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Role of Fuzzy Sets on Artificial Intelligence Methods: A literature Review

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Abstract. Machines can model and improve the human minds capabilities through artificial intelligence. One of the most popular tools of artificial intelligence is fuzzy sets, which can capture and model the vagueness and impreciseness in human thoughts. This paper, first of all, introduces the recent extensions of ordinary fuzzy sets and then presents a literature review on the integration of fuzzy sets with other artificial intelligence techniques such as automated reasoning, autonomous agents, multi-agent systems, machine learning, case-based reasoning, deep learning, information reasoning, information representation, natural language processing, symbolic reasoning, and neural networks. Graphical illustrations of literature review results are presented for each of these integrated artificial intelligence techniques. The results of a patent search on fuzzy artificial intelligence are also given.

AMS Subject Classification 2020: 03B52; 03E72; 03E75
Keywords and Phrases: Artificial intelligence, Fuzzy sets, Automated reasoning, Autonomous agents, Machine learning, Deep learning, Information reasoning, Neural networks.

1 Introduction

Fuzzy sets were first proposed in the literature by Zadeh [36] to apply human logic to solve engineering problems and representing human decision-making and evaluation processes in an algorithmic way. Fuzzy set theory, which tries to express vagueness and impreciseness numerically, provides another perspective in addition to deterministic and probabilistic models in the representation and solution of real-life problems. It facilitates researchers in processing and representing linguistic data that cannot be easily processed by other methods. Problems including linguistic data are quite complex since they are uncertain, imprecise, and incomplete. When there is so little uncertainty in the system being modeled or when all of the inputs can be accurately described, closed-form mathematical models are sufficient. Stochastic models are used to model complex systems when sufficient data are available. However, fuzzy logic guides our understanding of complex systems behavior by allowing us to draw an approximate conclusion based on the observed inputs and outputs when there are uncertain data or few quantitative data.
Fuzzy set theory is a sub-division of computational intelligence, which successfully represents any inference in artificial intelligence applications by providing a logical and conceptual structure under uncertainty. Fuzzy set theory is used to transfer human logical and flexible thinking processes to computational intelligence. Hence, it is used to handle incompleteness, unreliability, vagueness, randomness, and impreciseness in artificial intelligence applications [19].
Since 1965, studies on fuzzy sets have been continuing with great acceleration. Even in its early years, fuzzy

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sets have been often integrated with other intelligent systems such as symbolic reasoning, natural language processing, and knowledge representation [40], [16]. In this study, intelligent methods improved by fuzzy sets are examined and classified. Intelligent systems such as automated reasoning, autonomous agents, multi-agent systems, machine learning, case-based reasoning, deep learning, information reasoning, information representation, natural language processing, symbolic reasoning, and neural networks are selected as the focus areas. We also investigate how intelligent systems are elaborated using fuzzy sets. Skills such as natural language processing and knowledge representation, which are inherent in fuzzy numbers, have facilitated the development of fuzzy intelligent techniques. Especially with fuzzy sets, artificial neural networks and machine learning algorithms are widely used. In this study, we prepared an elaborative literature review to reveal the state of the art in intelligent methods that are enhanced with fuzzy sets. We used the Scopus database for conducting our research [40].

Real-world applications of intelligent techniques such as control systems, image processing, power engineering, industrial automation, robotics, consumer electronics, and optimization have widely benefited from fuzzy sets [28]. Along with the literature review, a patent analysis on fuzzy intelligent techniques can also provide a perspective to demonstrate the current integration of fuzzy sets and intelligent systems. In this study, a brief patent search, including examples of patents that combine fuzzy sets and artificial intelligence, has been conducted using Google Patent Search. The results of this patent analysis show that fuzzy machine learning, fuzzy deep learning and fuzzy case-based reasoning are among the most popular combinations in this area. The patent analysis results also reveal that fuzzy sets have been mostly used with machine learning and deep learning in the last decade.

The main objective of this study is to examine fuzzy set-based artificial intelligence applications both in the literature and in industrial applications in order to understand the role of fuzzy sets in artificial intelligence-based applications. For this purpose, the peer-reviewed fuzzy intelligence technique articles published in the Scopus database have been analyzed within the scope of this study. Furthermore, fuzzy set-based real-world applications have been investigated with a patent search to demonstrate the success of fuzzy sets in artificial intelligence-based applications.

The rest of this paper is organized as follows: Section 2 presents a brief explanation of artificial intelligence methods. Section 3 summarizes fuzzy set theory and its extensions. Section 4 provides a literature review on intelligent systems integrated with fuzzy sets. Section 5 presents real-world examples that combine artificial intelligence and fuzzy set theory. Finally, the concluding remarks are given in Section 6.

2 Artificial Intelligence Methods

Artificial intelligence applications are becoming more and more common nowadays. In fact, there are artificial intelligence technologies under many applications that most people are not aware of but that we use widely today. The most straightforward implementation is the algorithm used for the classification of e-mails. An algorithm decides whether an e-mail should be in the spam box or not, whether it contains advertisements or not, and then it forwards the e-mail to the corresponding folder. Moreover, machines or computers, including software or hardware, can imitate many human-specific and intelligence-expressing features such as voice recognition, speech, inference, and problem-solving. Devices can achieve these operations depending on the developments in the artificial intelligence field, including automated reasoning and inference, autonomous agents and multi-agent systems, artificial consciousness, case-based reasoning, machine learning and deep learning, knowledge reasoning and representation, natural language processing, neuro-inspired computing, and robotic process automation. This is a structure that extends from data collection to creating artificial consciousness. Indeed, the main objective is to figure out correlations and patterns in order to reveal tacit knowledge and make predictions about future situations by analyzing data collected from current and past experiences.

An AI-based system should receive different stimuli from its environment in order to achieve certain targets and decide by itself how to respond to the stimulus based on the relationship between the target and the stimulus. This component of AI is called an autonomous agent. Autonomous agents have been developed to figure out and succeed in the given tasks in distributed format by using multiple agents including several capabilities such as coordination, cooperation, analyzing, and learning by themselves. One of the agent-based applications of AI that have become widespread recently is robotic process automation. Robotic process automation is another application area of AI. The main objective of robotic process automation is to construct software robots that implement and control real-world operations by emulating human actions. These robots perform a wide range of defined actions regarding simple human tasks such as figuring out whats on a screen, completing the right keystrokes, navigating systems, and identifying and extracting data. In addition, they can do these tasks more consistently and faster than humans. To achieve common goals, the features, including learning from experience, dynamically evolving, and cooperation among agents, are vital in the development of agent-based systems [22]. Therefore, four cognitive skills which are knowledge representing, learning, reasoning, and self-correction, are the fundamental issues that should be addressed to develop an AI-based system.

First, the information and constraints on the problem should be well defined to solve complex real-world problems successfully. At this point, knowledge representation is responsible for the representation of the real world so that a computer can understand and utilize this knowledge. In other words, knowledge representation is interested in the symbolic representation of knowledge and the automated manipulation of knowledge [7]. There are five key factors for knowledge representation. These are (i) the ability of a generic representation, (ii) the ability to recognize, (iii) the ability of the combination of representations, (iv) the ability to extensive view, and (v) the ability to capture the real-world complexity [13]. For this reason, natural language processing is widely used to develop AI applications. Natural language processing refers to the ability of computer systems in order to understand written and spoken words as successfully as humans. So, natural language processing is related to machine-based technologies, including understanding, analyzing, manipulating, and interpreting human languages, and it consists of five steps: (i) lexical and morphological analysis, (ii) syntactic analysis, (iii) semantic analysis, (iv) discourse integration, and (v) pragmatic analysis. Based on these technologies, human tasks such as speech recognition, machine translation, and machine text reading can be quickly succeeded by computers.

Learning, which is the second issue, focuses on collecting data, revealing knowledge, and creating rules to turn data into action. For the learning process, machine learning and deep learning are the most commonly used AI methods that explore and discover data, learn from the collected data, and then apply these learnings to other sets to make a decision. Differing from machine learning, deep learning is a subset of machine learning that can learn and make intelligent decisions on its own.

The third issue, which represents the ability to make inferences, is expressed as reasoning. The mechanization of this process with information processing systems providing relationships among system variables is defined as automatic reasoning. In other words, it is a field of research that aims for computers to define the problem, use a language that represents the problem, and reach a solution through the analogy of experience. The main objective of automatic reasoning is to create deep learning systems similar to human inference without human intervention [14]. As a result, understanding how the human thinking process can deal with incomplete and imprecise information while still making precise decisions under fuzziness is critical for developing a successful automatic reasoning system. Therefore, to develop machine inference, researchers are inspired by biological structures or processes. Bio-inspired computing is the field of study in which algorithms developed by inspiration from nature and biology (animal or plant world) are used to solve complex optimization problems that cannot be solved by deterministic algorithms within a reasonable time. The main philosophy of these methods is generally based on the imitation of the learning processes of biological organisms. Genetic algorithms, neural networks, ant colonies, bee algorithms, and swarm optimization are some of the most widely used algorithms. These algorithms are widely used in solving various optimization problems by many researchers as they are superior in many complex problems when compared with traditional ones [31]. Another paradigm of inference is case-based reasoning, which solves new problems by revoking stored 'cases' describing similar prior problem-solving episodes and adapting the solutions of older problems to fit emerging requirements. Therefore, case-based reasoning, including the case retriever and the case reasoner components, is built on the concepts and techniques such as knowledge representation, reasoning, and learning from experience. The main objective of case-based reasoning research is to understand how humans generate hypotheses about new conditions based on their past experiences [27].

The last one is self-correction, and it is related to consciousness. Artificial consciousness or synthetic consciousness is defined as a non-biological system that can be aware of its own existence. Artificial consciousness is the most difficult subject to be answered among the other AI subjects since human consciousness is both so deep and so elusive. So, synthetic consciousness seems not to be possible soon since there are lots of questions that should be answered on this topic [32].

3 Fuzzy Sets Theory and Its Extensions

Starting with 0-1 logic, multivalued logic has found its ultimate destination with L. A. Zadeh's continuous fuzzy logic [36]. Ordinary fuzzy sets (OFS) introduced by Zadeh [36] are represented by singletons with an element and its degree of membership to the set. The non-membership of this element is the complement of the membership degree to 1. This complementary feature of ordinary fuzzy sets was criticized by various researchers [3], [33]. According to these researchers, there should be no necessity for this complementary feature of OFS. Thus, by removing this complementary feature, OFS has been extended to several new extensions that describe membership functions in more detail. The new extensions of OFS are historically illustrated in Fig 1.

A crisp membership value corresponding to any x value caused criticisms of type-1 membership functions. Thus, type-2 fuzzy sets and interval-valued fuzzy sets were developed, which introduced the fuzziness of membership functions [37]. Later, Atanassov [3] introduced intuitionistic fuzzy sets (IFSs) including x values with degrees of membership and non-membership whose sum can be at most equal to 1. The complement of the membership and non-membership degrees to one is the hesitancy or indeterminacy degree of the decision maker. Torra [30] introduced hesitant fuzzy sets (HFSs) to deal with a set of potential membership values of an element in a fuzzy set. Atanassov [4] introduced intuitionistic type-2 fuzzy sets (IFS2) in his book, which let the squared sum of membership and non-membership degrees be at most equal to one. Later, Yager [33] called IFS2 Pythagorean fuzzy sets (PFSs). Yager [34] also introduced q-rung orthopair fuzzy sets (Q-ROFSs) as a generalization of IFSs, in which the sum of qth powers of membership and non-membership equals at most one. Smarandache [29] introduced neutrosophic sets whose degrees of truthiness, indeterminacy, and falsity for each element in the universe can be equal to at most one and their sum can be at most 3. Coung [12] introduced picture fuzzy sets with three parameters which are called yes, no, and abstain, and their complement to one as refusal degree. Kahraman and Kutlu Gndodu [18], Kutlu Gndodu and Kahraman [20] introduced spherical fuzzy sets in which the squared sum of the same parameters as picture fuzzy sets can be at most equal to one. Figure 1 shows the historical development of fuzzy sets in the literature.

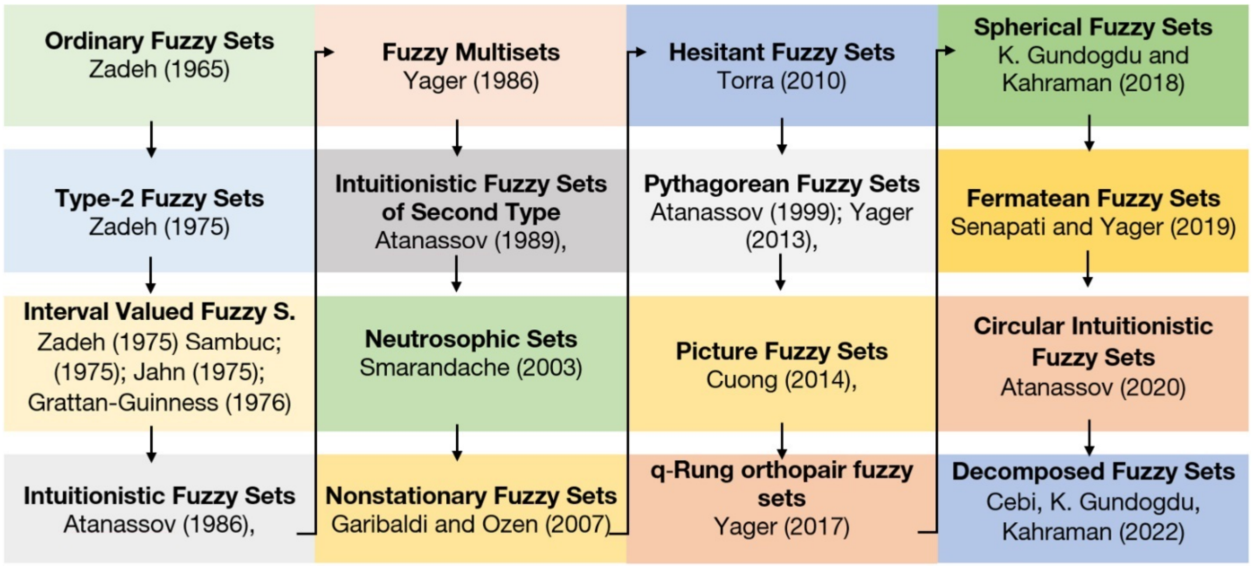

Figure 1: Extensions of fuzzy sets

The aim of all these extensions is to explain the membership of an element to a fuzzy set with more parameters and more details.

4 Intelligent Systems Integrated with Fuzzy Sets: a Literature Review

In this study, we prepared an elaborative literature study to reveal the state of the art on intelligent methods that are enhanced with fuzzy sets. We focused on nine intelligent systems, namely automated reasoning, autonomous agents & multi-agent systems, machine learning, case-based reasoning, deep learning, knowledge reasoning & representation, natural language processing, symbolic reasoning and regulation, and neural networks, and how they have been extended by using fuzzy sets. We used the Scopus database for conducting our research. The number of studies that combines fuzzy logic with intelligent techniques has been given in Figure 2. Neural networks and machine learning algorithms are the most used intelligent systems that are combined with fuzzy sets.

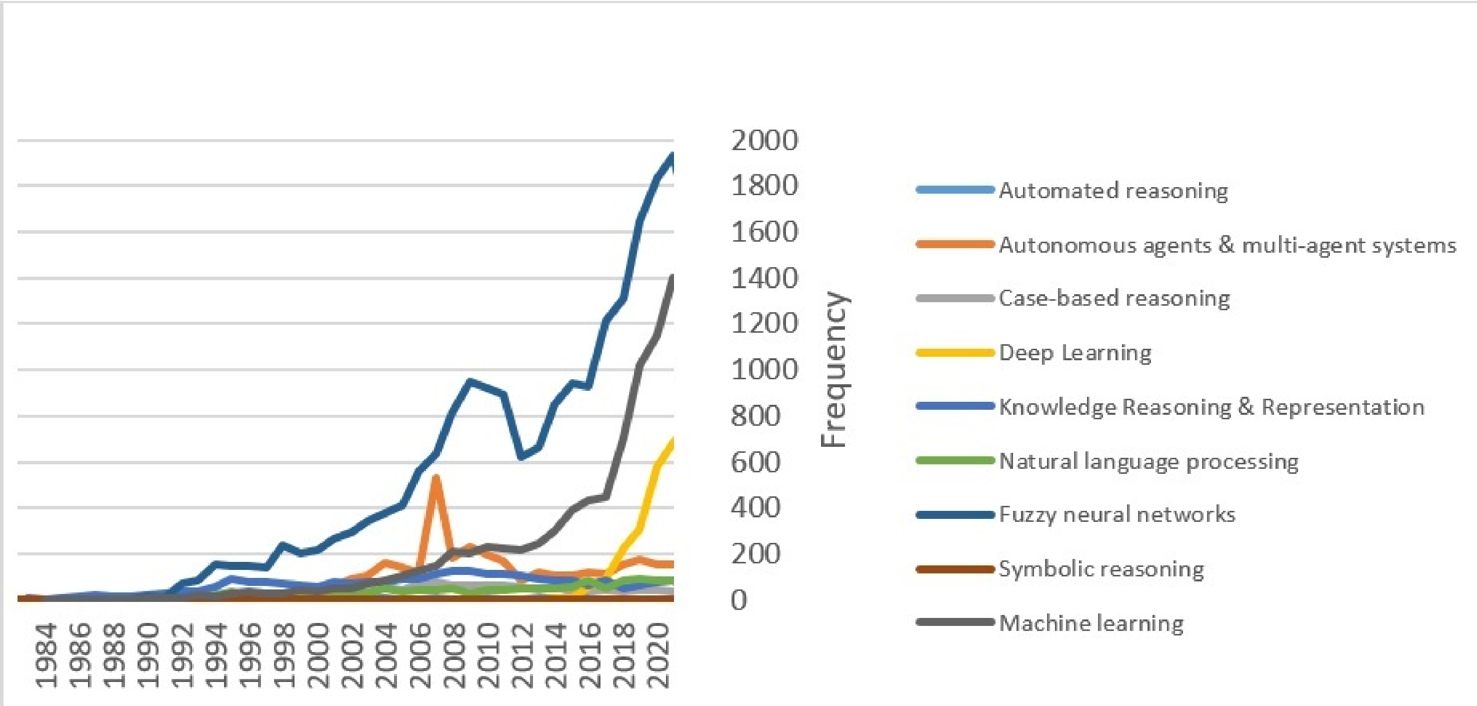

Figure 2: Intelligent techniques integrated with fuzzy sets (Scopus Database)

4.1 Automated Reasoning and Inference

In this study, we have utilized the Scopus database and searched for Automated reasoning and 'fuzzy' terms. Based on this research, there are a total of 104 studies using fuzzy logic in automated reasoning, the number of studies carried out over the years is given in Figure 3. The earliest studies date back to 1986 and the newest ones are from 2022. Ross et al. [26] developed an automated reasoning system for the damage assessment of protective structures within the Air Force. This new system uses fuzzy logic for representing uncertain knowledge and combines this data with data represented with crisp values. Zhu and Wang [41] developed a fuzzy comprehensive evaluation-based artificial consciousness model. In a newer study, Cordero et al. [11] developed a coding package that extends formal concept analysis by fuzzy sets in developing automated reasoning tools.

4.2 Autonomous Agents and Multi-Agent Systems

In this section, we have utilized the Scopus database and searched for Autonomous agents or multi-agent systems and 'fuzzy' terms. Based on this research, a total of 972 studies utilizes fuzzy logic in autonomous agents and multi-agent systems, the number of studies that have been conducted over the years has been given in Figure 4. The earliest studies date back to 1994 and the newest ones are from 2022. Bonarini [5] applied evolutionary learning of fuzzy rules for creating autonomous agents. This novel approach overcomes the problems such as evaluation function biases. Alcantud [2] uses hesitant fuzzy sets for developing a multi-agent decision process.

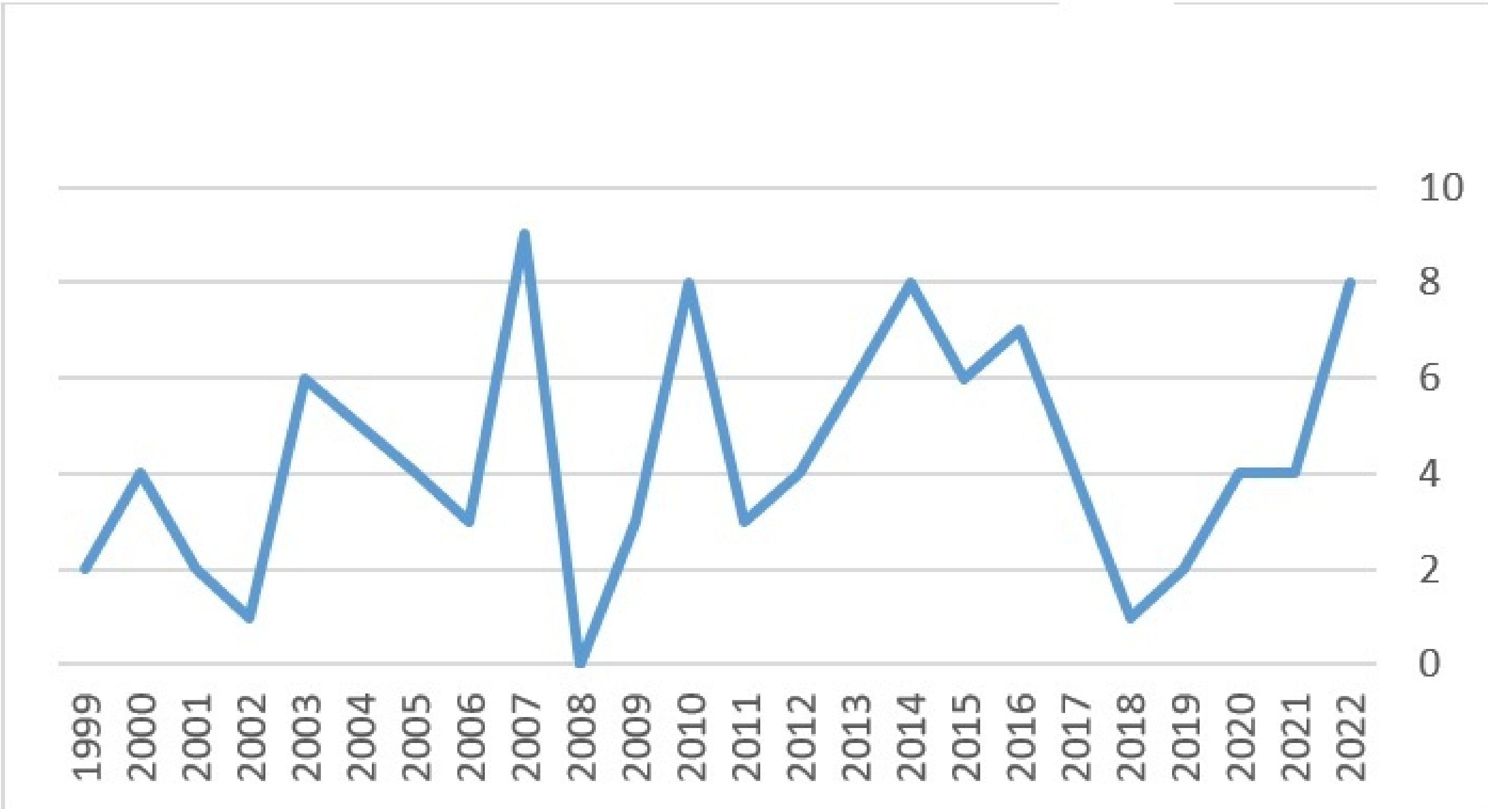

Figure 3: Fuzzy automated reasoning (Scopus Database)

4.3 Case-based Reasoning

In this section, we have utilized the Scopus database and searched for case-based reasoning and 'fuzzy' terms. Based on this research, a total of 1084 studies utilizes fuzzy logic in case-based reasoning, the number of studies that have been conducted over the years has been given in Figure 5. The earliest studies date back to 1989 and the newest ones are from 2022. MacKellar et al. [6] developed a knowledge system that uses case-based reasoning that has been enhanced with fuzzy logic. Gao et al. [15] developed an intuitionistic fuzzy entropy formula for constructing a case-based reasoning decision matrix.

4.4 Machine Learning

In this section, we have utilized the Scopus database and searched for machine learning and 'fuzzy' terms. Based on this research, a total of 9174 studies utilizes fuzzy logic in machine learning, the number of studies that have been conducted over the years has been given in Figure 6. Adlassnig and Kolarz [1] developed a machine learning program that is composed of a computer-aided medical expert system. The program uses 3530 rheumatological patient records to create inductive learning. In a recent study, Pascual et al. [25] utilized fuzzy random forests as a machine-learning classification method in which the linguistic scales can be represented with fuzzy sets. The fuzzy decision tree-based fuzzy random forests are claimed to be beneficial while dealing with imbalanced data between classes. The authors introduced a new fuzzy random forest method and applied to forecast the risk of developing diabetic retinopathy.

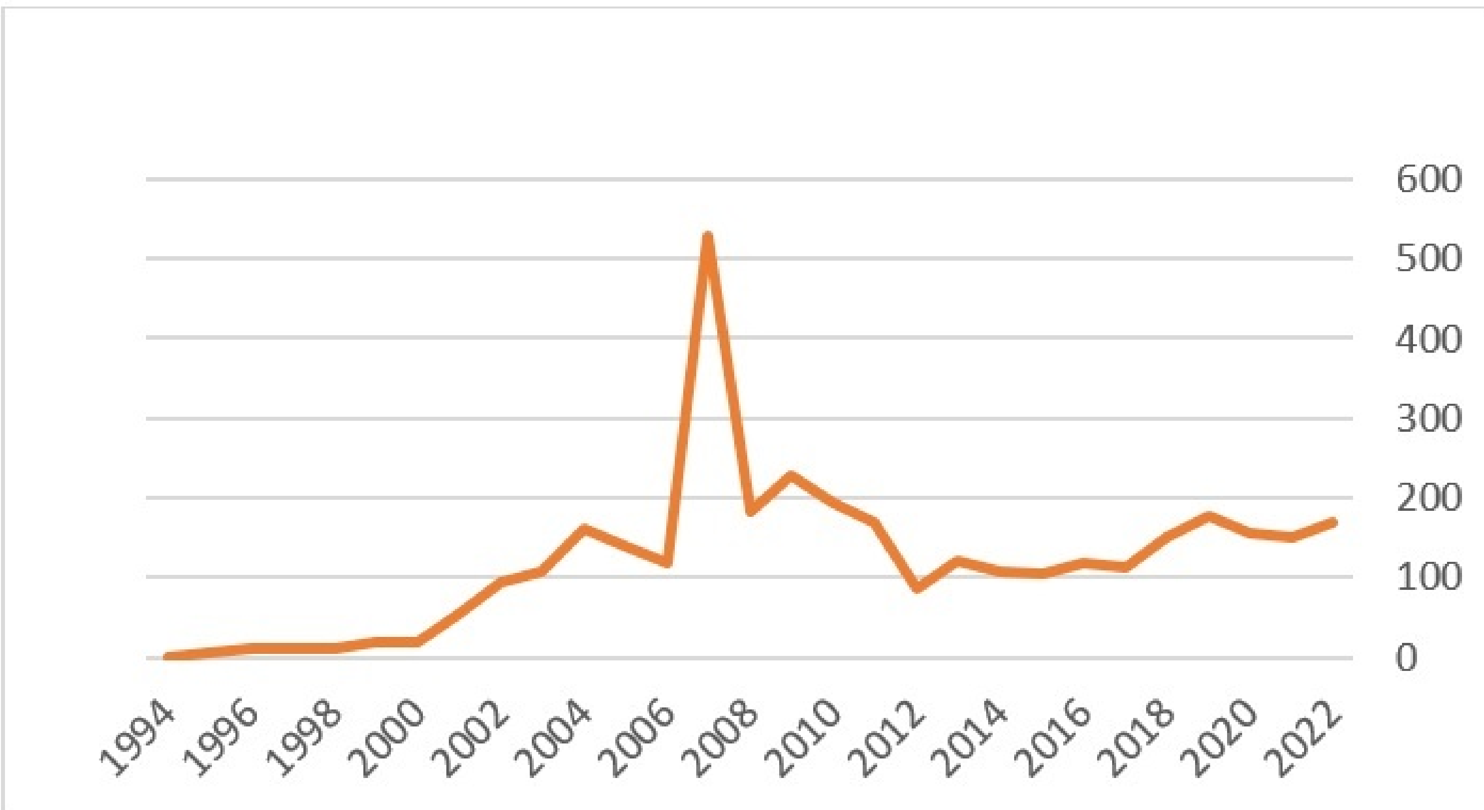

Figure 4: Fuzzy autonomous agents and multi-agent systems (Scopus Database)

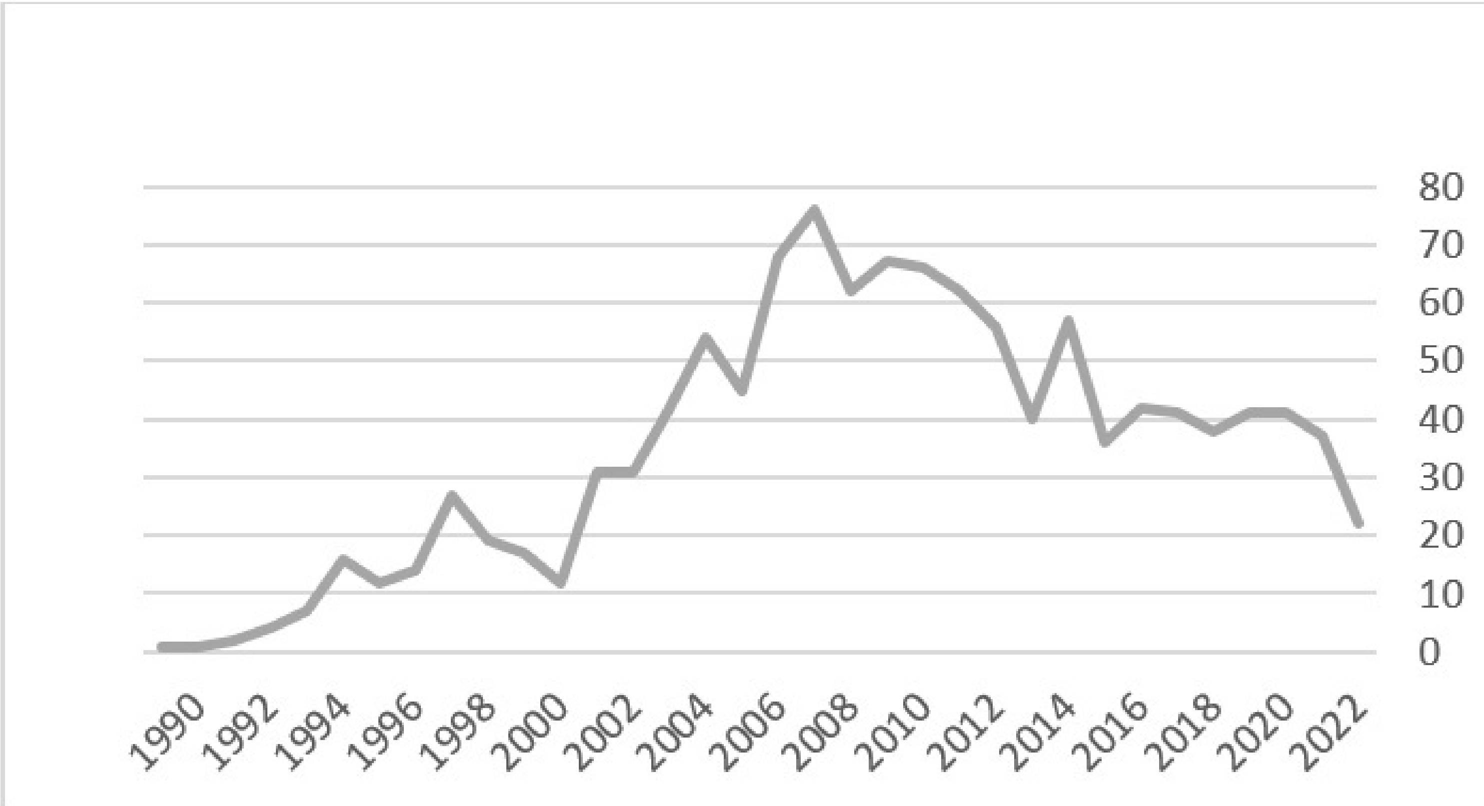

Figure 5: Fuzzy case-based reasoning (Scopus Database)

4.5 Deep Learning

In this section, we have utilized the Scopus database and searched for deep learning and 'fuzzy' terms. Based on this research, a total of 2734 studies utilizes fuzzy logic in deep learning, the number of studies that have been conducted over the years has been given in Figure 7. The pioneer studies that combine deep learning and fuzzy sets are relatively new when they are compared with other intelligent techniques. In one of the earlier studies, Hu et al. [17] developed granular deep learning where the granular system is defined by fuzzy logic. Parveen [24] developed a fuzzy set enhanced deep learning algorithm for disease risk prediction by using large healthcare information.

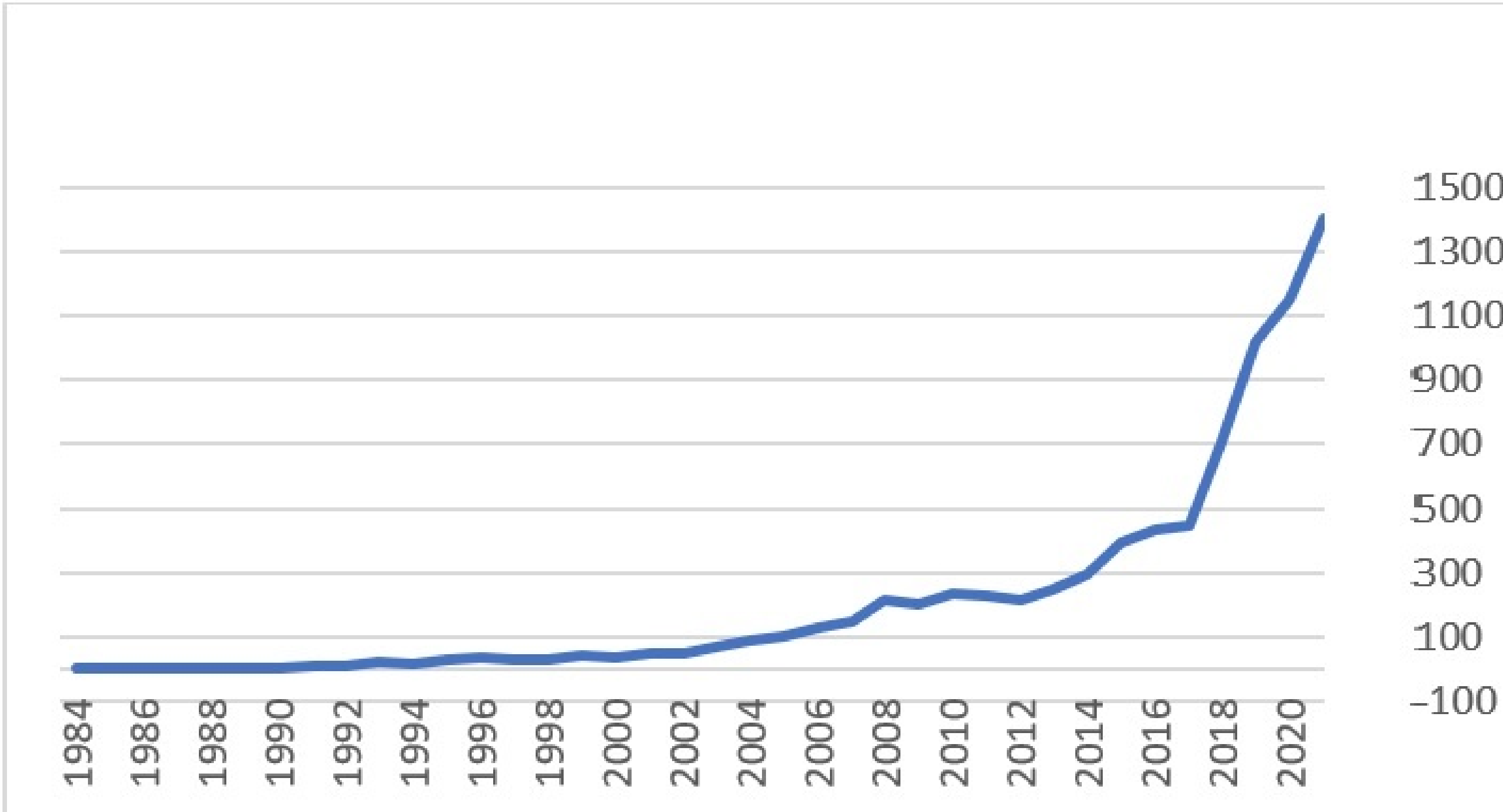

Figure 6: Fuzzy machine learning (Scopus Database))

4.6 Knowledge Reasoning and Representation

In this section, we have utilized the Scopus database and searched for knowledge reasoning and 'fuzzy' terms. Based on this research, a total of 1938 studies utilizes fuzzy logic in knowledge reasoning, the number of studies that have been conducted over the years has been given in Figure 8. The fuzzy set theory and fuzzy logic are valuable for uncertain knowledge representation and reasoning. Zadeh [39] revealed that the knowledge base of an expert system is imprecise, incomplete, or not reliable and thus involves uncertainty. This uncertain knowledge can be represented with fuzzy logic [40]. Chiu [10] developed a knowledge reasoning agent for modeling the computer-based problem-solving skills of a user. In a recent study, Yue et al. [35] developed a new fuzzy Petri net for modeling knowledge representation and reasoning.

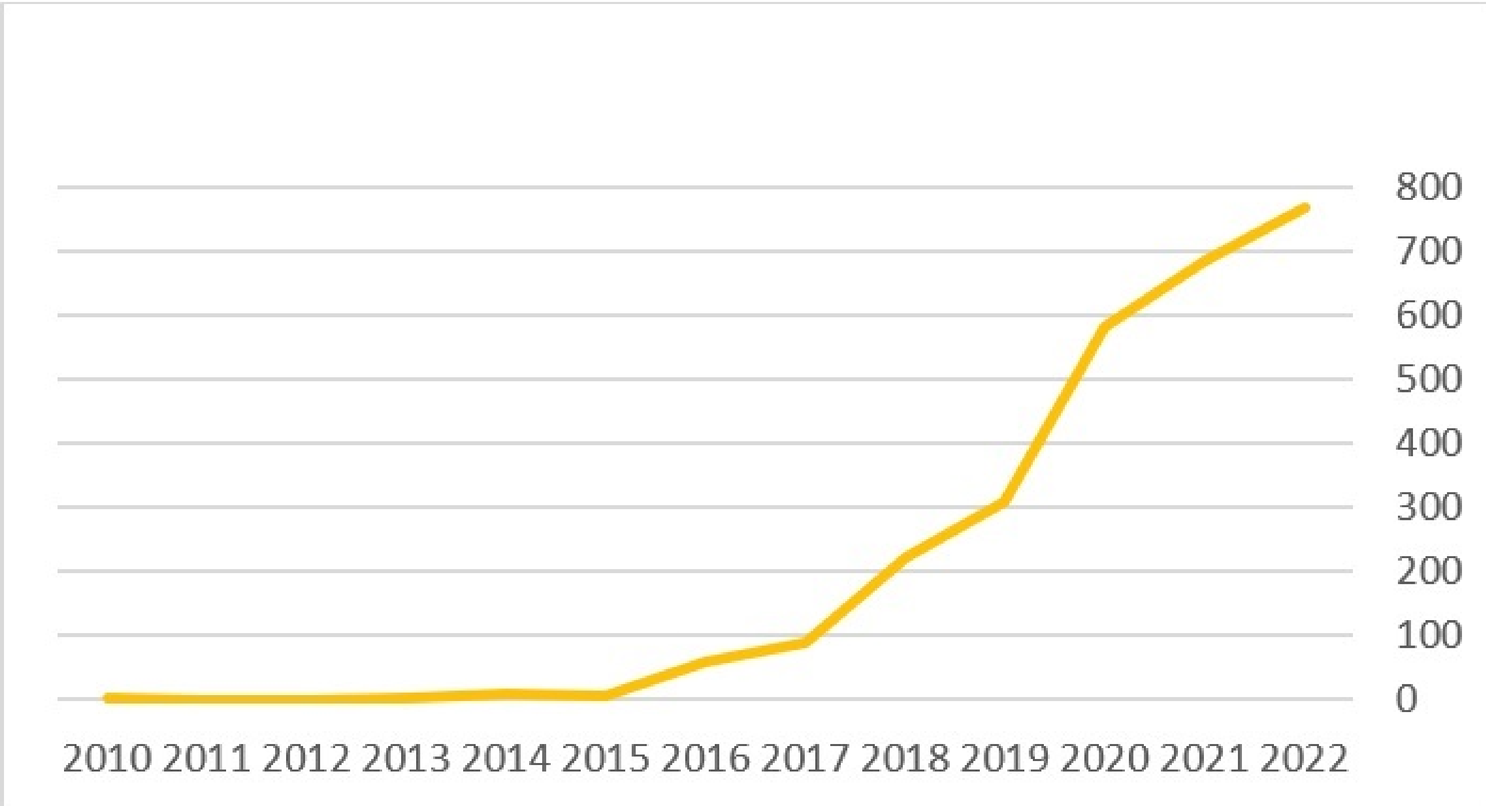

Figure 7: Fuzzy deep learning (Scopus Database)

4.7 Natural Language Processing

In this section, we have utilized the Scopus database and searched for natural language processing and 'fuzzy' terms. Based on this research, a total of 1217 studies utilizes fuzzy logic in natural language processing, the number of studies that have been conducted over the years has been given in Figure 9. Representing natural language is one of the key aspects of fuzzy sets. In his early studies, Zadeh [38] showed the benefits of fuzzy sets in representing natural language. Thus, many studies utilize fuzzy sets for representing and processing human language. In a recent study, Chen [9] used natural language processing to extract keywords from social media data and combines this information with fuzzy-based group decision model.

4.8 Neural Networks

In this section, we have utilized the Scopus database and searched for fuzzy neural network' terms. Based on this research, a total of 20422 studies utilizes fuzzy logic in neural networks, the number of studies that have been conducted over the years has been given in Figure 10. The use of fuzzy neural networks is very old. Lee and Lee [21] claimed that the insertion of fuzziness into the neuron model enhances the behavior of imprecisely defined systems. The authors developed a fuzzy neural network for dealing with this imprecision. In a recent study, Liu [23] developed an interval type-2 fuzzy neural network for modeling multiple energy-coupling devices.

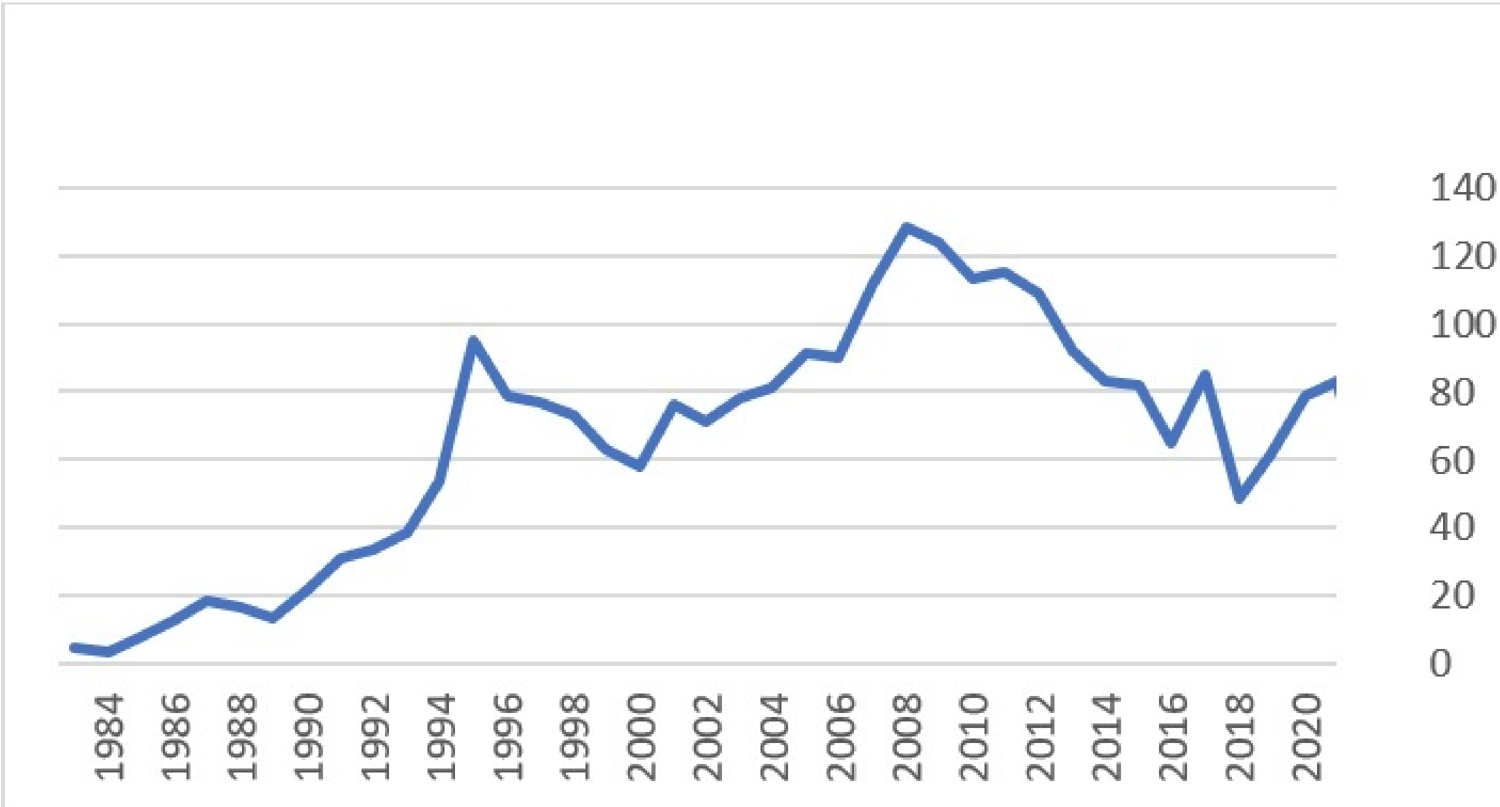

Figure 8: Fuzzy knowledge reasoning (Scopus Database)

4.9 Symbolic Reasoning and Regulation

In this section, we have utilized the Scopus database and searched for "symbolic reasoning and regulation" and "fuzzy" terms. Based on this research, a total of 25 studies utilizes fuzzy logic in symbolic reasoning and regulation, the number of studies that have been conducted over the years has been given in Figure 11. Cerutti et al. [8] developed a fuzzy-based decision-making approach to deal with computer-oriented medical decision-making. Hoitsma et al. [16] developed a symbolic explanation module that allows extracting useful insights and patterns from a trained fuzzy cognitive map-based classifier.

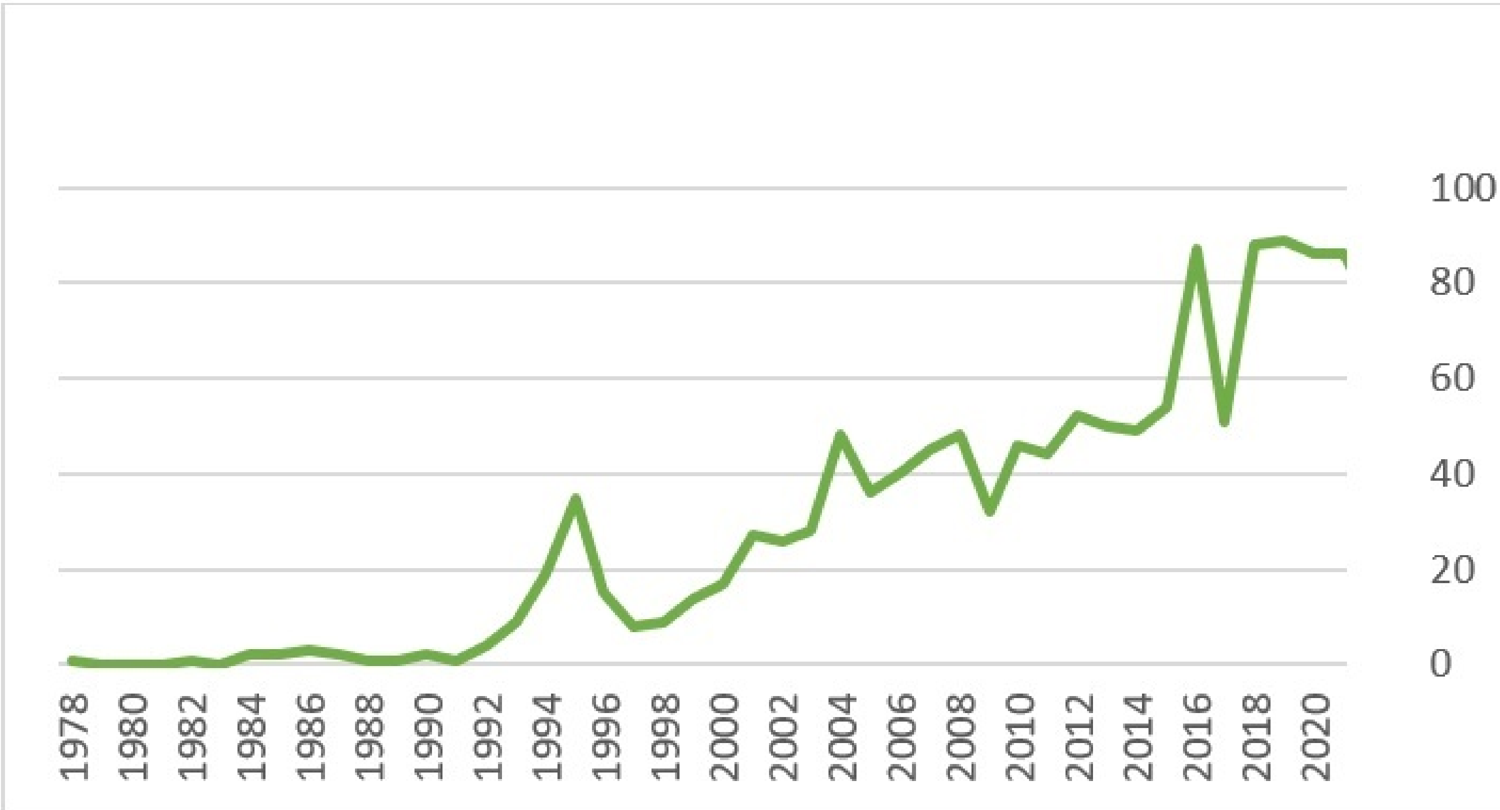

Figure 9: Fuzzy natural language processing (Scopus Database)

5 Real Applications and Patents on Artificial Intelligence Techniques & Fuzzy Sets

Many products have been and can be improved by integrating fuzzy sets with artificial intelligence. Self-driving cars is an example of fuzzy logic based artificial intelligence. Self-driving cars use a variety of sensors and machine learning algorithms to perceive and understand their environment, and to make decisions about how to navigate and move safely. Fuzzy logic is often used to handle the uncertainty and imprecision that can arise in this complex and dynamic environment. For example, fuzzy logic may be used to interpret sensor data and make decisions about how to respond to other vehicles, pedestrians, or road conditions. It may also be used to evaluate multiple criteria and make decisions about the most appropriate course of action in a given situation. Application areas of fuzzy logic can be exemplified as follows: Automotive Systems (automatic gearboxes, four-wheel steering, vehicle environment control), Consumer Electronic Goods (hi-fi systems, photocopiers, still and video cameras, dishwashers, television), Domestic Goods (microwave ovens, refrigerators, toasters, vacuum cleaners, washing machines), Environment Control (air conditioners/dryers/heaters, humidifiers) and Elevators, Language filters, Pattern recognition, and Video games. Especially the Japanese Firms such as Matshushita, Toshiba, Sanyo, Hitachi, Yamaichi, Sony, Cannon, Nippon, Subaru, Minolta, Ricoh, Panasonic, and Nissan used fuzzy logic in their products. Some technologies using fuzzy control are shown in Figure 12. Rice cookers carry computer chips on them that make proper adjustments to cooking time and temperature. Automatic control for Sendai subway trains provides a smoother, more efficient ride with a higher stopping precision. In fuzzy logic-controlled washing machines, there are several sensors that control the washing process, performing operations with respect to varying water intake, wash time, rinse

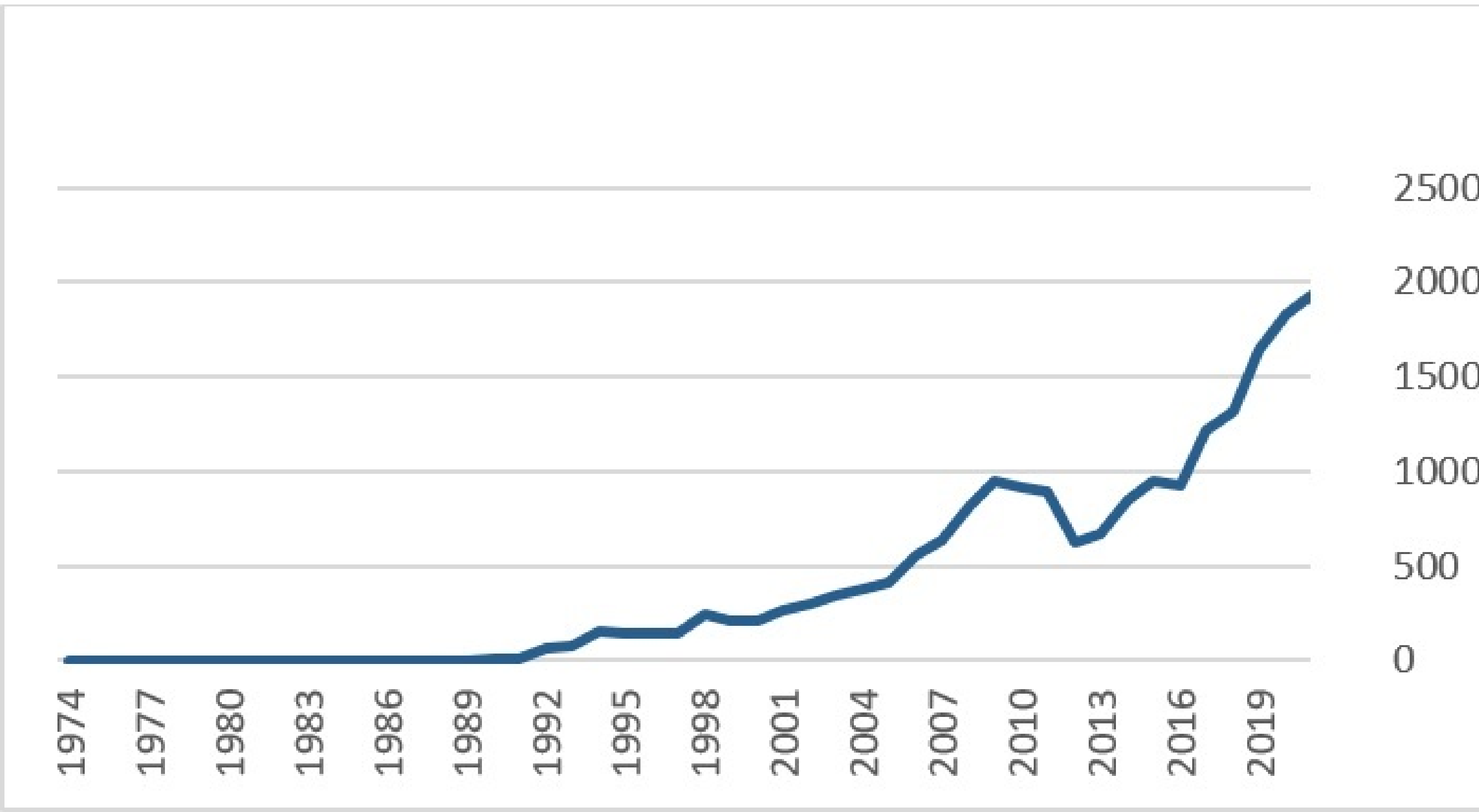

Figure 10: Fuzzy neural networks (Scopus Database

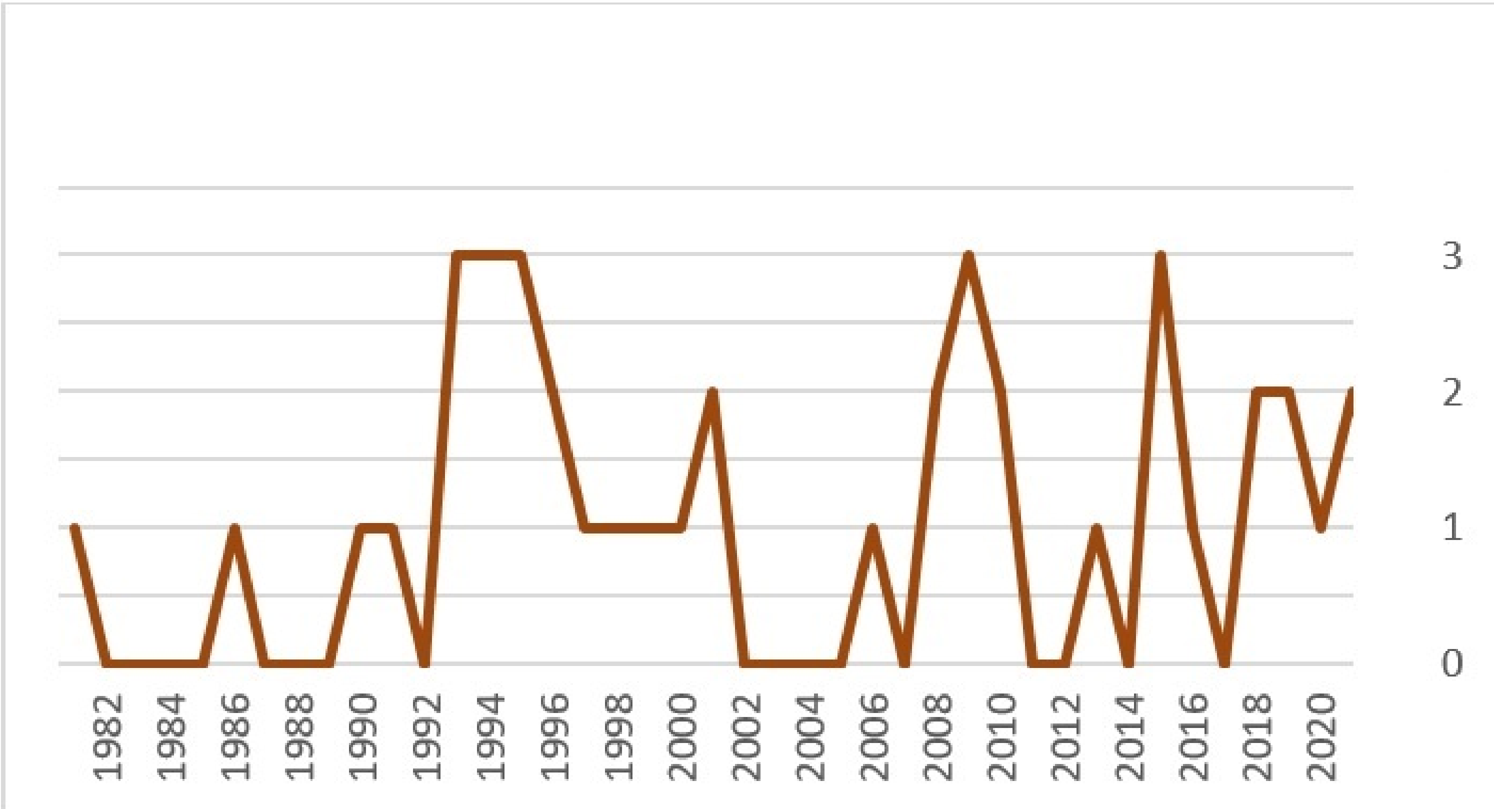

Figure 11: Fuzzy symbolic reasoning and regulation (Scopus Database)

performance, and spin speed. Some variables taken into account are the weight of the load, type of fabric, amount and temperature of the water, amount of detergent, speed and duration of the spin cycle. Fuzzy logic-controlled cameras have automatic exposure, automatic focus, and automatic white balance controls on them.

a) Rice cooker b) Sendai Metro c) Washing machine d) Camera

Figure 12: Fuzzy logic controlled technologies

In this section, we also try to outline the role of fuzzy sets in artificial intelligence from the patent

perspective. A patent is an exclusive right granted for an invention, which is a product or a process that provides a new way of doing something or offers a new technical solution to a problem. In order to see the current situation and trends in terms of patents, the number of patents obtained annually with the relevant keywords from Google Patents has been searched. The keywords included in the research are; Fuzzy automated reasoning inference, Fuzzy autonomous agents and multi-agent systems, Fuzzy artificial consciousness, Fuzzy Case-based reasoning, Fuzzy machine learning, Fuzzy deep learning, Fuzzy knowledge reasoning representation, Fuzzy Natural Language Processing, Fuzzy neuro-inspired computing, Fuzzy robotic process automation, Fuzzy symbolic reasoning regulation.
When the number of Patents containing the keywords taken in the last 10 years is examined, it is seen that the most popular keyword is "Fuzzy Machine Learning" in Figure 13. This is followed by the keywords "Fuzzy Deep Learning" and "Fuzzy Case-Based reasoning". The patents in which these first three keywords are included constitute 70% of the total patents examined.

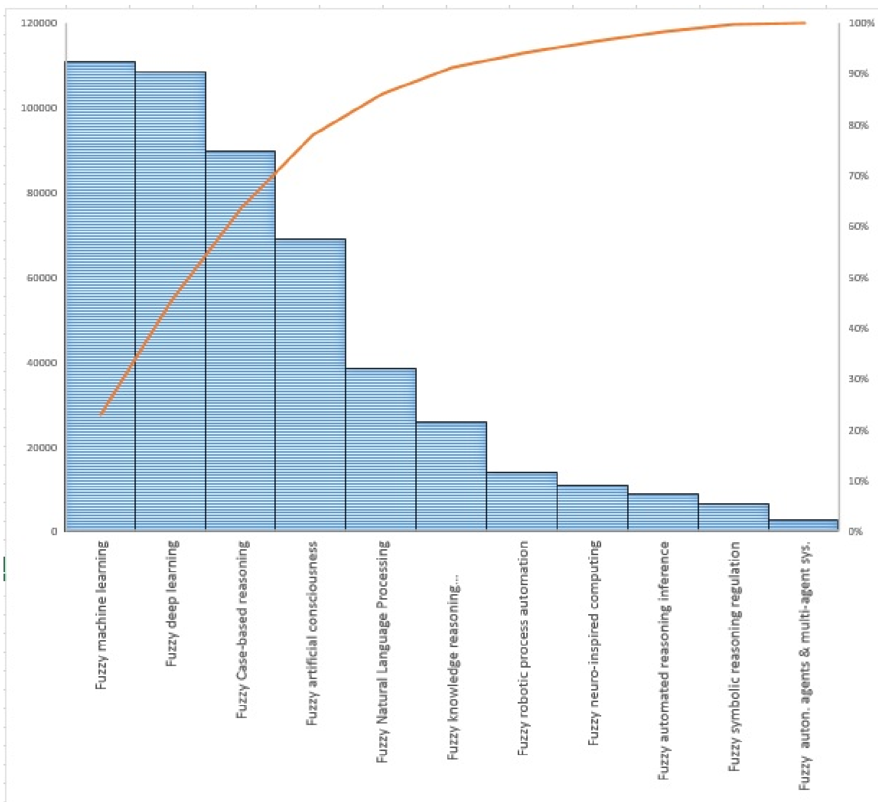

Figure 13: Patent numbers by fuzzy intelligent techniques

The annual numbers of total patents containing the keywords we mentioned before are given in Figure 14. There is a stable trend in this area until 2018. However, after 2019, a decrease in the number of patents in this field is noteworthy. It can be thought that the reason for this decrease is the pandemic that has taken over the world.

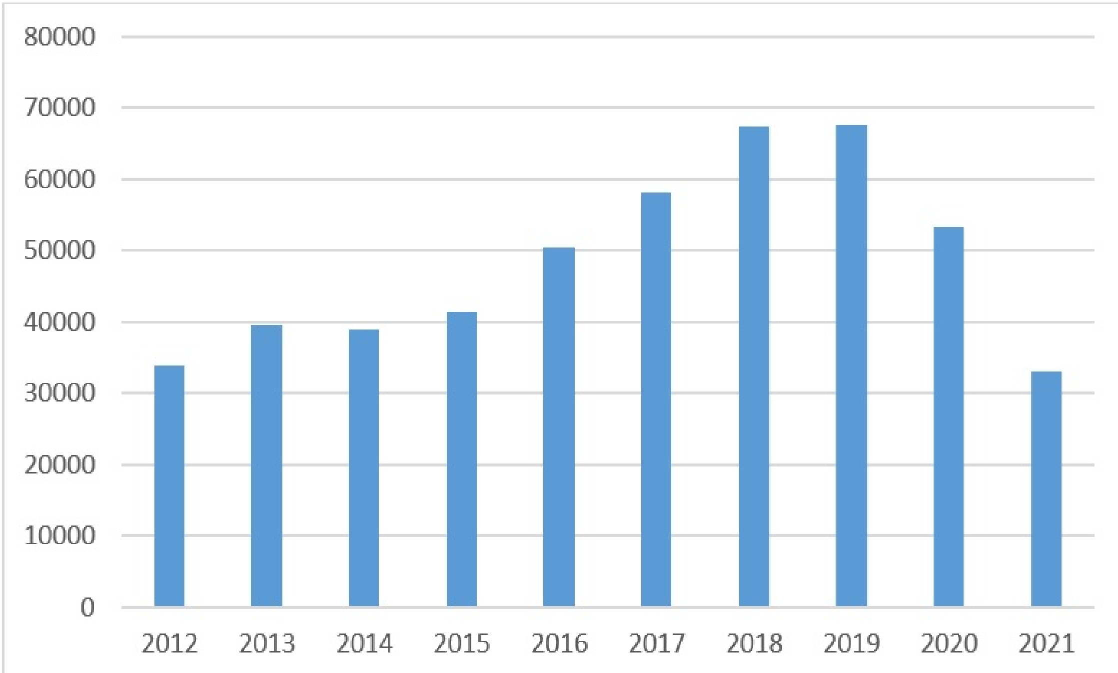

Figure 14: Annual patent numbers

It has been observed that there are changes in the number of patents containing the keywords examined over the years. In order to counteract this effect, the number of patents containing the keywords discussed was proportioned to the total number of patents of the relevant year and the relative patent numbers were determined. The results are shown in Fig 15.

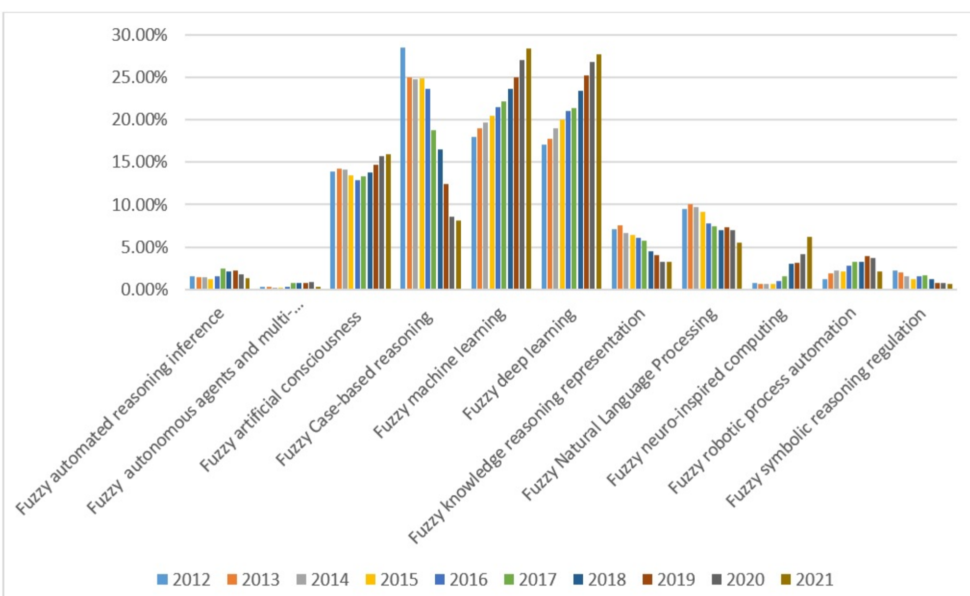

Figure 15: Yearly Trends with respect to relative patent numbers.

When Figure 15 is examined carefully, it is seen that the most important trend changes are in the fields of "Fuzzy machine learning" and "Fuzzy deal learning". These two keywords have been increasing their rate among all patents in the field of study over the years. While the keyword "Fuzzy Case-based reasoning" had close to 30% of all patents in 2012, it is seen that this ratio has steadily decreased and fallen below 10%. On the other hand, it is seen that patents related to "Fuzzy Artificial Consciousness" have increased steadily and exceeded 15%. Similarly, an increase is observed in the number of patents related to "Fuzzy neuro-inspired computing" and "Fuzzy robotic process automation". It is also noted in Figure 15 that the relative number of patents on "Fuzzy knowledge reasoning and representation" and "Fuzzy Natural Language Processing" is decreasing day by day.

6 Conclusion

Fuzzy Logic is a method of reasoning that resembles human reasoning. Artificial intelligence is a research area where human reasoning is an important part. Artificial intelligence presents several techniques and methods for handling different problems and complex systems. Fuzzy sets provide us with mathematical concepts to model human reasoning. Thus, fuzzy sets are quite important in human reasoning-based artificial intelligence applications such as humanoid robots and human decision-making. Besides, intelligent machines of manufacturing and service sectors such as televisions, washing machines, refrigerators, photocopy machines, cameras, and search engines use fuzzy logic. The literature review shows that Intelligent techniques integrated with fuzzy sets are used more and more each year.

Fuzzy automated reasoning shows a highly fluctuating usage frequency distribution, with the annual average frequency remaining constant. Fuzzy autonomous agents and multi-agent systems maintain their popularity with a usage frequency of 100-200 annually. The frequency of use of fuzzy case-based reasoning seems to be on a downtrend. Fuzzy machine learning and fuzzy deep learning frequencies have great acceleration. It seems to have entered a downward trend after 2008 when the frequency of fuzzy knowledge reasoning peaked. Fuzzy natural language processing and fuzzy neural networks have a great acceleration with slight up and down movements in the frequency of use. The annual frequency of use of fuzzy symbolic reasoning and regulation varies between 1 and 2 years after 2018.

Looking at the patent search results, fuzzy machine learning, fuzzy deep learning, and fuzzy case-based reasoning are the patented leading intelligent techniques. When these three techniques are examined on a yearly basis, an increasing number of patents have been observed in Fuzzy machine learning and Fuzzy deal learning techniques, while a decrease in the number of patents is observed in Fuzzy Case-based reasoning techniques over the years. There is a decrease in the number of patents received for fuzzy intelligent techniques after 2019. Although Fuzzy Artificial Consciousness has received fewer patents compared to these three techniques in total, the number of patents is increasing over the years.

For further research, we suggest a closer look at the artificial intelligence applications using the fuzzy set theory and present some of their fuzzy control mechanisms with illustrations.

Conflict of Interest: The authors declare no conflict of interest.

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