is obtained by using bibliometric data. Figure 5 shows the density visualization of the journals in this field. The most cited journals are identified by the software and marked with red areas and boldface font. Top journals in the field are *Fuzzy Sets and Systems* with 963 articles and 38,685 citations, *Expert Systems with Applications* with 1095 articles and 22,554 citations, *Information Science* with 453 articles and 17,642 citations and *European Journal of Operational Research* with 376 articles and 14,919 citations.

Research topics The text mining function of VOS viewer is also applied to identify and cluster the most common topics. Figure 6 illustrates the network visualization of the most frequent research topics and sub-fields. According to the frequency of keywords and their coincidence with other keywords, most common topics were identified, clustered, and visualized by the software.

As it is indicated in the figure, the most common topics in this field can be categorized into 5 groups. “Decision Making” is one of the hottest topics investigated in papers. This area of study is shown in the figure by keywords such as “AHP, ANP, MCDM, group decision making”. The words “feature extraction, natural language processing, database systems, and data structures” represent the “data mining” techniques which are widely used alongside with fuzzy set theory in operations management. Application of artificial intelligence in operations management is another frequent topic in this field. The words “neural network, genetic algorithm, simulation, ANFIS, and fuzzy time series” represent

Table 1 Top 20 countries in publishing articles related to operations management featuring applications of fuzzy methods

Most productive countries		Most influential countries		Most collaborative countries	
Country	Publication No.	Country	Citation No.	Country	International Network
Taiwan	1125	Taiwan	31297	United States	564
China	974	United States	28901	China	526
United States	855	China	22731	Canada	273
Iran	396	Turkey	10084	UK	258
Spain	396	Spain	9681	Hong Kong	237
Turkey	356	Hong Kong	8726	South Korea	196
Canada	319	UK	8329	Iran	174
India	307	Canada	7720	Taiwan	163
UK	285	Japan	6590	Australia	124
Hong Kong	248	India	6321	Spain	115
Japan	238	France	5876	Poland	114
France	214	Iran	5234	France	111
Italy	185	Poland	5038	Italy	97
Poland	162	Germany	4927	Japan	93
Australia	144	Italy	3590	Turkey	86
South Korea	131	Australia	3568	Germany	82
Germany	130	Belgium	3104	Belgium	72
Greece	93	South Korea	2820	India	72
Belgium	87	Greece	2530	Malaysia	65
Singapore	81	Singapore	2211	Georgia	61

this cluster. The next cluster is that of supply chain management as identified by “supply chains, SCM, collaboration, capacity management, and distribution” that is frequently explored alongside with “optimization, logistics, stochastic systems, and fuzzy programming”. The last category indicates the words related to sustainable management including “environmental protection, risk management, water supply, ecosystem, municipal solid waste, and reservoirs”.

Content analysis

The frequency of methodologies is calculated by QDAminer. As shown in Fig. 7, they are classified into 13 categories the most frequent of which is decision-making, while statistical methods and mathematical programming rank second and third.

As decision-making methods occupy a significant position in operations management studies, these techniques were independently analyzed to discover their frequencies as illustrated in Fig. 8. Multi-criteria decision is a complicated tool that facilitates decision making by incorporating quantitative and qualitative criteria. In recent years, the fuzzy set theory has been integrated into decision-making techniques to improve the decision-making process. Mardani et al. systematically extracted and analyzed the application of FMCDM techniques in 403 articles published between 1994 and 2014. The results of their

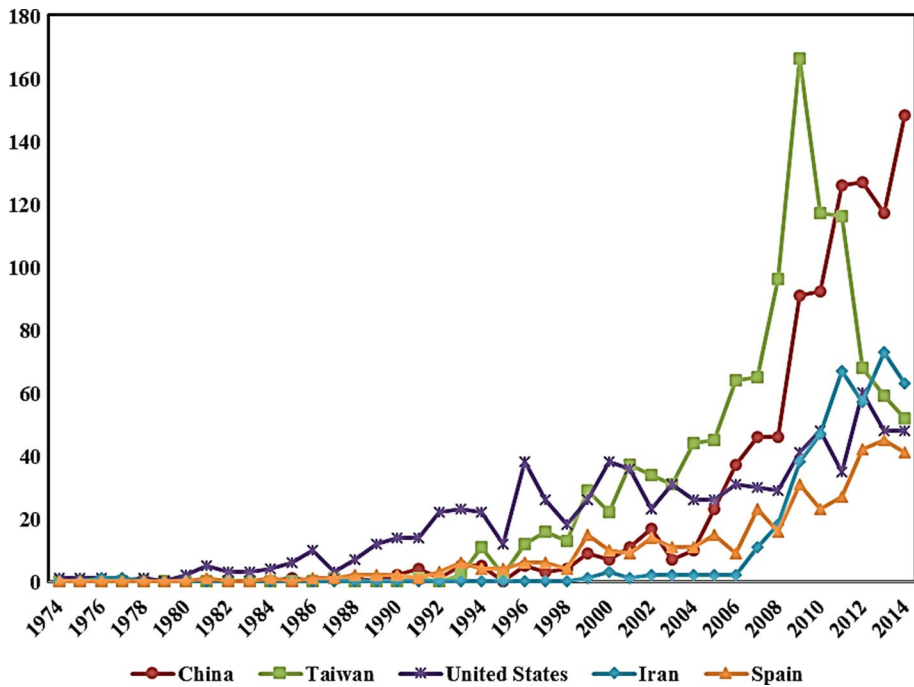


Fig. 4 Publication growth in top five countries based on their publication count

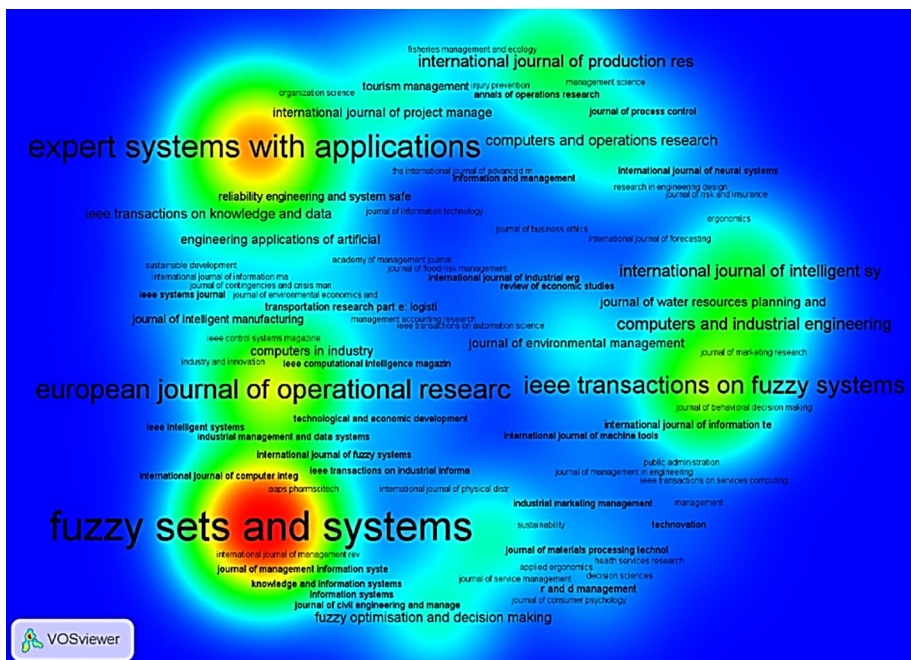


Fig. 5 Density visualization of journal titles

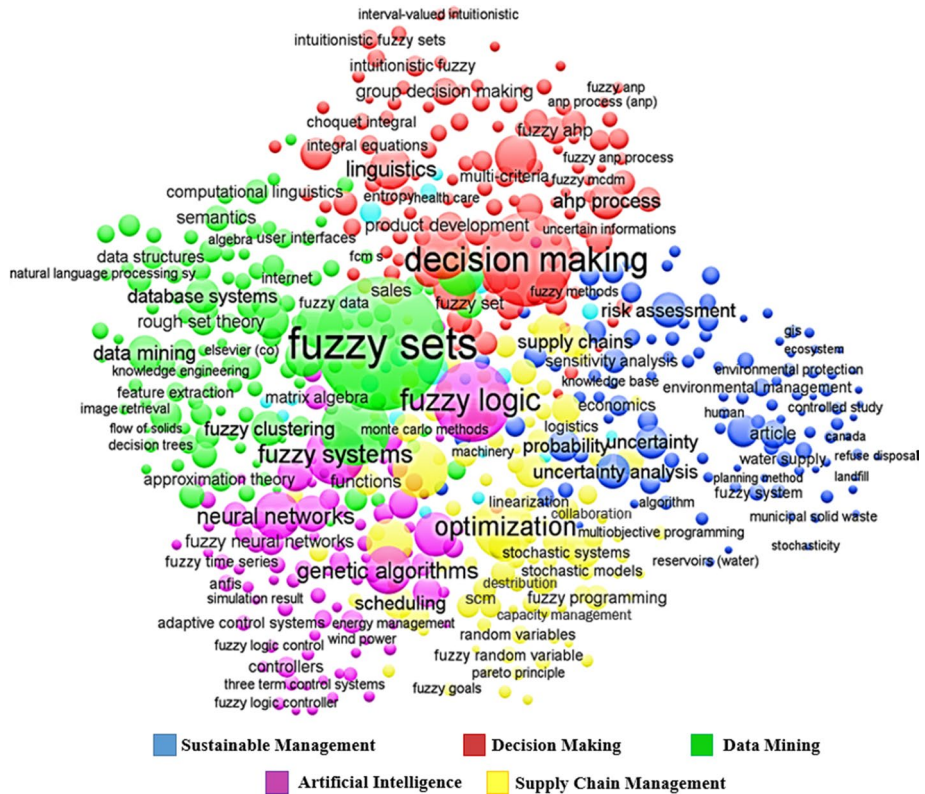


Fig. 6 Network visualization of the most common research topics and sub-fields

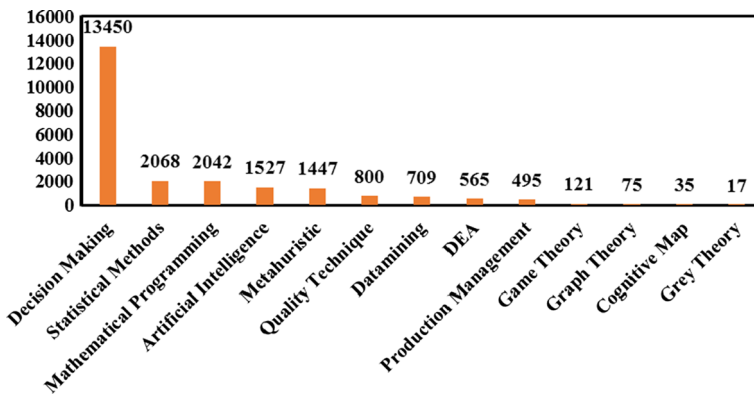


Fig. 7 Frequency of the methodologies

study showed that FMCMD is used in management, business, engineering, technology, and basic sciences and that the number of publications using these methods has considerably increased (Mardani et al. 2015). In another study, researchers found that the combination

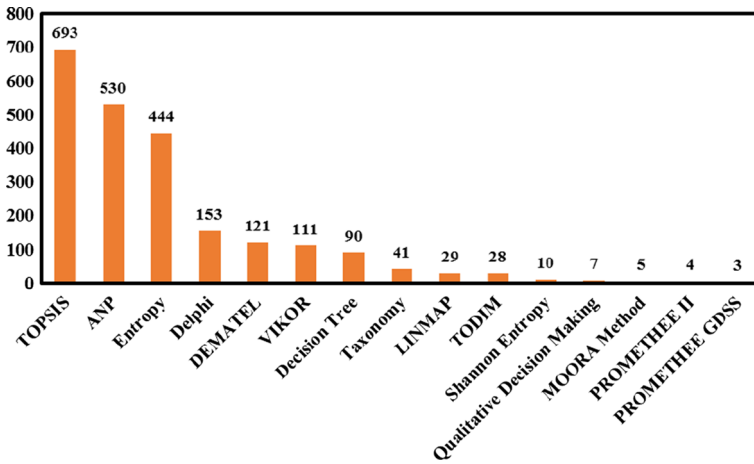


Fig. 8 Frequency of the decision-making methods

of fuzzy theory with meta-heuristic techniques has become very popular in the last decade (Wong and Lai 2011). The results presented in Fig. 8 verify the findings of these studies.

After the methodologies and countries of origin of the papers were identified, top countries in employing each methodology were also retrieved. The results are shown in Table 2. The United States is the most prominent country in applying “artificial intelligence,” “data mining,” “decision making,” “grey theory,” “Meta heuristic,” “production and operation management,” “statistical methods” and “quality techniques.” Chinese publications mostly follow “graph theory” and “mathematical programming,” and Korean, Iranian and Australian papers mostly use “cognitive map,” “DEA” and “meta-analysis,” respectively. These results were obtained from the papers whose methodologies could be specified through their bibliographic information. Those that their methodologies were not mentioned in their titles, abstracts or keywords were excluded in this specific analysis.

Table 2 Top countries in implementing each method

Method	Country
Artificial intelligence	United States
Cognitive map	Korea
Data mining	United States
DEA	Iran
Decision making	United States
Graph theory	China
Grey theory	United States
Mathematical programming	China
Meta-analysis	Australia
Meta heuristic	United States
Production management	United States
Statistical methods	United States
Quality techniques	United States

Table 3 Classification results based on main research themes and methods

Research themes		Research methods	
Decision making	1543	Artificial intelligence	638
Human resource management	146	Data mining	26
Information system	212	Decision making	2042
Inventory management	628	Mathematical programming	772
Marketing	38	Metaheuristic methods	361
New product development	131	Production management methods	93
Operations strategy	159	Quality techniques	192
Production and manufacturing management	1091	Simulation	317
Project management	477	Soft operations research methods	158
Quality management	601	Statistical methods	269
Supply chain management	167	Others	1208
Sustainability	441		
Others	442		

In Addition to analyzing the most common methods in each region, a classification technique is carried out with a text mining approach, classifying the papers of the database based on the most methods and research themes. Note that the result of this ‘classification’ technique is different from that of the ‘clustering’ approach done by VOS viewer software. In this step, at first, the experts indicated the most important (not frequent) research themes and methods. Then the relevant keywords and phrases of each category were specified. Next, the papers were classified based on their relevance to the indicated research themes. The classifications and the number of the relevant papers in each category are presented in Table 3. It should be mentioned that there are some papers that do not have a specific research method since they have done a literature review or have used a discussion attitude which are classified into the others section. In addition, 442 papers were not identified by the specific research themes.

Conclusion

The literature on the application of fuzzy theory in operations management has considerably increased over the past few years. This study conducted a systematic review on scientific articles by applying life-cycle analysis, bibliometrics and content analysis through text mining in order to map this research area and its developments. Life-cycle analysis was used to analyze the development trajectory of the field and to forecast its future trends. The results show that this field has great promises for future development and expansion as it currently stands half-way through its full flourishing. The number of articles in this field is expected to increase and reach its maximum at 2037 to 23,615 articles. It seems that a large part of the increase in the number of papers, predicted in Fig. 2, would concentrate on the application of new fields in fuzzy sets theory like “Intuitionistic fuzzy sets”, “Neutrosophic fuzzy sets”, “Bipolar fuzzy sets”, etc. on in operations management.

The bibliometric analysis shed light on the intellectual structure, current status, popular research topics and contributions of key figures in this field over the last 4 decades. Taiwan and the United States have made the largest contributions to literature at 31,297 and 28,901

citations, respectively. Most publications belong to Taiwan with 1125 and China with 974 articles, and top collaborative countries are the United States and China with 564 and 526 international publications. Core journals were identified to be *Fuzzy Sets and Systems* with 963 articles and 38,685 citations, *Expert Systems with Applications* with 1095 articles and 22,554 citations, *Information Science* with 453 articles and 17,642 citations and *European Journal of Operational Research* with 376 articles and 14,919 citations.

Checking top 20 countries in Table 1 based on their continent shows that 45% of most productive countries are located in Asia (Taiwan, China, Iran, Turkey, India, Hong Kong, Japan, South Korea, Singapore), 40% in Europe (Spain, United Kingdom, France, Italy, Poland, Germany, Greece, Belgium), 10% in America (United States, Canada) and 5% in Oceania (Australia). The ratios of publications in these continents are 49.9%, 20.08%, 28.13%, and 1.86%. These results show that Europe has rather a low share in number ratio despite the high diversity in countries communicated in publication.

The trend for the number of citations in different continents is completely similar to number of publications. Ratio for the citation is sequentially 53.55%, 24.02%, 20.42% and 1.99%.

Discovering a similar pattern for international collaboration in continents in the number of joint papers (50%, 35%, 10%, and 5%) and its ratio (48.03%, 24.37%, 24.03%, and 3.56%), shows overall schema for research quality and quantity in different continents. The most influential researchers in this area are Lotfi A. Zadeh, Zeshui Xu and Didier Dubois based on number of citations that are American, Chinese and French based on their affiliations. Zeshui Xu, Ronald R. Yager (American) and Didier Dubois are the most productive researchers based on the number of publications.

The database was also analyzed for the methodology of its items. Methods are classified into 13 categories the most common of which was decision-making, and TOPSIS is most frequent among different decision-making techniques. Institutions were also ranked according to their administration of each methodology. The results indicated that the United States is the most prominent country in implementing “artificial intelligence,” “data mining,” “decision making,” “grey theory,” “Metaheuristic,” “production and operations management,” “statistical methods” and “quality techniques.” Chinese publications mostly employ “graph theory” and “mathematical programming,” and Korean, Iranian and Australian papers are inclined toward utilizing “cognitive map,” “DEA” and “meta-analysis,” respectively. The first paper in the database is related to decision-making category and as is shown in Table 3, this category is the top by the number of papers. In fact, the most powerful trend in the development of fuzzy operations management papers has occurred in decision-making.

The results have provided a useful map which can help researchers identify the current status, patterns, key actors, hot topics and methods in this area. The most significant advantage of this systematic review as compared to traditional narrative reviews is that it minimizes the bias as frequently observed in the case of relying only on experts’ judgments. Moreover, the method for selecting documents is explicitly specified by reporting the database, search terms and strategies, and sampling and screening processes to avoid bias.

Although this paper attempted to provide a general bibliometric overview of the application of fuzzy sets theory in operations management, there are some limitations that should be noted. First, our study database covered all papers that had been published on the Scopus database from 1965 to 2014. Note that filtering more than 11,000 Papers and 30,000 words and phrases is a time-consuming task. Therefore, future researchers should consider this time-consuming research process for achieving acceptable results. According to the Scopus database, results of this study can help readers to identify some of the

most productive and influential research, journals and countries in the application of fuzzy sets theory in operations management. However, as a second limitation, there are more publications that have been published in other databases (Web of science, Emerald insight, etc.) that have not been included in this paper. For future studies, it can be a good idea that researchers include the required bibliometric information from other databases and compare acquired results with the present study. Moreover, it is recommended that future studies focus on top methods that have been identified in this study and analyze the lifecycle of their applications in operations management. Discovering the future trend and lifecycle of application of fuzzy set theory in operations management filed separately could be interesting.

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