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Revisiting Evolutionary Fuzzy Systems: Taxonomy, applications, new trends and challenges

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ABSTRACT

Evolutionary Fuzzy Systems are a successful hybridization between fuzzy systems and Evolutionary Algorithms. They integrate both the management of imprecision/uncertainty and inherent interpretability of Fuzzy Rule Based Systems, with the learning and adaptation capabilities of evolutionary optimization. Over the years, many different approaches in Evolutionary Fuzzy Systems have been developed for improving the behavior of fuzzy systems, either acting on the Fuzzy Rule Base Systems' elements, or by defining new approaches for the evolutionary components.

All these efforts have enabled Evolutionary Fuzzy Systems to be successfully applied in several areas of Data Mining and engineering. In accordance with the former, a wide number of applications have been also taken advantage of these types of systems. However, with the new advances in computation, novel problems and challenges are raised every day. All these issues motivate researchers to make an effort in releasing new ways of addressing them with Evolutionary Fuzzy Systems.

In this paper, we will review the progression of Evolutionary Fuzzy Systems by analyzing their taxonomy and components. We will also stress those problems and applications already tackled by this type of approach. We will present a discussion on the most recent and difficult Data Mining tasks to be addressed, and which are the latest trends in the development of Evolutionary Fuzzy Systems.

1. Introduction

Fuzzy systems have become a very popular tool in the Computational Intelligence and Soft Computing area for solving different problems in Data Mining and engineering [123]. This is due to their good properties for representing uncertain knowledge and therefore for adapting more smoothly to the context in which they are working at. Usually, model structure in the form of Fuzzy Rule Based Systems (FRBSs) is considered. FRBSs constitute an extension to classical rule-based systems, because they deal with "IF-THEN" rules, but its antecedents and consequents are composed of fuzzy logic statements, instead of classical ones. Additionally, in the case of fuzzy sets with linguistic labels, the output system has a higher interpretability degree for the expert to understand the working procedure of the former [73], and the inner details of the problem characteristics [62].

At the beginning of the 1990s, the combination between fuzzy systems and Evolutionary Computation was studied. The main idea behind this synergy was to take advantage of the optimization capabilities of Evolutionary Algorithms (EAs) [50] for improving the accuracy of fuzzy systems. Specifically, this was carried out by either by performing an automatic definition of the FRBSs, or by tuning some of the elements of their structure, i.e. Data Base (DB), Rule Base (RB), or inference system.

This hybridization had led to Evolutionary Fuzzy Systems (EFSs), which comprises an extension of the traditional and well-known Genetic Fuzzy Systems [39,75]. The former term was due to the use of Genetic Algorithms (GAs) as the primary part of this synergy. In this paper we focus on a generic type of evolutionary techniques. Indeed, EFSs have been recently extended by using Multi-Objective Evolutionary Algorithms (MOEAs) [32], considering multiple conflicting objectives, instead of a single one. These specific types of approaches are known as Multi-Objective Evolutionary Fuzzy Systems (MOEFSs), and they have become an important part of the more general EFSs [53].

In this paper we will revisit the different EFSs approaches that have been proposed in the specialized literature. Furthermore,

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we will analyze the latest trends and challenges for the development of new EFS methods. With this aim, we will divide this work into five main parts as follows:

- We will first introduce a complete taxonomy regarding three different aspects, i.e. the learning and/or optimization of the FRBSs' elements, the multi-objective approaches for achieving the tradeoff among different objectives, and the development of tuning algorithms for the definition of novel fuzzy representations. This will allow us to have a global view of the organization of the EFS models, so that we can have a better understanding of the evolution and characteristics of these types of systems in the current panorama.
  We want also to point out the significance of EFSs by studying all types of Data Mining problems in which they have shown a good behavior. In this way, we will stress the adapting capabilities of these systems by providing an exhaustive list of areas such as regression, classification, association rule mining, subgroup discovery and data streams, among others.
- Traditionally, the use of EAs over other optimization techniques has been considered as a natural choice due to their synergy with FRBSs. We seek to establish the reason behind this decision, understanding what the properties of EAs are, so that they make them to excel as opposed to other traditional approaches, i.e. neural networks.
- Since the beginning of EFSs, almost 25 years ago, there have been many real applications that stress that EFSs are still a valuable tool for solving different problems. Therefore, we will present a non-exhaustive list of several recent applications. Additionally, we will review some software tools that include EFSs. In this way, we may find algorithms of reference for contrasting any new developed method in this area.
- After this overview of the main aspects of current EFSs, we will focus on the central axis of this work, which is to set a discussion on the new trends and challenges for these types of systems. We will enumerate several novel problems and applications in which EFSs may achieve good results, especially those related to scalability and the scenario of Big Data [58,109], being defined as one hot topic that still needs to be addressed in detail. Furthermore, we will present additional topics and features that can help researchers focus on new possibilities for the continuous improvement of these techniques.
- Finally, we will carry out a critical evaluation on the design process for EFSs. In particular, we aim at establishing some guidelines for the definition of a systematic procedure in order to achieve the most correct development of EFSs.

We must point out that in this paper we do not aim at gathering an exhaustive list of references on the topic. We acknowledge that there has been an explosion of related works, which have already been partially covered in four previous reviews [36,38,53,75] and a book [39]. Within these works, we may find a profuse literature for EFSs, as well as in the following thematic Website at http://sci2s.ugr.es/gfs/.

The main contributions of the current paper with respect to the former references have been stressed in the fifth objective pointed out above. Specifically, we pay special attention to:

1. Extending the previous taxonomy on EFS [75] by proposing a new and more comprehensive one. As such, we have provided a more complete taxonomy by including those approaches that consider a trade-off between objectives (using MOEFs) and novel fuzzy representations.
2. Establishing why EAs are better suited for FRBS in contrast to other optimization techniques such as neural networks and ad hoc approaches
3. Presenting an overview and analysis of some of the most recent areas of Data Mining, such as classification with imbalanced data [101], mining of association rules [160], subgroup discovery [76], and low quality data [135], among others.
4. Enumerating some of the latest engineering applications with EFSs, in order to carry out a short overview for the significance of these types of techniques over real problems.
5. Introducing some software tools that allow researchers to work with EFSs, such as the KEEL Suite [11,9].
6. Developing an in-depth discussion for the new trends and challenges on the topic, thus analyzing hot and interesting areas for future work.

In order to face the aforementioned objectives, the remainder of this paper is organized as follows. In Section 2, we present the taxonomy on EFSs, and we describe the good properties that make EAs more suitable for FRBS over other optimization techniques. Section 3 reviews the use and behavior of EFSs over different types of Data Mining problems. Next, Section 4 introduces some recent real applications in which EFSs have shown to be a well-suited solution, whereas Section 5 describes the available software that includes these types of methods. Section 6 includes the main part of this manuscript in which we present and analyze several new trends and challenges for EFSs. Some brief remarks and guidelines for the development of new EFS are given in Section 7. Finally, in Section 8, we provide some concluding remarks.

2. Analyzing the Evolutionary Fuzzy Systems' models

The essential part of FRBSs is a set of IF-THEN fuzzy rules (traditionally linguistic values), whose antecedents and consequents are composed of fuzzy statements, related to with the dual concepts of fuzzy implication and the compositional rule of inference. Specifically, an FRBS is composed of a *knowledge base* (KB), that includes the information in the form of those IF-THEN fuzzy rules, i.e. the RB, and the correspondence of the fuzzy values, known as DB. It also comprises of an inference engine module that includes a fuzzification interface, an *inference system*, and a defuzzification interface.

EFSs are a family of approaches that are built on top of FRBSs, whose components are improved by means of an evolutionary learning/optimization process as depicted in Fig. 1. This process is designed for acting or tuning the elements of a fuzzy system in order to improve its behavior in a particular context. Traditionally, this was carried out by means of GAs, leading to the classical term of Genetic Fuzzy Systems [38,39,36,75]. In this paper, we consider a generalization of the former by the use of EAs [50].

Taking this into account, the first step in designing an EFS is to decide which parts of the fuzzy system are subjected to optimization by the EA coding scheme. Hence, EFS approaches can be

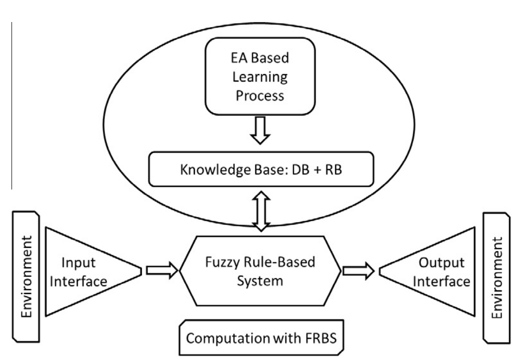

Fig. 1. Integration of an EFS on top of an FRBS.