

# Fuzzy Number, Fuzzy Difference, Fuzzy Differential: Theory and Applications

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## 1. Introduction to the Topic Issue

This Topic Issue comprises sixteen pioneering academic papers that delve deeply into the realm of fuzzy reasoning, optimization, decision making, and control. It serves as a testament to the evolving landscape of fuzzy mathematics, increasingly pivotal to addressing complex, real-world problems across diverse domains. At the heart of this reprint lies the exploration of fuzzy numbers, fuzzy differences, and fuzzy differentials foundational concepts which possess both theoretical significance and practical importance.

Fuzzy numbers, which generalize the concept of classical numbers to accommodate imprecision and uncertainty, have revolutionized the way we represent and manipulate data in various fields. Their introduction allows for a more nuanced understanding of inherently ambiguous or ill-defined phenomena. By assigning degrees of membership to elements within a set, fuzzy numbers provide a flexible framework for capturing and analyzing information that lies between the crisp boundaries of classical set theory. This, in turn, has facilitated advancements in fields such as engineering, economics, and medical diagnosis, where the ability to handle imprecise and uncertain data is crucial. The theoretical underpinnings of fuzzy differences and differentials build upon the foundation laid by fuzzy numbers. Fuzzy differences explore how changes in fuzzy values can be represented and analyzed, enabling a more robust understanding of dynamic systems. Similarly, fuzzy differentials extend the concept of classical derivatives to fuzzy-valued functions, providing insights into the behavior of these functions under small perturbations. These developments have been instrumental in refining models and simulations in areas like control systems, where the ability to predict and manage changes is essential for achieving optimal performance. In fuzzy reasoning, a method grounded in symmetric quintuple-implication principles is introduced to manage mixed information, demonstrating strengths in logical foundation and reductivity. This method not only enhances the precision of fuzzy inference but also broadens its applicability to complex, real-world scenarios. By leveraging the principles of symmetry and implication, this approach facilitates a more coherent and consistent reasoning process, making it well suited for tasks such as pattern recognition and decision making under uncertainty. The exploration of trapezoidal-type inequalities within fuzzy frameworks represents another significant contribution to fuzzy analysis. By deriving an equality using the integration-by-parts formula from fuzzy mathematical analysis, researchers have established a robust foundation for analyzing trapezoidal-type inequalities in fuzzy-valued spaces, with important implications for signal processing and image analysis, where the ability to accurately estimate and bind errors is crucial for



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achieving high-quality results. In the realm of fuzzy optimization and decision making, the formulation of fixed-point theorems for contractive mappings in fuzzy bipolar b-metric spaces provides novel tools for tackling complex equations. These theorems extend the reach of fixed-point theory into the realm of fuzzy mathematics, enabling more efficient and effective solutions to optimization problems. Additionally, the introduction of the intuitionistic fuzzy granular matrix within the context of intuitionistic fuzzy covering-based rough sets offers efficient computational methods for managing noise data in intuitionistic fuzzy environments. This work has important implications for data mining and machine learning, where the ability to handle noisy and uncertain data is essential for building robust and reliable models. The integration of fuzzy time series analysis with neural networks represents a significant step forward in enhancing integer time series model estimations. By leveraging the strengths of both fuzzy logic and neural networks, researchers have been able to improve the precision of spectral function estimates for models such as NSINAR (1), with important applications in finance, forecasting, and other fields where accurate predictions are crucial for making informed decisions. Within fuzzy set theory, the enumeration of  $(\odot, \vee)$ -multiderivations on a finite MV-chain contributes to a deeper understanding of MV-algebra structures. This work has important implications for the development of logical systems and formal languages that can handle uncertainty and ambiguity more effectively. Additionally, extensions of the Sugeno class of fuzzy negations give rise to new sets, which have the potential to expand the expressive power of fuzzy logic and enable more nuanced reasoning processes. In terms of fuzzy number applications, special discrete fuzzy numbers on countable sets are being studied, exploring their representation theorems, metrics, and triangular norm operations for image fusion and subjective evaluation aggregation. This work has important implications for fields such as computer vision and data fusion, where the ability to combine and analyze multiple sources of information is crucial for achieving accurate and reliable results. Furthermore, the definition of non-linear pentagonal intuitionistic fuzzy numbers and the proposal of a defuzzification method employing intuitionistic fuzzy weighted averaging based on levels (IF-WABL) have potential applications in the minimum spanning tree problem and other optimization tasks. In communication systems and decision support, the development of an enhanced fuzzy c-means (FCM) algorithm incorporating particle swarm optimization (PSO) and subtractive clustering represents a significant advancement in modulation identification in low signal-to-noise-ratio (SNR) environments. This work has important implications for wireless communication systems, where the ability to accurately identify and decode signals is crucial for maintaining reliable connections. Additionally, the introduction of a multi-attribute group decision-making method based on entropy weights with q-rung picture uncertain linguistic fuzzy information provides a reliable framework for decision making when weight information is unknown. This work has potential applications in fields such as supply chain management and project planning, where the ability to make informed decisions under uncertainty is essential for achieving successful outcomes. Lastly, in approximation theory, the investigation of best approximation results for fuzzy-valued continuous functions introduces a method to measure the distance between fuzzy- and real-valued continuous functions. The proof of the existence of the best approximation using the Michael selection theorem represents a significant theoretical contribution to fuzzy mathematics. This work has important implications for fields such as numerical analysis and computer-aided design, where the ability to approximate complex functions and systems is crucial for achieving accurate and reliable results.

## 2. Presentation of the Research Papers

Signal modulation recognition commonly relies on clustering algorithms. The fuzzy c-means (FCM) algorithm, which is widely used for such purposes, frequently converges to local optima, posing a challenge particularly in environments with low signal-to-noise ratios (SNRs). An enhanced FCM algorithm, incorporating particle swarm optimization (PSO), has been proposed to improve the accuracy of recognizing M-ary quadrature amplitude modulation (MQAM) signal orders in Contribution 1. This approach involves a two-phase clustering process. In the first phase, a subtractive clustering algorithm, tailored to SNR, utilizes the received signal's constellation diagram to determine the initial number of clustering centers, which are then refined by the PSO-FCM algorithm for greater precision. Accurate signal classification and identification are achieved by evaluating the relative sizes of the radii around the cluster centers within the MQAM constellation diagram and determining the modulation order. Evaluation results indicate that the SNR-based subtractive clustering-assisted PSO-FCM algorithm outperforms traditional FCM in terms of clustering effectiveness, notably enhancing modulation recognition rates in low-SNR conditions when tested against a variety of QAM signals, ranging from 4QAM to 64QAM.

In Contribution 2, a comprehensive study attempts to approximate a fixed fuzzy-valued continuous function to a specific subset of fuzzy-valued continuous functions, primarily focusing on identifying the optimal approximation within this particular context. Additionally, the authors introduce an innovative method specifically designed to quantify the distance between a fuzzy- and real-valued continuous function, providing a precise means to measure the discrepancy between the two types. Furthermore, the paper rigorously proves the existence of the best approximation of a fuzzy-valued continuous function within all real-valued continuous functions, utilizing the well-established Michael selection theorem, renowned in mathematical analysis, to establish a solid theoretical foundation for the approximation process.

In Contribution 3, the authors investigate new arithmetic operations for non-normal fuzzy sets, utilizing the extension principle and taking into account a general aggregation function. Typically, the aggregation functions used in such contexts are the minimum function or t-norms. However, this paper adopts a more general aggregation function to establish arithmetic operations for non-normal fuzzy sets. In practical applications, the arithmetic operations of fuzzy sets are often translated into corresponding operations on their  $\alpha$ -level sets. When the aggregation function is specifically the minimum function, this translation becomes straightforward. Given the use of a general aggregation function in this paper, the concept of compatibility with  $\alpha$ -level sets is introduced and defined, encompassing the traditional case where minimum functions are employed as a special instance.

In Contribution 4, the authors undertake a study of the concept of interval-valued fuzzy sets within the framework of the family  $SS(X, E)$ , which comprises all soft sets defined over a set  $X$  with a parameter set  $E$ . They delve into examining the fundamental properties of these interval-valued fuzzy sets. Subsequently, the researchers introduce the notion of an interval-valued fuzzy topology (or cotopology)  $\tau$  on  $SS(X, E)$ . Through their analysis, they derive an important finding: each interval-valued fuzzy topology constitutes a descending family of soft topologies. Furthermore, the paper explores various topological structures related to this concept. Specifically, it examines the interval-valued fuzzy neighborhood system of a soft point, as well as the base and sub-base of  $\tau$ . The authors meticulously investigate the relationships that exist among these structures. Additionally, the paper presents several key concepts, including direct sum and open and continuous mapping, considering the interconnections between them. To illustrate and support the theoretical results presented, several examples are provided throughout the paper.

Contribution 5 covers an investigation into the s-embedding of the Lie superalgebra  $\vec{\mathfrak{sl}}(1|1)$ , representing smooth vector fields on a (1,1)-dimensional super-circle. Its primary goal is to precisely define s-embedding, dissecting the Lie superalgebra into the superalgebra of super-pseudodifferential operators ( $S\psi D \odot$ ) on the super-circle  $S^1|1$ . Additionally, it introduces and rigorously defines the central charge within the framework of  $\vec{\mathfrak{sl}}(1|1)$ , utilizing the canonical central extension of  $S\psi D \odot$ . The study further explores fuzzy Lie algebras, aiming to elucidate connections between these seemingly distinct mathematical constructs. It covers various aspects such as non-commutative structures, representation theory, central extensions, and central charges, bridging the gap between Lie superalgebras and fuzzy Lie algebras. In summary, this pioneering work makes two key contributions: firstly, it provides a meticulous definition of the s-embedding of the Lie superalgebra  $\vec{\mathfrak{sl}}(1|1)$ , enhancing fundamental understanding of the topic. Secondly, it examines fuzzy Lie algebras, exploring their associations with conventional Lie superalgebras, and offers a novel deformed representation of the central charge based on these findings.

In Contribution 6, the concept of  $(\odot, V)$ -multiderivations on an MV-algebra  $A$  is introduced, exploring the relations between the former and  $(\odot, V)$ -derivations. The set  $MD(A)$ , comprising all  $(\odot, V)$ -multiderivations on  $A$ , can be endowed with a preorder. Furthermore, under a certain equivalence relation  $\sim$ , the quotient set  $(MD(A)/\sim, \leq)$  can be structured as a partially ordered set. Notably, for any finite MV-chain  $Ln$ , the quotient set  $(MD(Ln)/\sim, \leq)$  evolves into a complete lattice. Lastly, a counting principle is established to enumerate the elements of  $MD(Ln)$ .

The intuitionistic fuzzy (IF)  $\beta$ -minimal description operators within the framework of IF covering-based rough set theory are adept at managing noisy data, effectively identifying pertinent data within IF environments. In scenarios characterized by IF  $\beta$ -covering approximation spaces with high cardinality, employing IF set representations for calculations becomes cumbersome and intricate. Consequently, there is a pressing need for an efficient method to derive these descriptions. Contribution 7 introduces the concept of IF  $\beta$ -maximal description, building upon the foundation of IF  $\beta$ -minimal description, alongside the IF granular matrix and the notion of IF reduction. The authors further propose matrix-based computational methods for various aspects of IF covering-based rough sets, encompassing IF  $\beta$ -minimal and -maximal descriptions and IF reductions. Firstly, the IF granular matrix, a tool for computing IF  $\beta$ -minimal descriptions, is described, followed by IF  $\beta$ -maximal description and related matrix representations. Subsequently, two types of reductions for IF  $\beta$ -covering approximation spaces are presented, leveraging IF and fuzzy  $\beta$ -minimal descriptions, along with their corresponding matrix representations. Finally, experiments comparing the newly proposed matrix-based calculation methods with their set-based counterparts are conducted.

In multiple-attribute decision-making (MADM) problems, ranking alternatives is crucial for achieving optimal decision outcomes. Intuitionistic fuzzy numbers (IFNs) are highly effective in representing uncertainty and vagueness within these problems. However, current ranking methods for IFNs overlook the probabilistic dominance relationship between alternatives, potentially resulting in inconsistent and unreliable rankings. To address this issue, Contribution 8 introduces a novel ranking method for IFNs that integrates the probabilistic dominance relationship with fuzzy algebras, designed to handle incomplete and uncertain information effectively, ensuring consistent and accurate rankings. By incorporating these elements, the approach offers a significant advancement in the ranking of alternatives in MADM problems.

In recent years, the proliferation of digital objects as information sources has fueled rapid advancements in artificial intelligence (AI) and machine learning (ML). Effective utilization of AI and ML techniques necessitates the conversion of ambient information

into reliable data within the framework of information processing theory. It is imperative to model and transform information into data without discarding its inherent uncertainty. To this end, mathematical frameworks such as fuzzy theory and intuitionistic fuzzy theory are employed. The latter uses membership and non-membership functions to describe intuitionistic fuzzy sets and intuitionistic fuzzy numbers (IFNs), mathematically representing the characteristics of IFNs. Given the diverse uncertainties introduced by various information sources, there is a constant need for a more general and inclusive definition of IFNs in AI technologies. In Contribution 9, the authors propose a general and inclusive mathematical definition for IFNs, termed the non-linear pentagonal intuitionistic fuzzy number (NLPIFN), which accommodates a variety of uncertainties. As AI implementations are computer-based, IFNs must be transformed into crisp numbers for their practical application. The techniques used for this transformation are known as defuzzification methods. A shortcut formula for the defuzzification of NLPIFNs using the intuitionistic fuzzy weighted averaging based on levels (IF-WABL) method is introduced. Furthermore, the authors demonstrate the application of their findings in the minimum spanning tree problem by assigning weights as NLPIFNs to more precisely determine uncertainty in the process. This approach underscores the practical significance and versatility of their proposed NLPIFN definition and defuzzification method.

Contribution 10 introduces a novel concept termed *q*-rung picture uncertain linguistic fuzzy sets (*q*-RPULSs), offering a robust and comprehensive framework for depicting intricate and uncertain decision-making information. These sets facilitate the integration of quantitative and qualitative assessment inputs from decision makers. Addressing the challenge of multi-attribute group decision making under *q*-RPULs with unknown attribute weights, the authors propose an entropy-based fuzzy set approach tailored for *q*-rung picture uncertainty language, taking into account the interdependencies among attributes. Furthermore, the paper delves into the *q*-RPULMSM operator, which plays a pivotal role in aggregating *q*-RPULSs and achieving consensus in decision-making contexts, and its associated properties. To validate the efficacy, rationality, and superiority of the proposed methodology, a real-world case study on commodity selection is presented, underscoring the practical benefits and applicability of *q*-RPULSs in decision-making processes.

Certain drawbacks in the arithmetic and logic operations of general discrete fuzzy numbers hinder their widespread application. Specifically, the sum of general discrete fuzzy numbers, as defined by Zadeh's extension principle, may not itself qualify as a discrete fuzzy number. To address these limitations, Contribution 11 focuses on special discrete fuzzy numbers defined on countable sets. Given that the representation theorem of fuzzy numbers serves as a fundamental tool in fuzzy analysis, the Contribution first examines two types of representation theorems for special discrete fuzzy numbers on countable sets. Subsequently, metrics for these special discrete fuzzy numbers are defined, and their relationship to the uniform Hausdorff metric (also known as the supremum metric) of general fuzzy numbers is discussed. Furthermore, triangular norm and conorm operations (abbreviated as *t*-norm and *t*-conorm, respectively) are introduced for special discrete fuzzy numbers on countable sets, proving the properties of these operations. It is demonstrated that these operations satisfy the essential conditions for closure, and illustrative examples are provided. Finally, the Contribution proposes applications of special discrete fuzzy numbers on countable sets in the image fusion and aggregation of subjective evaluations.

In Contribution 12, two novel classes of fuzzy negations are introduced, extending the well-established Sugeno class and serving as the foundation for the first two construction methods discussed. The first method generates rational fuzzy negations through the utilization of a second-degree polynomial with two parameters. This approach necessitates an investigation into the specific conditions these parameters must meet to qualify as a

fuzzy negation. The second method replaces the parameter  $\delta$  of the Sugeno class with an increasing function, thereby producing fuzzy negations which are not limited to rational forms. Instead, by employing an arbitrary increasing function which meets certain criteria, a wider range of fuzzy negations can be generated. Furthermore, a comparison is made between the equilibrium points of the fuzzy negations produced by the first method and those of the Sugeno class. Leveraging the concept of equilibrium points, a novel method for generating strong fuzzy negations is presented. This method employs two decreasing functions that satisfy specific conditions. Additionally, the convexity of the newly introduced fuzzy negations is explored, and conditions are provided for the coefficients of the fuzzy negations generated by the first method to ensure convexity. Examples of the new fuzzy negations are presented, which are then utilized to generate new non-symmetric fuzzy implications using established production methods. Convex fuzzy negations are employed as decreasing functions to construct an Archimedean copula. Finally, the quadratic form of the copula is investigated, and the conditions that the coefficients of the first method and the increasing function of the second method must meet to generate new copulas of this form are discussed.

Contribution 13 delves into the application of fuzzy time series (FTSs) based on neural network models for estimating various spectral functions within integer time series models, with a particular emphasis on the skew integer autoregressive model of order one (NSINAR (1)). To facilitate this estimation, a dataset comprising 1000 realizations of the NSINAR (1) model is created. These input values are subsequently fuzzified using fuzzy logic techniques. The study leverages the powerful capability of artificial neural networks in identifying fuzzy relationships to enhance prediction accuracy by generating output values. A meticulous analysis is conducted to assess the improvement in the smoothing of spectral function estimators for the NSINAR (1) model when both input and output values are utilized. The effectiveness of the output value estimates is rigorously evaluated by comparing them to the input value estimates using a mean-squared error (MSE) analysis, providing insights into the superior performance of the former.

In Contribution 14, novel concepts are introduced within the framework of fuzzy bipolar b-metric spaces, particularly focusing on key mappings such as  $\psi_\alpha$ -contractive and  $F_\eta$ -contractive mappings, which play a crucial role in quantifying distances between dissimilar elements. This research establishes fixed-point theorems for these mappings, demonstrating the existence of invariant points under specific conditions. To further strengthen the credibility and applicability of the findings, illustrative examples are provided that support these theorems and contribute to expanding existing knowledge in this field. Moreover, the authors explore practical applications of these theoretical advancements, particularly in solving integral and fractional differential equations, demonstrating the robustness and utility of the proposed concepts. Symmetry, both in its traditional sense and within the fuzzy context, is a fundamental aspect of the study of fuzzy bipolar b-metric spaces. The introduced contractive mappings and fixed-point theorems not only expand the theoretical framework but also offer powerful tools for addressing practical problems in which symmetry is significant. These contributions enhance the understanding and applicability of fuzzy bipolar b-metric spaces in various domains.

Rule-based reasoning, which incorporates various forms of uncertain information, has been recognized in numerous real-world applications. Any reasoning method must be capable of coherently deriving inference results by combining “given if–then” rules with assertions based on input information. The symmetric quintuple-implication principle is formulated by incorporating symmetry into all five implication operators involved. Specifically, the first, third, and fifth implication operators exhibit symmetric properties, meaning they are treated as the same operator type, while the second and fourth operators also

satisfy symmetry, implying that they share the same type. Consequently, reasoning methods based on this principle offer significant advantages in terms of logical foundation and reductivity. In Contribution 15, reasoning methods for combining fuzzy and intuitionistic fuzzy information are derived and studied using the symmetric quintuple-implication principle, relying on the notion that the input and “given if–then” rule can only be combined for calculation when their information representations are consistent. An “if–then” rule with inconsistent representations in two different forms should be regarded as the combination of two distinct consistent “if–then” rules, each with its unique representation. The authors further elaborate on these methods by employing possibility and necessity operators along with the quintuple-implication principle, considering whether the representations of the rule antecedent and rule consequent are consistent or not. The reductivity of all proposed reasoning methods is also analyzed in detail. The main contribution is the development of a novel mixed-information reasoning framework incorporating the quintuple-implication principle. The proposed methods have been applied to pattern recognition, with experimental results demonstrating their superiority over corresponding methods based on the triple I principle.

Contribution 16 covers a thorough investigation into trapezoidal-type inequalities within the context of fuzzy settings. The theory of fuzzy analysis is examined in depth, with a particular focus on the integration-by-parts formula from fuzzy mathematics to establish a key equality. By combining this proven equality with the properties of a metric defined on the set of fuzzy-valued space, along with Hölder’s inequality, a trapezoidal-type inequality for functions with values in the fuzzy-valued space is proven. The results offer generalizations of previous findings in the field of mathematical inequalities. To validate the theoretical results, an example is designed, involving a function with values in the fuzzy-valued space. Numerical validation is carried out using the latest version (14.1) of Mathematica. Additionally, the  $p$ -levels of the defined fuzzy-valued mapping are graphically illustrated for various values of  $p$  within the interval  $[0, 1]$ . This Contribution mainly focuses on its advancement of the theory of fuzzy analysis and mathematical inequalities, as well as a practical demonstration of the results through numerical and graphical validation.

### 3. Conclusions

In summary, the Topic Issue titled “Fuzzy Numbers, Fuzzy Differences, Fuzzy Differentials: Theory and Applications” propels the theory of fuzzy mathematics forward and broadens its applications across a diverse array of domains. By delving into the theoretical foundations and practical implications of fuzzy numbers, fuzzy differences, and fuzzy differentials, researchers have paved new paths for innovation and discovery in various fields, spanning engineering, economics, medicine, and social sciences. This reprint stands as a testament to the profound power and versatility of fuzzy mathematics. It is our earnest hope that it will ignite the curiosity and passion of future generations of researchers, encouraging them to continue exploring and pushing the boundaries of this exhilarating and dynamic field.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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