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Blockchain Service Provider Selection Based on an Integrated BWM-Entropy-TOPSIS Method Under an Intuitionistic Fuzzy Environment

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ABSTRACT The emergence of blockchain technology has significantly changed the underlying infrastructure of existing information technology and will fundamentally affect the production modes of enterprises. However, because the application of blockchain is still in its infancy, it is difficult for an enterprise to develop a comprehensive assessment of various types of blockchain service providers in the market. Hence, enterprises need scientific decision tools to estimate which blockchain service provider is appropriate. However, few studies have focused on this phenomenon. Therefore, to address this challenge, this investigation proposes a novel integrated multi-attribute group decision-making (MAGDM) method to help enterprises estimate which blockchain vendor is more appropriate by considering more comprehensive influence factors. The proposed method is defined in an intuitionistic fuzzy environment and integrates entropy and the best-worst method (BWM) for comprehensive weighting of decision makers (DMs), subjective criteria and objective criteria in the decision-making process to make the decision results more reliable and reasonable. A numerical example and comparison are provided to illustrate the practicability and usefulness of the method. This study enriches the theory and methodology of blockchain technology and MAGDM analysis.

INDEX TERMS Blockchain, BWM, entropy, intuitionistic fuzzy set, TOPSIS.

I. INTRODUCTION

Blockchain is a technology that has the potential to disrupt many industries and organizations. With its diverse applications and rapid development, blockchain technology will exert influence on many industries and organizations, forcing them to rethink their strategies and capabilities while reshaping global economic systems, orders and infrastructure modes [1]. According to blockchain white papers, there are numerous opportunities for disruptive technologies, and the revolution in this area has just begun. Blockchain technology has been characterized as secure, which makes it attractive and reliable for application in many areas [2]. Blockchain is an essentially decentralized distributed database system consisting of a series of data blocks connected in timestamp order [3]. Each data block in the system contains multiple valid transaction confirmations between network nodes. Technically, the blockchain is not a single technological innovation but a distributed bookkeeping technology realized after the deep integration of many technologies [4], [5], including consensus mechanism, peer-to-peer (P2P) network technology, chain script and asymmetric encryption technology [6]. Blockchain technology uses an encrypted block structure to verify and store data [7]. P2P technology and consensus mechanisms are used to realize distributed node authentication communication and establish trust relationships. The chain script can realize the automation of the data chain through the data automation operation and the complex business logic function, thus forming a new data record storage and expression method. A survey of existing literature shows that blockchain technology has many desirable characteristics, including shared and public trust, low friction, peer verification, cryptography, immutability, decentralization, automation, and redundancy [8]–[10].

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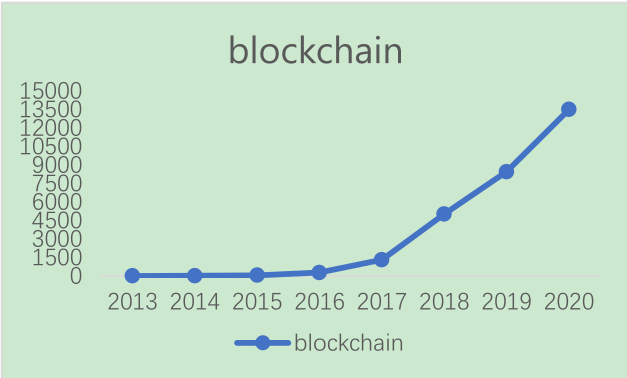

FIGURE 1. Statistics on the number of papers published with blockchain as the theme.

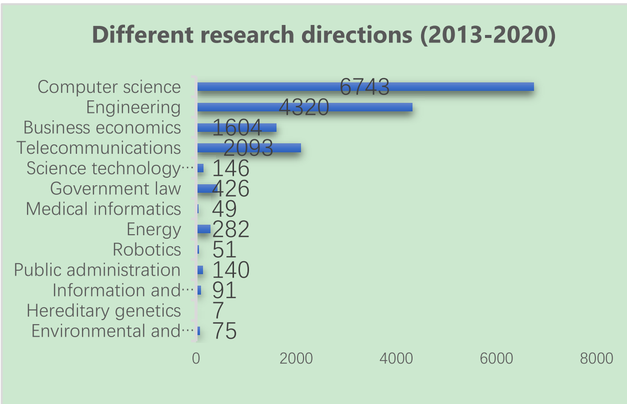

FIGURE 2. Different research directions and statistics on blockchain from 2013 to 2020.

Blockchain, as a technological means, was first promoted by industry to promote research and development, but only in recent years has it attracted wide attention from the academic community. As shown in Figure 1, from 2013 to 2020, 13497 retrieval results can be obtained from the Web of Science database. The number of research papers on blockchain technology has been growing rapidly in the past five years. Related fields include computer science [7], finance [11], e-commerce [1], [12], Internet [13], [14], Internet of Things (IoT) [15], [16], government [17], supply chain management [3], [18], digital medicine [10], [19], [20], energy [21], [22], and education [23], [24]. Figure 2 shows the relevant data. It can be predicted that with the evolution of network information technology, the use of blockchain will become increasingly popular and be applied to more fields [25].

Currently, blockchain technology is considered to be a tool that can make organizations more transparent, democratic, decentralized, effective and secure, can handle many unexpected applications, and can greatly expand the world of cryptocurrencies [1]. At present, blockchain has been applied in food, mining, banking, medicine, automobiles, energy, etc., but its practical application can extend far beyond these sectors. Companies applying blockchain technology are often ahead of other companies in the same industry, as is the case with BCG digital ventures, IBM, BP, etc. BCG digital ventures and WWF Australia have jointly developed a new blockchain food tracking platform, which uses cutting-edge technology to track the whole process of products from origin to consumers. The aim is to help businesses and consumers avoid illegally processing, damage to the environment and the production of unethical products, while improving accountability and transparency in the supply chain. IBM has collaborated with MineHub to use blockchain technology to improve supply chain management in the metals and mining industries. The solution aims to address the low efficiency in the global mining and metals markets due to immoderate paperwork and manual processing and lower transparency among supply chain partners. Leading global oil companies such as BP, Shell and Equinor have jointly established a block chain digital trading platform with large banks and trading companies for trading energy products.

Through literature review and practical examples, it can be seen that blockchain technology is popular in most industries. Even in industries that we never thought would be subverted, blockchain technology also shows great influence. There may be great changes ahead for the service provider selection problem in a blockchain environment, and it is therefore quite rational to study this type of problem. Moreover, the selection of appropriate blockchain service providers is directly related to the performance and success of an enterprise. To seek progress and development, enterprises will choose to cooperate with competent companies to develop blockchain technology and regard these companies as their own blockchain service providers. Therefore, how should enterprises measure the strength of technology companies? How should they choose appropriate blockchain service providers among many technology companies? To address these problems, we conducted this study. Our study contributes to the present research in two ways: (1) In the performance criteria aspect, we propose a four-dimensional evaluation criterion for blockchain service providers, and this criterion comprehensively measures the performance of blockchain service providers from multiple dimensions; (2) In the decision approach aspect, we present a novel multi-attribute group decision making (MAGDM) approach to solve the decision problem. This method improves the existing weight calculation method and determines the weights, considering the attributes of blockchain service suppliers both objectively and subjectively.

The organization of this article is structured as follows: The section 2 is related work. The section 3 puts forward the evaluation criteria for blockchain service providers. Section 4 introduces the methods and steps proposed in this paper. Section 5 compares this method with other methods. Section 6 provides a numerical example, and the last section is the conclusion of this paper.

II. RELATED WORK

A. BLOCKCHAIN TECHNOLOGY

Blockchain technology is a kind of technology that records and maintains a reliable transaction database collectively in a certain time sequence through distributed decentralization; that is, a public transaction data recording technology that combines data blocks into a chain data structure by means of distributed nodes in a certain time sequence [7], [13]. Its core essence is not to rely on the central organization to establish a trust mechanism without a trust foundation. It can complete the social value transfer without relying on the central organization and further change the existing social value transfer mode [26].

Compared with the traditional IT architecture, blockchain technology has a few unique characteristics [6], [27]: 1.Distributed database: Each block in the chain includes the full audit trail of all transactions to provide access to the entire database. The data within the entire database is not be controlled by either party and can testify the transaction information on the network with no need for a third trusted party; 2.Point-to-point communication: Each block communicates with other blocks on the network, and each ledger stores the data and transmits this information to all other linked blocks; 3. Accessibility: Each transaction and related data are accessible for all parties on the network and include unique blockchain addresses; 4. Immutability: The data stored in the blockchain is unchangeable and available to all nodes, because the data are duplicated on all blocks in the network; 5. Computational logic: Through the use of encryption algorithms, transactions can be triggered automatically with no need for any regulation from a central node.

In addition, there are three deployment modes for blockchain technology, according to [28]–[30]:

(1) Private blockchain, which is usually managed within an organization. The data-associated verification nodes are accessible and identifiable by a central database of the organization. This kind of blockchain deployment model is adopted by many financial institutions.

(2) Public blockchain, where anybody can take part in the verification process with no need for authorization. The service providers are often rewarded by computer resource utilization. This deployment model is a cost-effective way to deploy blockchain solutions, especially for small or medium sized businesses.

(3) Community blockchain, which is used and controlled by a group of organizations participating in the same ecological chain or supply chain and that have shared interests, such as a common mission or specific security requirements. In this deployment model, it is difficult to use a public or private blockchain solution alone. Therefore, a combination of public and private blockchain solutions is necessary.

The application of blockchain has become increasingly popular. Well-known blockchain providers, including big names such as Microsoft, IBM, Google, Amazon, Tencent, Alibaba, Huawei and so on, have successively launched their BaaS (Blockchain as a service) over the last two years. These blockchain businesses cover private, public and community blockchain services. For example, Hyperledge and Ethereum offer open-source blockchain platforms that can be applied as universal blockchain-based distributed ledgers to build public blockchains [8], [28]. IBM developed a private blockchain-based IT solution for Walmart to improve traceability of food items. With the blockchain-based system, Walmart has significantly improved the transparency of both international and domestic supply chains [28]. Hainan Airlines (HNA) group in China developed a community blockchain-based system to help its staff purchase products directly from third party suppliers. Over 2000 suppliers have participated the system, which is considered to be a successful blockchain practice implementation [1].

Based on the technical features and principles of blockchain, many scholars have participated in the investigation of blockchain, which has enriched the application connotation of blockchain [7]. Blockchain in the financial industry can make financial services more decentralized, innovative, interoperable, borderless and transparent [31], provide evidentiary records and information release for untrusted scenarios in the industrial Internet of Things [32], and help solve network threat problems such as information leakage or piracy in the 5G network environment [14]. Furthermore, the resource sharing system developed based on blockchain technology can be applied to improve the efficiency of e-commerce, logistics, real estate services [1], [12], medical data sharing [10], [19], [20], food safety traceability [33], etc.

However, although blockchain has many advantages, the application of blockchain is still in its infancy, and many businesses have remaining doubts. A survey conducted by PWC (PricewaterhouseCoopers) indicates that regulatory uncertainty (48%), lack of trust (45%) and whether the block chain network can be connected (44%), constitute major barriers to blockchain adoption [34]. Hence, is all blockchain service truly suitable for each organization at this stage? The answer is maybe not. The private, public and community blockchains all have their own advantages and disadvantages. Therefore, organizations should apply a scientific decision-making tool to estimate which blockchain service provider is more appropriate by considering both economics and other relevant factors.

B. MAGDM (MULTI-ATTRIBUTE GROUP DECISION MAKING)

At present, there are few studies on the selection of blockchain service providers. Enterprises need to use scientific evaluation tools to identify attributes and operational capabilities of different enterprises and then select appropriate blockchain service suppliers as reliable partners. Because it involves quantitative and qualitative factors, the blockchain service provider selection decision problem is a multi-attribute group decision-making problem (MAGDM) in essence. A lot of previous studies have applied such approaches to research IT/IS service provider selection problems. For example, Yang and Huang [35] applied the analytic hierarchy process (AHP) technique with the evaluation criterion of quality, management, economics, technology and strategy to choose the best IS provider. Wang and Yang [36] presented a MAGDM technique

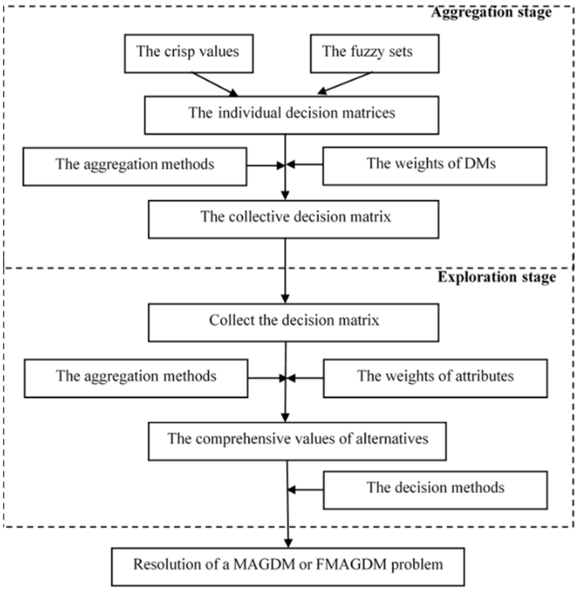

FIGURE 3. The basic process of resolving a MAGDM/FMAGDM problem.

that integrates PROMETHEE and AHP to study the IS/IT provider selection problem. Chen and Wang [37] proposed a fuzzy VIKOR approach to choose the best IS vendor. Chang *et al.* [38] integrated the AHP and Delphi techniques for an assessment model for SMEs to choose the best IT/IS service provider. Since the advent of cloud computing, many scholars have also used the MAGDM approach to deeply analyse the cloud service provider selection problem and achieved fruitful results. For instance, Liu *et al.* [39] proposed a combined MAGDM approach based on statistical variance (SV) and an improved TOPSIS to solve the cloud vendor selection problem. Nawaz *et al.* [40] developed an integrated Markov chain and a best-worst method-based MAGDM to select a cloud service. Sohaib *et al.* [41] proposed a new 2-tuple fuzzy linguistic MAGDM method combined with TOPSIS for cloud service selection by e-commerce enterprises.

MAGDM refers to a method in which the decision maker selects the optimal scheme or ranks each alternative, for a finite number of alternatives, by some criterion on the basis of considering multiple attributes and measuring their attribute values. Generally, the solution of the MAGDM and FMAGDM problems are composed of two phases: aggregation and exploration [42], [43]. In the aggregation phases, the decision makers (DMs) choose suitable language sets on basis of crisp values or a varied fuzzy sets, leading to a MAGDM or FMAGDM problem. Figure 3 indicates the basic process of solving a MAGDM/FMAGDM problem [44], [45].

From the above analysis, we can determine that there are four key steps in MAGDM problems:

(1) Determining the DMs weights. The DMs weights can be specified by the decision maker directly according to experience and preference [46] or calculated by a decision maker matrix [47]–[50]; (2) Determining the weights of attributes. There are mainly two types of research on attribute weights. One is when the weights are completely unknown, such as in [51] and [52]. The other is when information about attribute weights is incomplete; that is, the partial weights of attributes are known, such as in [53]–[56] etc.; (3) Selection of aggregation techniques. After the weights of experts and attributes are determined, different aggregation techniques are adopted to aggregate the individual decision matrix provided by experts into a comprehensive value evaluation system. Settlers are commonly used aggregation methods, for instance interval intuitionistic fuzzy arithmetic/geometrically weighted average operators [57]–[59], continuous interval intuitionistic fuzzy aggregation operators [60], arithmetic interval intuitionistic fuzzy generalized A-Shapley Choquet operators [61], and mixed weighted geometric operators [60]. (4) Selection of decision-making methods. At present, the existing decision-making methods can be divided into three types: an ideal solution [62], higher level than the method higher level than the method [63], [64]and the entropy weight method [52], [65].

It is easy to see that weighting for DMs and attributes in the decision-making process plays a vital role in both the aggregation and exploration stages. Hence, we focuses on the weighting methods for DMs and attributes in MAGDM. TABLE 1 reviews the representative literature on the computation of DM weights and attributes weights in MAGDM and FMAGDM.

By analysing the existing literature, we find the following limitations in the research field of weight calculation: (1) The rationality of both attribute weight and decision maker weight has a great influence on the accuracy of scheme ranking. However, scholars tend to consider only one type of weight when studying MAGDM problems. Few scholars consider weights simultaneously. (2) In the process of calculating the attribute weights, the objective facts are ignored using a single subjective method, and the opinions of DMs are ignored by applying a single objective method, failing to strike a balance between the objective facts and the suggestions of DMs. (3) Scholars consider the weights of DMs and attributes when one is known to solve the other but not to solve the problem when both sides are unknown.

In view of the above limitations, this paper improves the existing weight calculation method and proposes an optimal combination weighting technique to synthesize the information of multiple objective and subjective weights in the case of unknown attribute and decision-maker weights. We propose a method that integrates BWM, entropy and TOPSIS and can be classified as below steps: First, the DM opinions on alternatives are collected, and the decision matrix is calculated by using entropy to obtain the DMs weights. Second, the DMs weights and the decision matrix are synthesized by an intuitionistic fuzzy weighted average (IFWA) operation, and then the weights of subjective and objective attributes are obtained by using BWM and entropy weight, respectively. Finally, the intuitionistic fuzzy definition is used to combine

TABLE 1. Literature review of determination of weights of DMs and attributes.

Research field	Article	Method	Main research content
Determining the weights of DMs	[46]	Subjective giving	provided directly by the DMs based on their experience and preferences
	[47]	TOPSIS	defined the positive ideal matrix and a negative ideal matrix, calculated the closeness between the single-player decision matrix and the positive ideal matrix to determine the weights of DMs
	[48]	Entropy	used the entropy theory to determine the weights of DMs
	[49]	TOPSIS	used the distance between each expert and the decision matrix to determine the weights of DMs.
	[50]	AHP	established evaluation matrix to compare difference among DMs
Determining the weights of attributes	[51]	TOPSIS multi-objective nonlinear programming	solved the attribute weight with the help of TOPSIS idea and multi-objective nonlinear programming model
	[52]	Entropy	proposed a new method to determine attribute weights based on information entropy
	[53]	Interval intuitionistic fuzzy	set up a programming model to solve the attribute weight by maximizing the comprehensive value evaluation scheme
	[54]	Interval-valued intuitionistic fuzzy	set up a bi-objective programming model to determine the attribute weight by maximizing the consistency index and minimizing the inconsistency index
	[55]	TOPSIS	built a linear model to maximize the closeness coefficient of each scheme and obtained the attribute weights
	[56]	A linear programming model	by maximizing the comprehensive score of the scheme, a linear programming model was established to solve the attribute weights

the final weight with the decision matrix, and TOPSIS is used to calculate the comprehensive evaluation value of multi-blockchain service providers. Our work not only take the subjective and objective weights of the attributes into consideration but also considers the objective weights of the DMs, thereby making the decision result more rational and accurate.

We integrate BWM, entropy and TOPSIS in our method mainly for the below reasons: (1) Compared with other MAGDM methods, BWM requires fewer pairwise comparison data and has obvious advantages such as strong reliability and consistency of simple data processing results [66]; (2) The entropy method computes the weight of each criterion or decision support system through the degree of change of each criterion data point. The entropy weight method avoids the interference of subjective factors and has strong objectivity [67], [68], which is also a key reason for using this method in this paper;(3) The decision principle underlying the TOPSIS method is simple, and the calculation process is easy to realize [39], which provides an effective solution for complex decision problems [69]. Therefore, based on the above analysis, the integration of BWM, entropy and TOPSIS is recommended because it is well-suited to the selection of blockchain service providers.

III. THE EVALUATION CRITERIA FOR BLOCKCHAIN SERVICE PROVIDER SELECTION

The operation of blockchain service providers relies on blockchain technology to suit different companies' demands, including making intelligent contracts, providing customized development services and helping enterprises design blockchain applications with specific business logic.

With the involvement of blockchain service providers, companies can deal with intelligent contracts efficiently, orchestrate daily operational issues fluently, and enhance the information (document chain, information security, tampering protection, credible endorsement) security level substantially. Technical support via blockchain digitizes real assets and approval in a fashion of digital contracts and ensures the transparency of products and information circulation. At present, there are few studies on the selection of blockchain service providers. However, an increasing number of companies have realized that to make full use of their potential, they must have the aid of blockchain technology. Therefore, it is vital for them to find a reliable blockchain service provider to facilitate operations and seize business opportunities professionally, economically and efficiently.

In this study, we propose criteria from four dimensions to evaluate the performance of blockchain service providers, including service support capability, green development capability, integration capability of blockchain with the IoT, and technological capacity.

A. SERVICE SUPPORT CAPABILITY

Companies are committed to creating and maintaining effective customer retention programmes [70], especially in the Internet service provider industry. Enterprises must develop competitive service plans to retain customers [71], which for blockchain service providers need to be based on service support capabilities. Blockchain technology has many advantages and has achieved fruitful research results, but there are still many problems in the application and implementation of blockchain technology in various industries and services [72]. After the application of blockchain technology, enterprises need more professional blockchain service providers to offer professional support technically and operationally, but the problem for enterprises is that blockchain technology supplied by service providers has not yet matured. This lack of development is a challenge for blockchain service providers that requires a good assessment method, which can help customers quickly screen unqualified service providers who do not offer prolonged serviceability. The problems to be solved by blockchain service providers include the following: (1) Security of the blockchain platform [73]: mainly including the security of the blockchain itself and the security of the user accounts. (2) Anonymity and privacy [4]: One of the advantages of blockchain technology is public anonymity, but in digital cryptocurrency, as far as the actual situation is concerned, real anonymity and secure privacy cannot be achieved [5]. (3)Technical barriers: blockchain, as an emerging technology, has security issues such as the time confirmation of blockchain data, majority attacks (51% attacks), and regulation problems [8]. Blockchain is a distributed general ledger system that adds data but does not delete it. It still has many shortcomings and requires improvements in data processing. Due to the limitation of block capacity, large-scale data cannot be stored, which also limits the application of blockchain technology. Although blockchain technology has improved recently, there are still relevant technical regulatory measures and issues because of the absence of general guidance for technical applications and of core technical concept references in various industries at present. Blockchain service providers must respond to these problems.

B. GREEN DEVELOPMENT CAPABILITY

In recent years, the issue of green development has been a concern of academia and industry [74]. The establishment and implementation of a green Internet of Things has been one of the primary tasks of industrial development in various countries. For a blockchain service provider, having green development ability is the premise and foundation of responding to social development. First, with the application of blockchain technology in the industrial IoT, the information system will consume much energy and increase carbon emissions [75]. Enterprises need to effectively use energy or reduce emissions to achieve a green Internet of Things environment [76]. Second, green is the direction of future supply chain development and is critical to comprehensively evaluating the performance of enterprises [77]. With the improvement of public environmental awareness, the commitment of enterprises to environmental protection will attract public attention. In response to public appeals for environmental protection and compulsory government regulations, enterprises must take responsibility for preserving the environment by offering green services and products and actively reducing waste by managing randomly distributed energy to gain a competitive edge [78].

C. INTEGRATION CAPABILITY OF BLOCKCHAIN AND IOT

Blockchain technology has enormous potential in the IoT revolution and is seen as key to addressing scalability, privacy and reliability issues associated with the IoT paradigm [79], [80]. The integration of blockchain and IoT will identify, select, absorb, configure and organically integrate resources of different sources, levels, structures and contents, making them more flexible, organized, systematic and valuable. Blockchains can be used in the IoT to address privacy preferences, manage device configurations, store sensor data and support micropayments [80]. Through the integration and reconfiguration of resources, multiple participants can cooperate. Blockchain can provide reliable sharing services and accurate and traceable information for the IoT. Raw data can always be stored and identified at any time, but it cannot be tampered with, thus improving security [81]. For example, the thorough traceability of multiple foods is a key aspect of ensuring food safety [82], [83]. Food traceability requires the involvement of many participants: production, feeding, treatment, marketing, and so on. Any data leakage in the supply chain could lead to counterfeit or defective products. Once problems occur, they may seriously affect the lives of citizens and bring considerable economic losses to enterprises, industries and countries. The integration of blockchain and IoT will bring many benefits to both partners, including decentralization, scalability, autonomy, reliability, security, and secure code deployment. These are undoubtedly conducive to the development of partnerships. In our view, the IoT can benefit from the capabilities provided by blockchain and stimulate the development of IoT technologies.

D. TECHNOLOGICAL CAPACITY

With the rapid development of society, enterprises will sooner or later face the decision to choose Internet service providers [71]. In the selection process, enterprises must focus on technical attributes, because technology can directly reflect the technological innovation and research productivity of enterprises and can also greatly improve the comprehensive competitiveness of enterprises [84]. Technological capacity, as a component of a blockchain development strategy, is a critical element when selecting reliable blockchain service suppliers. With adequate technological advice, a blockchain service platform can function well, ensuring information transparency, monitoring and avoiding data abuse, protecting the network from attack, providing a coordination mechanism and generating more value on the whole chain. Service providers who master core technologies can provide a sharing platform for enterprises, which can offer transparent and accurate interactions by defining coded contracts, sharing interaction results and reducing transaction costs. Blockchain service providers who can develop this technology will be more likely to help enterprises realize trust and decentralization, assist enterprises to form a collaborative environment, and create credibility through a transparent and characteristic environment so that information can be accessed by the whole network publicly while processing and monitoring a large amount of information efficiently without affecting integrity or invariance of data. This capability can also lead to greater standardization and automation for customers [85]. This capability is expected to have a broad impact on existing service systems and contribute to the informatization procedure of service systems.

IV. METHODOLOGY

This section describes a method based on the integration of BWM, entropy and TOPSIS methods under the condition of an intuitionistic fuzzy environment. Before we start the steps, the decision expert group needs to determine the goal, alternatives, criteria, and linguistic terms for rating both the criteria and the alternatives.

The meanings of notations involved in this method are shown in Table 2.

A. DETERMINE THE INTUITIONISTIC FUZZY PREFERENCE RELATIONS (IFPRs) AND INDIVIDUAL DECISION MATRIX R_K

As an extended form of traditional fuzzy sets, intuitionistic fuzzy sets were developed by Atanassov [86]. The advantage of intuitionistic fuzzy sets (IFS) is that the preference information between the two alternatives is expressed by the membership degree, non-membership degree and hesitation degree on a scale from 0 to 1, which can better reflect the degree of approval, opposition and hesitation of DMs. In this section, several IFS definitions and operations are explained.

Definition 4.1. [86] Let X be a universal set and an IFS $\tilde{r}$ in X can be defined as

$$\tilde{r}\,\{(x, u_{\tilde{r}}(x), v_{\tilde{r}}(x))|x \in X\} \tag{1}$$

where $u_{\tilde{r}} : u_{\tilde{r}} \in [0,1]$, $X \rightarrow [0,1]$, $v_{\tilde{r}} : v_{\tilde{r}} \in [0,1]$, $X \rightarrow [0,1]$, $u_{\tilde{r}}$ and $v_{\tilde{r}}$ are membership and non-membership functions of an intuitionistic fuzzy set, respectively. $u_{\tilde{r}}(x)$ and $v_{\tilde{r}}(x)$ are degrees of membership and non-membership functions, respectively, satisfying

$$0 \leq u_{\tilde{r}} + v_{\tilde{r}} \leq 1, \quad \forall x \in \tilde{r} \subset X \tag{2}$$

In addition, $\pi_{\tilde{r}} = 1 - u_{\tilde{r}} - v_{\tilde{r}}$ is defined as the intuitionistic index used to measure the degree of hesitation. The elements composed of membership degree, non-membership degree and hesitation degree are called intuitionistic fuzzy numbers [87], [88], which can be expressed as $r = (u, v, \pi)$.

Definition 4.2. Let X be a universal set, r_1 and r_2 be the IFS of set X; then, the calculation rules are as follows [87]–[89]:

$$(1)\ r_1 \oplus r_2 = (u_1 + u_2 - u_1u_2, v_1v_2, (1-u_1)(1-u_2) - v_1v_2); \tag{3}$$

$$(2)\ r_1 \otimes r_2 = (u_1u_2, v_1 + v_2 - v_1v_2, (1-v_1)(1-v_2) - u_1u_2); \tag{4}$$

TABLE 2. Notation in this article.

Notations	Definitions of notations
$A=\{A1,\ldots Ai,\ldots Am\}$	The set of alternatives; m alternatives
$C=\{C1,\ldots Cj,\ldots Cn\}$	The set of criteria; n criteria
$\alpha=\{\alpha_1,\ldots\alpha_k,\ldots,\alpha_p\}$	The set of DMs; p DMs
R_k	Individual decision matrix of α_k
$E^{IFS}(R_k)$	The entropy value of α_k
d_{R^k}	The degree of divergence
w_d^k	The weight of α_k
$w_d=\{w_d^1,w_d^2,\ldots,w_d^p\}$	Set of the weights of the DMs
$\bar{R}$	A group decision matrix that aggregates the weights of DMs
F	0-1 matrix; used to determine the best and worst criteria
$a_{best,worst}$	The relative preference of best criterion to criterion worst
A_{best}^k	The best comparison vector of α_k
A_{worst}^k	The worst comparison vector of α_k
ξ^k	Minimum value of objective function when Calculating $w_s{}^k$
$w_s{}^k=\{w_s^1,w_s^2,\ldots,w_s^n\}$	The subjective weight set of criteria obtained by α_k
$w_s{}^j(0\leq j\leq n)$	Subjective weight of criterion j
$w_s=\{w_s^1,w_s^2,\ldots,w_s^n\}$	The set of subjective weights of criteria
$E^{IFS}(\bar{r_j})(j=1,2,\ldots n)$	The entropy value of Cj
$d_j(j=1,2,\ldots n)$	The degree of divergence
$\omega_o^j\,(j=1,2,\ldots n)$	Objective weight of Cj
$w_o=\{w_o^1,w_o^2,\ldots,w_o^n\}$	The set of objective weights of criteria
$\beta(0\leq\beta\leq1)$	Weight coordination coefficient
$w_j\,(j=1,2,\ldots n)$	Final weight of Cj; Integrated subjective and objective weights
$W=\{w_1,w_2,\ldots w_n\}$	The final set of criteria weights
$\bar{\bar{R}}$	Group decision matrix integrated W
Z_j^+	Intuitionistic fuzzy positive ideal solution
Z_j^-	Intuitionistic fuzzy negative ideal solution
$d_i^+\,(i=1,2,\ldots m)$	The distance between Ai and positive ideal solution
$d_i^-\,(i=1,2,\ldots m)$	The distance between Ai and negative ideal solution
$CC_i\,(i=1,2,\ldots m)$	The relative closeness coefficient of Ai

$$(3)\ \lambda r_1 = \left(1-(1-u_1)^{\lambda}, v_1^{\lambda}, (1-u_1)^{\lambda} - v_1^{\lambda}\right), \lambda > 0; \tag{5}$$

$$(4)\ r_1^{\lambda} = \left(u_1^{\lambda}, 1-(1-v_1)^{\lambda}, (1-v_1)^{\lambda} - u_1^{\lambda}\right), \lambda > 0; \tag{6}$$

(5) The Euclidean distance:

$$d_E(r_1, r_2) = \sqrt{\frac{1}{2}\sum_{j=1}^{n}\left[a^2 + b^2 + c^2\right]}; \tag{7}$$

The normalized Euclidean distance:

$$d_{nE}(r_1, r_2) = \sqrt{\frac{1}{2n}\sum_{j=1}^{n}\left[a^2+b^2+c^2\right]}; \quad (8)$$

where

$$a = u_{r1}(x_j) - u_{r2}(x_j);\, b = v_{r1}(x_j) - v_{r2}(x_j);\, c = \pi_{r1}(x_j) - \pi_{r2}(x_j).$$

According to the concept of an intuitionistic fuzzy set and the linguistic terms for rating the alternatives, k DMs evaluate each alternative with reference to each criterion, forming the individual decision matrix R^k.

$$\mathrm{R}^k = \left(\mathrm{R}_{ij}^k\right)_{m\times n} = \begin{bmatrix} r_{11}^k & \cdots & r_{1n}^k \\ \vdots & \ddots & \vdots \\ r_{m1}^k & \cdots & r_{mn}^k \end{bmatrix} = \begin{bmatrix} \left(u_{11}^k, v_{11}^k, v\pi_{11}^k\right) & \cdots & \left(u_{1n}^k, v_{1n}^k, \pi_{1n}^k\right) \\ \vdots & \ddots & \vdots \\ \left(u_{m1}^k, v_{m1}^k, \pi_{m1}^k\right) & \cdots & \left(u_{mn}^k, v_{mn}^k, \pi_{mn}^k\right) \end{bmatrix} \quad (9)$$

B. DETERMINE THE WEIGHTS OF DMS

The fuzzy degree of IFS can be described by if-entropy. The greater the if-entropy of the evaluation criteria, the greater the fuzzy degree of the judgement information provided by the criteria, the smaller the weight should be that is given; otherwise, the larger the weight should be that is given. The fuzzy degree of if-entropy considers both uncertainty and unknown degree, in which the deviation between membership degree and non-membership degree reflects the uncertainty degree, and hesitation degree reflects the unknown degree. The equation for calculating if-entropy is defined as [90]:

$$E^{IFS}(r) = -\frac{1}{m\ln 2}\sum_{i=1}^{m}\left[u_i \ln u_i + v_i \ln v_i - (1-\pi_i)\ln(1-\pi_i) - \pi_i \ln 2\right] \quad (10)$$

In this paper, Eqs. (11), (12) and (13) are used to compute the weights of DMs by entropy for each R^k. In these formulas, R^k indicates the individual IF-decision matrix of α_k. Eq. (11) is used to measure the entropy value of each criterion. Where $j = 1,2,\ldots n$; $i = 1,2,\ldots m$, and if $u_{ij} = 0, v_{ij} = 0, \pi_{ij} = 1$, then we have $u_{ij}\ln u_{ij} = 0$, $v_{ij}\ln v_{ij} = 0$ and $\left(1-\pi_{ij}\right)\ln\left(1-\pi_{ij}\right) = 0$.

$$\mathrm{E}^{IFS}\left(R^k\right) = -\frac{1}{\mathrm{mnln2}}\sum_{j=1}^{n}\sum_{i=1}^{m}\left[u_{ij}\ln u_{ij} + v_{ij}\ln v_{ij} - \left(1-\pi_{ij}\right)\ln\left(1-\pi_{ij}\right) - \pi_{ij}\ln 2\right] \quad (11)$$

The degree of divergence is calculated according to Eq. (12).

$$d_{R^k} = 1 - E_{LT}^{IFS}\left(R^k\right) \quad (12)$$

Eq. (13) is used to calculate the weights of DMs. We can obtain the set $w_d = \left\{w_d^1, w_d^2, \ldots, w_d^p\right\}$, where $w_d^k \geq 0$, and $\sum_{k=1}^{p} w_d^k = 1$.

$$w_d^k = \frac{d_{R^k}}{\sum_{k=1}^{p} d_{R^k}} \quad (13)$$

C. DETERMINE THE IFPR DECISION MATRIX $\overline{R}$

We use the IFWA operator in Eq. (14) to aggregate the decision matrix R^k of each DM into a group decision matrix R, which is represented by Eq. (15).

$$\begin{aligned}\overline{r_{ij}} &= \mathrm{IFWA}w_{\mathrm{d}}\left(r_{ij}^1, r_{ij}^2, \cdots, r_{ij}^k\right) \\ &= w_d^1 r_{ij}^1 \oplus w_d^2 r_{ij}^2 \oplus \cdots \oplus w_d^k r_{ij}^k \\ &= \left[1 - \prod_{k=1}^{k}\left(1-u_{ij}^k\right)^{w_d^k}, \prod_{k=1}^{k}\left(v_{ij}^k\right)^{w_d^k}, \prod_{k=1}^{k}\left(1-u_{ij}^k\right)^{w_d^k} - \prod_{k=1}^{k}\left(v_{ij}^k\right)^{w_d^k}\right]\end{aligned} \quad (14)$$

$$\overline{\mathrm{R}} = (\overline{r})_{m\times n} = \begin{bmatrix} \overline{r_{11}} & \cdots & \overline{r_{1n}} \\ \vdots & \ddots & \vdots \\ \overline{r_{m1}} & \cdots & \overline{r_{mn}} \end{bmatrix} = \begin{bmatrix} \left(\overline{u_{11}}, \overline{v_{11}}, \overline{\pi_{11}}\right) & \cdots & \left(\overline{u_{1n}}, \overline{v_{1n}}, \overline{\pi_{1n}}\right) \\ \vdots & \ddots & \vdots \\ \left(\overline{u_{m1}}, \overline{v_{m1}}, \overline{\pi_{m1}}\right) & \cdots & \left(\overline{u_{mn}}, \overline{v_{mn}}, \overline{\pi_{mn}}\right) \end{bmatrix} \quad (15)$$

D. SUBJECTIVE WEIGHTING FOR CRITERIA

Rezaei [91] proposed the BWM, which selects the best and worst criteria and then compares the other criteria with these two criteria. The optimal weight is determined by establishing the optimal model aiming at the optimal consistency.

1) DETERMINATION OF THE BEST AND WORST CRITERIA USING A 0-1 MATRIX

Suppose that there exist n criteria, members of set $A = (A_1, A_2 \ldots A_n)$. Compare the importance between A_g and A_b and use f_{gb} to show the degree of importance. If A_g is more important than A_b, then we can let $f_{gb} = 1$ and $f_{bg} = 0$. If $\mathrm{A_b}$ is more important than A_g, $f_{gb} = 0$ and $f_{bg} = 1$. If $\mathrm{A_b}$ and $\mathrm{A_g}$ are equally important, then $f_{gb} = f_{bg} = 1$. Then, the importance ranking matrix of the criterion values is:

$$\mathrm{F} = f_{\mathrm{n}\times n} = \begin{bmatrix} f_{11} & \cdots & f_{1n} \\ \vdots & \ddots & \vdots \\ f_{n1} & \cdots & f_{nn} \end{bmatrix}, \quad g,\ b = 1, 2, \ldots n \quad (16)$$

Calculate the rows of the F matrix and arrange them from largest to smallest, then determine the best and worst criteria. The greatest value corresponds to the best criterion, and the smallest value corresponds to the worst criterion. In this paper, the 0-1 matrix will be determined by the decision maker with the largest weight.

TABLE 3. Consistency Index (CI).

$a_{best,worst}$	1	2	3	4	5	6	7	8	9
CI	0	0.44	1.0	1.63	2.3	3.0	3.73	4.47	5.23

2) DETERMINE THE COMPARATIVE VECTORS AMONG CRITERIA BY THE DMs

After gaining the best and worst criteria, each DM compares the other criteria with the best and worst criteria by using the linguistic terms for rating the criteria, and we obtain the comparison matrix of experts as follows:

$$A^k_{best} = \left(a^k_{best,1}, a^k_{best,2}, \ldots a^k_{best,n}\right) \tag{17}$$

$$A^k_{worst} = \left(a^k_{1,worst}, a^k_{2,worst}, \ldots a^k_{n,worst}\right)^T \tag{18}$$

3) DETERMINATION OF SUBJECTIVE WEIGHTS OF CRITERIA

Through the comparison matrix of each DM, model (19) was established and calculated k times. Then, we obtain set $w^k = \left(\left(w^1\right)^{\mathrm{k}}, \left(w^2\right)^{\mathrm{k}}, \ldots. \left(w^n\right)^{\mathrm{k}}\right)$, which expresses the subjective weights of criteria by the kth decision maker α_k.

$$\begin{aligned} &\min \xi^k \\ &\left|\frac{\left(w^{\text{best}}\right)^{\mathrm{k}}}{\left(w^j\right)^{\mathrm{k}}} - a^k_{best,j}\right| \le \xi^k, for\ all\ j \\ &\left|\frac{\left(w^j\right)^{\mathrm{k}}}{\left(w^{worst}\right)^{\mathrm{k}}} - a^k_{j,worst}\right| \le \xi^k,\ for\ all\ j \\ &\sum_{j=1}^{n}\left(w^{\mathrm{j}}\right)^{\mathrm{k}} = 1 \\ &\left(w^j\right)^{\mathrm{k}} \ge 0, for\ all\ j \end{aligned} \tag{19}$$

The pairwise comparison of BWM requires the calculation of the consistency ratio. The value of the consistency ratio is close to 0, indicating that the consistency is good and the calculated result of the system is valid [91]. The consistency ratio is as follows:

$$\text{Consistency Ratio} = \frac{\xi^k}{\text{Consistency Index}} \tag{20}$$

The consistency index is known and can be obtained from TABLE 3.

We use Eq. (21) to aggregate the two weights; then, we can gain the set of subjective weights of criteria: $w_s = \left\{w^1_s, w^2_s, \ldots, w^n_s\right\}$.

$$w^{\mathrm{j}}_s = \sum_{k=1}^{p} w^k_d * \left(w^j\right)^k \tag{21}$$

E. OBJECTIVE WEIGHTING FOR CRITERIA

According to the context and Eq. (10), we can write Eq. (22). Using Eqs. (22), (23) and (24) to calculate the group decision matrix R, we can obtain the set of objective weights of criteria $w_o = \left\{w^1_0, w^2_0, \ldots, w^n_0\right\}$.

$$\begin{aligned} E^{IFS}\left(\overline{r_j}\right) = -\frac{1}{m\ln 2}\sum_{i=1}^{m}\Big[&\overline{u_{ij}}\ln\overline{u_{ij}} + \overline{v_{ij}}\ln\overline{v_{ij}} \\ &- \left(1-\overline{\pi_{ij}}\right)\ln\left(1-\overline{\pi_{ij}}\right) - \overline{\pi_{ij}}\ln 2\Big] \end{aligned} \tag{22}$$

$$d_j = 1 - E^{IFS}_{LT}\left(\overline{r_j}\right) \tag{23}$$

$$\omega^j_o = \frac{d_j}{\sum_{j=1}^{n} d_j} \tag{24}$$

F. INTEGRATED WEIGHTS OF THE CRITERIA AND DECISION MATRIX

The subjective and objective weights are fused, and the weighted operator is used to combine the weights and the decision matrix. The combined weight of Cj is expressed as:

$$w_j = \beta w^{\mathrm{j}}_s + (1-\beta)\,\omega^j_o \tag{25}$$

where β is the weight coordination coefficient, representing the contribution rate of subjective weight in the combined weight, and $1-\beta$ represents the contribution rate of objective weight. In this study, it is supposed that the weights obtained by subjective and objective weighting methods are of equal importance, that is $\beta = 1-\beta$. After n calculations, we obtain the final set of weights: $W = \{w_1, w_2, \ldots w_n\}$.

By combining W with the decision matrix $\overline{R}$, an integrated weighted intuitionistic fuzzy decision matrix $\overline{\overline{R}}$ is obtained.

$$\overline{\overline{R}} = \mathrm{W}\overline{R} = \left(\mathrm{w}_j\left(\overline{r_{ij}}\right)\right)_{m\times n} = \left(\overline{\overline{r_{ij}}}\right)_{m\times n} = \left(\overline{\overline{u_{ij}}}, \overline{\overline{v_{ij}}}, \overline{\overline{\pi_{ij}}}\right) \tag{26}$$

where $\overline{\overline{u_{ij}}} = 1 - \left(1-\overline{u_{ij}}\right)^{w_j}, \overline{\overline{v_{ij}}} = \overline{v_{ij}}^{w_j}, \overline{\overline{\pi_{ij}}} = \left(1-\overline{u_{ij}}\right)^{w_j} - \overline{v_{ij}}^{w_j}$.

G. DETERMINE THE RANKING

TOPSIS is one of the most famous classic ranking approaches. It is difficult for TOPSIS to deal with fuzzy and uncertain data. Fuzzy numbers are used to address uncertainty, inaccuracy, fuzziness and human language decision making in real life. The intuitionistic fuzzy set reflects a decision maker's approval, rejection and hesitation [92]. Thus, the improvement of TOPSIS by using fuzzy numbers can avoid the errors caused by the precision of fuzzy problems. By calculating intuitionistic fuzzy positive and negative ideal solutions, the computation method is as follows:

Intuitionistic fuzzy positive ideal solution Z^+_j:

$$\begin{aligned} Z^+_j &= \left(\overline{\overline{r_1}}^+, \overline{\overline{r_2}}^+, \ldots \overline{\overline{r_n}}^+\right), \\ \overline{\overline{r_j}}^+ &= \left(\overline{\overline{u_j}}^+, \overline{\overline{v_j}}^+, \overline{\overline{\pi_j}}^+\right), \quad j = 1, 2, \ldots n \end{aligned} \tag{27}$$

where

$$\overline{\overline{u_j}} = \left\{\left[\max_i\left(\overline{\overline{u_{ij}}}^+\right), j \in J_b\right], \left[\min_i\left(\overline{\overline{u_{ij}}}^+\right), j \in J_c\right]\right\}; \tag{28}$$

$$\overline{\overline{v_j}}^+ = \left\{\left[\max_i\left(\overline{\overline{v_{ij}}}^+\right), j \in J_b\right], \left[\min_i\left(\overline{\overline{v_{ij}}}^+\right), j \in J_c\right]\right\}; \tag{29}$$

$$\overline{\overline{\pi_j}}^+ = \left\{ \left[1 - \max_i \left(\overline{\overline{u_{ij}}}^+ \right) - \min_i \left(\overline{\overline{v_{ij}}}^+ \right), j \in J_b \right], \left[1 - \min_i \left(\overline{\overline{u_{ij}}}^+ \right) - \max_i \left(\overline{\overline{v_{ij}}}^+ \right), j \in J_c \right] \right\}; \quad (30)$$

Intuitionistic fuzzy negative ideal solution Z_j^-:

$$Z_j^- = \left(\overline{\overline{r_1}}^-, \overline{\overline{r_2}}^-, \ldots \overline{\overline{r_n}}^- \right), \quad \overline{\overline{r_j}}^- = \left(\overline{\overline{u_j}}^-, \overline{\overline{v_j}}^-, \overline{\overline{\pi_j}}^- \right), \quad j = 1, 2, \ldots n \quad (31)$$

where

$$\overline{\overline{u_j}}^- = \left\{ \left[\min_i \left(\overline{\overline{u_{ij}}}^- \right), j \in J_b \right], \left[\max_i \left(\overline{\overline{u_{ij}}}^- \right), j \in J_c \right] \right\}; \quad (32)$$

$$\overline{\overline{v_j}}^- = \left\{ \left[\max_i \left(\overline{\overline{v_{ij}}}^- \right), j \in J_b \right], \left[\min \left(\overline{\overline{v_{ij}}}^- \right), j \in J_c \right] \right\}; \quad (33)$$

$$\overline{\overline{\pi_j}}^- = \left\{ \left[1 - \min_i \left(\overline{\overline{u_{ij}}}^- \right) - \max_i \left(\overline{\overline{v_{ij}}}^- \right), j \in J_b \right], \left[1 - \max_i \left(\overline{\overline{u_{ij}}}^- \right) - \min_i \left(\overline{\overline{v_{ij}}}^- \right), j \in J_c \right] \right\}; \quad (34)$$

Compute the distance between each alternative and the positive ideal solution and negative ideal solution, respectively, (35) and (36), as shown at the bottom of this page.

The relative closeness coefficient of each alternative is calculated by Eq. (37). The alternatives can be ranked based on descending order of CC_i.

$$CC_i = \frac{d_i^-}{d_i^+ + d_i^-}, \quad i = 1, 2, \ldots n, \quad and\ 0 \le CC_i \le 1 \quad (37)$$

H. GENERAL STEPS IN DECISION ANALYSIS

Step 1. Individual decision matrix R_k is obtained by DMs and IFs.

Step 2. Obtain the weights of DMs by entropy (Eqs. (11), (12), and (13)). The entropy method is an objective weight method widely applied in MAGDM and comprehensive evaluation problems. According to the degree of variation of each criterion data point, entropy is used to calculate the weight of each criterion or of each DM, which avoids the interference of subjective factors and has strong objectivity.

Step 3. Determine the IFPR decision matrix $\overline{R}$ by IFWA operator (Eq. (14)).

Step 4. Obtain subjective weights of criteria by the 0-1 matrix and BWM (Eqs. (17), (18), (20), (21), and model (19)). BWM can simplify the comparison process, reduce the risk of inconsistency, and ensure the accuracy of judgement by selecting the best and the worst special criteria. Compared with the general analytic hierarchy process, this method has obvious advantages: simple data processing, strong reliability of results, and strong consistency.

Step 5. Obtain the objective weights of the criteria by entropy (Eqs. (22), (23), and (24)).

Step 6. Obtain the integrated weights of the criteria by Eq. (25) and determine the final decision matrix $\overline{\overline{R}}$ by Eq. (26).

Step 7. Determine the ranking by TOPSIS (Eq. (27)-Eq. (37)). The decision principle underlying the TOPSIS technique is simple and easy to execute, which provides an effective solution for practical complex decision-making problems. In addition, the improvement of TOPSIS by using fuzzy numbers can avoid the errors caused by the precision of fuzzy problems, and it has been widely used in many fields.

The conceptual framework of the proposed approach is shown in Figure 4.

V. ILLUSTRATIVE EXAMPLE

In this section, we apply an numerical example to demonstrate the effectiveness of the proposed method. Suppose a company wants to initiate a blockchain project and needs to find a suitable blockchain service provider. Currently, there are four blockchain service providers $A = \{A1, A2, A3, A4\}$ to choose from. The company employs four experts $\alpha = \{\alpha 1, \alpha 2, \alpha 3, \alpha 4\}$ to provide evaluations according to the criteria. They are required to assess the appropriateness of the blockchain service providers based on the four indicators presented in this paper: service support capability, green development capability, integration capability of blockchain with the IoT, and technical development capability. The linguistic terms [69] for rating the alternatives are shown in TABLE 4.

Step 1: Determine the IFPR individual decision matrix R_k based on ratings by the DMs.

First, each DM evaluates the three alternatives according to the criteria and the linguistic terms for rating the alternatives. We can obtain the individual evaluation results shown in TABLE 5.

Second, after sorting out the data in the above table, we can obtain the following individual decision matrix R_1–R_4, as shown at the bottom of the next page.

Step 2: Determination of the weights of DMs by Eqs. (11), (12), and (13).

$$d_i^+ \left(\overline{\overline{r_{ij}}}, Z_j^+ \right) = \sqrt{ \frac{1}{2} \sum_{j=1}^{n} \left[\left(\overline{\overline{u_{ij}}} - \overline{\overline{u_j}}^+ \right)^2 + \left(\overline{\overline{v_{ij}}} - \overline{\overline{v_j}}^+ \right)^2 + \left(\overline{\overline{\pi_{ij}}} - \overline{\overline{\pi_j}}^+ \right)^2 \right] } \quad (35)$$

$$d_i^- \left(\overline{\overline{r_{ij}}}, Z_j^- \right) = \sqrt{ \frac{1}{2} \sum_{j=1}^{n} \left[\left(\overline{\overline{u_{ij}}} - \overline{\overline{u_{ij}}}^- \right)^2 + \left(\overline{\overline{v_{ij}}} - \overline{\overline{v_j}}^- \right)^2 + \left(\overline{\overline{\pi_{ij}}} - \overline{\overline{\pi_j}}^- \right)^2 \right] } \quad (36)$$

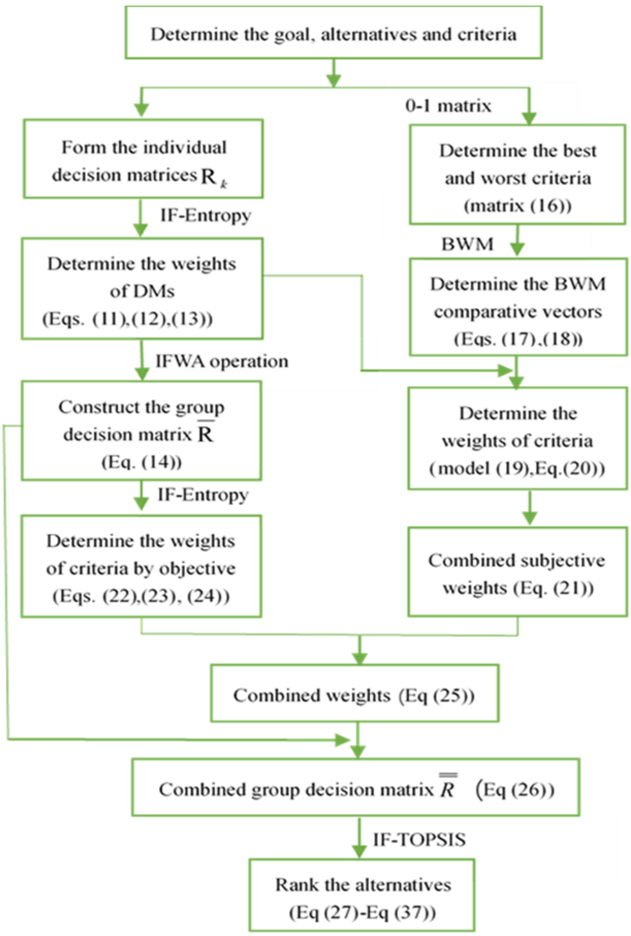

FIGURE 4. The conceptual framework of the proposed approach.

In this step, the entropy measure is applied to compute the weights of DMs. First, use Eq. (11) to calculate the entropy values. Second, use Eq. (12) to calculate the divergences. Finally, use Eq. (13) to compute the weights of DMs. The relevant values are shown in TABLE 6.

Step 3: Determine the IFPR decision matrix $\overline{R}$ by Eq. (14).

Eq. (14) is used to integrate the individual decision matrices into the group decision matrix, and the group decision matrix is shown as $\overline{R}$ at the bottom of the next page.

TABLE 4. Linguistic terms for rating the alternatives.

Linguistic variables	Intuitionistic fuzzy numbers
Extremely good (EG)/extremely high (EH)	(1.00, 0.00, 0.00)
Very, very good (VVG)/very, very high (VVH)	(0.90, 0.10, 0.00)
Very good (VG)/very high (VH)	(0.80, 0.10, 0.10)
Good (G)/high (H)	(0.70, 0.20, 0.10)
Medium good (MG)/medium high (MH)	(0.60, 0.30, 0.10)
Fair (F)/medium (M)	(0.50, 0.40, 0.10)
Medium bad (MB)/medium low (ML)	(0.40, 0.50, 0.10)
Bad (B)/low (L)	(0.25, 0.60, 0.15)
Very bad (VB)/very low (VL)	(0.10, 0.75, 0.15)
Very, very bad (VVB)/very, very low (VVL)	(0.10, 0.90, 0.00)

TABLE 5. Importance of alternatives based on opinions of DMs.

DMs	Alternative	Criteria			
		C1	C2	C3	C4
α_1	A1	MB	G	G	VVG
	A2	MB	MG	G	VG
	A3	M	MG	MG	VVG
α_2	A1	MB	G	G	VVG
	A2	MB	G	MG	VG
	A3	MB	G	MG	VVG
α_3	A1	B	VG	G	VVG
	A2	MB	MG	MG	G
	A3	M	MG	G	VVG
α_4	A1	MB	MG	G	VVG
	A2	MB	MG	M	VG
	A3	M	G	MG	VVG

Step 4: Determine subjective weights of criteria by the 0-1 matrix and model (19).

From TABLE 6, we can know that α_2 has the highest decision-maker weight, so the 0-1 matrix F is determined by α_2:

$$\mathrm{F} = f_{4\times 4} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix}$$

$$\mathrm{R}_1 = \left(R_{ij}^1\right)_{4\times 3} = \begin{bmatrix} (0.4, 0.5, 0.1) & (0.7, 0.2, 0.1) & (0.7, 0.2, 0.1) & (0.9, 0.1, 0.0) \\ (0.4, 0.5, 0.1) & (0.6, 0.3, 0.1) & (0.7, 0.2, 0.1) & (0.8, 0.1, 0.1) \\ (0.5, 0.4, 0.1) & (0.6, 0.3, 0.1) & (0.6, 0.3, 0.1) & (0.9, 0.1, 0.0) \end{bmatrix}$$

$$\mathrm{R}_2 = \left(R_{ij}^2\right)_{4\times 3} = \begin{bmatrix} (0.4, 0.5, 0.1) & (0.7, 0.2, 0.1) & (0.7, 0.2, 0.1) & (0.9, 0.1, 0.0) \\ (0.4, 0.5, 0.1) & (0.7, 0.2, 0.1) & (0.6, 0.3, 0.1) & (0.8, 0.1, 0.1) \\ (0.4, 0.5, 0.1) & (0.7, 0.2, 0.1) & (0.6, 0.3, 0.1) & (0.9, 0.1, 0.0) \end{bmatrix}$$

$$\mathrm{R}_3 = \left(R_{ij}^3\right)_{4\times 3} = \begin{bmatrix} (0.25, 0.6, 0.15) & (0.8, 0.1, 0.1) & (0.7, 0.2, 0.1) & (0.9, 0.1, 0.0) \\ (0.4, 0.5, 0.1) & (0.6, 0.3, 0.1) & (0.6, 0.3, 0.1) & (0.7, 0.2, 0.1) \\ (0.5, 0.4, 0.1) & (0.6, 0.3, 0.1) & (0.7, 0.2, 0.1) & (0.9, 0.1, 0.0) \end{bmatrix}$$

$$\mathrm{R}_4 = \left(R_{ij}^4\right)_{4\times 3} = \begin{bmatrix} (0.4, 0.5, 0.1) & (0.6, 0.3, 0.1) & (0.7, 0.2, 0.1) & (0.9, 0.1, 0.0) \\ (0.4, 0.5, 0.1) & (0.6, 0.3, 0.1) & (0.5, 0.4, 0.1) & (0.8, 0.1, 0.1) \\ (0.5, 0.4, 0.1) & (0.7, 0.2, 0.1) & (0.6, 0.3, 0.1) & (0.9, 0.1, 0.0) \end{bmatrix}$$

TABLE 6. The weights of DMs.

	α_1	α_2	α_3	α_4
E	0.801	0.789	0.793	0.818
d	0.199	0.211	0.207	0.182
w_d	0.249	0.264	0.259	0.228

TABLE 7. Subjective weight values and CRs for the criteria.

	w_d^k	w_s^1	w_s^2	w_s^3	w_s^4	ξ	CR
α_1	0.249	0.091	0.254	0.203	0.452	0.223	0.097
α_2	0.264	0.112	0.222	0.222	0.444	0.124	0.076
α_3	0.259	0.098	0.215	0.215	0.472	0.148	0.064
α_4	0.228	0.062	0.315	0.231	0.392	0.297	0.099
w_s	--	0.092	0.249	0.218	0.441	--	--

By analysing the 0-1 matrix, we can obtain $f_4 = 4 > f_2 = 3 > f_3 = 2 > f_1 = 1$, so the best and worst criteria are *C4* and *C1*. Then, four DMs each list the best comparison vector and the worst comparison vector, respectively:

$$A_{best}^1 = (5, 2, 2, 1), A_{worst}^1 = (1, 3, 2, 5),$$
$$A_{best}^2 = (4, 2, 2, 1), A_{worst}^2 = (1, 2, 2, 4),$$
$$A_{best}^3 = (5, 2, 2, 1), A_{worst}^3 = (1, 2, 2, 5),$$
$$A_{best}^4 = (6, 1, 2, 1), A_{worst}^4 = (1, 5, 4, 6).$$

Using model (19) and Eq. (20), we can obtain the subjective weight values and CRs for the criteria as shown in TABLE 7. CRs are close to 0, so the model has high consistency and reliability. Using Eq. (21), we can compute the integrated subjective attribute weight $w_s = \{0.092, 0.249, 0.218, 0.441\}$.

Step 5: Determine the objective weights of the criteria by Eqs. (22), (23), and (24).

This step also uses the entropy weight method to calculate the group decision matrix R to obtain the objective weights of the criteria. First, use Eq. (22) to compute the entropy values. Second, use Eq. (23) to compute the divergences. Finally, use Eq. (24) to compute the weights of criteria. The relevant values are shown in TABLE 8.

Step 6: Integrate weights of the criteria by Eq. (25) and integrate final weights with the decision matrix by Eq. (26).

TABLE 8. Objective weights of the criteria.

	C1	C2	C3	C4
E	0.990	0.838	0.866	0.516
d	0.010	0.162	0.134	0.484
w_o	0.013	0.205	0.170	0.613

TABLE 9. The intuitionistic fuzzy positive ideal solution and negative solution.

	Z_j^+	Z_j^-
C1	(0.033,0.956,0.011)	(0.023,0.967,0.010)
C2	(0.246,0.680,0.074)	(0.202,0.743,0.056)
C3	(0.208,0.732,0.060)	(0.166,0.787,0.047)
C4	(0.703,0.297,0.000)	(0.547,0.327,0.126)

According to Steps 4 and 5, the weights of subjective and objective criteria are calculated as follows:

$$w_s = \{0.092, 0.249, 0.218, 0.441\},$$
$$w_o = \{0.013, 0.205, 0.170, 0.612\}.$$

By Eq. (25), we can compute the final integrated weights:

$$W = \{0.052, 0.227, 0.194, 0.527\}.$$

With Eq. (26), we construct the following final decision matrix $\overline{\overline{R}}$, as shown at the bottom of this page.

Step 7: Determine the ranking by Eq. (27)-Eq. (37).

By using Eq. (27)-Eq. (33), the intuitionistic fuzzy positive ideal solution and intuitionistic fuzzy negative solution are computed as below:

The Euclidean distance between alternatives and the positive and negative ideal solutions of intuitionistic ambiguity are calculated by Eq. (35) and Eq. (36):

$$d_1^+\left(A1, Z_j^+\right) = 0.010; \quad d_1^-\left(A1, Z_j^-\right) = 0.161;$$
$$d_2^+\left(A2, Z_j^+\right) = 0.161; \quad d_2^-\left(A2, Z_j^-\right) = 0.003;$$
$$d_3^+\left(A3, Z_j^+\right) = 0.057; \quad d_3^-\left(A3, Z_j^-\right) = 0.144.$$

Then, by using Eq. (37) to compute the closeness coefficient of each alternative, we can obtain CC1 = 0.940, CC2 = 0.017, CC3 = 0.715, According to the obtained

$$\overline{R} = \begin{bmatrix} (0.364, 0.524, 0.112) & (0.712, 0.183, 0.105) & (0.700, 0.200, 0.100) & (0.900, 0.100, 0.0) \\ (0.400, 0.500, 0.10) & (0.629, 0.270, 0.101) & (0.608, 0.290, 0.102) & (0.778, 0.120, 0.102) \\ (0.475, 0.424, 0.100) & (0.653, 0.246, 0.101) & (0.629, 0.270, 0.101) & (0.900, 0.100, 0.0) \end{bmatrix}$$

$$\overline{\overline{R}} = \begin{bmatrix} (0.023, 0.967, 0.010) & (0.246, 0.679, 0.074) & (0.208, 0.732, 0.060) & (0.703, 0.297, 0.000) \\ (0.026, 0.964, 0.009) & (0.202, 0.742, 0.056) & (0.166, 0.787, 0.047) & (0.547, 0.327, 0.126) \\ (0.033, 0.956, 0.011) & (0.213, 0.726, 0.006) & (0.175, 0.776, 0.049) & (0.703, 0.297, 0.000) \end{bmatrix}$$

TABLE 10. The characteristics of articles utilized for computational experiments.

Related Article	Approach	Method of DM weighting	Approach of criteria weighting
[96]	IF-TOPSIS	—	Objective weighting based on entropy
[94]	IF-TOPSIS	Objective weighting according to Euclidean distance measure	Subjective weighting giving by DMs
[95]	IF-VIKOR	Objective weighting according to similarity measure	Subjective weighting
[46]	IT2-FNs--ELECTRE	Subjective weighting	Objective weighting based on IT2 neural network
Proposed Study	IF-BWM-Entropy-TOPSIS	Objective weighting based on entropy	The combination of subjective and objective methods (BWM-Entropy)

results, the ranking is A1, A3, and A2, with A1 as the best alternative.

VI. COMPARISON

The issue of blockchain service provider selection pertains to a MAGDM question. In previous studies, many scholars have adopted traditional techniques and methods to solve the problem of MAGDM, such as mathematical programming, AHP, ANP, DEA, TOPSIS, VIKOR, or fuzzy sets, or have integrated several of the above methods [39], [93]. The methods for determining weights can be roughly classified into two categories: subjective weighting and objective weighting. Subjective weighting is a approach used to compare, assign and compute the weights of attributes based on the knowledge, experience or preferences of DMs (or expert groups). At present, the main methods for solving subjective weights include the analytic hierarchy process (AHP), preference ratio method, expert survey method (Delphi method), etc. Objective weighting is a approach used to obtain the weight of each criterion based on the difference in objective data for each alternative. At present, methods for solving objective weights include principal component analysis, the entropy method, the deviation maximization method, etc.

As shown in TABLE 10, we compared other articles based on three aspects: the scientific research method of a MAGDM framework, the determination of decision-maker weight and the determination of attribute weight. When solving MAGDM problems, some scholars ignore expert weights and only consider attribute weights from an objective perspective. Yue [94] and Roostaee *et al.* [95] considered decision-maker weights from an objective perspective and obtained attribute weights through expert preferences.

TABLE 11. Value analysis of weight coordination coefficient.

Weight coordination coefficient	Relative closeness coefficient	Remarks
$\beta=0$	$CC1=0.984$; $CC2=0.004$; $CC3=0.730$.	The subjective weights of the criteria are not considered at all
$\beta=\frac{1}{3}$	$CC1=0.954$; $CC2=0.013$; $CC3=0.720$.	Subjective weight 1/3, objective weight 2/3
$\beta=\frac{1}{2}$	$CC1=0.940$; $CC2=0.017$; $CC3=0.715$.	Subjective weight 1/2, objective weight 1/2
$\beta=\frac{1}{2}$	$CC1=0.652$; $CC2=0.119$; $CC3=0.548$.	Subjective weight 1/2, objective weight 1/2, without considering w_d^k
$\beta=\frac{2}{3}$	$CC1=0.652$; $CC2=0.119$; $CC3=0.548$.	Subjective weight 1/3, objective weight 2/3
$\beta=1$	$CC1=0.902$; $CC2=0.028$; $CC3=0.698$.	The objective weights of the criteria are not considered at all

However, Zhong and Yao [46] considered decision-maker weights from a subjective perspective and obtained attribute weights through an IT2 neural network. Most studies reported in the literature calculate weights based on expert preferences or objective calculation in the process of attribute determination. Expert preference is closer to judgement and expert experience in actual situations, and objective calculation is more in line with the internal logic of real data. Therefore, this study obtains the weights of DMs from the objective perspective and attribute weights from the subjective and objective perspective, realizing a favourable combination of subjective and objective methods.

In this paper, by changing the value of the coordination coefficient, the importance of considering the weights of DMs, subjective weights and objective weights of criteria at the same time is illustrated. As shown in TABLE 11, when $\beta = 0$ (the subjective weights of the criteria are not considered at all) changes to $\beta = 1$ (the objective weights of the criteria are not considered at all), although the ranking results of the three alternatives have not changed, the relative closeness coefficient has changed, which means that the distance between each alternative and the ideal solution has changed. In this case, there is a large gap among the three alternatives, so when the coordination coefficient is changed, the ranking result is not easy to change. However, if the difference between schemes is small, changing the coordination

TABLE 12. Comparison of the results of computational experiments with articles.

Related Article	Ranking	Ranking obtained by this paper	
		Weight coordination coefficient	Ranking
[96]	A3>A1>A4>A2	β=0	A3>A1>A4>A2
[48]	A2>A1>A3	β=0	A2>A1>A3
[46]	A4>A1>A5>A3>A2	β=1	A4>A1>A5>A3>A2
[94]	A2>A3>A4>A1	β=1	A2>A3>A4>A1

coefficient can directly affect the final ranking result. Therefore, in the MAGDM problem, it is necessary to fully consider the weights of all aspects to achieve a favourable combination of the weights.

The comparison between the results of relevant ranking methods from the literature and the results calculated by this research method is shown in TABLE 12.

We can see from TABLE 12, when $\beta = 0$, the proposed method and that of Joshi and Kumar [96] yield the same preference order of alternatives; i.e., A3>A1>A4>A2. In addition, when β= 1, the proposed method and that of Zhong and Yao [46] yield the same preference order; i.e., A4>A1>A5>A3>A2. Hence, by adjusting the coordination coefficient of the method in this paper, we can obtain the same supplier ranking results as in the original text, effectively reflecting the decision results of [96], [48], [46], etc., which proves the effectiveness and practicability of this method. Furthermore, by setting different coordination coefficients, some ranking orders are the same as in the existing research, and some new ranking orders can be obtained; that is, different decision results can be obtained by adjusting the coordination coefficient. For example, as shown in TABLE 11, when the weights of subjective and objective criteria are considered to the same degree (when β= 1/2), or when the weights of subjective and objective criteria are considered to different degrees (when β = 1/3, or 2/3,etc.), the same case may yield different decision data. Therefore, through the comprehensive analysis of TABLE 11 and TABLE 12, the proposed method is more applicable and effective than other methods.

VII. CONCLUSIONS

This paper presents a novel method to select blockchain service providers. First, we propose a four-dimensional set of evaluation criteria. Second, the entropy approach is applied to obtain the DMs weights, and it is embedded into the BWM method to get the subjective attribute weights. At the same time, the attribute weights are obtained by entropy weights. Then, these two types of weights are fused. Finally, the intuitive fuzzy definition is used to integrate the decision matrix, and the comprehensive evaluation values of alternatives are determined by the TOPSIS method, so the most suitable blockchain service provider is selected, referring to the degree of closeness.

The contribution of this work includes two components: (1) In the performance criterion aspect, the criteria developed by our research comprehensively measure the performance of blockchain service providers in multiple dimensions, making it more practicable in comparison with general service supplier selection criteria. (2) In the decision method aspect, we present a novel MAGDM method to resolve the decision problem. In addition, a hybrid approach proposed in this paper also has the below advantages: 1) Intuitionistic fuzzy theory is used to reflect the uncertainty and hesitation in real life and more accurately present the preferences of DMs. 2) The BWM and entropy methods are hybridized and fused by the weights of DMs and the decision matrix to address the ambiguity and vagueness of the criteria subjectively and objectively.

This study has the following practical significance: (1) enterprise managers can refer to the evaluation criteria of this paper when choosing or evaluating blockchain service providers; (2) our method makes full use of the information of DMs, and the results are objective and reliable. (3) The method has good ductility. By adding an adjustable weight coordination coefficient to the decision-making process, it has more extensive adaptation scenarios than the general MAGDM. In addition, it can be applied to many practical fields, such as supplier selection, supplier evaluation, information retrieval, risk assessment and supplier segmentation.

The limitations and future direction: (1) The number of standards proposed in this paper needs to be improved, because it is not enough to fully measure the strength of blockchain service providers. Follow-up research will refine and improve the evaluation criteria system of this paper. (2) We use crisp values to evaluate the criteria when using BWM to calculate subjective criterion weights. This approach must be improved in future studies. To make the decision system information more accurate, this method should be extended to other language sets. (3) Although the method is explained by numerical examples in this paper, more practical and comprehensive verification is still needed. Therefore, future research will verify the effectiveness of this method through real cases and data.

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