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Prioritizing Energy Blockchain Use Cases Using Type-2 Neutrosophic Number-Based EDAS

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ABSTRACT The modern power systems are evolving in parallel to the development of other technological trends such as decarbonization and digitalization. While the penetration of renewable energy resources is increasing within the national and regional energy mix, emerging digitalization technologies, such as artificial intelligence and blockchain technology are shaping modern power systems. Especially blockchain technology has a very high potential to disrupt the current and future energy sector landscape by enabling various use cases in this domain. This paper aims to prioritize different energy use cases where blockchain technology can actively be utilized to create additional value. This study proposes a Type-2 Neutrosophic Number (T2NN) based Evaluation based on Distance from Average Solution (EDAS) to evaluate and rank a set of existing use cases of an energy blockchain system. Testing and validation of the model is done through a comparison against one alternative T2NN based Multi-Criteria Decision Making (MCDM) model and an existing approach from literature. In addition, a sensitivity analysis is performed, revealing that changing criteria weightings do not affect the ranking order of the use cases of the energy blockchain system. Prioritizing the use cases can assist the companies, standardization bodies, and related government authorities to make better decisions for their operations, such as ranking the investment decisions.

INDEX TERMS Blockchain, distributed ledger technology, energy use case, fuzzy sets, multi-criteria decision making, neutrosophic numbers.

I. INTRODUCTION

The traditional power system was designed highly centralized, which in return led to unidirectional power flow. However, rapid integration of Distributed Energy Resources (DERs), Electrical Vehicles (EVs), Energy Storage Systems (ESSs), responsive loads, and demand response programs are causing a paradigm shift in the grid's behavior, leading to a Transactive Energy system [1], [2]. Transactive energy is defined as a system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a critical operational parameter [3]. As this transactive network is already designed as an interconnected matrix of devices, Blockchain is an excellent fit, operating in a matrix structure of nodes with no centralized authority. This trend is also being accelerated due to the integration of smart meters, IoT devices and other ICT technologies leading to the deregulation, decentralization, decarbonization, digitalization, and democratization of the market participants. The inclusion of Distributed Ledger Technology (DLT) in energy markets can further utilize digitalization to achieve more control and consensus across the prosumers, allowing an open market.

DLT can be considered an umbrella term for distributed databases across different locations with multiple users [4]. The first widespread application of DLT was concentrated on cryptocurrencies acting as an alternative medium of exchange. The second utilization of DLT enabled distributed data storage with online ledgers, as the name of the technology also suggests. The third and current application of DLT focuses on smart contracts for scaled and distributed computing. Even though in industry and media the terms are using interchangeably, the blockchain technology is a heavily used sub-category of DLT [5]. In blockchain, as the name

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suggests the information is stored in "blocks" which connects to each other via cryptographic hash functions, hence the "chain" connection. Blockchain is a specific format of DLT with potential applications in supply chain management, telecommunications, transportation, medical, energy systems, and more [6]. For energy systems, there is a vast number of use cases for blockchain. [1] With the inclusion of DLT, energy sector can further utilize the digitalization for achieving more control and consensus across the multiple participants which will lead to reduced operational, planning and infrastructure costs. Detailed review of application of blockchain and challenges lying ahead can be found in [7]–[9].

Work done in [10], [11] proposed a systematic methodology to demonstrate the value of blockchain in various power system use cases. However, there has not been any systemic study or consensus among the experts to indicate which one of these use cases has the highest priority in implementing and creating blockchain applications for energy systems. Prioritization of the possible use cases can provide various solutions to the industry, academia, and the standardization bodies. As Business-as-Usual practice, the companies planning innovative digitalization investments like integrating blockchain technology into their ongoing or new processes spend several months even years to make the most effective decisions for their investments. The decision-making process relies on various, primarily sophisticated investigations and analyses considering multiple technical, economic, sustainability, and political issues. However, some criteria and aspects can be quantifiable, making the decision-making process relatively less complicated and manageable. Furthermore, standardization bodies like IEEE Standards Association (SA) have dedicated working groups (WGs) that focus on various industrial verticals such as health, energy, and supply chain management. IEEE SA P2418.5 a WG that intends to propose an open, common, and inter-operable standard reference framework for the potential use of blockchain in the energy sector. The ranking of the high potential energy blockchain use cases plays an important role for such organizations to proceed with a clean workflow based on solid consensus-based methodologies.

Ranking all the potential uses cases of blockchain for energy systems is essentially a Multi-Criteria Decision-Making (MCDM) problem as the evaluation of use cases relies on the chosen criteria. In decision-making problems, it is not easy to accurately characterize evaluation information with exact numbers. Decision-makers may have different opinions, and this may reveal uncertainty in information [12]. Type-2 Neutrosophic Numbers (T2NNs) was introduced in [13] as an efficient tool to handle vagueness, imprecision, ambiguity, and inconsistency of such MCDM problems [14]. T2NNs have been successfully implemented in various MCDM problems such as: developing supplier selection using a T2NN based TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) approach [13], a public transportation pricing system selection using a two-stage hybrid MCDM model including CRITIC (CRiteria Importance Through Intercriteria Correlation) and MABAC (Multi-Attributive Border Approximation area Comparison) approach under T2NNs [15], two-stage decision model for the location selection of an Automobile Lithium-ion battery [16], and more. However, literature review shows that there has not been any research to apply advanced decision-making methods approach in energy blockchain.

[1] In this work, DLT and blockchain are used interchangeably to stay inline with the trend in academia and industry.

A. CONTRIBUTIONS

1) This work proposes two T2NN based models to evaluate and rank the use cases of an energy blockchain system. This work does not propose a new energy DLT use case but explores the application of Fuzzy set theory to rank/prioritize the existing and commonly implemented use cases where DLT/blockchain is utilized in the field of energy domain. To the best of our knowledge, this work is the first in this category to merge emerging topics such as energy blockchain and advanced decision-making methods in an orchestrated manner.
2) The proposed models use neutrosophic numbers, which can handle uncertainties such as vagueness, imprecision, and inconsistency [13]. The first proposed model is a T2NN based EDAS which is a very effective method in case of having some incompatible parameters. The second proposed model is a T2NN based hybrid model that includes WASPAS, MABAC, and CODAS. We use the distance measures in the second model to calculate the difference degree between T2NNs.
3) Comparison of the two proposed models against a T2NN based CODAS model [16] is also completed along with sensitivity analysis of the two proposed models with respect to a threshold parameter (can be set by a decision-maker).

The paper is organized as follows. Section II details the use cases considered in the work where Section III illustrates the criteria used to evaluate the use cases for prioritizing them. Section IV provides preliminaries on fuzzy set and the proposed methodology. Section V shows the application of the proposed methodology on survey results collected from various experts on the application of blockchain on energy systems and shows the ranking based on the survey results. The results of the analysis indicate that the use case **Grid Management and Transactions** is the most suitable alternative among six alternative use cases. Note that the proposed methodology is independent of the number of collected survey results and can be extended for a different set of use cases evaluated with respect to a different set of evaluation criteria.

II. ENERGY BLOCKCHAIN USE CASES

The global energy landscape is rapidly digitalizing alongside "Industry 4.0" technologies such as artificial intelligence (AI), advanced ICT, quantum computing, and DLT as integral parts of the daily business and operations. The digital transition leverages various digital technologies and tools to increase the efficiency of existing processes, create new revenue streams, and increase the safe and secure operation of the businesses. DLT is among the most disruptive digital technologies with the potential to impact the existing energy market and systems as an enabler. It is possible to eliminate unnecessary third parties, increase transaction and processing speeds, improve the operations' cyber-physical security, and even create new unlocked business territories by effective use of DLT. However, DLT can not be proposed as a unique solution to multiple energy-related problems but can be considered one of the most promising enablers of digital solutions besides other digital technologies. While designing a DLT-based system, one shall consider the potential limitations of existing DLTs, such as inter-operability, transaction speeds, energy consumption levels, and transaction fees of the selected DLT ecosystems. If the investigated use case does not necessarily require decentralized databases like DLT, it is better not to increase the complexity of the existing system and overload the ecosystem. Figure 1 visualizes the segmentation for the following energy blockchain use cases alongside with the entire value chain of power systems and markets.

- Energy financing,
- Renewable energy certificate (REC) trading,
- Labelling and energy provenience,
- EV charging ans payment settlement,
- Retail trading,
- Wholesale trading,
- Flexibility management,
- Grid management and operation,
- P2P energy trading,

Each energy use case is cross-segmented under the relevant value chain section. For instance, EV charging use case can be operated between grid edge (prosumer and consumers) to power distribution system depending on the location of the EV charging station. Moreover, DLT accommodates three dimensions in terms of flow: data, financial, and power transactions, which can be beneficial for the P2P energy trading use case. In this use case scenario, electrical power flows as a physical commodity, and smart metering-based systems can be used to track-record the energy transaction feature immutably to the blocks or on-chain databases of the crypto-network. Besides, financial transactions can be accomplished via DLT-based cryptocurrencies or classical fiat currency as a medium, depending on the preference of the business owners.

Among variety of use cases, this work shows the proposed methodology based on the following short-listed use cases based on popularity [7]–[9]:

A1: P2P Energy Trading
A2: Sustainability Attributions and Green Energy Certification
A3: EV Charging and E-Mobility
A4: Grid Management and Transactions
A5: E-Metering and Payment Settlement
A6: Energy Finance

A. P2P ENERGY TRADING

Increasing utilization of DER, smart meters, and two-way communication technologies allows the classical customers to be more active in the electrical energy supply chain [17]. In return, this phenomenon results in the reconstruction of classical energy markets from a top-down approach to a bottom-up approach where customers can act as producers, resulting in the new term "prosumers." Utilizing blockchain can accelerate the transition securely while removing Trusted Third Parties, thus providing faster transaction validations and more privacy to market participants. Additionally, blockchain can act as an enabler for achieving multiple Local Energy Markets (LEM) across different communities where prosumers can sell their excess energy to their communities (ideally for a cheaper price then the spot electricity prices) or towards the main grid.

Currently, transforming the existing grid network into an operational P2P energy network is the most utilized application of blockchain in the energy industry [18]. The P2P market structure can be classified into fully decentralized markets, community-based markets, and hybrid markets [19]–[21]. However, a fully functional and scaled real-world P2P energy network is unlikely to be achieved soon despite various startups and businesses because many projects are still in the virtual domain and depend on the existing grid structure. Blockchain networks enabled with communication technologies that have a bandwidth of smaller than 1000 kbit/s such as Narrow-Band IoT (NB-IoT), LoRa, Wireless Personal Area Network (WPAN) will lead to bottlenecks and low output in real-life scenarios [22]. Therefore, more technological maturity is needed before various blockchain-enabled markets can be realized in real-world applications. However, for the areas without a grid and with low population density, P2P networks can prove to be beneficial earlier than expected by connecting local homes for faster and more secure energy transactions [23].

B. SUSTAINABILITY ATTRIBUTIONS AND GREEN ENERGY CERTIFICATION

DER is expected to present unprecedented advantages compared to traditional centralized approaches such as lowered electrical transmission losses, security of supply, and advanced efficiency [24]. Individuals (either residential, industrial, or commercial) or a collective entity (aggregator, [25]) can be the source of local generation which then can act as a generator agent or can perform various ancillary services (such as load shaving) [26]. However, due to several economic, technical, social, and regulatory problems, the worldwide deployment rate of DER is still relatively low despite the advantages [27].

By the laws of physics, once power is injected into the main grid, the energy from Renewable Energy Sources (RES) and classical generation techniques are indistinguishable. Thus, there is no way for a consumer to ensure that the consumed electricity comes from RES-based DER. However, by

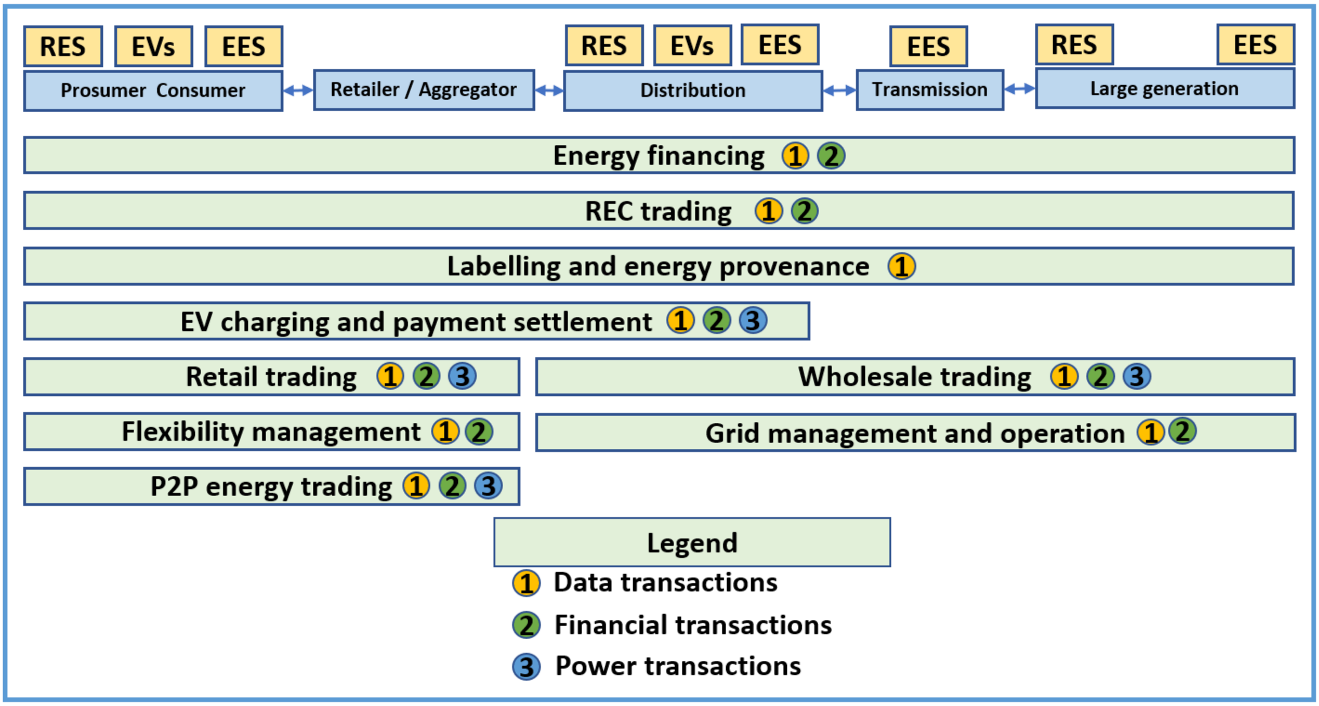


FIGURE 1. **Energy blockchain segmentation analysis.**

utilizing Green Certificates (also known as Renewable Energy Certificates or REC), the origin of energy can be logged in an immutable and distributed manner [28]. This will allow the consumers to feel a sense of support towards DER integration by ensuring that the energy being consumed is coming from RES [29], thus acting as an encouraging agent for consumers to prioritize renewable energy over conventional methods.

REC trading is a credible way to buy and sell renewable energy. The framework works by assigning a REC certificate to the energy produced and fed to the grid (usually a certificate per MWh), which can later be traded. The price per certificate depends on various parameters such as electricity supply and demand, certificate generation frequency, and scarcity. Currently, various REC trading market places exist across different regions such as China, the European Union (EU), the United States of America (USA), and India [30]–[33]. Integration of DLT can pave the development of efficient, transparent, and secure trading of REC. It is currently an active research field where various consensus mechanisms such as Proof of Generation (PoG) are being developed for efficient and scalable trading across participating agents [34].

C. EV CHARGING AND E-MOBILITY

Although the worldwide adaptation of EVs is relatively low due to the scarcity of public charging infrastructure, the utilization rate of EVs is still increasing [35] due to innovations in the development of such as autonomous vehicles and shared mobility. However, this increased utilization of EVs is posing challenges for the management of modern power systems in the areas of; increased peak demand, voltage instabilities, higher rate of equipment degradation, cyber security, and more [36]. Therefore, securing new mobility, developing efficient data management, and handling quick complex transactions are necessary. Blockchain can act as an enabler with distributed and immutable track recording, allowing many small transactions to be performed securely and privately for small power units [37]. Blockchain can ensure a secure identity, communication through a standard messaging format, and automatic recording of charging, generation, and exchange transactions on a distributed ledger for EVs, chargers, and electricity producers. Smart contracts can allow users who have excess electricity to sell to the charging stations. In addition, EV users can leverage electronic wallets to pay the charging bills. The development of such an automatic-payment system using DLT can reduce human interaction and increase trust, transparency, and privacy among EV participants [38].

However, a real-world system should be scalable, considering that the number of EVs on the road increases due to wide-scale adaptation [39]. Thus the proposed blockchain-based systems must be able to perform a higher number of Transactions per Second (TPS) [40]. EV charging and E-mobility is an active research field in DLT; thus, many start-ups and organizations are working on real-world deployments and realization [41], [42].

D. GRID MANAGEMENT AND TRANSACTIONS

Compared to the P2P network, grid transactions are less radical in decentralization and are a research field supported by energy companies. These transactions happen in a way that keeps the power grid integrated even if its function fundamentally changes, such as wholesale energy markets where transactions can be verified quickly and efficiently while being transparent to market participants, hence increasing the efficiency [5]. Compared to the classical wholesale markets, these markets can handle smaller transactions in a quicker way which would put increased pressure on centralized systems [43]. In addition to wholesale power markets, new ancillary markets can be realized by DLT, which will allow distribution network balancing by DER without the need for expensive infrastructure upgrades [40].

Unlike "traditional" centralized generating units, DERs at the prosumer level come in small capacities and are connected to low and medium voltage electricity distribution grids. The distributed nature of these resources can enable new services through DER aggregation to create economic value by providing these services at scale. By acting as intermediaries between prosumers and a deregulated energy market, aggregators can provide hedging solutions by procuring demands from consumers and selling to purchasers, thus reducing risk to individual market participants [44]. Ensuring security, transparency, and privacy in an aggregator-based market is achievable by integrating blockchain while reducing communication latency and computation time [25].

E. E-METERING AND PAYMENT SETTLEMENT

Grid operators must be aware of the electricity consumption patterns of their users for an efficient and stable electricity market [45]. Thus, information security is even more critical amid the decentralized markets with multiple smaller participants. This change leads to the need of answering who oversees the following parameters in the power market such as:

- The owner of the customer data,
- Regulation of the use and access of the customer data,
- The data security and privacy

By utilizing a smart meter, market participants can share information (energy consumption, production, voltage, current, power factor, and more) to their utility. Blockchain integrated with metering infrastructure can pave the path for an automated billing in energy services for prosumers, with the potential of administrative cost reduction. Traceability of energy produced and consumed can inform prosumers about the origins and cost of their energy supply, making energy charges more transparent, thus incentivizing behavioral change and demand response. After the data acquisition, a blockchain-based information system can provide data consistency, and security [46] against communication dropouts [47], and cyber-attacks [37] and can ensure a robust state verification [25]. Moreover, recent development has shown the application of a proof-of-authority consensus mechanism for metering infrastructure that uses significantly less energy than computation-heavy and energy-intensive proof-of-work blockchain systems [48].

F. ENERGY FINANCE

Additional utilization of blockchain in the energy sector is the capital funding via crowdfunding for various energy-related investments such as solar PV, energy storage, and more. The main idea behind this type of energy finance is the allowance of digital partial ownership of the said investments by the investors in exchange for cryptocurrencies, Initial Coin Offerings (ICOs), Security Token Offerings (STOs) [49]–[51] and more. The currency ownership and transaction records can be kept in a distributed digital ledger across every node via various consensus mechanisms for cryptocurrencies. However, utilizing cryptocurrencies in capital funding can lead to unsuccessful financing due to their inherited market volatility. ICO can be defined as utility tokens offered in an unregulated environment, mainly to circumnavigate the required regulatory government bodies, making them more prone to market volatility and fraud. Unlike ICOs, STOs can be launched only after passing the required controls from various government regulatory bodies. Therefore, STOs anchored to a fiat currency are more protected from market speculations and frauds.

Thus, blockchain based crowdfunding has the benefit of allowing multiple smaller investors to participate in an clean energy related investment for easier capital raising and provide a feeling of support towards RES and increase their utilization factor [52] with the added benefit of lowering LCOE values of various energy investments such as PV panels and wind turbines and allowing additional countries to achieve grid parity [49].

III. EVALUATION CRITERIA OF ENERGY BLOCKCHAIN USE CASES

This section describes the set of criteria used to evaluate the blockchain energy use cases described in Section II.

C_1**-Technological Maturity:** Technological maturity is an essential convention in research and development, emerging technology-centered strategic planning, and the decision-making process related to digital infrastructure investments. Technology maturity stages are used to indicate and address a given technology's position on the evolutionary curve.

C_2**-Interoperability** Interoperability in blockchain for energy applications refers to various cyber-physical components' interconnection and interaction within a multi-dimensional and multi-layer ecosystem, which satisfies the safe and robust operation of the proposed system and sub-systems.

C_3**-Scalibility:** For energy blockchain use cases, the scalability aspects refer to multiple dimensions such as an upper limit on the number of stakeholders of the energy market or systems landscape like power generators, utilities, power traders, prosumers and in some business models, aggregators that can actively participate in the blockchain network. Therefore, for an energy blockchain network, an essential evaluation criterion is to ensure that a vast number of customers can participate in the blockchain-enabled energy market at the same time.

C_4**-Transaction Speed:** Transaction speed for energy blockchain use case refers to how fast the power market and systems related operations and transactions can be performed with respect to transaction numbers [25]. For a day-ahead market for instance, the effect of transaction speed is less compared to an hourly market or a 15-min market. Hence, any blockchain solution needs to be evaluated with respect to the maximum parallel transactions per second it can allow at any given time without overloading the network.

C_5**-Cybersecurity:** Cybersecurity aspects investigate risks associated with the cross-sectional fields between cybersecurity, Blockchain DLT and energy use cases. Cryptographic and performance aspects including the management of key generation, storage, transmission, update, escrow, revocation and distribution as well as various corresponding metrics, the various scalability and permission related fields such as the identifying the thresholds for Blockchain DLT scalability and functionality of permission mechanisms and their impacts can be considered as important elements of cybersecurity analysis. Furthermore, evaluation of the Smart Contracts in terms of cybersecurity and attack surface aspects of Blockchain DLT use cases in the field of Energy are other perspectives to be improved.

C_6**-Economic Viability (OPEX and CAPEX):** Like any other investment, it is essential to check the economic viability of a digitalization investment project that uses some form of DLT. Capital Expenditures (CAPEX) of such investments may include project management, system design, and development of both the hardware and the software component. Meanwhile, the Operational Expenditures (OPEX) are the cost components associated with the operation and maintenance of the established system. For energy blockchain, OPEX can also include the associated transaction fees.

C_7**-Economic Value Creation:** This criterion is related to the degree of value created by using DLT for a specific use case by eliminating the third parties, accelerating the processes, increasing the efficiencies, reducing the costs, and/or increasing the benefits.

C_8**-Energy Consumption:** A growing concern of adopting blockchain for various solutions is it's high energy requirement [53]. A permissioned DLT framework (for instance, Hyperledger Fabric) allows consensus protocols that are far less energy-intensive than the consensus protocols (for example, proof-of-work) employed by a permissionless DLT architecture [25], [54]. While both types of architectures have a possible application in energy blockchain, it is crucial to evaluate the use cases with respect to their corresponding effect on overall energy consumption.

C_9**-Contribution to UN SDG:** This work also proposes to evaluate the use cases with respect to some of the goals of the 17 Sustainable Development Goals (SDGs). For example, the adoption of blockchain for energy can lead to innovating new technologies towards industry practice (goal number 9), resulting in affordable and clean energy (goal number 7) and paving the way to develop sustainable cities and communities (goal number 11).

C_{10}**-Legal and Legislative Inter-operability:** Legal and legislative aspects are regulating the rules of the game. The policy-makers are responsible to regulate any official market in a country. Legal documents and laws are used to declare the specific sets of the rules. Various legal and legislative shall successfully interoperated between each other and various regions where different set of legislative documents are valid.

C_{11}**-Political Support:** Support of the policy makers and the dynamics behind them such as public acceptance are among important criteria which have potential to influence the investment decisions.

IV. APPLICATION OF FUZZY SET FOR RANKING BLOCKCHAIN ENERGY USE CASES

A. PRELIMINARIES ON FUZZY SETS

Fuzzy set theory was introduced in [55] to deal with the uncertainties in the information. Later, work done in [56] extended the theory of intuitionistic fuzzy set, as a generalisation of fuzzy sets, which characterize with membership and non-membership degrees. The concept of neutrosophic sets was introduced as an extension of fuzzy sets in [57]. Various types of fuzzy sets and their membership functions are depicted in Figure 2. Membership functions were first introduced in [55]. Membership functions can be characterize the fuzziness; in other words, a membership function represents the degree of truth.

1) TYPE-1 NEUTROSOPHIC SET

A neutrosophic set can be represented by three membership functions including truth membership function T, an indeterminacy membership function I, and a falsity membership function F [13].

Definition 1: Let $\check{X}$ be a fixed set. A neutrosophic set Q in $\check{X}$ denoted by $\check{x}$.

$$\check{Q} = \left\{ \langle \check{x} : \omega_{\check{Q}}(\check{x}), \phi_{\check{Q}}(\check{x}), \pi_{\check{Q}}(\check{x}) \rangle | \check{x} \in \check{X} \right\}, \quad (1)$$

where $\omega, \phi, \pi : \check{X} \rightarrow]^{-}0, 1^{+}[$ represent the degree of truth membership (T), the degree of indeterminacy I, and the degree of falsity membership (F) of the element $\check{x} \in \check{X}$ to the set $\check{Q}$, respectively. There is no restriction on the sum of $\omega_{\check{Q}}(\check{x})$, $\phi_{\check{Q}}(\check{x})$, and $\pi_{\check{Q}}(\check{x})$ [58]. Therefore, the sum of all three membership values changes $0^{-} \leq \omega_{\check{Q}}(\check{x}) + \phi_{\check{Q}}(\check{x}) + \pi_{\check{Q}}(\check{x}) \leq 3^{+}$.

2) TYPE-2 NEUTROSOPHIC SET

Some fundamental definitions of T2NN are as follows:

Definition 2: A type-2 neutrosophic number $\check{Q}$ are characterized by a truth $\omega_{\check{Q}}$, indeterminacy $\phi_{\check{Q}}$, and falsity $\pi_{\check{Q}}$

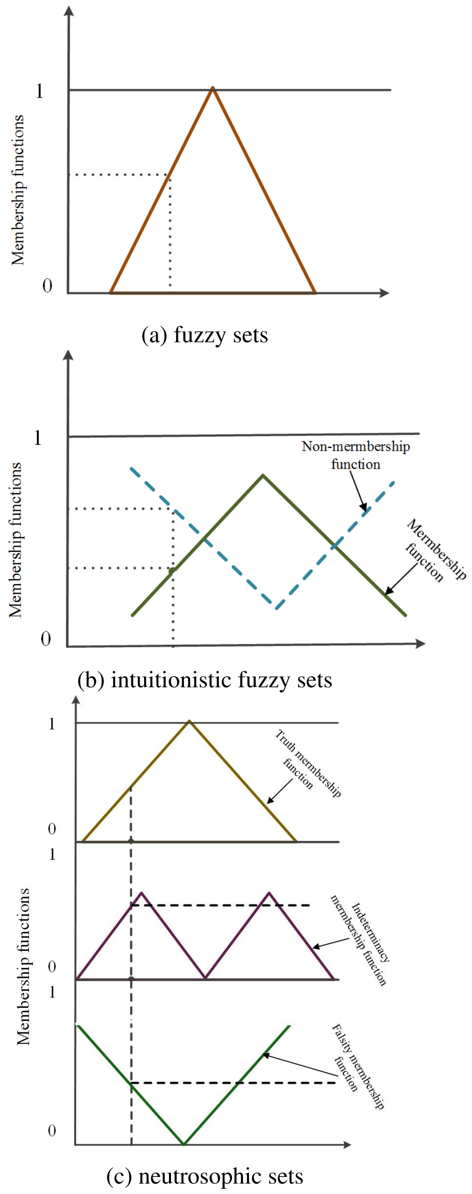


FIGURE 2. Various types of fuzzy sets and their membership functions.

membership functions. A T2NN set $\breve{Q}$ in $\breve{X}$ is defined by [13]:

$$\breve{Q} = \left\{ \left\langle \breve{x}, \omega_{\breve{Q}}(\breve{x}), \phi_{\breve{Q}}(\breve{x}), \pi_{\breve{Q}}(\breve{x}) \right\rangle \middle| \breve{x} \in \breve{X} \right\}, \tag{2}$$

where $\omega_{\breve{Q}}(\breve{x}), \phi_{\breve{Q}}(\breve{x}), \pi_{\breve{Q}}(\breve{x}) : \breve{X} \rightarrow [0, 1]^3$. The elements of the T2NN set can be defined as follows:

$$\omega_{\breve{Q}}(\breve{x}) = \left(\omega_{\omega_{\breve{Q}}}(\breve{x}), \omega_{\phi_{\breve{Q}}}(\breve{x}), \omega_{\pi_{\breve{Q}}}(\breve{x}) \right)$$
$$\phi_{\breve{Q}}(\breve{x}) = \left(\phi_{\omega_{\breve{Q}}}(\breve{x}), \phi_{\phi_{\breve{Q}}}(\breve{x}), \phi_{\pi_{\breve{Q}}}(\breve{x}) \right)$$
$$\pi_{\breve{Q}}(\breve{x}) = \left(\pi_{\omega_{\breve{Q}}}(\breve{x}), \pi_{\phi_{\breve{Q}}}(\breve{x}), \pi_{\pi_{\breve{Q}}}(\breve{x}) \right)$$

Another way of representing a T2NN set is:

$$A = \left((\omega_\omega, \omega_\phi, \omega_\pi), (\phi_\omega, \phi_\phi, \phi_\pi), (\pi_\omega, \pi_\phi, \pi_\pi) | \breve{x} \in \breve{X} \right)$$

$$\omega_{\breve{Q}}(\breve{x}) = \left(\omega^1_{\breve{Q}}(\breve{x}), \omega^2_{\breve{Q}}(\breve{x}), \omega^3_{\breve{Q}}(\breve{x}) \right)$$
$$\phi_{\breve{Q}}(\breve{x}) = \left(\phi^1_{\breve{Q}}(\breve{x}), \phi^2_{\breve{Q}}(\breve{x}), \phi^3_{\breve{Q}}(\breve{x}) \right)$$
$$\pi_{\breve{Q}}(\breve{x}) = \left(\pi^1_{\breve{Q}}(\breve{x}), \pi^2_{\breve{Q}}(\breve{x}), \pi^3_{\breve{Q}}(\breve{x}) \right)$$

where $\omega_{\breve{Q}}(\breve{x}), \phi_{\breve{Q}}(\breve{x})$ and $\pi_{\breve{Q}}(\breve{x})$ are $\breve{X} \rightarrow [0, 1]^3$, For every $\breve{x} \in \breve{X} : 0 \leq \omega^1_{\breve{Q}}(\breve{x}) + \phi^1_{\breve{Q}}(\breve{x}) + \pi^1_{\breve{Q}}(\breve{x}) \leq 3$, $0 \leq \omega^2_{\breve{Q}}(\breve{x}) + \phi^2_{\breve{Q}}(\breve{x}) + \pi^2_{\breve{Q}}(\breve{x}) \leq 3$, and $0 \leq \omega^3_{\breve{Q}}(\breve{x}) + \phi^3_{\breve{Q}}(\breve{x}) + \pi^3_{\breve{Q}}(\breve{x}) \leq 3$ are stated.

Let two T2NNs $\breve{Q}_1$ and $\breve{Q}_2$ be defined as the following:

$$\breve{Q}_1 = \Big\langle \left(\omega_{\omega_{\breve{Q}_1}}(\breve{x}), \omega_{\phi_{\breve{Q}_1}}(\breve{x}), \omega_{\pi_{\breve{Q}_1}}(\breve{x}) \right), \left(\phi_{\omega_{\breve{Q}_1}}(\breve{x}), \phi_{\phi_{\breve{Q}_1}}(\breve{x}) \phi_{\pi_{\breve{Q}_1}}(\breve{x}) \right), \left(\pi_{\omega_{\breve{Q}_1}}(\breve{x}), \pi_{\phi_{\breve{Q}_1}}(\breve{x}), \pi_{\pi_{\breve{Q}_1}}(\breve{x}) \right) \Big\rangle,$$
$$\breve{Q}_2 = \Big\langle \left(\omega_{\omega_{\breve{Q}_2}}(\breve{x}), \omega_{\phi_{\breve{Q}_2}}(\breve{x}), \omega_{\pi_{\breve{Q}_2}}(\breve{x}) \right), \left(\phi_{\omega_{\breve{Q}_2}}(\breve{x}), \phi_{\phi_{\breve{Q}_2}}(\breve{x}), \phi_{\pi_{\breve{Q}_2}}(\breve{x}) \right), \left(\pi_{\omega_{\breve{Q}_2}}(\breve{x}), \pi_{\phi_{\breve{Q}_2}}(\breve{x}), \pi_{\pi_{\breve{Q}_2}}(\breve{x}) \right) \Big\rangle$$

Definition 3: The addition of two T2NNs is given by [13], [15], [59]:

$$\begin{aligned} \breve{Q}_1 \oplus \breve{Q}_2 = \Big\langle \Big(& \omega_{\omega_{\breve{Q}_1}}(\breve{x}) + \omega_{\omega_{\breve{Q}_2}}(\breve{x}) - \omega_{\omega_{\breve{Q}_1}}(\breve{x}) \cdot \omega_{\omega_{\breve{Q}_2}}(\breve{x}), \\ & \omega_{\phi_{\breve{Q}_1}}(\breve{x}) + \omega_{\phi_{\breve{Q}_2}}(\breve{x}) - \omega_{\phi_{\breve{Q}_1}}(\breve{x}) \cdot \omega_{\phi_{\breve{Q}_2}}(\breve{x}), \\ & \omega_{\pi_{\breve{Q}_1}}(\breve{x}) + \omega_{\pi_{\breve{Q}_2}}(\breve{x}) - \omega_{\pi_{\breve{Q}_1}}(\breve{x}) \cdot \omega_{\pi_{\breve{Q}_2}}(\breve{x}) \Big), \\ & \Big(\phi_{\omega_{\breve{Q}_1}}(\breve{x}) \cdot \phi_{\omega_{\breve{Q}_2}}(\breve{x}), \phi_{\phi_{\breve{Q}_1}}(\breve{x}) \cdot \phi_{\phi_{\breve{Q}_2}}(\breve{x}), \\ & \phi_{\pi_{\breve{Q}_1}}(\breve{x}) \cdot \phi_{\pi_{\breve{Q}_2}}(\breve{x}) \Big), \Big(\pi_{\omega_{\breve{Q}_1}}(\breve{x}) \cdot \pi_{\omega_{\breve{Q}_2}}(\breve{x}), \\ & \pi_{\phi_{\breve{Q}_1}}(\breve{x}) \cdot \pi_{\phi_{\breve{Q}_2}}(\breve{x}), \pi_{\pi_{\breve{Q}_1}}(\breve{x}) \cdot \pi_{\pi_{\breve{Q}_2}}(\breve{x}) \Big) \Big\rangle. \end{aligned} \tag{3}$$

Definition 4: The multiplication of two T2NNs is given by [13], [15], [59]:

$$\begin{aligned} & \breve{Q}_1 \otimes \breve{Q}_2 \\ & = \Big\langle \Big(\Big(\omega_{\omega_{\breve{Q}_1}}(\breve{x}) \cdot \omega_{\omega_{\breve{Q}_2}}(\breve{x}), \omega_{\phi_{\breve{Q}_1}}(\breve{x}) \cdot \omega_{\phi_{\breve{Q}_2}}(\breve{x}), \\ & \quad \omega_{\pi_{\breve{Q}_1}}(\breve{x}) \cdot \omega_{\pi_{\breve{Q}_2}}(\breve{x}) \Big), \Big(\phi_{\omega_{\breve{Q}_1}}(\breve{x}) + \phi_{\omega_{\breve{Q}_2}}(\breve{x}) - \phi_{\omega_{\breve{Q}_1}}(\breve{x}) \cdot \\ & \quad \phi_{\omega_{\breve{Q}_2}}(\breve{x}) \Big), \Big(\phi_{\phi_{\breve{Q}_1}}(\breve{x}) + \phi_{\phi_{\breve{Q}_2}}(\breve{x}) - \phi_{\phi_{\breve{Q}_1}}(\breve{x}) \cdot \phi_{\phi_{\breve{Q}_2}}(\breve{x}) \Big), \\ & \quad \Big(\phi_{\pi_{\breve{Q}_1}}(\breve{x}) + \phi_{\pi_{\breve{Q}_2}}(\breve{x}) - \phi_{\pi_{\breve{Q}_1}}(\breve{x}) \cdot \phi_{\pi_{\breve{Q}_2}}(\breve{x}) \Big) \Big), \\ & \quad \Big(\Big(\pi_{\omega_{\breve{Q}_1}}(\breve{x}) + \pi_{\omega_{\breve{Q}_2}}(\breve{x}) - \pi_{\omega_{\breve{Q}_1}}(\breve{x}) \cdot \pi_{\omega_{\breve{Q}_2}}(\breve{x}) \Big), \\ & \quad \Big(\pi_{\phi_{\breve{Q}_1}}(\breve{x}) + \pi_{\phi_{\breve{Q}_2}}(\breve{x}) - \pi_{\phi_{\breve{Q}_1}}(\breve{x}) \cdot \pi_{\phi_{\breve{Q}_2}}(\breve{x}) \Big), \\ & \quad \Big(\pi_{\pi_{\breve{Q}_1}}(\breve{x}) + \pi_{\pi_{\breve{Q}_2}}(\breve{x}) - \pi_{\pi_{\breve{Q}_1}}(\breve{x}) \cdot \pi_{\pi_{\breve{Q}_2}}(\breve{x}) \Big) \Big) \Big\rangle. \end{aligned} \tag{4}$$

Definition 5: The arithmetic operation for a T2NN can be expressed by [13], [15], [59]:

$$\begin{aligned} \breve{Q} = \Big\langle \Big(& 1 - (1 - \omega_{\omega_{\breve{Q}}}(\breve{x}))^\alpha, \\ & 1 - (1 - \omega_{\phi_{\breve{Q}}}(\breve{x}))^\alpha, 1 - (1 - \omega_{\pi_{\breve{Q}}}(\breve{x}))^\alpha \Big), \end{aligned}$$

$$\left((\phi_{\omega_{\breve{Q}}}(\breve{x}))^{\alpha}, (\phi_{\phi_{\breve{Q}}}(\breve{x}))^{\alpha}, (\phi_{\pi_{\breve{Q}}}(\breve{x}))^{\alpha}\right),$$
$$\left((\pi_{\omega_{\breve{Q}_1}}(\breve{x}))^{\alpha}, (\pi_{\phi_{\breve{Q}}}(\breve{x}))^{\alpha}, (\pi_{\pi_{\breve{Q}}}(\breve{x}))^{\alpha}\right)\Big\rangle, \quad (5)$$

where $\alpha > 0$.

Definition 6: The exponent of a T2NN is given by [13], [15], [59]:

$$\breve{Q}^{\alpha} = \Big\langle\left((\omega_{\omega_{\breve{Q}}}(\breve{x}))^{\alpha}, (\omega_{\phi_{\breve{Q}}}(\breve{x}))^{\alpha}, (\omega_{\pi_{\breve{Q}}}(\breve{x}))^{\alpha}\right),$$
$$\left(1-(1-\phi_{\omega_{\breve{Q}}}(\breve{x}))^{\alpha}, 1-(1-\phi_{\phi_{\breve{Q}}}(\breve{x}))^{\alpha},\right.$$
$$\left.1-(1-\phi_{\pi_{\breve{Q}}}(\breve{x}))^{\alpha}\right),$$
$$\left(1-(1-\pi_{\omega_{\breve{Q}}}(\breve{x}))^{\alpha}, 1-(1-\pi_{\phi_{\breve{Q}}}(\breve{x}))^{\alpha},\right.$$
$$\left.1-(1-\pi_{\pi_{\breve{Q}}}(\breve{x}))^{\alpha}\right)\Big\rangle \quad (6)$$

where, $\alpha > 0$.

The convergent classification values of each alternative are arranged with the help of score and accuracy values in order to identify the superior alternative [13].

Definition 7: The score function $S(\breve{Q}_1)$ of T2NN $\breve{Q}_1$ is defined as follows [13]:

$$S(\breve{Q}_1) = \frac{1}{12}\Big\langle 8 + \left(\omega_{\omega_{\breve{Q}_1}}(\breve{x}) + 2\,\omega_{\phi_{\breve{Q}_1}}(\breve{x}) + \omega_{\pi_{\breve{Q}_1}}(\breve{x})\right)$$
$$- \left(\phi_{\omega_{\breve{Q}_1}}(\breve{x}) + 2\,\phi_{\phi_{\breve{Q}_1}}(\breve{x}) + \phi_{\pi_{\breve{Q}_1}}(\breve{x})\right)$$
$$- \left(\pi_{\omega_{\breve{Q}_1}}(\breve{x}) + 2\,\pi_{\phi_{\breve{Q}_1}}(\breve{x}) + \pi_{\pi_{\breve{Q}_1}}(\breve{x})\right)\Big\rangle \quad (7)$$

It can be said that the larger the score value, the more appropriately the corresponding alternative meets the expectation of the decision maker [60].

Definition 8: If the score values of two q-ROFs are equal, then the accuracy values are checked. The accuracy function $A(\breve{Q}_1)$ of T2NN $\breve{Q}_1$ is defined as follows [13]:

$$A(\breve{Q}_1) = \frac{1}{4}\Big\langle\left(\omega_{\omega_{\breve{Q}_1}}(\breve{x}) + 2\left(\omega_{\phi_{\breve{Q}_1}}(\breve{x})\right) + \omega_{\pi_{\breve{Q}_1}}(\breve{x})\right)$$
$$- \left(\pi_{\omega_{\breve{Q}_1}}(\breve{x}) + 2\left(\pi_{\phi_{\breve{Q}_1}}(\breve{x})\right) + \pi_{\pi_{\breve{Q}_1}}(\breve{x})\right)\Big\rangle \quad (8)$$

Definition 9: The relations between $S(\breve{Q}_i)$ and $A(\breve{Q}_i)$ can be defined as follows [13]:

1) If $S(\breve{Q}_1) > S(\breve{Q}_2)$, then $\breve{Q}_1$ is bigger than $\breve{Q}_2$, denoted $\breve{Q}_1 > \breve{Q}_2$
2) If $S(\breve{Q}_1) = S(\breve{Q}_2)$, then their accuracy values are compared as follows:
   a) $A(\breve{Q}_1) > A(\breve{Q}_2)$, then $\breve{Q}_1 > \breve{Q}_2$,
   b) $A(\breve{Q}_1) = A(\breve{Q}_2)$, then $\breve{Q}_1 = \breve{Q}_2$.

For example, consider two T2NNs in the group of real numbers:

$$\breve{Q}_1 = (0.7, 0.8, 0.9), (0.25, 0.2, 0.35), (0.1, 0.15, 0.05)$$
$$\breve{Q}_2 = (0.4, 0.35, 0.5), (0.3, 0.4, 0.25), (0.2, 0.3, 0.35)$$

Following Eqs. (7) and (8), score and accuracy values can be calculated as follows:

1) Score value of $\breve{Q}_1, S(\breve{Q}_1) = (8+(3.2-1.0-0.45))/12 = 0.81$, and of $\breve{Q}_2$, $S(\breve{Q}_2) = (8 + (1.6 - 1.35 - 1.15))/12 = 0.59$;
2) Accuracy value of $\breve{Q}_1, A(\breve{Q}_1) = (83.2-0.45)/4 = 0.69$, and of $\breve{Q}_2$, $A(\breve{Q}_2) = (1.6 - 1.15)/4 = 0.11$.

It can be clearly seen that $\breve{Q}_1 > \breve{Q}_2$.

Definition 10: Distance methods basically calculate crisp distance values between two fuzzy numbers. However, a logical problem arises when the distance is calculated in an uncertain frame due to the presence of uncertainty. Therefore, a measure of distance is used for uncertain numbers and can be defined as follow considering the followings two T2NNs:

$$\breve{Q}_1 = \left((\omega_1, \omega_2, \omega_3), (\phi_1, \phi_2, \phi_3), (\pi_1, \pi_2, \pi_3)\right)$$
$$\breve{Q}_2 = \left((T_1, T_2, T_3), (I_1, I_2, I_3), (F_1, F_2, F_3)\right)$$

The distance measure $F(\breve{Q}_1, \breve{Q}_2)$ between them is defined as follows [61]:

$$F(\breve{Q}_1, \breve{Q}_2) = 1 - \frac{\sum_{i=1}^{3}\left(\omega_i T_i + \phi_i I_i + \pi_i F_i\right)}{\left(\sum_{i=1}^{3}[\omega_i^2 + \phi_i^2 + \pi_i^2\,]\right)\times\left(\sum_{i=1}^{3}[T_i^2 + I_i^2 + F_i^2]\right)} \quad (9)$$

B. PROPOSED METHODOLOGIES

In this section, two different models using T2NN have been proposed to rank the use cases and then select the best DLT use case using reviews from experts. The flowchart of proposed models is shown in Figure 3.

1) MODEL-I: T2NN BASED EDAS

Model-I is structured based on EDAS approach introduced in [62] under T2NN. The steps of the proposed model are as follows:

Step 1: Construct the fuzzy decision matrix $\tilde{X} = (x_{ij})_{m\times n}$. x_{ij} is the evaluation value of the alternative a_i $(i = 1, 2, \ldots, m)$ according to the criteria $s_j (j = 1, 2, \ldots, n)$,

$$\tilde{X} = (x_{ij})_{m\times n} = \begin{array}{c} \\ P_1 \\ P_2 \\ \vdots \\ P_n \end{array}\begin{array}{c} \begin{array}{cccc} A_1 & A_2 & \cdots & A_m \end{array} \\ \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{1m} & x_{2m} & \cdots & x_{mn} \end{pmatrix}\end{array} \quad (10)$$

where m indicates the number of alternatives and n indicates the number of criteria.

Step 2: Calculate the score values of alternatives in terms of each criterion using decision matrix with the help of score function $S(\breve{Q}_1)$ in given in Eq. (7).

Step 3: Calculate the average solution $AV = \left[AV_j\right]_{1xm}$ considering all criteria. Average solution of each criterion is found using (11).

$$AV_j = \frac{\sum_i^n x_{ij}}{n} \quad (11)$$

Step 4: Two important measures of the EDAS, the positive distance from average (PDA) and the negative distance from

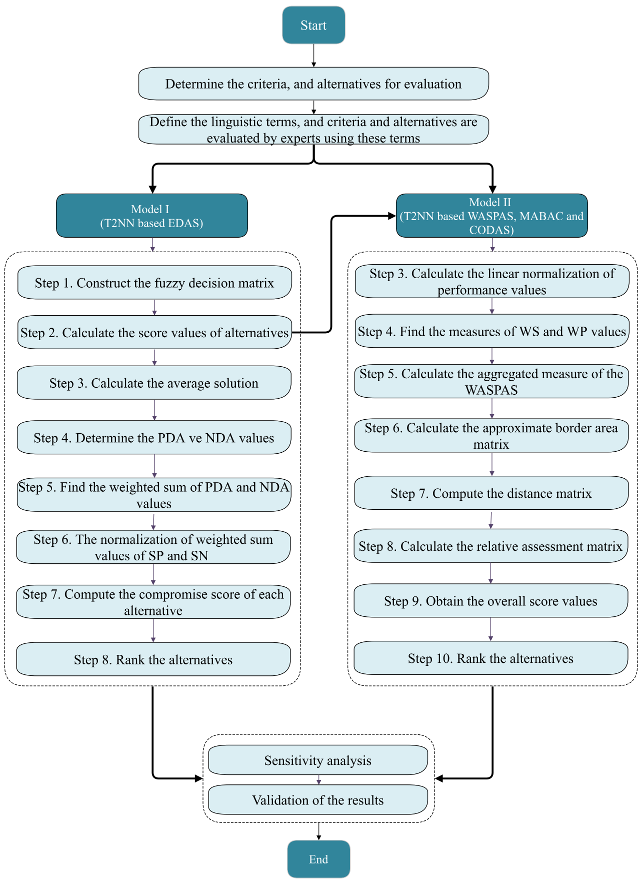


FIGURE 3. **T2NN based proposed models.**

average (NDA) matrix are structured based on the type of criteria (benefit and cost).

If j^{th} criterion belongs to benefit group, then PDA and NDA values are calculated using Eqs. ((12)-(13):

$$PDA_{ij} = \frac{\max(0, x_{ij} - AV_j)}{AV_j} \tag{12}$$

$$NDA_{ij} = \frac{\max(0, AV_j - x_{ij})}{AV_j} \tag{13}$$

If j^{th} criterion belongs to cost group, then PDA and NDA values are calculated using Eqs. (14)-(15):

$$PDA_{ij} = \frac{\max(0, AV_j - x_{ij})}{AV_j} \tag{14}$$

$$NDA_{ij} = \frac{\max(0, x_{ij} - AV_j)}{AV_j} \tag{15}$$

where PDA_{ij} and NDA_{ij} represent the positive and negative distance of i^{th} alternative from average solution with respect to j^{th} criterion, respectively.

Step 5: Weighted sum of PDA and NDA values are found using Eqs. (16)-(17) with the help of weight coefficient of each criteria (w_j):

$$SP_i = \sum_{j}^{m} w_j PDA_{ij} \tag{16}$$

$$SN_i = \sum_{j}^{m} w_j NDA_{ij} \tag{17}$$

Step 6: The normalization of weighted sum values of SP and SN are calculated using Eqs. (18) and (19), respectively.

$$NSP_i = \frac{SP_i}{\max_i(SP_i)} \tag{18}$$

$$NSN_i = 1 - \frac{SN_i}{\max_i(SN_i)} \tag{19}$$

Step 7: Compromise score of each alternative is found by (20).

$$AS_i = \frac{1}{2}(NSP_i + NSN_i) \tag{20}$$

Step 8: Alternatives are ranked by the descending order of values of their AS, i.e., the alternative with the highest value of the compromise score is the highest ranked alternative.

2) MODEL-II: T2NN BASED MODEL INCLUDING WASPAS, MABAC, AND CODAS

This proposed model is designed as an integrated model including WASPAS [63], MABAC [64], and CODAS [65] based on T2NN. The proposed model can be described in the following steps.

Steps 1-2: Same as the first two steps of Model-I.

Step 3: Linear normalization of performance values are obtained as follows [63]:

$$\tilde{r}_{ij} = \begin{cases} \frac{x_{ij}}{\max_i x_{ij}} & \forall i \quad \text{if } j \in B \\ \frac{\min_i x_{ij}}{x_{ij}} & \forall i \quad \text{if } j \in C \end{cases} \tag{21}$$

where B and C denote sets of benefit and cost criteria, respectively. Alternatives and criteria are defined by $i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, n$, respectively.

Step 4: The measures of weighted sum (WS) (Δ_i^1) and weighted product (WP) (Δ_i^2) for each alternative are defined as follows [63]:

$$\Delta_{ij}^1 = \sum_{j=1}^{m} w_j \tilde{r}_{ij} \quad \forall i \tag{22}$$

$$\Delta_{ij}^2 = \prod_{j=1}^{m} (\tilde{r}_{ij})^{w_j} \quad \forall i \tag{23}$$

Step 5: The aggregated measure of the WASPAS method are calculated as follows [63]:

$$\Delta_{ij} = \mu \Delta_{ij}^1 + (1 - \mu)\Delta_{ij}^2 \quad \forall i \tag{24}$$

where μ is defined as the parameter of the WASPAS method and this parameter is the set of numbers between 0 and 1. If μ is $=$ 1, WASPAS method is transformed into WS, whereas $\mu = 0$ leads to WP.

Step 6: Calculate the approximate border area matrix H. Border Approximate Area (BAA) for each criterion is obtained as follows [64]:

$$h_j = \left(\prod_{i=1}^{m} \Delta_{ij} \right)^{1/m} \tag{25}$$

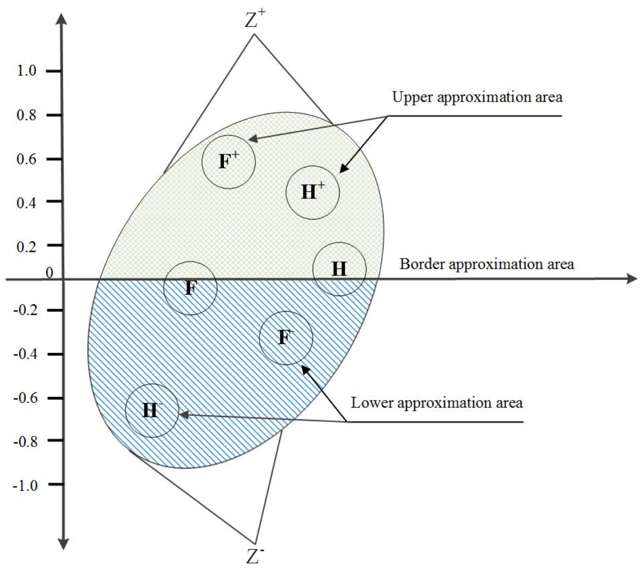


FIGURE 4. The upper (H^+) and (F^+), lower (H^-) and (F^-), and border (H) and (F) approximation areas.

where h_j and m represent the border approximation area for criterion C_j and the total number of alternatives, respectively. The border approximation area vector H can be also expressed in another form ($1 \times n$) as in the following:

$$H = \begin{array}{c} \\ \end{array}\begin{matrix} P_1 & P_2 & \cdots & P_m \\ \end{matrix}$$
$$H = \begin{pmatrix} h_1 & h_2 & \cdots & h_n \end{pmatrix}$$

Step 7: Calculate distance matrix $\rho = (d_{ij})_{m \times n}$. The distances of alternative from the border approximation area are calculated as follows [64]:

$$\rho^1 = \Delta - H \Rightarrow \begin{bmatrix} \Delta_{11} - h_1 & \Delta_{12} - h_2 & \ldots & \Delta_{1n} - h_n \\ \Delta_{21} - h_1 & \Delta_{22} - h_2 & \ldots & \Delta_{2n} - h_1 \\ \vdots & \vdots & \ddots & \vdots \\ \Delta_{m1} - h_1 & \Delta_{m2} - h_2 & \cdots & \Delta_{mn} - h_n \end{bmatrix} \tag{26}$$

Calculate the ideal distance as follows:

$$F = [f_j]_{1xm} \quad \text{and} \quad f_j = \min\{\Delta_{ij}\}, \tag{27}$$

where f_j represents the distance.

$$\rho^2 = \Delta - F \Rightarrow \begin{bmatrix} \Delta_{11} - f_1 & \Delta_{12} - f_2 & \ldots & \Delta_{1n} - f_n \\ \Delta_{21} - f_1 & \Delta_{22} - f_2 & \ldots & \Delta_{2n} - f_1 \\ \vdots & \vdots & \ddots & \vdots \\ \Delta_{m1} - f_1 & \Delta_{m2} - f_2 & \cdots & \Delta_{mn} - f_n \end{bmatrix} \tag{28}$$

The alternative Z_i may belong to the upper approximate area (H^+) and (F^+), lower approximate area (H^+) and (F^-) or border approximation area, respectively $\forall i \in \{H \vee H^+ \vee H^-\}$ and $\{F \vee F^+ \vee F^-\}$ as shown in Figure 4. H^+ and F^+ are an area in which the ideal alternative is found (Z^+), while the H^- and F^- are an area in which the anti-ideal alternative (Z^-).

TABLE 1. Linguistic terms and their corresponding values for weighting of criteria [Weakly important (WI); Equal important (EI); Strong important (SI); Very strongly important (VSI); Absolutely important (AI)].

Linguistic terms	T2NN
WI	((0.20,0.30,0.20), (0.60,0.70,0.80), (0.45,0.75,0.75))
EI	((0.40,0.30,0.25), (0.45,0.55,0.40), (0.45,0.60,0.55))
SI	((0.50,0.55,0.55), (0.40,0.45,0.55), (0.35,0.40,0.35))
VSI	((0.80,0.75,0.70), (0.20,0.15,0.30), (0.15,0.10,0.20))
AI	((0.90,0.85,0.95), (0.10,0.15,0.10), (0.05,0.05,0.10))

Belonging of the alternative (Z_i) to the approximate area (H^+, H or H^-) and (F^+, F or F^-) are calculated by:

$$Z_i \in \begin{cases} H^+ & \text{if } d_{ij} > 0 \\ H & \text{if } d_{ij} = 0 \\ H^- & \text{if } d_{ij} < 0 \end{cases} \quad \text{and} \quad Z_i \in \begin{cases} F^+ & \text{if } d_{ij} > 0 \\ F & \text{if } d_{ij} = 0 \\ F^- & \text{if } d_{ij} < 0 \end{cases} \tag{29}$$

Step 8: Calculate the relative assessment matrix (ϑ) as follows [65]:

$$\vartheta = [\upsilon_{il}]_{m \times m}$$
$$\text{where, } \upsilon_{il} = (\rho_i^1 - \rho_l^1) + \left(\Psi(\rho_i^1 - \rho_l^1) \times (\rho_i^2 - \rho_l^2)\right) \tag{30}$$

Here $l \in \{i = 1, 2, \ldots, m\}$ and Ψ is a threshold function that can be defined as follows:

$$\Psi(x) = \begin{cases} 1 & \text{if } |x| \geq \psi \\ 0 & \text{if } |x| < \psi \end{cases} \tag{31}$$

ψ denotes the threshold parameter of Ψ function which can be set by decision makers.

Step 9: Obtain the overall score (λ_i) for each alternative as follow:

$$\lambda_i = \sum_{l=1}^{m} \upsilon_{il} \tag{32}$$

Step 10: The alternative are ranked according to the descending ordering of the overall score values, i.e., the alternative with highest λ is the highest ranked alternative.

V. EXPERIMENTAL RESULTS

In this section, we present the results of applying the two proposed models on survey results collected from experts. Firstly, each criterion is evaluated by four experts using the linguistic terms presented in Table 1. The expert evaluations for each criterion are presented in Table 13 in Appendix VI. Secondly, the experts provide their opinions (reported in Table 14 in Appendix VI) about the ratings of six energy blockchain use case alternatives (refer to Section II) with respect to eleven criteria using the linguistic terms (shown in Table 2).

TABLE 2. Linguistic terms and their corresponding values for rating of alternative.

Linguistic terms	T2NN
Very bad (VB)	((0.20,0.20,0.10), (0.65,0.80,0.85), (0.45,0.80,0.70))
Bad (B)	((0.35,0.35,0.10), (0.50,0.75,0.80), (0.50,0.75,0.65))
Medium bad (MB)	((0.50,0.30,0.50), (0.50,0.35,0.45), (0.45,0.30,0.60))
Medium (M)	((0.40,0.45,0.50), (0.40,0.45,0.50), (0.35,0.40,0.45))
Medium good (MG)	((0.60,0.45,0.50), (0.20,0.15,0.25), (0.10,0.25,0.15))
Good (G)	((0.70,0.75,0.80), (0.15,0.20,0.25), (0.10,0.15,0.20))
Very good (VG)	((0.95,0.90,0.95), (0.10,0.10,0.05), (0.05,0.05,0.05))

TABLE 3. The score values of alternatives for each criterion.

Alternatives	Criteria					
	C_1	C_2	C_3	C_4	C_5	C_6
A1	0.898	0.898	0.911	0.889	0.906	0.889
A2	0.846	0.827	0.846	0.807	0.875	0.875
A3	0.890	0.889	0.911	0.858	0.911	0.875
A4	0.911	0.911	0.911	0.911	0.914	0.898
A5	0.846	0.875	0.906	0.878	0.898	0.872
A6	0.903	0.897	0.884	0.899	0.911	0.908
Alternatives	C_7	C_8	C_9	C_{10}	C_{11}	
A1	0.890	0.886	0.875	0.860	0.838	
A2	0.898	0.872	0.906	0.875	0.860	
A3	0.875	0.863	0.860	0.857	0.835	
A4	0.875	0.898	0.878	0.842	0.853	
A5	0.838	0.856	0.853	0.863	0.838	
A6	0.908	0.794	0.826	0.910	0.739	

TABLE 4. The average solution matrix.

Criteria	C_1	C_2	C_3	C_4	C_5	C_6
AV_j	0.882	0.883	0.895	0.874	0.902	0.886
Criteria	C_7	C_8	C_9	C_{10}	C_{11}	
AV_j	0.881	0.862	0.866	0.868	0.827	

A. RESULTS OF THE T2NN BASED EDAS APPROACH

Step 1: The fuzzy decision matrix is structured using the evaluation of alternatives given in Table 14 with the help of the T2NNs values in Table 2.

Step 2: The score values of alternatives for each criteria are calculated using Eq. (7) and are presented in Table 3.

Step 3: The average solution matrix (AV_j) calculated using the score values in Table 3 and Eq. (11) is presented in Table 4.

Step 4: Using the values in Table 3 and Table 4, the positive and negative distance from average for each alternative are calculated using Eqs. (12)-(15) and reported in Table 5 and Table 6, respectively.

Step 5: The weights of criteria are determined using Eq. (7) and the normalized criteria weights are presented in Table 7. Later, following Eqs. (16)-(17), the weighted PDA and NDA are calculated using the Tables 5-6 and are presented in Tables 8 and 9, respectively. After that, the weighted sum of PDA and NDA (SP_i and SN_i) are obtained and reported in Table 10.

TABLE 5. The values of positive distance from average of DLT alternatives.

Alternatives	Criteria					
	C_1	C_2	C_3	C_4	C_5	C_6
A1	0.018	0.018	0.018	0.017	0.004	0.003
A2	0.000	0.000	0.000	0.000	0.000	0.000
A3	0.008	0.007	0.018	0.000	0.009	0.000
A4	0.032	0.032	0.018	0.042	0.012	0.014
A5	0.000	0.000	0.012	0.005	0.000	0.000
A6	0.024	0.016	0.000	0.029	0.010	0.025
Alternatives	C_7	C_8	C_9	C_{10}	C_{11}	
A1	0.010	0.000	0.010	0.000	0.013	
A2	0.020	0.000	0.045	0.008	0.039	
A3	0.000	0.000	0.000	0.000	0.009	
A4	0.000	0.000	0.014	0.000	0.031	
A5	0.000	0.007	0.000	0.000	0.013	
A6	0.031	0.078	0.000	0.049	0.000	

TABLE 6. The values negative distance from average of the alternatives.

Alternatives	Criteria					
	C_1	C_2	C_3	C_4	C_5	C_6
A1	0.000	0.000	0.000	0.000	0.000	0.000
A2	0.041	0.063	0.055	0.077	0.031	0.013
A3	0.000	0.000	0.000	0.017	0.000	0.013
A4	0.000	0.000	0.000	0.000	0.000	0.000
A5	0.041	0.009	0.000	0.000	0.005	0.016
A6	0.000	0.000	0.012	0.000	0.000	0.000
Alternatives	C_7	C_8	C_9	C_{10}	C_{11}	
A1	0.000	0.029	0.000	0.009	0.000	
A2	0.000	0.012	0.000	0.000	0.000	
A3	0.007	0.002	0.007	0.013	0.000	
A4	0.007	0.043	0.000	0.029	0.000	
A5	0.048	0.000	0.015	0.006	0.000	
A6	0.000	0.000	0.046	0.000	0.107	

TABLE 7. The normalized weights of eleven criteria.

Criteria	C_1	C_2	C_3	C_4	C_5	C_6
Weights	0.094	0.093	0.093	0.088	0.093	0.093
Criteria	C_7	C_8	C_9	C_{10}	C_{11}	
Weights	0.094	0.089	0.084	0.092	0.086	

Steps 6-7: The values of SP_i and SN_i given in Table 10 are normalized using Eqs. (18)-(19), respectively. Later, the compromise score of each alternative is calculated using Eq. (20). The normalized values (NSP_i and NSN_i) and the compromise score (AS_i) are given in Table 10.

Step 8: Based on the results of AS_i, the alternatives are ranked. The rank of six alternatives is $A4 > A6 > A1 > A3 > A5 > A2$. Table 10 shows that $A4$ is the best among the six DLT alternatives because it has the highest value of AS, while $A2$ is the worst alternative.

TABLE 8. The weighted PDA.

Alternatives	Criteria					
	C_1	C_2	C_3	C_4	C_5	C_6
A1	0.002	0.002	0.002	0.002	0.000	0.000
A2	0.000	0.000	0.000	0.000	0.000	0.000
A3	0.001	0.001	0.002	0.000	0.001	0.000
A4	0.003	0.003	0.002	0.004	0.001	0.001
A5	0.000	0.000	0.001	0.000	0.000	0.000
A6	0.002	0.002	0.000	0.003	0.001	0.002
Alternatives	C_7	C_8	C_9	C_{10}	C_{11}	
A1	0.001	0.000	0.001	0.000	0.001	
A2	0.002	0.000	0.004	0.001	0.003	
A3	0.000	0.000	0.000	0.000	0.001	
A4	0.000	0.000	0.001	0.000	0.003	
A5	0.000	0.001	0.000	0.000	0.001	
A6	0.003	0.007	0.000	0.004	0.000	

TABLE 9. The weighted NDA.

Alternatives	Criteria					
	C_1	C_2	C_3	C_4	C_5	C_6
A1	0.000	0.000	0.000	0.000	0.000	0.000
A2	0.004	0.006	0.005	0.007	0.003	0.001
A3	0.000	0.000	0.000	0.002	0.000	0.001
A4	0.000	0.000	0.000	0.000	0.000	0.000
A5	0.004	0.001	0.000	0.000	0.000	0.001
A6	0.000	0.000	0.001	0.000	0.000	0.000
Alternatives	C_7	C_8	C_9	C_{10}	C_{11}	
A1	0.000	0.003	0.000	0.001	0.000	
A2	0.000	0.001	0.000	0.000	0.000	
A3	0.001	0.000	0.001	0.001	0.000	
A4	0.001	0.004	0.000	0.003	0.000	
A5	0.005	0.000	0.001	0.001	0.000	
A6	0.000	0.000	0.004	0.000	0.009	

TABLE 10. The ranking results of T2NN based EDAS model.

Alternatives	SP_i	SP_i	NSP_i	NSN_i	AS_i	Rank
A1	0.010	0.003	0.424	0.872	0.648	3
A2	0.010	0.027	0.413	0.000	0.206	6
A3	0.005	0.005	0.198	0.801	0.500	4
A4	0.018	0.007	0.738	0.733	0.735	1
A5	0.003	0.013	0.142	0.516	0.329	5
A6	0.024	0.014	1.000	0.468	0.734	2

B. RESULTS OF THE T2NN BASED MODEL INCLUDING WASPAS, MABAC, AND CODAS

The survey results are used with the model proposed in Section IV-B2 and the final ranking results of proposed Model-II is shown in Table 11. Ranking results from best to worst are $A_4 > A_6 > A_1 > A_3 > A_5 > A_2$. Each model found A_4 to be the best alternative while A_2 is the less suitable alternative for two proposed model. The main reason for A_2 being the worst alternative is that it has the lowest transaction speed and highest power consumption.

TABLE 11. The ranking results of T2NN based WASPAS, MABAC and CODAS model.

Alternatives	A1	A2	A3	A4	A5	A6	λ	Rank
A1	0.000	0.022	0.007	-0.004	0.016	-0.003	0.041	3
A2	-0.022	0.000	-0.016	-0.055	-0.008	-0.053	-0.100	6
A3	-0.007	0.016	0.000	-0.011	0.009	-0.010	0.007	4
A4	0.004	0.055	0.011	0.000	0.020	0.001	0.089	1
A5	-0.016	0.008	-0.009	-0.020	0.000	-0.019	-0.038	5
A6	0.003	0.053	0.010	-0.001	0.019	0.000	0.083	2

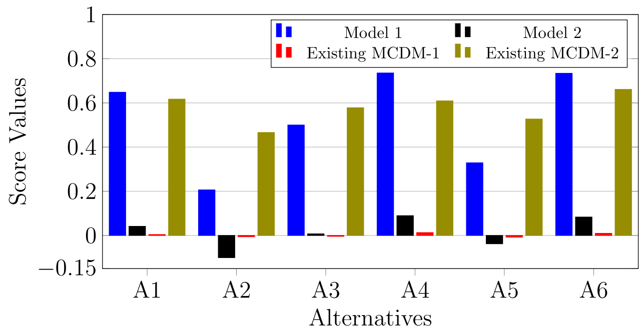


FIGURE 5. Comparative analysis of proposed models against existing MCDM models.

C. COMPARISON WITH EXISTING METHOD

This section shows a comparison of the two proposed models with the following two existing MCDM methods:

Existing MCDM-1 : T2NN based CODAS approach presented in [16]
Existing MCDM-2 : T2NN based fuzzy TOPSIS [13]

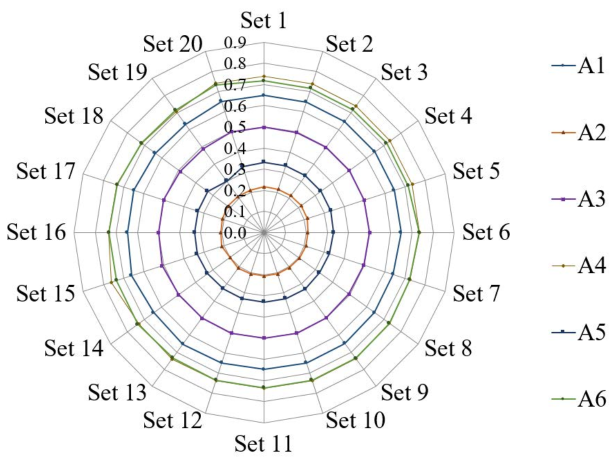
The ranking results for each of model and existing MCDM models are given in Table 12 and shown in Fig. 5.

The existing MCDM-1 is not based on weighted sum and product. Comparison with the proposed models indicate that A_4 is still the most suitable use case of energy blockchain system for the three models while A_2 is the worst alternative for the two proposed models. The only difference found between the models and existing MCDM model is the ranking of A_2 and $A5$. The main reason for this small difference lies in the properties of the distance calculations of the existing MCDM model-1. The proposed hybrid model uses a linear normalization to eliminate the units of criterion values. The measures of weighted sum and weighted product using WASPAS approach are implemented to aggregate the fuzzy values. The border approximation area is applied to close the ideal solution. Using the MABAC method as a reliable tool for rational decision making allows comprehensive evaluation of the potential value of gains and losses [64]. CODAS which includes two types of distances are used to evaluate the desirability of alternatives [66]. Thus combining all three to form the proposed hybrid MCDM model can better express uncertainty.

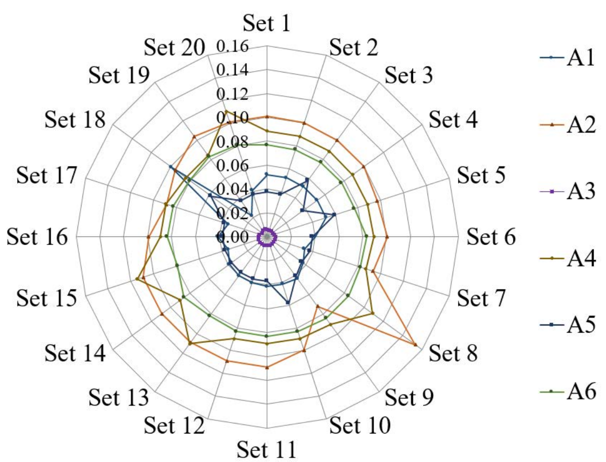
Applying the existing MCDM-2 method shows the ranking of alternatives to be $A_6 > A_2 > A_4 > A_3 > A_5 > A_2$, which shows a bigger difference with the proposed two models. The results of this model were different from other

TABLE 12. The comparison ranking of the proposed models and two existing MCDM models.

Alt.	Proposed Model I		Proposed Model II		Existing MCDM-1		Existing MCDM-2	
	Score	Ranking	Score	Ranking	Score	Ranking	Score	Ranking
A1	0.648	3	0.041	3	0.004	3	0.617	2
A2	0.206	6	-0.100	6	-0.006	5	0.466	6
A3	0.500	4	0.007	4	-0.004	4	0.578	4
A4	0.735	1	0.089	1	0.013	1	0.609	3
A5	0.329	5	-0.038	5	-0.007	6	0.527	5
A6	0.734	2	0.083	2	0.010	2	0.661	1



(a) T2NN based EDAS



(b) T2NN based WASPAS, MABAC and CODAS

FIGURE 6. Sensitivity analysis for the proposed models.

models as the normalization technique used has a different structure.

D. STABILITY ANALYSIS

Sensitivity analysis is performed with respect to change in priority weights to investigate the stability of the solution. The sensitivity analysis process is completed by changing the

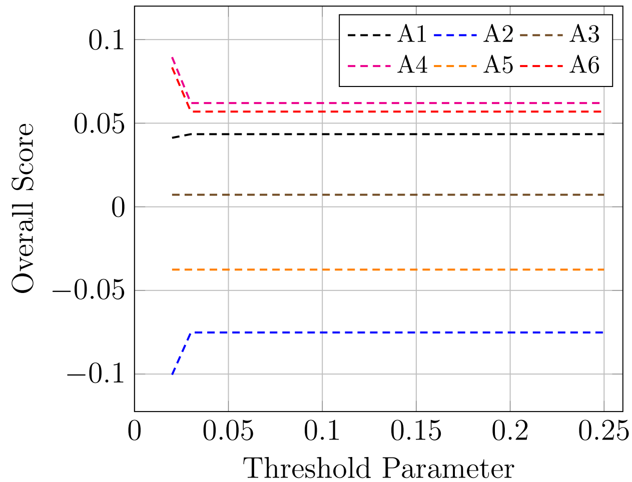


FIGURE 7. The analysis of the impact of the parameter ψ.

weights of each criterion with other criteria weights. Therefore, experiments are done with 20 different sets. In each experiment, we examine the overall scores. Results of each experiment are illustrated in Figure 6 that illustrates that varying criteria weights did not affect the ranking results. In addition, the impact of different values of the threshold parameter on the ranking results of the T2NN based integrated WASPAS, MABAC, and CODAS model is shown in Figure 7. The results indicate that the ranking of the alternatives is not changed for different threshold values.

E. DISCUSSION

The outcome of the proposed algorithm yielded the following results: $A4 > A6 > A1 > A3 > A5 > A2$. According to the finding of this study, **Grid Management and Transactions** use case yielded as the most significant use case among the six alternatives/use cases. This use case accommodate various multi-layer, sophisticated and interconnected tasks

Likewise, **Sustainability Attributions and Green Energy Certification** use case landed to the last position in terms of ranking among the other five options. As stated in Section I, the contribution of the paper is to apply complex decision-making frameworks to a multi-criteria decision making problem, and the results illustrated here depend on the

TABLE 13. The importance ratings of the criteria by experts.

Experts	Criteria										
	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}
E1	AI	VSI	VSI	SI	VSI	VSI	AI	SI	SI	VSI	SI
E2	VSI	VSI	VSI	SI	AI	AI	AI	VSI	EI	EI	SI
E3	AI	AI	AI	VSI	AI	VSI	AI	VSI	SI	AI	VSI
E4	AI	AI	AI	SI	VSI	AI	VSI	SI	SI	AI	EI

TABLE 14. The ratings of the DLT alternatives in terms of criterion and each experts.

Alternatives	Experts	Criteria										
		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}
A1	E1	G	G	VG	G	MG	G	G	G	VG	G	MG
	E2	VG	VG	VG	VG	VG	G	G	G	MG	M	M
	E3	G	G	VG	G	VG	MG	G	VG	G	MG	G
	E4	G	G	G	MG	VG	VG	G	M	MG	G	M
A2	E1	MG	MG	MG	B	MG	MG	G	MG	VG	G	MG
	E2	MG	MG	MG	MG	MG	VG	VG	VG	VG	M	G
	E3	MG	MG	G	MG	G	MG	G	G	G	G	G
	E4	G	MG	MG	M	VG	G	G	M	G	G	M
A3	E1	G	G	VG	MG	VG	G	VG	MG	G	G	G
	E2	G	VG	G	MG	G	MG	MG	MG	M	MB	MB
	E3	G	MG	VG	VG	VG	MG	MG	G	MG	MG	MG
	E4	G	G	VG	MG	VG	VG	G	G	G	G	M
A4	E1	VG	VG	G	VG	VG	VG	VG	G	G	G	G
	E2	VG	VG	VG	VG	VG	MG	MG	VG	MG	M	M
	E3	VG	G	VG	VG	VG	G	MG	G	G	MG	G
	E4	G	VG	VG	G	VG	VG	G	G	G	MG	MB
A5	E1	MG	G	VG	MB	MG	G	M	M	MB	MG	MG
	E2	MG	M	M	M	G	M	M	M	M	G	M
	E3	G	G	VG	VG	VG	MG	MG	G	G	G	G
	E4	MG	G	VG	VG	VG	VG	G	G	G	MG	M
A6	E1	G	MB	M	MG	VG	VG	G	MG	VG	VG	MG
	E2	G	MG	MG	MG	G	G	G	M	M	VG	G
	E3	MG	MG	G	MG	G	G	VG	MG	G	MG	G
	E4	G	MG	G	MG	VG	G	G	MG	MG	G	M

reviews of the experts. The framework and proposed methods are independent of the choice of use cases, evaluation criteria and number of expert reviews.

VI. CONCLUSION

This study presented two models – a T2NN based EDAS model and a T2NN based integrated WASPAS, MABAC, and CODAS model to evaluate and rank the use cases of an energy blockchain system. Comparison against a T2NN based CODAS approach is illustrated too to test the applicability of the two proposed models. Moreover, a sensitivity analysis is performed with a set of weights for each criterion to investigate the effect of the weightings on the ranking order of the alternatives. However, since the study uses only four experts' opinions, primarily academicians, the result does not reflect a comprehensive and representative ranking. Nevertheless, this work can be considered an early prototype of a functional decision-support tool that can incorporate a more diversified and higher number of expert opinions to yield better results.

This work aims to develop a methodology that can be used to prioritize the energy blockchain use cases. The proposed approach is based on advanced decision-making algorithms that can capture consensus-based expert opinion via a dedicated survey as an interface. The main contributions of this study are: (i) representing and handling higher degrees of uncertainties such as vagueness, imprecision, and inconsistency in the decision process of prioritizing energy blockchain under T2NNs, (ii) handling multiple uncertainties in the decision-making problem through a new type-2 neutrosophic fuzzy numbers (T2NN) based EDAS and hybrid model, and, (iii) proposing alternatives and evaluation criteria for energy blockchain use cases.

The energy blockchain use cases considered in this work represents a small subset of numerous possible use cases of DLT for power systems. Also, the set of criteria used is limited, and the formulation has been tested with only four survey results. Therefore, wider adoption of the presented formulation will require evaluating the proposed models with more use cases, a broader set of criteria and more survey results, which will increase the complexity of the calculation. One path to resolve This limitation will require solving the presented algorithm with more user-friendly software. Secondly, the λ value for Model-II does not affect the results after a certain value which may depend upon the use of chosen values shown in Table 1 and Table 2.

The future research includes using Type-3 and higher Neutrosophic Numbers, extending the model using Pythagorean Fuzzy sets [67], using MACBETH or Best Worst Method to calculate criterion weights instead of T2NN score function, and more. These approaches are well-known approaches in decision-making to determine criteria weights. Further comparison will be completed by applying the EDAS method to calculate the alternatives. Moreover, the authors are currently working on extending the scope of the work by adding more use cases and criteria while increasing the collected survey results. Furthermore, the developed models can also be applied in other decision-making problems such as transportation, manufacturing, healthcare management, business management, and other management decisions problems.

APPENDIX A DATA USED FOR IMPLEMENTING T2NN

See Tables 13 and 14.

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