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Neutrosophic Logic Theory and Applications

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Abstract: *Neutrosophic logic is a very powerful and effective concept. It has different application areas due to its ability to capture the stochasticity in many complex real-life use cases. This paper presents the main types of neutrosophic sets. It also surveys and analyzes its most common applications.*

Keywords: Neutrosophic Set; Single-Valued Neutrosophic Set; Multi-Valued Neutrosophic Set; Fuzzy Set

1. Introduction

The term Neutrosophic means neutral thought knowledge. It is a combination of two terms (Neuter) and (Sophia), wherein Latin Neuter means "Neutral" and Sophia means "Wisdom". In general, Neutrosophic set and logic are generalizations of classical fuzzy and intuitionistic fuzzy [40], while neutrosophic Probability and Statistics are generalizations of classical and imprecise probability and statistics [3]. Neutrosophic Logic (NL) is a framework for unifying many existing logics, such as fuzzy logic, paraconsistent logic, intuitionistic logic, etc. [34, 37]. The main idea of NL is to characterize each logical statement in a 3D-Neutrosophic space, where each dimension of that space represents the truth (T), the indeterminacy (I), and the falsehood (F) of the statement respectively under consideration; where T, I, and F are standard or non-standard real subsets from $]0,1[$ with not necessarily any connection between them [2]. Many examples can be represented only by neutrosophic logic and neither by fuzzy nor intuitionistic fuzzy. One of those examples is "Voting" [36]. In general, the neutrosophic set depends on three membership functions (T, I, and F). These functions are independent, and their sum does not add up to 1. Meanwhile, it should add up to 3 [39]. Neutrosophic logic is considered a bigger umbrella of Fuzzy logic. Also, it has many applications; however, it has not been used so far alongside Q-learning. Although, by combining it with Q-learning, more realistically and flexible long-term values for Q are expected to be obtained.

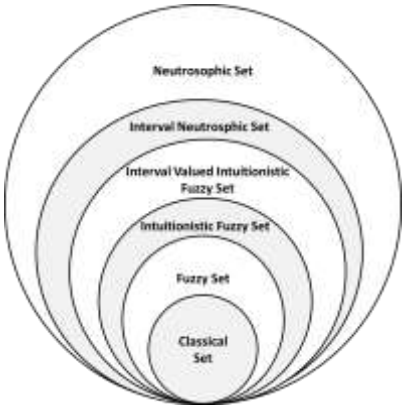

Figure-1: Relationship between neutrosophic set and other sets

Many methods were invented to deal with uncertainty. Starting from Fuzzy logic [109], which represents the "partial Truth" concept as the true value ranges between 0 and 1 according to whether it is entirely false or completely true. Meanwhile, Fuzzy logic had many drawbacks that encouraged the researchers to propose interval-valued sets to allow interval membership values within the same set. Then, an intuitionistic fuzzy set was a generalization for the traditional fuzzy sets. In an intuitionistic fuzzy set, each element has a degree of membership and even non-membershsip [110]. Meanwhile, it had drawbacks that encouraged some researchers to propose a neutrosophic set [111]. Figure-1 demonstrates the relationship between neutrosophic set and other sets, while, Table-1 lists sample advantages and disadvantages of each of these concepts [112].

Table-1: Advantages and Disadvantages of uncertainty algorithms

Algorithm	Advantages	Disadvantages
Fuzzy Sets	- The first algorithm to deal with uncertainty - Ability to solve complex problems - Generates output even if only a few input data are at hand - Flexible algorithm and its rules can be modified - Easy to implement	- It depends on human knowledge and expertise - Its rules have to be regularly visited and updated - Sometimes its accuracy is not entirely reliable when it works on inaccurate inputs - No single and systematic approach for solving a problem might lead to confusion - Assume only crisp values for representing True/False
Intuitionistic Fuzzy Sets	- Assume a value for not only the belongingness of a number to a set (i.e., membership) but also a non-membership value	- It ignores the indeterminacy component - Sometimes might generate confusing results [113] - It contradicts the intuitionistic logic in some cases [113]

Interval-Valued Intuitionistic Fuzzy Sets	- Introduce interval for representing True and False values	- It ignores the indeterminacy component
Neutrosophic Sets	- It is a generalization of other fuzzy concepts - Flexible - Takes into consideration the indeterminacy component that captures any vagueness and uncertainty - Solves many complex problems that have incomplete and imprecise information - Generates reliable results in many multi-criteria decision-making problems - Ability to deal with information that comes from different data sources	- Assume single value for each component, and his might not lead to completely certain results
Interval-Valued Neutrosophic Sets	- Perfectly capture the uncertain and inconsistent information that exist in real-world - Assume an interval for each neutrosophic component (T, I, F)	- There are only a few research in this area. Hence it still needs proof of its robustness

Due to the significance of CLV and the effectiveness of Q-learning, fuzzy logic, and neutrosophic logic algorithms, many researchers compete in developing models to utilize these algorithms separately in the marketing context. Meanwhile, each of their implementations has a specific drawback. For instance, neutrosophic logic is not applied yet in a real-life marketing context to maximize CLV [11]. Also, fuzzy logic is not utilized to maximize CLV, but for many other purposes, including clustering the customer base according to their profitability level or measuring it with RFM values instead of CLV [28, 6]. Finally, Q-learning has been combined with different machine learning and deep learning algorithms for that purpose. For instance, some researchers utilized deep learning to predict Q's optimal value that maximized the long-term profitability of the customers within the firm [31, 19]. Meanwhile, these algorithms overestimated Q's action values, hence generating unrealistic actions [14].

Single-Valued Neutrosophic Set

Two types of membership functions for the NQL model are illustrated (Trapezoidal and Triangular). The goal is to utilize the neutrosophic model to learn the optimal Q value that maximizes long-term rewards. The stochastic nature of the problem is captured by assuming three values for Q (i.e., T, I,

and F) instead of a single value, each of which follows the Trapezoidal or Triangular membership function illustrated in the upcoming sub-sections.

2.2.1. Trapezoidal Neutrosophic Q-Learning

In light of neutrosophic logic's definition mentioned in Section-1, which depends upon 3 core values (T, I, and F), this section illustrates how to calculate these values and how to calculate the model performance measurements [17].

Let H be a universal set. Hence, a single-valued neutrosophic set B in H is calculated in Eq. (1)

$$B = \{h, < T_B(h), I_B(h), F_B(h) > | h \in H\}, \quad (1)$$

Where truth membership function (T_B (h)), indeterminacy membership function (I_B (h)), and falsity membership function (F_B (h)) satisfy the following conditions:

$$T_S(z) = \begin{cases} t_S\left(\frac{(z-k)}{(l-k)}\right), & k \le z \le l \\ t_S, & l \le z \le m \\ t_S\left(\frac{(n-z)}{n-m}\right), & m \le z \le n \\ 0, & otherwise \end{cases} \quad (2)$$

$$I_S(z) = \begin{cases} \frac{l-z+(z-k')i_S}{(l-k')}, & k' \le z \le l \\ i_S, & l \le z \le m \\ \frac{z-m+(n'-z)i_S}{(n'-m)}, & m < z \le n' \\ 1, & otherwise \end{cases} \quad (3)$$

$$F_S(z) = \begin{cases} \frac{l-z+(z-k'')f_S}{(l-k'')}, & k'' \le z \le l \\ f_S, & l \le z \le m \\ \frac{z-m+(n'-z)f_S}{(n''-m)}, & m < z \le n'' \\ 1, & otherwise \end{cases} \quad (4)$$

Where S is a trapezoidal neutrosophic number, $\boldsymbol{k, l, m, n} \in \boldsymbol{R}$. Then $\boldsymbol{S} = ([\boldsymbol{k, l, m, n}]; \boldsymbol{t_s, i_s, f_s})$ is called trapezoidal neutrosophic number (TrNN); and it has one of three possibilities (Positive TrNN, negative TrNN, or normalized TrNN). $\boldsymbol{m}$ is called positive TrNN, if $\boldsymbol{0 \le k \le m \le n}$. While, if $\boldsymbol{k \le l \le m \le n \le 0}$, then $\boldsymbol{S}$ is called negative TrNN. If $\boldsymbol{0 \le k \le l \le m \le n \le 1}$ and $\boldsymbol{T_s, I_s, F_s} \in [\boldsymbol{0, 1}]$, then $\boldsymbol{X}$ is called normalized TrNN. The membership function is demonstrated in Fig.4.

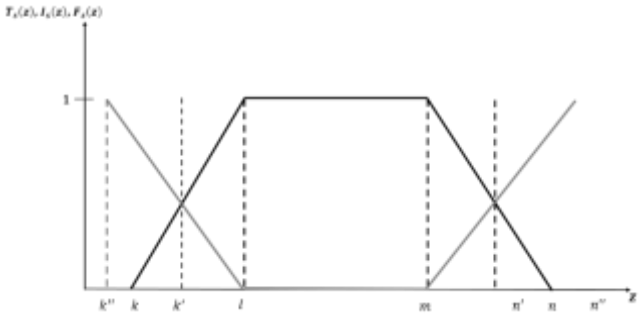

Figure 4 TrNN membership function for truth, indeterminacy, and falsity functions

Multi-Valued Neutrosophic Set

Assume X is a space of points (each of which is x), then multi-valued neutrosophic set $A\ in\ X$ has membership functions $(\widetilde{T_A}(x), \widetilde{I_A}(x), \widetilde{F_A}(x))$ defined on multiple-valued as follows

$$A = \left\{\left(x, \widetilde{T_A}(x), \widetilde{I_A}(x), \widetilde{F_A}(x)\right)\middle|\ x\epsilon X\right\}$$

Where each of the membership functions $T, I, and\ F\ \epsilon\ [0,1]$, and is defined as a set of finite discrete values that satisfies the following conditions $(\ 0 \leq \gamma, \eta, \xi \leq 1, 0 \leq\ \gamma^+ + \eta^+ + \xi^+ \leq 3\ )$, where $\gamma \epsilon \widetilde{T_A}(x), \eta \epsilon \widetilde{I_A}(x), \xi \epsilon \widetilde{F_A}(x), \gamma^+ = sup\widetilde{T_A}(x), \eta^+ =\ sup\widetilde{I_A}(x), \xi^+ =\ sup\widetilde{F_A}(x)$ [74]. Multi-valued neutrosophic can be converted to single-valued neutrosophic set iff each of $\widetilde{T_A}(x), \widetilde{I_A}(x), \widetilde{F_A}(x)$ has only one value.

Classification of Neutrosophic applications

Neutrosophic logic plays a significant role and has many application areas [37]. This section presents a few of these applications. It starts with listing a set of theoretical contributions, then mentioning the role of neutrosophy in some practical application areas, including medicine, marketing, image processing, strategic planning, supply chain, and many other areas.

Theoretical Contributions of Neutrosophic Logic

Neutrosophic set is a powerful research area that proved its effectiveness and robustness in many application domains. Meanwhile, most of the contributions were theoretical and confirmed only by mathematical examples or few data-sets and were not generalized using other applications. In [50] they conducted a survey and listed the theoretical contributions of neutrosophic sets. They also proposed a method for designing the single-valued neutrosophic set. Their proposed method depended on creating neutrosophic membership functions through experimental data. Yet, their contribution needed to be applied to a real-life dataset. While in [52] they listed its applicability in medical applications. The researchers in [1] investigated different concepts, including (weighted average operator and weighted geometric operator) on neutrosophic cubic sets. This is for the sake of aggregating the neutrosophic cubic information. Their developed algorithm helped in multiple criteria decision-making. Their proposed algorithm was applied in a mathematical example to prove its usefulness and applicability. Yet, it was not implemented in a real-life business situation, which was on top of their limitations. Another theoretical contribution was done in [8]. They criticized the non-standard Neurtrsophic logic for the sake of its better understanding, although it was never used in practical applications. Their analysis we structured and well-formulated, yet it was not applied in cf situations or even in case studies to prove its robustness. An instance of a neutrosophic set called "interval neutrosophic set" was introduced in [10]. Meanwhile, their contribution was not applied to a real-life dataset. In [11] two special models of traditional neutrosophic logic, were introduced: Single-valued linguistic complex neutrosophic set, and Interval linguistic complex neutrosophic set. These models proved their applicability when they were applied in the University of Economics and Business for lecturer selection. As proposed by the researchers, this work might be extended by using

different membership functions, including trapezoidal and triangular. In [18] the researcher tried to investigate some properties of neutrosophic sets and subsets.

Blending neutrosophic logic with Q learning attracted many researchers. In [22], they studied the relationship between those two algorithms. They applied their proposed algorithm in online education during Covid-19 pandemic. Their proposed model's goal was to select the best Information Communication Technology (ICT) tool as an online learning platform. Their model was illustrated through a numerical example, but it still needed to be applied in reality to prove its robustness and generalization. Interval neutrosophic sub-algebra and its properties were introduced in [26]. In [33] they focused on labor issues and tried to solve the untimely dismissal in Ecuador problem. To solve this, they integrated the IADOV method with neutrosophic logic. Their model obtained trusted results on their case study but still needed to be generalized to other datasets. In [36] they tried to test the effectiveness of neutrosophic logic in image processing. They expected to have good results when applying neutrosophic logic in imperfectly defined images. During their work, they studied different types of distance measures between neutrosophic sets. Although their work was theoretical, they expected to have outstanding results when applying their proposed model in image processing on real-life use cases. In [39] they tried to list the main concepts in single-valued neutrosophic sets. Meanwhile, they did not mention practical examples or real-life use cases to prove its practicality. While in [40], they studied the hybridization between single-values neutrosophic sets and machine learning.

In [42] they introduced a new concept in neutrosophic sub-algebra (i.e. MBJ neutrosophic sub-algebra) and listed its applications. While in [45] they introduced neutrosophic generalized topological spaces. They discussed closed and open mappings, as well as their related attributes. Meanwhile, they did not mention the practical application of these concepts. In [49] they introduced neutrosophic social structures based on the three neutrosophic components (T, I, and F). In [53] they proposed a python based open-source implementation for basic concepts of neutrosophic logic. It was an awesome contribution that might be an atom for many neutrosophic logic implementations. In [59] they focused on neutrosophic sets and neutrosophic soft-sets. They mainly studied new algebraic operations and fundamental properties of these neutrosophic sets. Their analysis was well presented and well documented, but it still needed to be applied in real-life application areas to make it more concrete and reliable. In [60] they made an extended theoretical overview over the neutrosophic set and its instances. Meanwhile, it would be great if they mentioned the applicability of these models in real-life.

On top of the applicable and powerful proposed model was that one in [62]. They combined neutrosophic logic with neural networks. Their built neural network model consisted of single input and one output. Their hidden layer contained two activation functions (i.e. Chebyshev neutrosophic orthogonal polynomial function and neutrosophic sigmoid activation function). Their model's main drawback was that it was not applied to a real-life dataset but only on illustrative examples. It could also be extended by implementing it using multiple inputs and/or multiple outputs. A contribution in empowering the multi-criteria decision-making by neutrosophic was mentioned in [65]. They utilized a bipolar neutrosophic set with both positive and negative membership functions. They illustrated their model using an illustrative example but not a real-life application. Hence, it would be recommended to apply it in the real-life use case to prove its reliability. While in [67] they proposed fuzzy equivalence concept on the standard concepts of neutrosophic sets and rough neutrosophic set

for cluster analysis. Their model was illustrated through numerical examples. Applying it to real-life clustering problems was highly recommended. In [71] they had many contributions in single-valued neutrosophic sets. On top of them was that they combined single-valued neutrosophic sets with rough sets. They presented their proposed models using illustrative examples but did not mention any practical applications. This is on top of the way forward steps of their work. Also, multi-valued neutrosophic sets might be applied instead of single-valued ones. While [72] focused on the inclusion relations of neutrosophic sets. They also built a ranking method using a neutrosophic set that proved its effectiveness on set of practical examples.sMeanwhile, their model was recommended to be applied in real-life application areas to confirm this effectiveness and prove its reliability.

In [75] they proposed a model that combined data mining concepts to single-valued neutrosophic logic. They focused on machine learning and similarity measures concepts from the data mining umbrella. Other researchers could think of applying this proposed model in real-life datasets. While in [76] they combined single-valued neutrosophic (SVN) logic to a weighted correlation coefficient (CC) measure. They mentioned practical examples for their decision-making proposed method. Meanwhile, it was recommended to apply it in engineering and scientific applications. They also suggested generalizing it to other application areas. The work in [81] was also applied to combine neutrosophic set and correlation concept. But their main focus was interval neutrosophic set instead of single neutrosophic set. They illustrated their proposed model using an example. Yet, would be better to apply it in real-life use cases due to its effectiveness in empowering the decision-making process. Also in [77] they didn't apply their proposed model in real-life applications. Their model that combined SVN to minimum spanning tree was illustrated using a set of examples. They implemented it in two phases (i.e., defined the distances between SVNs, and then constructed the minimum spanning tree as a clustering algorithm for SVN. Their proposed model could be applied in many application areas. Hence it still needed generalization. The same researchers contributed in [82] by combing the correlation concept to a single neutrosophic set. Their proposed multiple attribute decision-making process ranked the alternatives in an imprecise environment. It helped to select the best option out of all options at hand. This was proved through an illustrative example. Meanwhile, it still needed to be applied in reality to prove its reliability.

Also in [78] the researchers were interested in combing SVN and even interval neutrosophic set to score function and accuracy function. Meanwhile, they did not apply their proposed models in real-life cases. A bit different than this was the work in [79]. They focused mainly on interval neutrosophic numbers. They improved the entropy formula of interval neutrosophic number. They tried to mimic the attitude of the decision-maker towards risks and under indeterminacy. They did not apply their proposed model in reality but illustrated it throughput through mathematical examples. Meanwhile, it was recommended to apply their proposed model in real-life cases to prove its robustness. In [89], they listed a set of applications related to multi-attribute decision-making and applying it under the neutrosophic environment. Highlighting that the top applications in this area were related to medical diagnosis and pattern recognition. In [90] their contribution was a bit different. They proposed a method that utilized interval –valued neutrosophic set properties to generate formal concepts of interval-valued neutrosophic concepts and even refined some parameters (i.e., α,β,γ) cuts. They illustrated their proposals through mathematical examples not real-life applications.

Neutrosophic Logic in Data Mining

In [93] they utilized a multi-refined neutrosophic set in sentiment analysis. Their model consisted of two positive (T), two negative (F), and three indeterminate (I) membership functions. Their model showed outperforming results when analyzing tweets on ten different topics related to the Indian scenario and other international scenarios. While in [94] they proposed a neutrosophic association rules algorithm. sTheir algorithm-generated association rules through an item's neutrosophic attributes (i.e., T, I, F). Their model was compared to fuzzy to prove its effectiveness. Yet, it was recommended to be applied to different real-life applications to prove its effectiveness. In [95] they proposed a single-valued neutrosophic set algorithm that measured the factors that impacted students' engagement and their overall attitude in mathematics achievements. They relied upon trends of international mathematics and science study. Although their model showed outperforming results, it still needed to be generalized. In [96] they proposed a neutrosophic based Dixon's test due to its significance and applicability. Their model was illustrated through a mathematical example. In [105] they proposed a sentiment analysis model for large documents. Their model consisted of binary and ternary classifiers and combined neutrosophic logic to particle swarm optimization (PSO) algorithm. Their proposed model was tested on a real-life dataset, and the ternary classifier gave outperforming results. Meanwhile, other researchers might think of generalize it to other data sets and applications for both short and large text. While in [106] they developed a clustering model using k-means but reduced the number of attributes using rough neutrosophic sets. Their model was applied to a real-life dataset but still needed to be generalized. A bit different than this was the contribution in [108]. They proposed a domain generation algorithm using a neutrosophic set. They classified their data to benign, malicious, and indeterminacy domain names. Their model showed outperforming results when being applied to a real-life dataset. Yet, it might be generalized to other datasets.

Neutrosophic in Blockchain

In [97] they proposed utilized single-valued and interval-valued neutrosophic graphs in Blockchain and bitcoin application. They also listed the advantages and limitations of Blockchain graphs. While in [98] their main focus was to select the most appropriate Blockchain model for providing a secure and trustworthy healthcare Blockchain solution. Their proposed model was well-presented yet had a set of limitations, including its generalization.

Neutrosophic Logic in marketing

Neutrosophic PROMETHEE method in one-to-one marketing. They proved the necessity of analyzing different aspects of potential buyers, including their emotional and physiological states. One of the main obstacles of their model was the collection, and governance of the customers' emotions related data, especially under the existence of the data privacy rules exist in many companies. Consequently, collecting the proper data needed time and cost [3]. A single-valued neutrosophic set was combined with multi-criteria group decision-making in [69]. They used their hybrid proposed model in market segment selection and evaluation. Their model was effectively

applied in a real-life dataset related to smart bike-sharing firm. As future work related to their contribution might be to employ weighting methods to provide the market segments' ranking. It could seven be applied in other applications. In [87] the researchers proposed a method that combined neutrosophic logic to Q learning. They compared its results to another developed model that combined fuzzy logic to Q learning. Both models were applied in two benchmark datasets. Yet, it was encouraged to apply them in real-life business cases to prove their reliability. Other researchers might also think of combining their model with neural networks to optimize the Q values. The researchers in [91] proposed a clustering algorithm based on single-valued neutrosophic and similarity measures. Their proposed model proved its effectiveness when it was applied in a car market. Meanwhile, it was recommended to be generalized to other applications.

Neutrosophic in Medicine

The researchers in [57] survived the contributions of neutrosophic logic in image segmentation. They focused on medical images. They recommended blinding the contributions they mentioned with deep learning for more effective, robust, and reliable outcomes. A neutrosophic login-based model was applied in the medical domain to act as a medical decision eid for the physicians. Their model outperformed the other fuzzy-based models. Their work's main limitation is its dependency on a huge amount of data for obtaining accurate and reliable outputs [2]. While in [4] they proposed a recommender system based on neutrosophic logic that contributed to medicine through predicting the disease. They could design the formulation of algebraic formulas using their proposed algebraic similarity measure. Their proposed algorithm proved its robustness when being applied to different medical datasets, including heart, Breast Cancer, Diabetes, and more from the University of California Irvin (UCI) benchmark datasets repository [6]. The limitation of their work was that it was generalized and even not applied to other real-life datasets. The researchers in [7] developed an automatic choroidal segmentation method from Enhanced Depth Imaging Optical Coherence Tomography (EDI-OCT) images. This was done in neutrosophic space. Their model started by transforming the images to the neutrosophic space, after that, calculating the weights between the nodes. Then applied Dijkstra algorithm to detect the Retinal Pigment Epithelium layer. Finally, defining the false set using a gamma homomorphic filter. Their model was applied and tested on real-life datasets and proved its robustness by obtaining relatively small and acceptable error values. Their model was well defined, and well-presented especially its experimental results.

The researchers in [9] utilized offsets and off uniforms Neutrosophic sets in image processing. Mainly for a segmentation and edge detection of an image. They did not apply their model in real-life cases, but in demonstrated examples. This is on top of the limitations of their work. While, researchers in [16] developed a multi-criteria decision-making technique using neutrosophic algorithm to help physicians in diagnosing those who suffer from heart failure. Their model was already applied to real-life case studies and proved its effectiveness when was compared to other techniques. Meanwhile, their technique might be applied to larger dataset to confirm its robustness.

In [17], they conducted a study that combined Neutrosophic logic to Convolutional Neural Networks. Their main goal was to classify a brain tumor as either benign or malignant. Their model could prove its robustness and reliability with was compared to other classifiers. Although their model was well written and presented, it still needed to be applied to a real-life dataset. While the researchers in

[20] proposed cosine similarity measures that help diagnose bipolar disorder using neutrosophic logic. They verified their proposal on numerical examples. Their technique could prove its robustness; meanwhile, it might be applied to other case studies to prove its robustness and generalizability. The researchers in [32] conducted another contribution in cosine similarity. They build improved weighted single-valued neutrosophic cosine similarity measures. Their main goal was to help in the medical diagnosis. They applied their proposed model in two real case studies. Meanwhile, it still needed to be applied in other fields and other case studies to prove its reliability. The usage of single-valued neutrosophic sets has been presented in [21]. They projected their illustration in medicine. They utilized their model to help in the disease diagnosing based on the preliminary symptoms of each patient. This is done by formulating new distance measures for single-valued neutrosophic sets. Their model has been applied in medical examples, yet it still needed to be applied to many real-life cases to prove its reliability. In comparison, the researchers in [29] illustrated the divergence measure in neutrosophic sets. They formulated this relationship and mentioned its properties. Finally, they applied their proposed model in a medical problem. Yet, their model still needed to be applied in other case studies. In [34] they introduced proposed types of distance measures for single-valued neutrosophic sets. Their proposed models were illustrated with pattern recognition, and medical case studies. Yet, these models still needed to be applied in other use cases to prove their generalization.

The contribution of neutrosophic login in the early diagnosing of COVID-19 based on the patients' medical images was discussed in [38]. Their model combined neutrosophic logic with deep learning. They applied their model to a real-life dataset. In conclusion, they encouraged using deep learning with neutrosophic logic to obtain reliable results to diagnose and overcome COVID-19. Hence, their model still needs to be applied in many datasets to increase its reliability. In [46] they introduced a refined technique of single-valued neutrosophic cosine similarity measure. They applied their proposed technique in medical diagnosis. Their model still needed to be generalized on other applications and might be extended by applying interval neutrosophic instead of single neutrosophic set. One of the most interesting application for neutrosophic logic was that one mentioned in [47]. They utilized neutrosophic statistics in analyzing dental fluorosis. Their analysis was well presented and expected to have a huge impact on improving human's tooth health (especially children). In [68] they constructed a comprehensive framework using a single-valued neutrosophic set to capture both incomplete and/or inconsistent information. They applied their proposed framework in a real-life healthcare case study. Meanwhile, it was encouraged to generalize it in other application areas, especially smart cities. In [104] they proposed a framework that combined interval neutrosophic to a neural network. They compared their interval neutrosophic rough neural network to other algorithms, and it outperformed them. Meanwhile, it still needed to be generalized using other real-life applications.

Neutrosophic in COVID-19

From 2020 until publishing this survey, the whole world is struggling with different generations of Coronavirus (i.e., COVID-19). Many researchers tried to contribute to developing models for dealing with COVID-19 using a different algorithm, and neutrosophic logic was on top of these utilized

algorithms. In [101] they developed a framework that combined COVID-19's disruptive technologies for analyzing this pandemic virus. Their framework had many advantages, including restricting COVID-19's outbreaks and ensuring the healthcare team's safety. The power of their model was applying it in an empirical case study. Meanwhile, it would be great to be generalized on other use cases. In [99] they identified priority tanking of insurance companies related to healthcare services. They mainly built a multi-criteria performance evaluation methodology with the help of experts' opinions. Their main focus was on Turkey. Meanwhile, their model could be generalized to other countries. They mainly focused on intuitionistic fuzzy logic, but it was encouraged to utilize neutrosophic logic instead for more effective results. While in [100] contributed to COVID-19's vaccine. They identified a set of criteria and sub-criteria that helped identify priority groups for COVID-19's vaccine doses distribution. Their proposed priority groups model was well-presented and well-illustrated; meanwhile, it still needed generalization. On the other hand, the researchers in [102] focused on the diagnosis part of COVID-19. They developed a framework for this purpose. Their framework not only focused on COVID-19's early diagnosis but also on its treatment. Their proposed framework combined deep learning with a neutrosophic classifier. It was a well-presented and effective contribution, yet suffered from data availability limitations and a set of weaknesses of big data architectures. While the researchers in [103] differentiated between COVID-19 and other four chest diseases that had some common symptoms. They utilized neutrosophic logic for this purpose to diagnose COVID-19 using only the CT scan and the primary symptoms. They also studied the effect of the internet of things (IOT) in helping the medical staff monitor the spread of COVID-19. Their proposed model achieved 98% detection accuracy. Yet, it was recommended to update their study by including other COVID-19's symptoms added by the World Health Organization (WHO) related to the virus's evolution.

Neutrosophic in Image Processing

In [25] they proposed a neutrosophic similarity clustering algorithm. They applied their model in image processing field for segmenting gray-level images. Their model was applied in many images, both artificial and real images. This proved the effectiveness of their proposed model in image processing and computer vision. In [44] they applied neutrosophic logic in grayscale image processing. Meanwhile, they did not mention real-life use cases to prove the effectiveness of their model. Another contribution of neutrosophic logic in image processing was mentioned in [48]. It was mainly used with Dice coefficients to deal with the missing data uncertainty. Their proposed model was experimentally validated. Their model had high applicability not only in image processing but only in natural language processing. Also, in [51] they utilized neutrosophic sets in image processing. They added two operations to the traditional neutrosophic membership functions (i.e., α-mean and β-enhancement). These added operations could reduce the indeterminacy of the set. Their model was effective as it was able to segment different types of images, even noisy ones. Hence, it was recommended to be applied in real application areas to confirm its applicability. A bit different than this, is the contribution in [55]. They utilized a neutrosophic set in grayscale images. They analyzed the effect of applying bipolar neutrosophic set in grayscale images and came up with their proposed model. Their model could extract useful information from even the noisy images, and was tested on

different images, including human brain images. This could prove its effectiveness in the medical field. In [114] they proposed a particle swarm neutrosophic algorithm to cluster liver tumors in CT images. They evaluated the indeterminacy of the neutrosophic set using entropy. Their proposed showed outperforming results on both CT and non-CT images.

Neutrosophic in Supply Chain

In [12] the researchers combined neutrosophic techniques with AHP method. Their main goal was to support enterprise decision-making in the internet of things (IoT) era. Their proposed algorithm was applied in different enterprises, including Smart Village in Egypt and Smart City in U.K. and China. Meanwhile, involving more companies in their model validation would enrich its results. The researchers in [20] designed an interval complex neutrosophic set and listed its characteristics. To prove their model's practicality, they applied it in supplier selection related to a transportation company. Meanwhile, it still needed to be applied to more real-life datasets to prove its robustness. Another contribution in IoT field was proposed by the researchers in [24] who developed a model that helped detect cancer early. The data was extracted from a set of smart devices (i.e., sensor networks). Their model would help in the early prediction, detection, and treatment of cancer. Their proposed model was well presented, yet it still needs to be applied to many real-life case studies to prove its reliability.

The effect of neutrosophic login in Blockchain has been proved in [28]. They developed single and interval-values neutrosophic Blockchain graphs. They applied their proposed model to various graphs of Blockchain. In [30] they utilized neutrosophic sets to build a ranking technique in a supply chain environment. Their main goal is to handle the economic and environmental vague performances. Their proposed model was applied in two real-life use cases: the petroleum industry and a manufacturing firm in China. Their model was an atom for a combination of analytics and neutrosophic sets. Consequently, it could be extended to predict future trends. In [35] they proposed a fuzzy neutrosophic approach based on trapezoidal neutrosophic variables. It was a decision-making aid for supplier evaluation and selection. Their model was applied in a resilient supply chain management context, in a real-life business case study. Meanwhile, it could be applied in many other areas to test its reliability. It can also be integrated with other fuzzy tools (i.e. rough sets) to enrich its effectiveness. In [41] they proposed a model for the analysis of failure mode and effect. They applied their proposed algorithm in an empirical, real-life case study, and it showed its effectiveness and reliability yet still needed to be generalized. In [61] they had a different perspective in illustrating neutrosophic numbers (i.e., both linear and non-linear). They also tackled both neutrosophication and de-neutrosophication. They applied their proposed concepts in two application areas related to project evaluation review technique (PERT) and route selection. Their proposals could be applied in different applications, and also other neutrosophic numbers' types could be used.

The researchers in [81] developed a supply chain-related multi-criteria group decision-making method. Their proposed model combined analytical network process method to ViseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method. Their model that was developed for a neutrosophic environment that had incomplete information, utilized triangular membership function

was applied in a real case study. It showed outperforming results. Its main limitation was the dependency on experts' opinions and it was hard to find those experts fulfilled the researchers' predefined requirements. Also, its dependency on a forecasting phase that needed to have large input data to have robust results. Meanwhile, it was recommended to generalize it to other applications. The researchers in [83] also utilized VIKOR method to guide the decision-making process in an uncertain environment. For this purpose, they combined VIKOR method to the cubic neutrosophic number. This combination was illustrated through an example but was recommended to be applied in real applications. The contribution in [84] was mentioned to be the first contribution that combined Delphi method to neutrosophy. It was illustrated in a hypothetical case study. Meanwhile, it was recommended to apply it in practical use cases to prove its reliability and robustness. In [86] they proposed a dynamic interval valued neutrosophic set that was applied to a university of languages and international studies. Their proposed model proved its robustness yet still needed to be applied in other application areas.

They also proposed a modified combination between correlation coefficient and single-valued neutrosophic set [86]. Their main objective was to build a decision-making method that helped in selecting the best alternative out of all these given alternatives. They applied their proposed model in an illustrative example for choosing between investment alternatives. Meanwhile, it was recommended to be applied in real-life business cases.

Neutrosophic in Strategic Planning

Neutrosophic analytic hierarchy process model would help select the best strategy out of many different possible strategies under the existence of vague and incomplete information situations. They integrated their model with SWOT analysis. They applied their model in "Starbucks" company. Their model proved its reliability and robustness based on the "Starbucks" dataset; meanwhile, it was flexible enough to be generalized to many other fields and industries [4].

The researchers in [13] were interested in multi-attribute decision-making. Hence, they developed an outranking approach in a bipolar neutrosophic environment. They applied their model to a real example of an investment company. Yet, they did not compare their model's results with another traditional model to prove its effectiveness. A bit similar to this is the study conducted by the researchers in [14] to empower the decision-making using neutrosophic. They mainly designed a proactive approach to analyze and then determine the set of factors that would influence suppliers' selection in supply chain management. In conclusion, they found that "Quality" was the most influential criterion in suppliers' selection. Generalizing their work might face some obstacles related to its need for a huge amount of data, large processing, and complex calculations.

On the other hand, the researchers in [15] contributed to IoT companies' decision-making by proposing a hybrid analytical hierarchal process and neutrosophic theory combination. Their proposal detected and handled the challenges of uncertainty and inconsistency.

In [23] the researchers presented the applicability of intuitionistic neutrosophic on the graph structure. They listed a set of applications using their proposed model that could boost the decision-making process. Meanwhile, they did not report applying it in a real-life case study step by step.

In [27] the researchers combined soft-sets and bipolar sets in their proposal of bipolar neutrosophic soft-sets. They illustrated their proposed model using only numerical examples but did not apply it in real-life. This is on top of their limitations. In [32] they presented some real number-based operational laws for single-valued neutrosophic numbers. They also developed a set of weighted averaging models and geometric aggregation operators. These operators have been utilized to build a multi-attribute decision-making model. Their model is illustrated on a real numerical example. Meanwhile, it still needed to be applied in many real-life use cases to prove its effectiveness and reliability. In [34] they developed a Hierarchical Neutrosophics Analytical model to solve bus routes expected to meet tourists' demands. They achieved satisfactory results. The researchers in [54] studied the applications on entropy and similarity measures in decision-making (DS), especially multi-attribute DS. They mainly focused on hamming distance, contingent, and cosine functions. They confirmed their proposed model's applicability and efficiency, but they did not mention a real-life application that proved its applicability.

In [56] they made a different contribution compared to the above contributions. They utilized rough neutrosophic multisets to support the decision-making in marketing strategy. Their proposed model could be extended to other application areas to prove its effectiveness. Other neutrosophic multisets relations could also be applied than Max, Min, and composition of two rough multisets. In [58] they proposed three neutrosophic models, i.e., single-values hypersoft set, tangent similarity measure for single-valued neutrosophic hypersoft sets, and multi-values hypersoft set. They applied their proposed models in players' match selection. Their models helped in selecting the best option for each player. Meanwhile, it could be applied in many other application areas to validate its effectiveness. In [63] they utilized logarithmic operations for two purposes. First, developing aggregation operators, second, a multi-criteria decision-making approach for a single-valued neutrosophic environment. Their model was tested on a practical case study and proved its effectiveness and selecting the best alternative. Hence, it was encouraged to be applied in other application areas to confirm its effectiveness. While in [64] their main focus was the interval neutrosophic sets. They studied its similarity and entropy. They also mentioned its applicability in multi-attribute decision-making. Their model showed its effectiveness and robustness. Yet, it was still needed to be applied in other applications to prove this effectiveness. An interesting contribution was in [66]. They studied the pathogenic hypersoft set. This concept covered most of the cases in fuzzy and neutrosophic sets. They presented this concept using an illustrative example. Then they built a multi-criteria decision-making model based on this concept and was applied in a real-life application. Meanwhile, it could be extended to other applications, especially graph theory and pattern recognition, to prove its reliability. In [70] validated the pedagogical strategy implementation through two case studies. Their main goal was to increase scientific knowledge through extending the implementation of Iadov method and neutrosophic analysis. Their model could be extended through developing a software tool that could facilitate its applicability in other areas. In [88] they utilized single valued neutrosophic set for multi-attribute decision-making process mainly for school choice. They illustrate their idea through a numerical example, yet would be great to apply it in a real-life use case to prove its effectiveness. In [92] they utilized neutrosophic normal cloud concept, cloud aggregator, and many other concepts to build a multi-criteria group decision-making model. Their model was effectively applied in a real-life use case related to an online retailer. But it would be useful to generalize it to other applications. The researchers in [107] introduced the concept of

neutrosophic soft rough topology. They aimed to develop a multi-criteria decision-making method for ambiguous real-life problems. Meanwhile, their model might be integrated with other algorithms (i.e., TOPOSIS and AHP) to enhance its applicability to other application areas.

Conclusion and Future Work

Neutrosophic set is a very powerful and reliable algorithm. It proved its superiority in many application areas, including image processing, natural language processing, multi-criteria decision-making, strategic planning, Blockchain, and many more. In this paper, sample contributions in these research areas have been presented. Meanwhile, there are a lot of other research points that other researchers might tackle. For instance, combing deep learning, Q learning, and deep Q learning with neutrosophic is an open research area. The researchers in [87] introduced the combination of Q learning with a neutrosophic set, but it still needs a generalization to prove its robustness. Also, combing machine learning to neutrosophic sets still a rich research area. Finally, most of the paper's contributions were not generalized to different application areas to confirm their reliability, which might be another future research direction.

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