# Fuzzy Logic, Soft Computing, and Applications*

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**Abstract.** We survey on the theoretical and practical developments of the theory of fuzzy logic and soft computing. Specifically, we briefly review the history and main milestones of fuzzy logic (in the wide sense), the more recent development of soft computing, and finalise by presenting a panoramic view of applications: from the most abstract to the most practical ones.

## 1 Fuzzy Logic

Although there are authors that establish the origin of *Fuzzy Logic* in the introduction of multiple-valued logics by Jan Łukasiewicz in 1920, it is commonly accepted that it emerged from the theory of fuzzy sets introduced by Lotfi Zadeh in [49]. In this paper, fuzzy subsets were used as a formalization of vagueness (in the sense of a predicate that applies to a certain degree, not in absolute terms), with the underlying notion of soft membership, in which objects might neither belong nor not belong to a set and that there may be borderline cases.

Joseph Goguen also participated in the initial developments of fuzzy logic with his "logic of inexact concepts." Since then, the theory of fuzzy logic has been constantly growing and, moreover, has been applied to very diverse fields from control theory to artificial intelligence. Although statisticians tend to prefer probabilistic logic, and control engineers prefer traditional two valued logic, nowadays, it cannot be discussed that fuzziness has become a mainstream theory and, as we will notice in next section, a mainstay of *Soft Computing*.

Now, two important question arise: what is really fuzzy logic? and what is not fuzzy logic? Related to these questions, Zadeh recently [52] wrote

> Fuzzy logic is not fuzzy. Basically, fuzzy logic is a precise logic of imprecision and approximate reasoning [ . . . ] Paradoxically, one of the principal contributions of fuzzy logic is its high power of precisiation of what is imprecise. This capability of fuzzy logic suggests that it may find important applications in the realms of economics, linguistics, law and other human-centric fields.

A typical source of confusion is the duality of meaning of the term *fuzzy logic*. In a wide sense, it is much more than a logical system, and different branches can

* Partially supported by projects TIN2006-15455-C03-01, TIN2007-65819 (Science Ministry of Spain) and P06-FQM-02049 (Junta de Andalucía).

be observed: (i) Logical systems aiming at formalizing approximate reasoning, that is *fuzzy logic in narrow sense*, mathematical fuzzy logic systems such as those in the monographs [5, 16, 18, 39] have become standard in this research line; (ii) *General theories of fuzzy sets* such as $L$-fuzzy sets, bipolar fuzzy sets, intuitionistic fuzzy sets, research on t-norms and/or copulas as adequate extensions of the intersection of fuzzy sets; (iii) The *epistemic approach*, knowledge representation and reasoning using fuzzy logic, natural language, information systems, fuzzy databases, etc. [11]; (iv) The *relational approach*, or the study of fuzzy relations and, more generally, fuzzy dependencies [2, 48]. This aspect focuses on the representation and manipulation of imprecisely defined functions and relations. It is this facet of fuzzy logic that plays a pivotal role in its applications to system analysis and control.

Several notions in crisp mathematics can be translated into the corresponding notions in fuzzy mathematics in a uniform way by Zadeh Extension Principle [50]. A natural question is: Given a crisp deduction rule, does there exist a canonical way to extend it in a fuzzy context? Deduction in fuzzy logic is governed by a collection of rules of deduction which, in the main, are rules that govern propagation and counterpropagation of imprecise constraints. The principal rule is the compositional rule of inference [14]. Concerning reasoning and knowledge representation, it is worth to refer to the several generalizations of logic programming to a fuzzy framework, such as [7, 17, 27, 34–36].

## 2 Soft Computing

Most of the attempts for defining the evolving term *Soft Computing* coincide in that it is a collection of techniques which uses the human mind as a model and aims at formalizing our cognitive processes. These methods are meant to operate in an environment that is subject to uncertainty and imprecision. The objective is to study, model and analyse complex phenomena for which more conventional methods have not yielded low cost, analytic, and complete solutions. According to Zadeh [51] the guiding principle of soft computing is to exploit the tolerance for imprecision and uncertainty to achieve tractability, robustness, and low solution cost. The notion soft computing is to computational intelligence as traditional hard computing is to artificial intelligence, and usually is viewed as a foundation component for the emerging field of conceptual intelligence.

Soft computing replaces the traditional time-consuming and complex techniques of hard computing with more intelligent processing techniques. The key aspect for moving from hard to soft computing is the observation that the computational effort required by conventional approaches which makes in many cases the problem almost infeasible, is a cost paid to gain a precision that in many applications is not really needed or, at least, can be relaxed without a significant effect on the solution. A basic difference between perceptions and measurements is that, in general, measurements are crisp whereas perceptions are fuzzy.

According to scientific folklore, the name Computational Intelligence is chosen to indicate the link to and the difference with Artificial Intelligence. Artificial Intelligence techniques are top-down whereas Computational Intelligence techniques are generally bottom-up, with order and structure emerging from an unstructured beginning.

It is widely accepted that the main components of Soft Computing are Fuzzy Logic, Probabilistic Reasoning, Neural Computing and Genetic Algorithms. This four constituents share common features and they are considered complementary instead of competitive. The mentioned technologies can be combined in models which exploit their best characteristics. As an important consequence, some real problems can be solved most effectively by using hybrid systems what is increasing the interest on them. The first and probably the most successful hybrid approach till now are the so-called neurofuzzy systems [43], although some other hybridations are being developed with great success as, for instance, the genetic fuzzy systems [6].

In the partnership of the mentioned collection of computational techniques that compose soft computing, fuzzy logic, which has been widely referred in previous section, is concerned with imprecision, approximate reasoning and representation of aspects that are only qualitatively known; Probabilistic Reasoning such as Bayesian Belief Networks, with uncertainty and belief propagation; the main characteristic is its ability to update previous outcome estimates by conditioning them with newly available evidence [41]; Neural Computing focuses on the understanding of neural networks and learning systems, self-organising structures, and the implementation of models from available data [15, 44]; last but not least, Genetic and Evolutionary Computing [13, 19, 45] provide approaches to computing based on analogues of natural selection, such as, the optimisation methods based on ant colonies [10, 46] or on particle swarms [25, 42].

## 3 Applications

The new wave of theoretical contributions and practical applications that followed the seminal works by Zadeh has had a remarkable inspirational effect on numerous disciplines. Activities in soft computing have increased since the field started. They do not only focus on theoretical descriptions, but also provide a collection of real-world problems and techniques that are used to solve them.

Industry has benefited from adopting these techniques to address a variety of problems that can be seen also by the diverse range of products developed. Lately, it has been noticed that publications tend to combine the different subfields which seems to indicate that there are much more applications to come.

Last but not least, it is important to note the number of books and special issues of journal dedicated to applications of fuzzy logic and soft computing that have been recently published [1, 3, 4, 8, 9, 12, 20–22, 26, 28, 30, 38, 47].

The applications range from the purely theoretical ones, those which develop new lines in abstract mathematics or logic, passing across the areas of multimedia, preference modelling, information retrieval, hybrid intelligent systems, image processing, etc., to practical applications domains such as robotics and manufacturing, actuarial science, nuclear or medical engineering.

*Pure and Applied Mathematics.* Theoretical foundations of soft computing techniques stem from purely mathematical concepts. The basic mathematical formalisms of fuzzy logic and soft computing have triggered a renewed interest in some old theories, such as that of residuated lattices or the theory of t-norms and copulas, and have initiated a complete redesign of well-established areas such as the theory of differential equations (with the addition of fuzziness), topology (including similarity spaces, tolerance spaces, approximation spaces), development and algebraic study of new logical systems for dealing with vagueness, imprecision and uncertainty, etc [33].

*Extended tools for fuzzy and similarity-based reasoning.* Existing tools for knowledge representation and reasoning, such as Prolog-based implementations, are being extended to the framework of fuzzy logic or, even, lattice-valued logics. In this sense, we can cite the works [24, 37]. Some other approaches also include the adaptation of enhancements and specific optimization methods, such as the tabulation (or tabling) methods for logic programming.

*Case-based reasoning.* This model of reasoning incorporates problem solving, understanding and learning, and integrates all of them with memory processes. It involves adapting old solutions to meet new demands, using old cases to explain new situations or to justify new solutions, and reasoning from precedents to interpret a new situation. Recent research is demonstrating the role of soft computing tools, both individually and in combination, for performing different tasks of case based reasoning with real life applications [32].

*Multimedia processing.* Due to their strong learning and cognitive ability, soft computing techniques have found applications in multimedia processing and, nowadays, there is a wide range of research areas of soft computing in multimedia processing including video sequence, color quantization, image retrieval, meeting video, document image analysis, image segmentation and biometric application. The increased possibilities to capture and analyze images have contributed to create the new scientific field of image processing that has numerous commercial, scientific, industrial and military applications [29].

*Preference modelling and decision making.* Although standard approaches to decision-making problems assumed by default that all the information is expressed in the same preference representation format, in real practice this is hardly possible. As a result, new fuzzy approaches to integrating different preference representation formats in decision-making are of great importance. Moreover, missing information poses additional difficulties that have to be addressed when dealing with real decision-making problems, which leads to topics that are naturally included within the boundaries of fuzzy logic and soft computing. In this respect, theoretical studies on areas such as extensions of fuzzy sets (type-2 fuzzy sets, $L$-fuzzy sets, interval-valued fuzzy sets, fuzzy rough sets) or aggregation operators (fuzzy measures, linguistic aggregators, inter-valued aggregators) are specially useful. Some specific application domains of preferences modelling are the following: data-base theory, classification and data mining, information retrieval, non-monotonic reasoning, recommendation systems, etc [23].

*Knowledge engineering applications.* With the advent of artificial intelligence, the emphasis on knowledge engineering moved from social and philosophical concepts to the problem of knowledge representation in computers. The inherent synergy of the different methods of soft computing allows to incorporate human knowledge effectively, deal with imprecision and uncertainty, and learn to adapt to unknown or changing environments for better performance. One can see applications to several areas related to management of knowledge, such as knowledge representation, knowledge acquisition, knowledge-based inference, modeling and developing knowledge-based systems, knowledge integration, and knowledge discovery.

*Ontologies and the semantic web.* When analysing information on the web one has to note the difference between information produced primarily for human consumption and that produced mainly for machines; on the other hand, one has to keep track of information uncertainty. The increasing interest in ontology-based, standard representations of belief-based, possibilistic and probabilistic information, as well as other types of uncertainty, is bringing soft computing techniques for uncertainty representation and processing to the forefront of semantic web research. In the last few years, a number of seminal workshops and seminars have spread the interest for these issues within both the Semantic Web and the fuzzy logic or soft computing communities. Fuzzy logic has been used to bridge the gap among intuitive knowledge and machine-readable knowledge systems. Much research is also being done on techniques for extracting incomplete, partial or uncertain knowledge, as well as on handling uncertainty when representing extracted information using ontologies, e.g. to achieve semantic interoperability among heterogeneous systems. Semantic Web demands the management of large amounts of fuzzy data and the extraction of fuzzy information. Therefore, automatic tools for reasoning about fuzzy dependencies are necessary, in this line we can cite [40].

*Business and economics.* Soft computing methods can be used in an uncertain economic decision environment to deal with the vagueness of human thought and the difficulties in estimating inputs. There is a plethora of applications of soft computing in business and economics, which range from marketing (analysis of customer's purchasing attitudes, fraud detection, service quality), to finance (stock market predicting schemes, portfolio selection, risk management, loan assessment systems), electronic business (e-commerce decisions, personalization, risk analysis in e-commerce), etc.

*Medical engineering.* Successful diagnoses and surgical outcomes depend on the experience and skill of examiners and surgeons, but dependence on the subjective abilities of these healthcare professionals carries with it the risk of failure. Teaching these feelings to beginners is a very difficult task, because the skill of diagnose the feelings is based on subjective evaluation. Thus, the medical industry requires new engineering technologies, such as soft computing techniques, to assess information objectively. While recent developments in medical engineering have been achieved by state-of-the-art of intelligent computing techniques, including computer-aided diagnosis, computer-aided radiography, computer-assisted surgery, developments in soft computing, including information processing, signal/image processing, and data mining seems to be specially promising in this field.

*Information retrieval.* Information retrieval aims at defining systems able to provide a fast and effective content-based access to a large amount of stored information. Currently, soft computing techniques are being used to model subjectivity and partiality in order to provide a adaptative environment of information retrieval, one which learns the user's concept of relevance. The modelling is performed by the knowledge representation components of SC such as fuzzy logic, probabilistic reasoning, and rough sets. This way, the application of soft computing techniques can be of help to obtain greater flexibility in IR systems.

*Fuzzy control applications.* The first application of fuzzy logic to control systems was the design of a fuzzy algorithm for regulating a steam engine by given Mamdani and Assilian [31]. After this starting point, the research and applications of fuzzy control progressed rapidly. Hard computing methodologies are not useful for the construction of the robot control systems of acceptable cost, it is the use of soft computing techniques what allows to overcome the problem of complexity of control systems and, in addition, provides them with abilities of tolerance for imprecise data, and high efficiency and performance.

*Robotics.* This field has a number of subareas which can profit from soft computing techniques. For instance, the drive control of a robot is often performed by a neuro-fuzzy system that generates action commands to the motors, the input of this systems comes from the surrounding information, in terms of data obtained by the vision subsystem and the goal identifying device. Then, fuzzy inference mechanisms are usually provided by neural networks. Moreover, the systems are taught how to behave by means of adjusting its knowledge base by a neural network learning technique.

## 4 Conclusions

We have briefly recalled the basics of fuzzy logic and soft computing, and have surveyed a range of applications of these fields ranging from the purely theoretical to the most practical ones.

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