A Survey of Fuzzy Systems Software:
Taxonomy, Current Research Trends, and Prospects

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Abstract

Fuzzy systems have been used widely thanks to their ability to successfully solve a wide range of problems in different application fields. However, their replication and application requires a high level of knowledge and experience. Furthermore, few researchers publish the software and/or source code associated with their proposals, which is a major obstacle to scientific progress in other disciplines and in industry. In recent years, most fuzzy system software has been developed in order to facilitate the use of fuzzy systems. Some software is commercially distributed but most software is available as free and open source software, reducing such obstacles and providing many advantages: quicker detection of errors, innovative applications, faster adoption of fuzzy systems, etc. In this paper, we present an overview of freely available and open source fuzzy systems software in order to provide a well-established framework that helps researchers to find existing proposals easily and to develop well founded future work. To accomplish this, we propose a two-level taxonomy and we describe the main contributions related to each field. Moreover, we provide a snapshot of the status of the publications in this field according to the ISI Web of Knowledge. Finally, some considerations regarding recent trends and potential research directions are presented.

Key words: Fuzzy logic, fuzzy systems, fuzzy systems software, software for applications, software engineering, educational software, open source software.

1. Introduction

Fuzzy systems are one of the most important areas for the application of fuzzy set theory [1]. They use fuzzy logic to provide a conceptual framework for knowledge representation and reasoning under imprecision and the consequent uncertainty [2]. Fuzzy systems have been successfully applied to many application fields (such as control [3], modelling [4, 5], classification [6], data mining [7], etc.) due to their ability to incorporate human expert knowledge and granular computing [8], to handle imprecision and uncertainty, and to describe the behavior of complex systems without requiring a precise mathematical model.

Since the 1990s, although it already had a successful history, the field of fuzzy systems has grown due to increasing interest in augmenting fuzzy systems with learning and adaptation capabilities [9]. This growth

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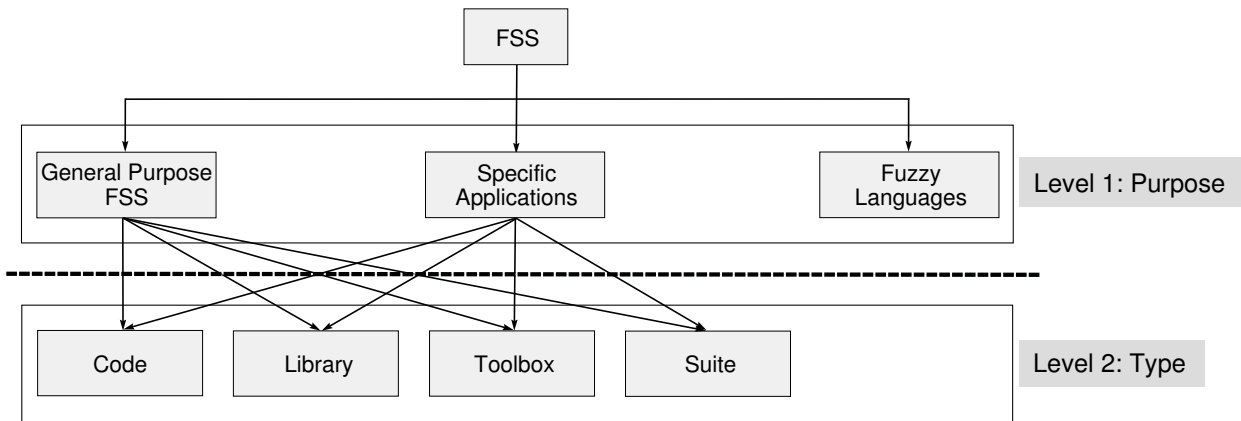
Figure 1: Taxonomy based on the purpose (first level) and the type (second level) of the FSS.

has produced a wide variety of fuzzy systems that allow us to solve different kinds of problems in various application domains, with their replication and application to new problems crucial to scientific progress in other disciplines and in industry. However, this task requires a high level of knowledge and experience, and many researchers with less knowledge would not be able to apply these fuzzy systems to their problems successfully. Moreover, few researchers publish the software and/or source code associated with their papers, and numerous algorithms and source codes published in journals and books contain errors, even to the point of not being compilable as published [10].

In the last few years, most fuzzy systems software (FSS) has been developed in order to facilitate the use of fuzzy systems. Although some software is commercially distributed, such as the Fuzzy Logic Toolbox for Matlab [11] or the Fuzzy Logic 2 add-on for Mathematica [12], many are developed by the scientific community and are available as free and open source software, such as FisPro [13], KEEL [14], etc. Notice that open source sharing of FSS plays a very important role in removing obstacles, offering many advantages that will lead to the quicker detection of errors, innovative applications, the faster adoption of fuzzy systems in other disciplines and in industry, and so on [15, 16, 17].

The objective of this paper is to analyze the state of the art of the freely available and open source FSS and to provide a well-established framework that will help researchers to find existing proposals that are related to a particular branch easily and to focus on significant further developments. To this end, we propose a two-level taxonomy to classify the available contributions and we describe the main proposals that focus on this field. The first level of the taxonomy is based on the purpose of the software, i.e., the aim for which it was developed, and the second level is based on the type of software: library, toolbox and so on. Both levels determine the search space that involves different proposals on FSS. Moreover, we present a quick snapshot of the status of the publications on FSS according to the Thomson Reuters Web of Science. Finally, we discuss the main current trends and prospects.

To keep this study up-to-date, improving its visibility and providing additional materials, we have developed an associated web page that can be found at `http://sci2s.ugr.es/fss/`. This presents additional information related to the topic of FSS: an introduction to FSS, some of the most popular FSS, research topic repositories, etc. Moreover, this web page also includes the proposed taxonomy and a bibliographical compilation of papers on FSS (from 2009 to present).

This paper is organized as follows. Section 2 introduces the proposed two-level taxonomy to organize the freely available and open source FSS. The following sections describe the main and most recent proposals related to each field. Section 3 presents proposals dealing with FSS applied to the design of fuzzy systems in relation to all research areas addressed by the fuzzy community. Section 4 focuses on works related to solving specific problems in different application areas such as control, software engineering, educational

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Formerly the Institute for Scientific Information (ISI) Web of Knowledge: [`https://apps.webofknowledge.com/`]

purposes, and so on. Section 5 briefly sketches some initiatives aimed at defining languages to represent fuzzy systems. Section 6 presents a careful bibliographical study of FSS, revealing the main current research trends. In Section 7 we discuss some critical considerations of the recent publications on the topic. We also pay attention to further research directions. Finally, some concluding remarks are made in Section 8.

2. Taxonomy

In this paper, we take into consideration a large number of proposals in which FSS has been proposed as free and open source software. Both types of software can be used free of charge and include different types of license depending on the requirements of the developers [18]. Although there are many different software licenses, the two most widely used are GNU and Creative Commons due to the fact that they offer several variants attending to specific licensing terms, such as copyleft. Notice that the open source FSS is also distributed together with the related source files, which allows us to unlock the true potential of FSS. This open source model makes it easier for other researchers to develop and adapt their own software to their problems and provides many advantages [15, 16, 17]: the quicker development and detection of errors, innovative applications, the faster adoption of fuzzy systems in other disciplines and in industry, etc.

In order to provide a well-established framework that allows us to jointly analyze the different proposals, we propose a two-level taxonomy, shown in Fig. 1. The first level organizes FSS depending on the purpose for which it was developed: general purpose FSS, applications, and languages. The second gathers proposals based on the type of software generated to solve a given problem: code, library, toolbox, and suite. These two levels allow us to classify the search space in which we may find the existing proposals.

In the first level, the first category (general purpose FSS) gathers contributions in which FSS is developed with a general purpose. This kind of FSS allows us to design and to analyze fuzzy systems (fuzzy rule systems, fuzzy multicriteria decision-making systems, etc.) for different problems in relation to all research areas addressed by the fuzzy community (clustering, classification, regression, and so on). The second category (applications) is related to contributions that describe FSS for specific application purposes. The third main category includes contributions in which new languages for fuzzy systems are proposed. Such languages provide researchers with a way of working that makes it easier to exchange fuzzy systems between FSS and improves the reusability of the developed fuzzy systems. Several contributions can be found in the literature in which these languages are used to describe the fuzzy systems developed.

In the second level of the taxonomy, discovering the right categories becomes a difficult task because the terminology commonly used in the literature is somewhat misleading. Notice that researchers have sometimes used different terms or/and definitions to refer to the same type of software. To clear up this confusion and to make future research easier, we have studied the terminology used in the literature and we have proposed four terms which attempt to capture the essence of the different types of software appearing in the literature. These types are: code, library, toolbox and suite. Code gathers contributions in which single fuzzy system algorithms written in a programming language are shared, for instance a clever implementation of a certain class of algorithms. Library makes reference to groups of contributions in which sets of functions with a related functionality (encapsulated code) are presented, written in terms of a language, and with a well-defined Application Programming Interface (API) that facilitates its integration with different software. Tool or Toolbox includes contributions which propose FSS that allows us to perform useful tasks with fuzzy systems. This FSS can use one or more libraries and it can be executed as a stand-alone program through command line, graphical user interface (GUI), or even web interface. Finally, Suite is related to contributions in which larger frameworks are presented that allow us to use (among other features) a collection of tools and/or libraries of related functionality, considering a common user interface and some ability to smoothly exchange data with each other.

Here, we give some additional details about each of the three top categories of the proposed taxonomy. Notice that a brief description of related works, paying particular attention to the most up-to-date proposals, will be provided in the following sections.

GNU project: [http://www.gnu.org/]

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2.1. General Purpose Fuzzy Systems Software

Since Zadeh's seminal ideas on fuzzy sets and systems [2] were published fifty years ago, many researchers have worked hard on them [19] and nowadays fuzzy systems are considered to be one of the most important areas for the application of fuzzy set theory.

The flexibility of fuzzy systems makes them applicable to a wide range of problems. In the 1990s fuzzy systems started to be successfully used in control applications. The first success stories in real-world control applications were the Danish cement kiln (1982) and the Sendai subway (1986) and since then, fuzzy systems have been successfully applied to many real-world applications such as industrial applications [3], domotic control [20], etc. Because of this, FSS has been proposed over the years as a potencial support in the design of fuzzy control systems.

However, other research areas (such as data mining, pattern recognition, etc.) have rapidly gained relevance since the mid-1990s. In the fuzzy community, these areas have become even more prevalent than control for fuzzy systems. Moreover, the rapid growth of such varied areas has yielded a large diversity of fuzzy systems ready to face many different problems in a high number of application domains. In consequence, researchers have become aware of the need to shift the focus from control applications to general purpose FSS, which facilitates and improves the design of fuzzy systems with regard to all research areas addressed by the fuzzy community.

In recent years, FSS has been extensively proposed with this aim. Although some FSS is commercially distributed, such as the Fuzzy Logic Toolbox for Matlab [11], there is FSS provided by the scientific community that is available as free and open source software. Moreover, most of this freely available and open source software has recently attained a high level of development and is ready for use not only in academia but also in industry.

Considering the importance of this kind of FSS for the fuzzy community, the first category in the taxonomy includes contributions in which FSS is designed to handle general purpose fuzzy systems. Because of the huge number of existent works, we have organized them into a second level according to the type of software used (see Fig 1).

2.2. Fuzzy Systems Software for Specific Application Purposes

Most of the real applications share several characteristics that complicate the system modeling with classical strategies. The problems start when the system processes are imprecisely described, without recourse to mathematical models, algorithms or a deep understanding of the physical processes involved. In these cases, fuzzy logic represents a powerful tool with which to design accurate models in complex and ill-defined systems in which, due to complexity or imprecision, classical tools are unsuccessful.

Thus, fuzzy systems have been successfully applied to a wide variety of practical problems. As noted above, at the beginning of the 1990s fuzzy systems started to be successfully used in control applications but, in the middle of the 1990s, other research areas (Image Processing, Telecommunication Networks, Medicine, etc.) underwent a rapid growth in the fuzzy community and many fuzzy systems were proposed to solve specific problems in these areas [21, 22, 23, 24, 25]. Because of this, a large amount of software has been devoted over the years to the design of fuzzy systems for a specific part of the development cycle or for a specific problem in different research areas, among others: control, decision-making, software engineering, and so on.

2.3. Languages for Fuzzy Systems

In accordance with the previous subsections, we may find different state-of-the-art FSS with which to design and analyze fuzzy systems for many problems. Nevertheless, some industrial and process engineers trained in traditional theories, calculus, and related disciplines, have often shown hesitation in adopting fuzzy systems because of their impression that there are no well-defined and standard guidelines for designing, developing and maintaining such systems. Moreover, many engineers and/or researchers have emphasized the necessity of a universal language for the use of fuzzy systems due to the impossibility of using the fuzzy systems developed with one software with any other software and hardware [26].

In recent years, some languages for fuzzy systems have been proposed for different areas in order to bridge this gap. These proposals seek to design a generic language which allows us to represent all the fuzzy logic-based formalisms and to consider the constraints of the final system implementation. However, the improvement of one objective leads to the deterioration of another and nowadays there is no single language that simultaneously optimizes all objectives for all areas of the fuzzy community.

Recently, Acampora (vice chair of the IEEE Computational Intelligence Society Standards Committee) has formed a working group to develop a standard language based on the Fuzzy Markup Language (FML) [27]. The new language is expected to allow the design, implementation, testing and interoperability of transparent fuzzy systems within engineering-oriented and visual development environments. This proposal will provide a common language with which to exchange fuzzy systems among different platforms and improve the reusability of the developed fuzzy systems.

Considering the importance of a standard language for the fuzzy community, this third category includes contributions in which languages for fuzzy systems are proposed to handle this gap.

3. Review of General Purpose Fuzzy Systems Software

Nowadays, the design of fuzzy systems is assisted by the general purpose FSS that has been actively developed during recent years. Most of this FSS is released to free and open source libraries and toolboxes with the aim of being reusable and easy to integrate with software developed for specific application purposes. In the following, we present some of the most up-to-date contributions, in which general purpose FSS is developed, for each of the categories in the second level of the proposed taxonomy (see Fig. 1).

3.1. General Purpose Fuzzy Systems Source Code

A search of the Internet for fuzzy codes reveals the existence of several sites from which researchers can obtain codes for different methods. Among them, the Research group NNandFS, at the University of Magdeburg, offers documentation and code for Neural Networks and Fuzzy Systems [28]; Lin and Chen published an easy to understand and to reuse modular code for those researchers who want to develop and customize their own Java applications based on fuzzy expert systems [29]; etc.

3.2. General Purpose Fuzzy Systems Libraries

We can distinguish two groups of general purpose fuzzy libraries. The first group includes fuzzy libraries that are already integrated with other engineering and math libraries. For instance: DANA-FLSA [30] is a library for sensitivity analysis in fuzzy systems which results from integrating the SimLab library in the data analysis and assessment (DANA) development environment; Fuzzy Web Service (FWS) [31] is a service-based inference engine library developed in the context of CASSANDRA (Cognizant Adaptive Simulation System for Applications in Numerous Different Relevant Areas); MODELICA-ANFIS [32] implements the adaptive neuro-fuzzy inference scheme under the object-oriented environment MODELICA, which is aimed at modeling complex systems described in increasing detail; etc.

The second group considers libraries for developing fuzzy systems that are released alone, in contrast to the previous group. In this group, we have identified three main subgroups of libraries according to their programming language (C++, Java and R):

- We can find some libraries written in C++, such as SHARK for example [33], which consists of a set of object-oriented routines for the design of adaptive systems, supporting supervised and unsupervised machine learning, evolutionary algorithms, fuzzy systems, etc.

- However, most existing libraries are currently written in Java, mainly due to the multi-platform nature of this programming language. Some examples are: BPJ [34], which is concerned with the development of switched fuzzy systems under the paradigm of behavioral programming; JUZZY [35], which aids the design of type-2 fuzzy systems; etc.

- Nowadays, the R programming language is gaining importance as a non-commercial solution that is competitive with Matlab. Some of the most outstanding R libraries (usually called packages by the R community) include the following: FRBS [36], which implements functionality and algorithms to build and use fuzzy rule-based systems; SETS [37], which handles generalized and customizable sets (including fuzzy sets); finally, SAFD [38], which provides basic tools for elementary statistics with fuzzy data.

Notice that some fuzzy libraries written in other languages (such as Python) can be found on the Internet but most of them do not have related publications yet.

3.3. General Purpose Fuzzy Systems Toolboxes

Most FSS is released by the fuzzy community as free and open source toolboxes. We have grouped them by research areas in order to make it easier for the reader to obtain a complete picture of the different proposals.

Firstly, we can find several toolboxes regarding data mining and pattern recognition. Among them: FUAT [39] aims at fuzzy clustering analysis; NIP [40] handles imperfect information in datasets; CI-LQD [41] deals with knowledge extraction from low quality datasets, which automates the calculations involved in the statistical comparisons of different algorithms, with both numerical and graphical techniques; SAMT [42] combines statistical data analysis with semi-automatic training of fuzzy rules; FID [43] learns fuzzy decision trees from datasets; VisualFCM [44] supports the generation and visualization of fuzzy cognitive maps; FingramsGenerator [45] addresses generation, visual representation and expert analysis of the so-called fuzzy inference-grams that are fuzzy rule bases represented as social networks; etc.

Many toolboxes have been proposed in relation to fuzzy modeling. Here, we cite some of them: GUAJE [46, 47] deals with the design of interpretable fuzzy systems. It combines expert knowledge with knowledge automatically extracted from data. Fispro [13, 48] also stands out because of the care taken to ensure the interpretability of fuzzy systems automatically learnt from data. Moreover, as far as we know it is the only toolbox that implements gradual implicative rules [49]. Xfuzzy [50, 51] offers several complementary modules to cope with the complete design of fuzzy systems from their description to their synthesis in C, C++ or Java (to be embedded in software projects) or even in VHDL (for hardware projects). E-Fuzz [52] focuses on the design of embedded fuzzy systems.

Another research area in which several toolboxes have been proposed is logical reasoning. Some examples are: KIRQ [53], which extends fsQCA to accommodate contradictory conditions; VisualFLOPER [54], which provides the Fuzzy Logic Programming Environment for Research (FLOPER) with a graphical interface aimed at handling fuzzy truth-degrees; RFuzzy [55], which offers knowledge representation, modeling and reasoning with fuzzy information based in Prolog; etc.

There are also several toolboxes for the fuzzy decision-making area. Among them: FuzzME [56] considers both quantitative and qualitative multiple-criteria for the aggregation of partial evaluations in the context of fuzzy decision making; MaxAgr [57] focuses on group decision making, aiding in the aggregation of heterogeneous opinions provided by a set of experts; etc.

Finally, we would like to cite some R and Matlab toolboxes. Notice that, although Matlab is commercially distributed, the toolboxes enumerated below are freely released by their authors. Some examples of Matlab toolboxes are: IT2FLS [58], which extends the Matlab fuzzy logic toolbox in order to support the design of interval type-2 fuzzy systems; XTRIG [59], which performs fuzzy qualitative trigonometry in terms of 4-tuple fuzzy numbers; Fuzzy Calculus CORE [60], which supports various fuzzy algebras dealing with fuzzy linear systems of equations and inequalities; etc. An example of R toolbox is the R fuzzy-toolbox [61], which is expected to be somewhat equivalent to the well-known fuzzy toolbox provided by Matlab [11].

3.4. General Purpose Fuzzy Systems Suites

KEEL [14] is likely to be the most well-known suite for knowledge extraction based on evolutionary learning. It includes a wide variety of fuzzy algorithms for regression, classification, clustering, pattern mining, and so on. Moreover, it allows a complete analysis of evolutionary learning models in comparison

to existing software tools to be carried out. In order to do so, it provides several modules regarding both research and teaching activities.

Two other well-known suites for machine learning, which offer some fuzzy capabilities, are Weka [62] and KNIME [63]. Weka includes some fuzzy rule learning algorithms that can be analyzed together with a wide collection of machine learning algorithms for data mining tasks. KNIME offers some plugins for fuzzy systems that are mainly devoted to fuzzy clustering, although they can also be used to learn fuzzy rule-based classifiers from datasets.

4. Review of Fuzzy Systems Software for Specific Application Purposes

In this Section, we introduce some of the most up-to-date proposals of FSS to solve specific problems in different research areas. In contrast to general purpose FSS, here the emphasis is on specialization instead of generalization. Therefore, most available FSS corresponds to toolboxes and suites.

Because of the huge number of specific problems for which FSS has been proposed, we present existent works for each category of the second level in the taxonomy (see Fig 1) classified by research areas, in order to provide the reader with a picture as complete as possible regarding the main application domains. Notice that, for the sake of space, we will only introduce works from those areas in which we found a higher number of contributions in the literature.

4.1. Fuzzy Systems Software for Solving Specific Problems of Control

Fuzzy control [64, 65, 66] is likely to be the application domain with the oldest tradition and the largest number of contributions in the literature. We can find FSS in the category *Code*, such as hardware and software implementations, along with the comparison of defuzzification methods supported by Texas Instrument's Code Composer Studio [67]. There are several libraries for control applications, such as jFuzzyLogic [68], which are noteworthy for making the design of fuzzy logic controllers easier. Many toolboxes can be found for different control problems, among which are the following: the dynamic powertrain simulation tool WARPSTAR2 for the modelling of electric vehicles [69]; a graphical tool aimed at controlling and monitoring temperature and relative humidity in the context of fine agriculture [70]; ASAFES2, a neuro-fuzzy function approximator, which combines the Takagi-Sugeno fuzzy reasoning method with stochastic reinforcement learning [71]; etc. Moreover, we can find some Matlab toolboxes for control applications, for instance: CIAPS [72] is an open source package based on artificial neural networks and fuzzy logic simulations for the assessment of electrical power systems; Zeng et al. developed an expert system which combines ANFIS with genetic algorithms for designing in situ toughened Si_3N_4 [73]; etc. Finally, several suites are available for fuzzy control, such as MEANDER [74], which evaluates the performance of agent-based systems.

4.2. Fuzzy Systems Software for Solving Specific Problems of Decision-Making

Fuzzy Decision-Making [75, 76] is a flourishing research area to which many theoretical and applied works have been contributed along with related FSS. We can find a lot of toolboxes, such as: FMCGDSS-DECIDER [77], which is a toolbox for linguistic multi-criteria group decision-making applied to fabric hand-based textile material evaluation; VisualFCM [44], which applies fuzzy cognitive maps to decision support in several scenarios of financial planning; Xfuzzy, which has been used to generate fuzzy systems to be integrated into a real estate market decision making tool [78]; etc. Some decision support toolboxes have also been integrated with geographic information systems (GIS). Among them are the following: ArcGIS is a toolbox for handling spatial analysis and it was extended by Eldrandaly and Abdelaziz in order to handle multi-criteria decision analysis [79]; GeoFIS DSS [80] is an open source suite aimed at providing GIS with new functionalities such as fuzzy modelling and reasoning with georeferenced data in Agronomy (notice that the use of GIS in agriculture is becoming very popular); etc. Moreover, some researchers have proposed specific Matlab toolboxes for decision-making tasks. For instance: Angulo et al. [81] developed a toolbox related to measuring water quality episodes from the behavior of variables measured at water control networks; FCM-uUTI-DSS [82] deals with uncomplicated urinary tract infection treatment management based on fuzzy cognitive maps; etc.

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4.3. Fuzzy Systems Software for Solving Specific Problems of Image Processing

Image processing [21] is another research domain in which FSS has emerged as a powerful tool. We can find several suites in the literature, such as InterIMAGE [83], which is a knowledge-based framework for the automatic interpretation of remote sensing GIS images. There are also several libraries for image processing available, such as Gestur [84], which is an open source library for software developers wishing to incorporate static and dynamic hand gesture recognition into their applications. Image processing and analysis is especially important in medical applications and therefore specific FSS has been developed for medical applications. Among them, Mandelias et al. [85] developed a toolbox for automatic image segmentation combining fuzzy cognitive maps and wavelet transform, which is applied to lumen border extraction and strut detection in intravascular optical coherence tomography. Moreover, some researchers have developed specific Matlab toolboxes for image processing, such as: FuzzyUPWELL [86], which was devoted to the fully automatic and unsupervised precise segmentation (based on fuzzy clustering) of upwelling images; Hosseini et al. [87] integrated the Matlab IT2FLS toolbox into a lung image classification system; etc.

4.4. Fuzzy Systems Software for Solving Specific Problems of Biomedicine

Biomedicine is the branch of medical science that deals with the application of the principles of the natural sciences to clinical medicine [88]. In the context of biomedicine, there are many challenging FSS applications. Several toolboxes can be found to solve specific problems, such as: MSClust [89], which is a toolbox aimed at performing fuzzy clustering with the information from metabolites; Fuzzy SPike Sorting (FSPS) [90], which provides neuroscience laboratories with a new tool for fast and robust online classification of single neuron activity; etc. Moreover, we can find some specific Matlab toolboxes in the literature. For instance, Pinti et al. proposed a toolbox for the multiple correspondence analysis of morphometric skull datasets [91].

4.5. Fuzzy Systems Software for Solving Specific Problems of Information Retrieval

The information retrieval application domain deals with the collection of relevant resources to answer a given query [92]. Thus, researchers face the big challenge of automatically accessing the information/data/services relevant to a specific user's needs. This is a very active research domain in the Soft Computing community which comprises not only fuzzy techniques but also neural networks, evolutionary computation, and so on [93]. In consequence, there is FSS for information retrieval too. Some examples are: SIRE2IN [94], which is actually a recommender system for research resources that is supported by fuzzy linguistic modeling; PaleoSearch [95], which deals with paleo-journal articles by content word or ontology-supported browse categories; etc.

4.6. Fuzzy Systems Software for Solving Specific Problems of System Dynamics

System dynamics is the discipline which deals with the understanding of complex systems over time [96]. There are many papers regarding the use of fuzzy systems in the context of system dynamics [24]. For instance, Karavezyris et al. [97] designed a system for waste management based on fuzzy system dynamics. This kind of task can be carried out using the simulation tools provided by Matlab [98]. Moreover, most system dynamics software (such as Stella [99], iThink, Vensim, and so on) are ready to embed fuzzy systems built with general purpose open source fuzzy modeling tools such as those introduced in Section 3.

4.7. Fuzzy Systems Software for Solving Specific Problems of Prognosis and Time Series Prediction

Prognosis and time series prediction are based on the use of advanced statistical and computational intelligent models in charge of forecasting future values based on previously observed ones [100]. Fuzzy systems play a key role in this challenging application domain [101]. We can find several toolboxes in the literature for time series prediction, such as, for example, the software system for time series prediction

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http://iseesystems.com
http://vensim.com

based on F-transform which was proposed by Habiballa et al. [102]; and for prognosis applications, among which are the following: Prognostic software, which is able to estimate the remaining useful life of failing components in turbine engines [103]; Surety Qualification [104], which allows interaction between the user and an optimized fuzzy expert system for estimating contractor default in the context of surety bonding; etc.

4.8. Fuzzy Systems Software for Solving Specific Problems of Risk Analysis

Risk assessment, characterization, communication, management, and so on are usually considered under the umbrella of risk analysis [105]. Risk analysis deals with the process of defining and analyzing potential dangers of concern to individuals, to public and private businesses, and to government and society at all levels, from a local to a global level. In such contexts, dealing properly with uncertainty becomes a key issue. Therefore, risk analysis constitutes another application domain for which FSS has been developed. Pool Evidence and Linguistic Belief are toolboxes aimed at evaluating the risk of terrorist acts [106]. Risk Criticality Analyzer and Fuzzy Reliability Analyzer are toolboxes which provide a comprehensive framework for the risk evaluation of the construction industry [107]. RCSUEX stands for Certainty Representation of the Exploratory Success and it is the name of a toolbox that facilitates the evaluation of petroleum exploration prospects [108]. Moreover, there are also some Matlab toolboxes for the specific problem of risk analysis, such as KKAnalysis [109], which is a toolbox capable of performing the unsupervised classification of volcanic tremor data.

4.9. Fuzzy Systems Software to Support Software Engineering

Software Engineering [110] is a discipline encompassing both the study and application of engineering to the entire development cycle, considering construction, analysis and management of software. It covers the following research issues: a) quality assessment methods (software tests and validation, reliability models, test and diagnosis procedures, software redundancy and design for error control, measurements and evaluation of processes and products, etc.) [111, 112, 113]; b) software project management tasks (paying attention to productivity factors, cost models, schedule and organizational issues, standards, etc.) [114, 115, 116]; and so on. Many classical modeling techniques have been used in the different areas of Software Engineering, however in the last decade the software industry has been challenged as the size and complexity of software systems have grown exponentially. This growth has led to a situation in which researchers have had to deal with highly complex and nonlinear problems.

In recent years, many FSS tools have been proposed in order to help researchers solve the different tasks of this discipline. Thus, the fuzzy community has developed many works with respect to the design, development and maintenance of software. There are several libraries for different tasks such as FADAlib [117], which is a C++ library that implements the Fuzzy Array Dataflow Analysis (FADA) method. Many toolboxes can also be found, among which are the following: MRES [118] is a toolbox for selecting resources in software project management; CMMI-ASS [119] is developed to help self-assessment software companies to accomplish the appraisal process; SEffEst [120] combines fuzzy logic and neural networks for effort estimation in software projects; etc.

4.10. Fuzzy Systems Software for Educational Purposes

There are several undergraduate and graduate courses, in computer science and other related fields, which are aimed at teaching subjects that require the learning of advanced fuzzy techniques. In order to properly understand the advantages and disadvantages of such techniques, the students are required to carry out practical work. Unfortunately, such work usually becomes (more frequently than desired) mere programming tasks and the students forget the main goal of analyzing the components that characterize each technique. As a result they are unable to discern which technique is better suited to a particular case.

Therefore, the aim of educational FSS is to enable students to focus on the intrinsic characteristics (advantages and disadvantages, strengths and weaknesses, and so on) of the fuzzy techniques under study in courses related to the teaching of fuzzy sets and systems theory and applications, instead of wasting their time on programing tasks.

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Several libraries for teaching tasks can be found in the literature, such as COALA [121], which is a set of Eclipse plug-ins (Library) that constitutes a computer assisted environment designed to make it easier for students of computer science and engineering studies to learn algorithms. We can also find some educational toolboxes. Among them are the following: Cavus [122], which is a web-based system to aid in the evaluation of learning management systems; eRiskGame [123], which is used as a support teaching tool in software engineering courses; VirtualLab [124] and FEUP [125], which are aimed at teaching fuzzy control; EDUrobot [126], which facilitates the understanding of mobile robotics; FIRS-trainer [127], which focuses on courses related to fuzzy information retrieval systems; etc.

The use of Matlab commercial software in technical schools (especially in computer science and engineering schools) is widespread. Because of this, many Matlab toolboxes in the literature have been proposed as free and open source software for teaching tasks. For instance: Fuzzy RAMSET [128] has been applied to software engineering courses in order to give students a practical experience; Real-time laboratory environment [129] combines dSPACE DS1103 DSP and Matlab/Simulink/RTW with the aim of helping students to model and control induction motor drives; MNTOOL [130] provides a visual and friendly environment to help students in experimenting with multi-net neural systems; etc.

Finally, we can also find some suites in the literature, such as Omega [131], which is a collection of open-source libraries and tools that are easily customizable and adaptable to pre-existing e-learning platforms, providing plugins for communication, interaction, reasoning, etc. Another example is the framework for automatic concept map generation applied to e-Learning that was developed by Lau et al. [132].

5. Review of Languages for Fuzzy Systems Software

It is widely admitted by the fuzzy community that there is a need for a universal standard language to foster the interoperability of FSS [26]. Nevertheless, obtaining a standard language supported by most fuzzy researchers is a challenging task that is still in progress. However, there have been a few attempts at defining formal languages to facilitate the reusability of fuzzy systems developed in different research areas.

Most proposals are related to the fuzzy information retrieval domain. One of the first fuzzy query languages (FQL), which relates fuzzy queries and tuples in relational databases, was proposed by Takahashi [133]. Then, Bosc and Pivert [134] presented SQLf, which handles gradual predicates formalized in the framework of fuzzy set theory. Moreover, Kacprzyk and Zadrozny [135] proposed FQUERY as an approach to data mining in databases.

Nowadays, XML is recognized as the de-facto standard of information representation for interoperability and most queries on XML data are made primarily by means of the languages XPath and XQuery. Several researchers have proposed different extensions of these languages in order to introduce fuzzy logic concepts into the queries, among them: FuzzyXPath [136], which is a fuzzy extension of XPath language, which provides the degree of similarity between two XML trees; Almendros-Jiménez et al. [137] defined an extension of the XPath query language in the fuzzy logic programming environment for research, known as FLOPER; FuzzyXQuery [138] is a fuzzy-set-based extension to XQuery language, which allows preferences on XML documents to be expressed and retrieves documents discriminated by satisfaction degree; Seto et al. [139] developed a query builder with a graphical user interface, which generates XQuery statements with fuzzy qualifiers; etc. As an alternative, some researchers have proposed different languages with which to make fuzzy queries, such as: f-SPARQL [140], which is a flexible extension of the SPARQL query language which was designed to express queries over RDF datasets; De Maio et al. [141] extended f-SPARQL for use in context recognition in ambient intelligence applications; Liu et al. [142] introduced QXMLSum, which is a query-oriented XML summarization system; etc.

There are also some proposals regarding fuzzy modeling. In the following, we present some of the most significant ones. XFSML is an XML-based language for modeling fuzzy systems that was implemented in Xfuzzy [51]. FML [27] is another XML-based language that was initially focused only on modeling fuzzy controllers [143]. However, in recent years some authors have shown how FML may be used beyond the fuzzy control research domain, for example: Liu et al. presented an FML-based knowledge management system for university assessment in Taiwan [144]; Acampora et al. described the utility of FML for ambient intelligence applications [145, 146]; etc.

FCL is the only standard for fuzzy control programming that is recognized on a global scale. It was published by the International Electrotechnical Commission (IEC) in part 7 of the IEC 61131 norm [147], which provides guidelines for the integration of fuzzy control applications in control systems. Nowadays, Acampora leads a working group aimed at establishing a new fuzzy standard language based on FML. This proposal is supported by the Standards Committee of the IEEE Computational Intelligence Society.

6. Fuzzy Systems Software Bibliographical Study

In this section we provide a snapshot of the status of publications in the field of FSS according to the ISI Web of Knowledge, which is globally recognized as the premier research platform. It handles over 2.6 million records and backfiles dating back to 1898, indexing the most prestigious, high impact research journals in the world. This platform provides a unique search method that allows users to navigate through the literature to uncover all the information relevant to their research (filtering works by authors, publication types, time spans, etc.) and to access electronic full text journal articles. Moreover, the ISI Web of Knowledge offers advanced tools that guarantee seamless access to multidisciplinary information in order to facilitate both the tracking of prior research and the monitoring of current developments.

With the aim of exploring the visibility of FSS at the ISI Web of Knowledge, we introduced the following query into the link for "Advanced Search":

TS=("toolbox*" OR "developer kit*" OR "integrated framework" OR "software package*" OR "librar*" OR "software environment*" OR "software mod*" OR "software tool*" OR "software metric*" OR "software project*" OR "GUI" OR "model?ing environment*" OR "programming environment*" OR "open source*" OR "markup language*" OR "*query language*" OR "based language*") AND (TS="fuzzy*" OR SO="fuzzy*" OR CF="fuzzy*")

The TS field means that the search process looks at the "Topic" (which refers to the Title, Abstract, Author keywords, and Keywords Plus®) of the indexed manuscripts. Notice that we have tried to make the query sufficiently general to cover all the key terms that usually refer to FSS issues in the specific literature, including papers which present new fuzzy software, papers which describe the use of existent software in practical cases, and so on. In this way we were provided with a full overview of the field. Because of this, we have made three analyses with different levels of detail from the query results, starting with a general overview of all the reported papers and ending with a detailed discussion of only a few selected papers:

- In subsection 6.1, we make a global analysis of FSS visibility regarding the total number of publications and citations in this research field over a period of 21 years (from 1994 to 2014).

- In subsection 6.2, we focus on works published in the last six years (from 2009 to 2014) with the aim of finding out the current research trends in the field with respect to the taxonomy presented in this paper. Notice that in this analysis we have filtered all the works reported in answer to the query in order to consider in the analysis only those papers in which proposals of FSS related to any of the three groups included in the first level of the proposed taxonomy are presented (see Fig 1 in Section 2): general purposes FSS (G1-SW-FUZZY), FSS for specific application purposes (G2-SW-APPS), and languages for fuzzy systems software (G3-LANG).

- In subsection 6.3, we highlight some of the most outstanding and up-to-date contributions in the FSS research field. These are likely to become important milestones related to research in the future.

6.1. Fuzzy Systems Software Visibility at the ISI Web of Knowledge

Research into FSS is a growing field which has now reached a stage of maturity with a huge number of relevant publications. Nevertheless, after more than twenty years there is much research yet to be carried out. An active world-wide research community is currently working on challenging related issues.
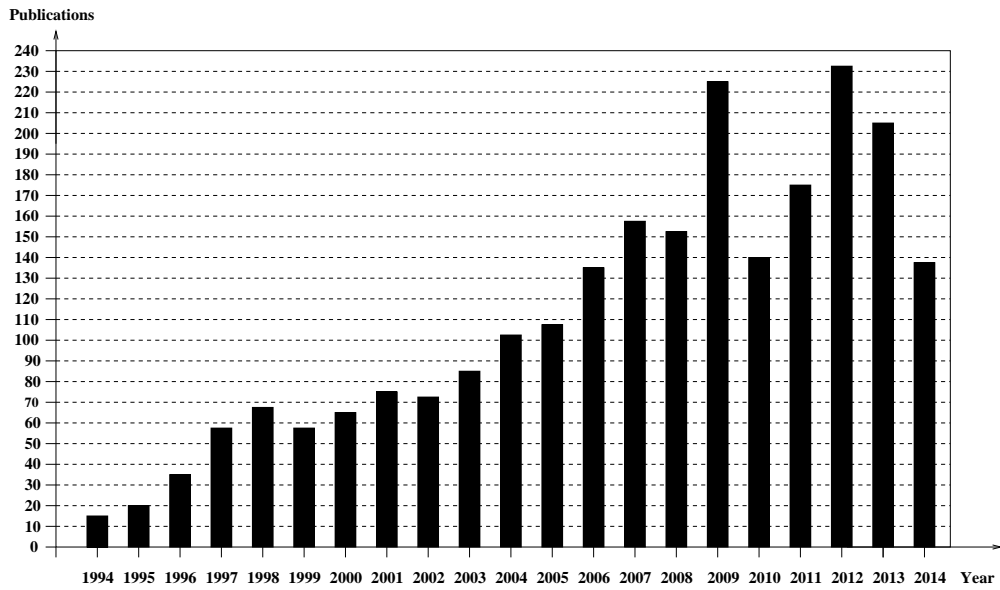
(a) Publications.
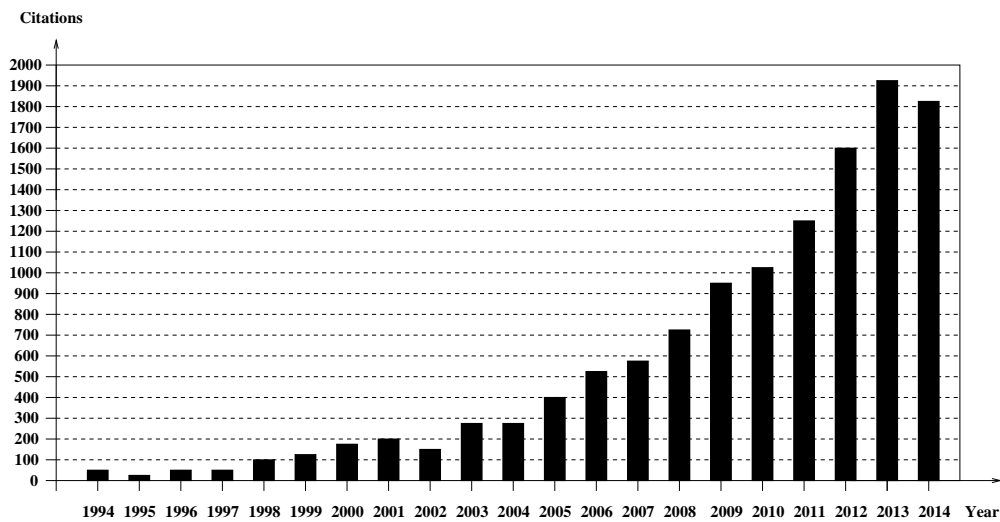
(b) Citations.

Figure 2: Citation report (April 14, 2015) produced by the ISI Web of Knowledge. The total number of papers is 2339, the sum of the times cited is 11741, the average citations per item are 5.28, and the related h-index rises up to 47.

Fig. 2 shows the number of published items (image at the top) and citations per year (image at the bottom) in the FSS research area during the last 21 years. The number of publications has dramatically increased from 1994 to 2006. We observe some kind of stabilization (around 140 items per year) from 2006 to the present. Moreover, two main peaks (above 220) occur in 2009 and 2012. As a result, the number of publications has fluctuated in the last six years. Nevertheless, the number of citations has grown in each of the 21 years (except in the last year when citations slightly decreased). Every day more FSS is freely downloadable and its visibility is rapidly growing. In consequence, FSS is increasingly used by the research community and this causes the number of citations to go up.

In addition, we perceive an exponential growth since 2002, with two main milestones: the pace of growth significantly increases first from 2007 to 2009 and then from 2010 to 2013. Notice that both periods led to

Table 1: Percentages of publications in the Top-10 ISI Web of Knowledge categories.

ISI Web of Knowledge Category	Publications (%)
Computer Science Artificial Intelligence	35.940
Engineering Electrical Electronic	28.295
Computer Science Theory Methods	15.026
Computer Science Information Systems	13.181
Computer Science Interdisciplinary Applications	11.424
Automation Control Systems	9.578
Operations Research Management Science	7.030
Computer Science Software Engineering	6.415
Engineering Multidisciplinary	5.009
Engineering Mechanical	4.657

the two main peaks in publications. In 2007, Nauck organized the first special session related to FSS held at a FUZZIEEE conference. He emphasized the need to create a GNU fuzzy community [16]. As a side effect, researchers became aware of the need to increase the visibility of their work by publishing already developed but as yet unpublished software. In consequence, we find the largest peak ever in the number of publications two years later, in 2009. Afterwards, researchers began to develop either new software modules for already published tools or new software packages from scratch. As is readily appreciated, software development requires some time to yield packages ready for publication. The result was a second peak (close in height to that of 2009) only three years later (in 2012). Last year, 2014, the number of publications fell down to almost half the total of the year 2012, however the number of citations is similar to 2013. It is worth noting that the same behavior was evident in 2010: after a year with a huge number of publications, the number of publications was strongly reduced the following year, while citations have tended to remain almost the same.

We would aver that this behavior is somehow cyclic and will be repeated in the future. Thus, if this behavior continues in the foreseeable future then we should expect another peak in 2015.

6.2. Current Research Trends in Fuzzy Systems Software

This section only deals with publications from the last six years, with the aim of uncovering the main research trends that have attracted the attention of researchers recently. We first analyze the main ISI categories in which a higher number of publications have been proposed. Secondly, we search for the most relevant topics which are addressed in all the previously identified areas, indicating how such research topics are related to each category of the proposed taxonomy. Finally, we study the distribution of works according to the type of publication (Journal versus Conference).

Table 1 shows the Top-10 ISI Web of Knowledge categories based on the percentage of publications belonging to each ISI category with respect to the total number of reported publications. It is worthy to note that the same publication can belong to more than one ISI category, and that is the reason why the addition of values in the second column of the table does not sum up to 100%. In addition, we can highlight how there are publications belonging to very varied ISI categories, denoting a wide interest in FSS. As can be seen, a high number of publications are concentrated into two main categories: *Computer Science* and *Engineering.*

In order to analyze how the publications were distributed among ISI categories over the last six years, we have performed a study based on co-citation among the publications of the different categories, analyzing the evolution between the periods 2009-2011 and 2012-2014. Notice that the notion of manuscript co-citation represents the frequency with which two documents are simultaneously cited by others [148]. To accomplish this, we have generated a scientogram or visual science map [149] for each period (see Fig. 3) where the nodes represent ISI categories (the darkness and size of nodes are proportional to the number of publications) and the edges among nodes represent the degree of co-citation between the two linked categories (the darkness

(a) From 2009 to 2011.
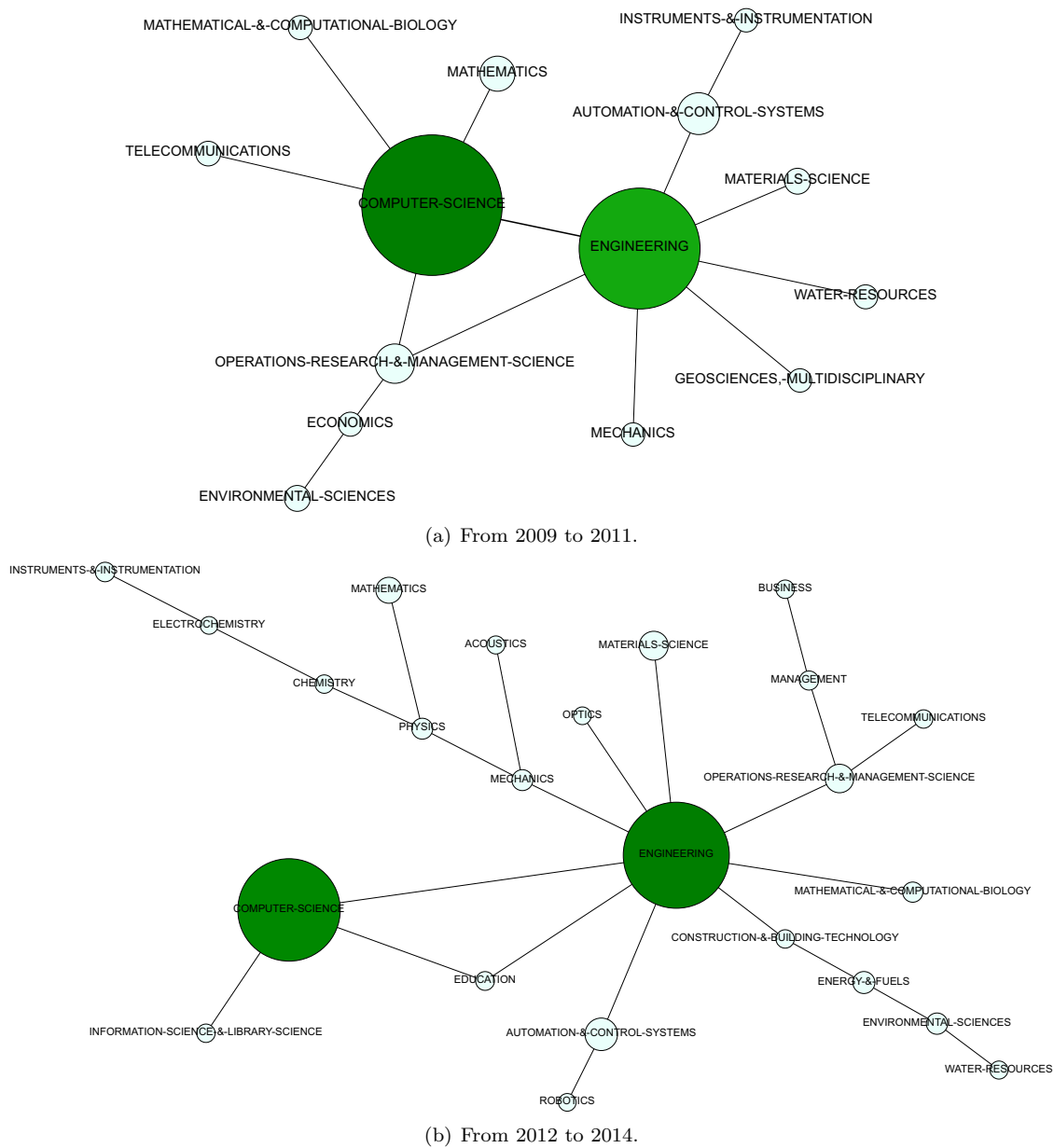

(b) From 2012 to 2014.

Figure 3: Relations (co-citations) among the most relevant ISI Web of Knowledge categories for FSS.

and thickness of edges are proportional to the number of co-citations). These pictures were made using the free software SciMAT [150] and Gephi.

A careful comparison between Figs. 3(a) and 3(b) provides a clear view of how publication trends (regarding ISI categories) have evolved in the last six years. From 2009 to 2011, we can appreciate how the categories *Computer Science* and *Engineering* have emerged as the two main categories, with *Computer Science* presenting a slightly higher number of publications than *Engineering* and with both sharing a
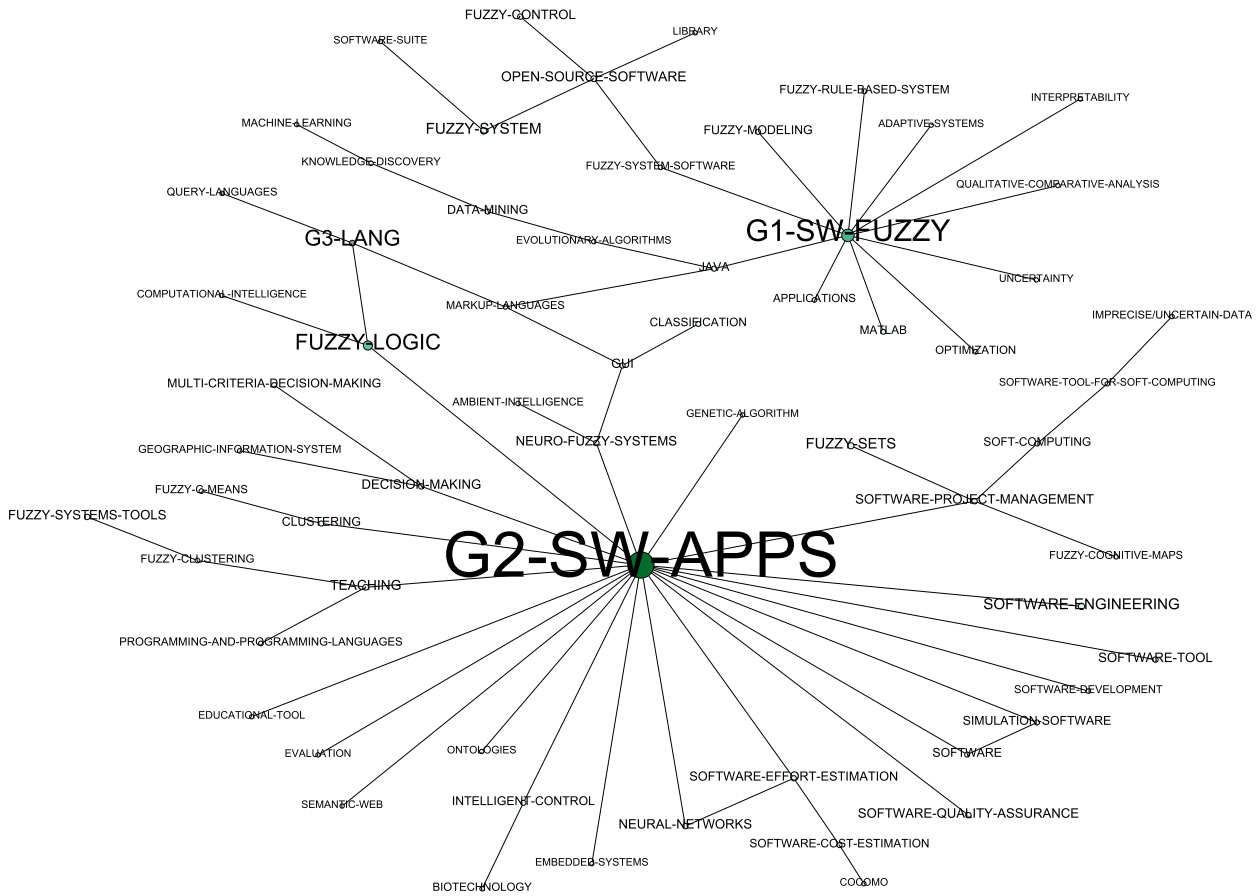
Figure 4: Research topics related to the three main groups in the proposed taxonomy (G1-SW-FUZZY, G2-SW-APPS, and G3-LANG).

strong link with each other. In addition, the two main categories are connected with twelve more categories, of which *Automation & Control Systems* and *Operations Research & Management Science* are the most fruitful. Notice that the category *Operations Research & Management Science* is the only one that is directly connected to the two main categories. Although from 2012 to 2014 the two main categories present almost the same number of publications and are still connected, their link has become thinner. Moreover, the number of surrounding categories has increased, passing from 12 to 22 in this period and with most of them linked to the category *Engineering*. Notice that the categories *Automation & Control Systems* and *Operations Research & Management Science* are still the two main categories behind *Computer Science* and *Engineering*. Two of the old categories have disappeared while twelve new emergent categories are identified at the end of the period. Among them, *Education* and *Energy & Fuels* seem to be the most promising emergent categories with the fastest growth in recent years. It is worth noting that *Education* is the only category acting as a bridge between *Computer Science* and *Engineering*.

Having thoroughly analyzed the main publication trends in the field of FSS with respect to ISI categories, we will now pay attention to the main research topics and how they have been addressed, over the last six years, according to the three main groups in the proposed taxonomy (G1-SW-FUZZY, G2-SW-APPS, and G3-LANG). To do this we have built a scientogram (see Fig. 4) which connects the main research topics in terms of co-citation among keywords provided by the authors in their publications. In this case, the nodes represent the research topics (the darkness and size of nodes are proportional to the number of publications related to each research topic) and they are organized around the three main groups in the taxonomy. In addition, the edges represent the degree of relationship (co-citation) between the topics and groups involved

Table 2: Percentage of publications related to the main categories in the taxonomy.

Category	From 2009 to 2011			From 2012 to 2014			From 2009 to 2014		
	Journal	Conference	Total	Journal	Conference	Total	Journal	Conference	Total
G1-SW-FUZZY	33.33	66.67	**20.51**	56.76	43.24	**32.74**	47.54	52.46	**26.52**
G2-SW-APPS	50.59	49.41	**72.65**	83.1	16.9	**62.83**	65.38	34.62	**67.83**
G3-LANG	37.5	62.5	**6.84**	40	60	**4.43**	38.46	61.54	**5.65**
Total	**46.15**	**53.85**	-	**72.57**	**27.43**	-	**59.13**	**40.87**	-

(the darkness and thickness of edges are proportional to the closeness between the involved topics). We can see how there is a wide range of topics associated with the publications, in which the more theoretical topics addressed by the fuzzy community are concentrated around G1-SW-FUZZY while the more applied ones are plotted around G2-SW-APPS. Moreover, the relationships among the topics concentrated around G1-SW-FUZZY are stronger than those among the topics concentrated around G2-SW-APPS, due to the high number of application domains that are covered by the publications in the category G2-SW-APPS. Notice that G3-LANG is represented by a small node because it is an emergent field which still has few publications.

Finally, we have analyzed the main trends with respect to the type of publication (Journal versus Conference) in accordance with each category in the taxonomy, analyzing the last six years (from 2009 to 2014) and the evolution between the periods 2009-2011 and 2012-2014. Table 2 shows the percentages of publications for each main category: Journal is the percentage of journal papers with respect to the total number of journal papers published in the target period; Conference is the percentage of conference papers with respect to the total number of conference papers published in that period; and Total is the percentage of published papers of each in respect to the total number of journal and conference papers published in that period. Notice that the percentages reported provide complementary and qualitative information about how the published papers are distributed according to the type of publication (Journal versus Conference) but also according to the different categories in the taxonomy.

Regarding the entire period under study (from 2009 to 2014), we can observe in Table 2 how more papers are published in journals (59.13%) but the percentage of publications in conferences (40.87%) is not much smaller, presenting a good trade-off between publications in journals and conferences. Nevertheless, the distribution of the publications with respect to the three main groups in the taxonomy is highly unbalanced. G3-LANG (5.65%) is the smallest group by far, which is a promising group but with a lot of papers remaining to be written. The largest percentage of publications corresponds to G2-SW-APPS (67.83%), which is about 40% bigger than the percentage of publications in G1-SW-FUZZY (26.52%). This fact shows that most papers in the FSS area are driven by the need to solve problems which require the development of software for specific application domains.

With respect to the evolution from the beginning to the end of the target period, we observe in Table 2 how the distance between the categories G1-SW-FUZZY and G2-SW-APPS tends to decrease. This shows how authors have become aware of the fact that general purpose FSS is easier to reuse, as it is applicable later on to very varied application domains. On the other hand, the percentage of publications in journals tends to increase while the percentage of publications in conferences tends to decrease, improving the visibility of FSS in the scientific community. Moreover, although there were initially more publications in conferences, the distribution between the publications in journals and conferences has been inverted at the end of the period, when the greater percentage of papers is published in journals.

6.3. Some of the Most Outstanding Works in the Field of Fuzzy Systems Software

This section is aimed at highlighting recent papers (those published since 2009) that are nowadays actively supported because they might have a very high impact on the research community in the near future. Thus, we have identified the papers with the highest number of citations according to the ISI Web of Knowledge for each category in the taxonomy. Notice that the publication year, journal title and the number of citations corresponding to each paper is shown in brackets:

16

- Fuzzy Systems Software with General Purpose (G1-SW-FUZZY): Alcala-Fdez et al. (2009, *Soft Computing*, 263) [14] presented the suite KEEL. Even though it was initially designed for both research and educational purposes, it is worth noting the high visibility it has achieved in the genetic fuzzy systems research community.

- Fuzzy Systems Software for Specific Application Purpose (G2-SW-APPS): Porcel et al. (2009, *Expert Systems with Applications*, 47) [94] developed SIRE2IN, a recommender system to assist users in their online information access process at the University of Granada. Thanks to the use of content-based filtering and multi-granular fuzzy linguistic modeling the system is endowed with the flexibility required to handle qualitative concepts, thus improving the user-system interaction.

- Languages for Fuzzy Systems Software (G3-LANG): Campi et al. (2009, *Journal of Intelligent Information Systems*, 10) [136] proposed a fuzzy XML querying framework called FuzzyXPath. This is actually a fuzzy extension of the XPath query language that is mainly used in the context of information retrieval and e-Learning. As we have already discussed in Section 5, the fuzzy community is aware of the lack of a standard language for fuzzy systems software. This is the reason why the Standards Committee of the IEEE Computational Intelligence Society is currently supporting a working group in charge of defining a new standard fuzzy language. This initiative is based on the FML proposed by Acampora and Loia (2005, *IEEE Transactions on Industrial Informatics*, 84) [143], which was one of the pioneering works regarding languages for fuzzy systems software. Notice that we include this paper here because of its strong impact (paying attention to the high number of citations) as well as its continuing relevance (in connection with the standardization initiative in progress), even though the publication date is 2005.

7. Critical Considerations and Potential Prospects

In recent years, a lot of publications have presented novel proposals in the area of FSS. When we read the abstracts we feel a great interest in reading the specific aspects of the proposals and, more importantly, in what these proposals provide us with in respect to the rest of the proposals in the FSS literature. The question is therefore posed as to what are the critical aspects of a large number of recently published papers. We focus our attention on four aspects (interoperability, novelty, usability and relevance) which should guide further research directions in FSS in the future:

- We can find different FSS in the literature to design and to analyze fuzzy systems for many problems. However, we can rarely operate on those systems with other software because each FSS usually stores the developed fuzzy systems in its own format. Because of this, researchers cannot take advantage of the different proposals that we find in the literature. Of course, some researchers have included some options in their proposals to export and import the developed fuzzy systems to other formats, allowing us to use other software for their analysis, visualization, etc. Moreover, many researchers are currently working to develop standard languages which will allow us to exchange fuzzy systems across different platforms and thus improve their interoperability. The integration of this kind of standard into FSS will facilitate the extension of the available functions as well as the level of application to new proposals.

- The development of novel FSS requires a previous analysis based on the functionality criteria of the existing software in the literature to enable researchers to identify the software needs that the current software cannot provide. This analysis should include a set of basic characteristics (such as programming language, interoperability, and so on) and a set of specific characteristics related to the application domain and the type of software proposed (such as heterogeneous data support, medical standard support, etc.) that allow us to detect the major differences between software and to categorize the proposal as an alternative to the existing software when other requirements are needed. This analysis provides developers with a good basis to explain why their proposals should be developed in a certain way and to note their principal benefits. However, we can find many contributions in the

literature without this kind of analysis. The underlying problem here is that many of these proposals are very similar to other previous FSS and they do not provide novel benefits. This makes it more difficult for other researchers to analyze the software needs for significant further developments, or to select a suitable proposal to solve their particular problems.

- FSS has been proposed in recent years to solve diverse problems. However, the true potential of the available software is not realized because the source files are not always openly shared, resulting in software with low usability and weak interoperability. The open source model makes it easier for other researchers to develop and adapt available software to their problems and provides many advantages. This model can play a very important role in removing obstacles, essential to improving the level of application of the fuzzy technology to industry.

- Another problem arises with the fact that many proposals in the literature are unavailable on the original web sites or else these are no longer maintained. When researchers present a new proposal they should guarantee that users can download their software and that it will be maintained, if they want their work to remain relevant. Today, most researchers use public hosting to share their proposals in order to avoid problems with servers and to provide better maintenance. On the other hand, there is FSS available on the Internet which does not have an associated publication, which complicates the question of broadcasting. Moreover, FSS proposals should be published with the correct title and meaningful keywords in order to maximize their visibility in public search engines.

Despite these critical considerations, we consider that the field of FSS is today a mature field that is spreading towards new research areas (see Section 6). In addition to the usual ISI categories (such as: *Computer Science*, *Engineering*, *Control*, *Operations Research & Management science*, etc.) several new ISI categories (such as: *Energy & Fuels*, *Material-Science*, *Education*, etc.) represent promising emergent categories which have grown rapidly in recent years. Moreover, many researchers are currently working on the definition of a new standard language in order to improve interoperability among different platforms. Furthermore, in recent years the interest in general purpose FSS has increased due to the fact that it can be used on a highly varied range of application domains and by a high number of users. Finally, the relevance and visibility of FSS is increasing in the light of the increase in the number of papers published in high impact factor journals in a variety of domains.

8. Conclusions

In this paper we have analyzed the state of the art of the freely available and open source FSS in order to provide a well-established framework that helps researchers to easily find existing proposals that are related to a particular branch and to focus on significant further developments. To accomplish this, we have proposed a two-level taxonomy to classify available contributions and we have described the main proposals that focus on this field. The first level in the taxonomy is based on the purpose for which the software was developed, and the second level is based on the type of software. Moreover, a snapshot of the status of the publications on FSS according to ISI Web of Knowledge has been presented.

The most prolific category is related to contributions that describe FSS for specific application purposes due to the applied nature of fuzzy systems. However, in recent years the number of contributions in which general purpose FSS has been developed has tended to increase since it can be applied to solve different kinds of problems in various application domains. Publications related to languages for fuzzy systems software represent a minor group in the taxonomy that is not sufficiently mature yet but which is likely to grow faster in the future. Moreover, many researchers are nowadays working to develop a standard language which will allow us to exchange fuzzy systems across different platforms in order to improve interoperability.

With respect to specific application domains, control and decision-making research areas are the focus of most FSS. In addition, FSS is ready to assist software engineers and developers in most of the common tasks related to software engineering. Moreover, the visibility of FSS for educational purposes is slowly but steadily growing.

Furthermore, the bibliographical study shows how this area presents mature research, presenting more than 100 papers (with peaks of above 200) and a higher number of citations each year. Moreover, the number of contributions in journals has tended to increase in recent years, improving the broadcasting of the proposals and the cooperation with other research areas.

Finally, the most outstanding current trends and open problems (paying attention to novelty, interoperability, usability and the relevance of FSS) have been highlighted, in order to attract the attention of the research community, since these are either unsolved or have still not been properly addressed.

Acknowledgement

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