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Evaluation of Production of Digital Twins Based on Blockchain Technology

Nada A. Nabeeh [1], Mohamed Abdel-Basset [2], Abduallah Gamal [2] and Victor Chang [3,*]

[1] Information Systems Department, Faculty of Computers and Information Sciences, Mansoura University, Mansoura 35516, Egypt; nadaadel@mans.edu.eg
[2] Faculty of Computers and Informatics, Zagazig University, Zagazig 44519, Egypt; mohamedbasset@zu.edu.eg (M.A.-B.); abduallahgamal@zu.edu.eg (A.G.)
[3] Department of Operations and Information Management, Aston Business School, Aston University, Birmingham B4 7ET, UK
* Correspondence: victorchang.research@gmail.com

Abstract: A blockchain, as a form of distributed ledger technology, represents the unanimity of replication, synchronization, and sharing of data among various geographical sites. Blockchains have demonstrated impressive and effective applications throughout many aspects of the business. Blockchain technology can lead to the advent of the construction of Digital Twins (DTs). DTs involve the real representation of physical devices digitally as a virtual representation of both elements and dynamics prior to the building and deployment of actual devices. DT products can be built using blockchain-based technology in order to achieve sustainability. The technology of DT is one of the emerging novel technologies of Industry 4.0, along with artificial intelligence (AI) and the Internet of Things (IoT). Therefore, the present study adopts intelligent decision-making techniques to conduct a biased analysis of the drivers, barriers, and risks involved in applying blockchain technologies to the sustainable production of DTs. The proposed model illustrates the use of neutrosophic theory to handle the uncertain conditions of real-life situations and the indeterminate cases evolved in decision-makers' judgments and perspectives. In addition, the model applies the analysis of Multi-criteria Decision Making (MCDM) methods through the use of ordered weighted averaging (OWA) and the Technique of Order Preference Similarity to the Ideal Solution (TOPSIS) to achieve optimal rankings for DT production providers based on consistent weighted decision-maker's judgments in order to maintain and to assure sustainability. An empirical study is applied to the uncertain environment to aid decision-makers in achieving ideal decisions for DT providers with respect to various DT challenges, promoting sustainability and determining the best service providers. The Monte Carlo simulation method is used to illustrate, predict, and forecast the importance of the weights of decision-makers' judgments as well as the direct impact on the sustainability of DT production.

Keywords: digital twin; blockchain technologies; sustainability; IoT; AI; industry 4.0; neutrosophic theory; OWA; TOPSIS

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1. Introduction

Blockchains may lead to unpredictable economic and industrial change on a global scale. A blockchain is a digitized transaction in the form of blocks that are linked together on the same distributed ledger. Blockchains and current internet technology differ in several significant dimensions [1]. Only information and copies of things are transmitted on the internet; the original information cannot be transmitted. By using a blockchain, the value represented in a timestamped transaction is kept in a shared ledger in a secure manner [2]. Blockchains record the digital transactions of cryptocurrencies (e.g., Bitcoin, Ethereum, etc.), and the technology is expected to renovate the world's digital economy [3]. Industry 4.0 aims to enhance industrial developments by focusing on transitional factors for environmental conditions and related technologies to assist advancements in automatic industries [4]. Blockchain technology can change the methodologies of production for industrial construction [5]. Indeed, the impression of any new technological production can induce strong feelings in an audience due to the deactivation of traditional methodologies. For example, International Business Machines Corporation (IBM) was anticipated to disable the traditional techniques of industry [6]. However, the IBM Blockchain Platform was developed to handle a full-stack blockchain-as-a-service (BaaS) to allow the deployment of blockchain components for any certain environment. Users are granted privileges in building, operating, and expanding their own BaaS networks and production. In addition, building information modeling (BIM) for professionally intelligent modeling, construction, and engineering are supported by technologies and contracts to generate and manage digital representations of physical places [6]. The blockchain approach can detect the proper aspects of applications further from the focused applications for providers to be constructed and developed.

Blockchain technology supports the development of cryptocurrencies. Hence, blockchain 1.0 is decentralized in transferring values between untrusted entities, mainly considered applications that support the transactions of cryptocurrency. In contrast, blockchain 2.0 is the smart connections and extended applications behind the transactions of cryptocurrency, especially for economic and financial developments [7]. Blockchain 3.0 adopts the main characteristics of blockchain in the trustless decentralization leger, e.g., transparency, no intermediates, and immutability, for applications (e.g., currency and investments) developed according to the technology of blockchain [8]. Indeed, cryptocurrency markets are decentralized and have no central authority, and thus cannot be predictable either in the development of technologies or financial systems. Therefore, barriers and risks must be considered to guarantee the safe development of blockchain technology to promote trust in competitive environments [9]. However, the building and maintenance of new technology are costly and difficult to maintain. This study's focus on DTs is based on blockchain technology as a substantial technology that can allow industries to be developed and evolve with high service quality.

The extraordinary propagation of Cyber-Physical Systems (CPS), high-performance computing technologies, and data analytics is leading to a comprehensive and revolutionary transition to industry 4.0 [10]. DTs are regarded as a fundamental element of the concept of CPS, being a virtual representation of a substantial system, process, or smart object. The vital role of DTs lies in the optimization of industrial operations to provide virtual manufacturing and physical resources before the process of real manufacturing begins. The DTs act in the digitized environment in the form of physical twins of real-world physical objects [11]. The construction of DTs fulfills the gap between virtual considerations and real-world constraints. DTs can use data generated from sensors to aid proactive maintenance and construct predictive simulation models [12]. Many industrial processes can achieve optimization using the digitized creation of DTs based on real instruments such as smart containers, spacecraft, etc. [13].

In addition, healthcare systems can be directly influenced by improved production of medical devices using various experiments and examples of operations on real patients to create DTs. The recent technologies of industry 4.0, AI, and IoT and modeling and data analytics can be integrated to match real environments with virtual worlds. It was predicted that by 2020 DTS could be adopted in industrial organizations and become a prevailing technology for smart industry [1]. The blockchain technology of decentralized and distributed ledgers can be used with DTs to attain security, privacy, and history tracking [14,15]. DTs are mainly occupied with uncomplicated centralized tools that lead to a single point of failure-type vulnerabilities.

The use of DTs based on blockchain technology in business is becoming more and more popular nowadays as a result of the spread of this technology [2]. Blockchains provide a complete solution for data storage, data access, data sharing, and data authenticity, where any overwritten action will be captured and recorded. Today, business models are changing to adapt to the digital economy and evolving consumer demands. This requires new and existing companies to be equipped with the appropriate supply chain strategy to meet these standards [16]. DTs can help alleviate the main challenges related to supply chains [17]. The present shift of companies to investing in DTs is based on the significant value of the product. Additionally, it enables product or asset owners to control and manage their products or assets across supply chains in more organized ways. The value of DTs can lie in a scalable product structure or an asset structure in which multiple models can be added or modified and then linked to enhance cross-functional collaboration [17]. Organizing and implementing the right digital supply chain management strategies can enable companies to grow and expand their profit margins.

The production of DTs has various criteria and alternatives that are considered to be MCDM problems. To our knowledge, the different criteria and alternatives related to DT production using MCDM technology have not been studied so far. This study provides a resource for companies that need ideal DT providers in order to achieve sustainability regarding the challenges of IoT, AI, and Industry 4.0 technologies. As DTs are considered a new discipline within technologies of IoT, AI, and industry 4.0, the uncertainty and risks involved are an issue that may threaten sustainability. Therefore, the present study focuses on the main drivers, barriers, and risks that directly impact the production of DTs. In addition, it focuses on the optimal methods that can aid decision-makers in reaching ideal decisions that lead to sustainability [18]. The proposed model is focused on accounting for decision-makers' judgments in the quantitative format due to the novelty of the DT field. Decision-makers' judgments are very vital and sensitive. Certain perspectives and judgments are not consistent or ideal due to limited experience or bias on the part of decision-makers [19].

A neutrosophic set was used in the present study to handle and present the indeterminate cases in proper quantitative and qualitative formats [20]. OWA was used to consider the effect of various risk impacts on the final results. The OWA illustrated random weights in the problem's criteria and then obtained the optimum and consistent weights. Considering the novelty of DT, this study relies on OWA to evaluate risk and benefit through random weighting to reach the final optimum priorities for criteria. The study further adopts the TOPSIS method for ideal solutions. The TOPSIS method depends on computing positive and negative regions to reach relative closeness between solutions for final optimized ranked solutions.

The structure of this study is organized as follows: Section 2 presents a literature review on the potential of DTs with respect to blockchain technologies and the achievement of sustainability; Section 3 presents an analysis of the challenges involved in using blockchains and their impact on the production of DTs; Section 4 illustrates the proposed model used to achieve ideal solutions and sustainability using neutrosophic theory, OWA, and TOPSIS considering the emerging technologies of Industry 4.0, AI, and IoT; Section 5 presents an empirical study to validate the applicability of the model; Section 6 illustrates the model using a Marlo Carlo simulation to estimate and predict the outcome of the model; Section 7 summarizes the conclusions of the paper by highlighting possible future works and future trends.

2. Literature Review of Blockchain Technology and DT Products

In this section, the management of DTs is described in order to show the need for blockchain technologies. The main aspects of blockchain technologies that are necessary for the production DTs in the proposed model are discussed as follows: (1) The management of DT products; (2) the main technologies of blockchain; and (3) blockchain technology-based Digital Twins and uncertainty. In addition, the uncertainty associated with blockchains and their influence on the performance of DTs are discussed.

2.1. Management of DT Products

DTs are generally defined as the integration of multi-physics, multi-scale, and probabilistic simulations of a complex product or system to reflect the life of its corresponding twin [11]. Essentially, the components of DTs are classified as follows: (1) a physical product, (2) a virtual product, and (3) the connection between the real and virtual products. The connection between the real product and digital/virtual product sustains a vital influence on industries in various aspects. The direct connection and data transmission between physical and virtual products support industry 4.0, allowing higher performance, efficiency, optimization, and maintenance to be reflected in the real product. The DT life cycle as a product follows the stages of (1) development, (2) growth, (3) maturity, and (4) decline. Hence, the huge amount of data generated over a product's life cycle data should be efficiently handled [2]. Moreover, in order to ensure that all procedures for the product life cycle are under control, the digital twin approach can perform full monitoring of production activities over the full product life cycle to optimize production activities according to the reports of the digital twin simulation [21].

2.2. Blockchain Technologies

A blockchain is an increasing list of records that are linked via cryptography such that each block has a cryptographic hash for the preceding block, transaction data, and timestamp. Blockchain records reside in a distributed ledger that cannot be changed until applying the modifications for all subsequent blocks. Lischke and Fabian analyzed the network of Bitcoin [22]. The following sections mainly focus on the main technologies for the development of DTs based on blockchains.

2.2.1. Peer-to-Peer Networks and Blockchains

DTs are developed based on the blockchain behind the technology. Initially, the blockchain was feigned using a peer-to-peer network to propose a distributed ledger for cryptocurrency to form an ongoing chain hash to produce unchangeable data records. The peer-to-peer network is decentralized and each peer, called a node, takes responsibility for providing the needed services to the network [23]. The block must be validated with consensus mechanisms and reflected in the updated block in the updated ledger before residing on the distributed ledger. As a result, all nodes have the authority to access data and to share and provide data with other nodes.

2.2.2. The Hash Algorithm in Blockchain Technology

The blockchain is composed of linked blocks that form chains of blocks. The structure of a block in a blockchain consists of a header and a body for each block, the value of the previous block hash, the timestamp for identifying the time of block creation, the random root hash for the current block according to the network regulations, and the body containing encoded and hashed vital transactions; each block can reside in more than one transaction [2]. Blockchain hash values are unique, such that if any modifications are applied to any block in the blockchain, the block's corresponding hash value would be directly modified [24]. 'Proof of work' is one applied mechanism for checking the validity of a blockchain.

2.2.3. Transactions in Digital Twin-Based Blockchains

DTs have been adopted in the 'fourth industrial revolution' to address emerging issues and challenges. Therefore, this section mainly focuses on blockchain transaction blocks, which are the basic component for recording and sharing the public key, private key, timestamp, and product life cycle of a DT. The public key is a shared key unique to all network members, while each user owns the private key to access his/her cryptocurrencies. A key pair is used to securely and safely utilize data sharing over the product life cycle. The timestamp specifies the induction time of a transaction. The data over the product life cycle are identified with the enterprise that owns the product. Therefore, according to a transaction in the blockchain, any change in the DT will be recorded using the public key and the private key with different timestamp values as well as the relevant life cycle data.

2.3. Blockchain Technology-Based Digital Twins and Uncertainty

Blockchain technology has obtained a great deal of attention, especially with respect to cryptocurrencies. In blockchain systems, miners used to use transactions to search for smart contracts or use existing ones. Each block has only a limited number of transactions, leading miners to prioritize selection of the most appropriate contract [25], although miners do not have enough information to decide and can only detect the maximum income from contact. Therefore, uncertainty in the blockchain environment needs to be addressed with nontraditional solutions, which decision-makers must aid with a clear vision to enhance the process of decision-making.

The DT, interrelated with industry 4.0 and IoT, collects information from remote devices such as sensors, physical models, etc., to optimize the system parameters in order to achieve optimized results in industrial fields [26]. DT manufacturing is surrounded by uncertainty factors; Karve et al. have proposed an intelligent planning approach to handle these uncertainty conditions [26].

2.4. Applications of Blockchain

The blockchain and DT are the main elements that permit continuous data acquisition [27]. Therefore, this section describes blockchain applications according to different fields of interest. Table 1 shows eight vital applications along with brief explanations and benefits [7,28,29].

Table 1. Applications of blockchain according to various fields of interest.

Application	Explanation	Benefits
1. Financial applications	Blockchain enhances the sustainable development of the global economy, providing valuable benefits for either organizations or customers [30].	Blockchain technology enhances capital markets to perform efficient operations such as securities and derivatives transactions [31], digital payments [32], cryptocurrency payments, and exchanges.
2. Governance	**Citizenship services:** used to determine citizens' basic attributes (e.g., name, address, and other personal data)	The internet of agreements (IoA) establishes a connection between digital content and real materials; for example, it represents an IoA system to manage blockchain-related legal rights with respect to physical and IP rights [7].
	Public sectors: used to provide citizens with remote services such as virtual notaries, reputation, and dispute resolution	Applications can be used to attain distributed, efficient, authenticated, and inexpensive persistent official documents [33].
	Electronic voting: the use of technology to remotely perform the process of elections can reduce cost and ensure democracy.	Blockchains provide decentralized peer-to-peer technology to assure confidence in election organizations [34].
3. Internet of Things	As IoT has been widely adopted, IoT applications can be blended with blockchain technologies to acquire the needed capabilities for dedicated computation for the underlying devices [35].	The application of decentralized IoT platforms can support blockchains (Novo, 2018). Moreover, the IoT can secure data exchange in multiple context-aware scenarios [36] with several interconnected smart devices.
4. Healthcare	In healthcare, blockchain technology provides a crucial role in various applications such as healthcare management, online patient access, sharing of patient medical data, user-oriented medical research, drug counterfeiting, clinical trials, and precision medicine [37].	Blockchains can overcome challenges regarding the scientific credibility of findings in clinical trials and patients' informed consent [38].
5. Privacy and security	Blockchains apply asymmetric cryptography to secure transactions between users, providing users with enhanced techniques for security, transparency, and traceability [39].	Privacy and security with blockchains can be applied to many emerging fields, including big data [40], DNS (The Decentralized Library of Alexandria, 2015), distributed networks, and transactional privacy.

Table 1. *Cont.*

Application	Explanation	Benefits
6. Business and industrial applications	Blockchain technology is estimated to increase transparency and accountability in supply chain management to attain flexible supply chains [16].	The applications of blockchain include the fields of visibility, optimization, and demand (IBM Corporation, 2016). Blockchain in logistics can be used to determine counterfeit products, enhance origin tracking [41], and allow customers and vendors to apply directly without any brokers.
	Energy sector: blockchain applications can directly influence the terms of processes and platforms [42].	Blockchains can be used for green energy production and renewable energy sources [43], create energy management schemes for electric vehicles, and facilitate decentralized energy sources [44].
7. Education	Blockchains can store educational records and ensure security and privacy purposes [45].	Blockchain applications can be used for educational records and reputations [46]. Blockchains can enhance data security and trust in digital infrastructure and credit management [45].
8. Data Management	The applications of blockchain technology can improve data management and facilitate audibility [47].	The blockchain-enhanced data management can enable fast, simple, and coherent interactions across data providers.

3. Enhancing the Production of Digital Twins by Analyzing Challenges in Blockchain Adoption

Digital twins allow visualization of the current status of equipment as well as predicting trends by analyzing the manufacturing context via learned operating behavior patterns. Each digital twin has a specific advantage in product lifecycle management [48]. This section illustrates the main drivers, barriers, and risks that influence the production and manufacture of DT with respect to Industry 4.0, AI, IoT technologies and the achievement of sustainable DT production. A detailed description of the related concepts and factors is provided in Table 2 [3].

Table 2. A detailed explanation of the main drivers, barriers, and risks affecting the manufacturing of DTs.

ID	Concept	Factors	Explanations
D_1	**Drivers**	**Security**	Blockchain records are secured through cryptography [49]. Users across networks exchange their private and public keys to transactions and act as a personal digital signature.
D_2		**Anonymity**	Unidentifiable personal details are needed between users (sender or receiver) in the blockchain. In order to perform transactions, only the private and public keys are required, without the need to reveal any related identity information [50].
D_3		**No Single Point of Trust**	In the blockchain, the distributed ledger is decentralized technology to overcome competent authorities without any third party to a transaction, e.g., a banking transaction [51].
D_4		**Fraudulence Reluctance**	It is not easy for invaders to attack or alter any data on a blockchain [14]. Transactions are executed remotely and smartly without human intervention.
D_5		**Non-physicality**	All physical transactions are transformed into digital ones. Digital transactions securely overcome any bank bills and reduce costs [28].
B_1	**Barriers**	**Privacy**	Unfortunately, the public blockchain has limitations in terms of data privacy. There are no privileges or grand rules, and all users can access any information in the distributed ledger [52].
B_2		**Data Storage**	The huge amount of data generated from transactions and sensors are not suitable for storage on the blockchain. Public blockchains have restrictions on the amount of data stored [3].
B_3		**Scalability**	The blockchain must efficiently detect a wide-scale serialization with applicable scalability concerns [53]. Blockchain technology can efficiently trouble many users on networks.
B_4		**High Computation Power**	The blockchain requires a great deal of computational power and electricity. Therefore, many researchers have focused on novel applications in the field of the energy sector [54].
R_1	**Risk**	**Vulnerability**	Smart and virtual contracts are conducive to vulnerabilities that can be exploited by hackers. The risks and opportunities of emerging business models are adopted to overcome vulnerabilities [55].
R_2		**Private key security**	The private key is an essential security credential [56]. Therefore, if the private key is hacked or lost, it is challenging to trace the hacked data to permit recovery [57].

Table 2. *Cont.*

ID	Concept	Factors	Explanations
R_3		**Criminal activity**	Cryptocurrencies may be used for illegal issues, and competent authorities may not be able to detect or trace the real parties.
R_4		**Exposing identity**	Hackers can identify and trace the IP address of users, then make illegal modifications that may lead to the loss of users' cryptocurrencies; e.g., any payment transaction can change the original IP address to another to be received in the updated location by the hackers [3].

4. Evaluation Model for DT Products Based on Blockchain

The model for the production of DTs is concerned with the DT architecture, evaluation methodology, and Monte Carlo Simulation, as mentioned in Figure 1. The DT architecture includes IoT technologies, AI, and Industry 4.0. The evaluation methodology is built on the drivers, risks, and barriers to DT architecture. The methodology includes methods and data in addition to an analysis of MCDM. Monte Carlo simulation is used to reflect the impact of decision-makers' judgments as input with the outcomes. A detailed overview of the proposed model is in Figure 2.

4.1. Methods and Data

The use of blockchain technology as a basis for DT adoption has various drivers and challenges to attaining sustainability in the production of DTs. The present study integrates expert surveys to present a general image of the performance of blockchain technology that could affect the production of DT. The experts' opinions are specifically focused on the aspects of blockchain technology drivers, barriers, and risks. As shown in Figure 1, this represents the model for ranking drivers, barriers, and risks related to DT. Indeed, the decision-makers' and experts' opinions can be characterized as confused, and do not have any restrictions. Decision-makers' opinions may produce a consistent or inconsistent state. Therefore, this study focused on the process of decision-making in the production of digital twins based on blockchain technology, which can be classified according to three dependent factors:

- **Personality conditions:** The personality conditions depend on the decision-maker's perspectives, policies, and professional conscience [4].
- **Environmental conditions:** The uncertain and unclear conditions in real situations are unpredictable, e.g., changes in economy, technologies, society, epidemics [19], and crises.
- **Multiple criteria and alternatives** (MCDM): these are complex situations for decision-makers and are composed of various forms of factors, either quantitative or qualitative [18].

This study collected specialists' perspectives based on discussion, meetings, and qualitative discrete choice experiments [29]. These various decision-making experts were aggregated through the adoption of the Ordered Averaging Operator (OWA) [58]. MCDM methods were applied to the decision-makers' perspectives for criteria and alternatives. The robustness of the results were checked by a Monte Carlo simulation.

4.2. MCDM Analysis

The current problem has various criteria and alternatives, which are referred to as MCDM. The MCDM was analyzed and evaluated by a set of experts in academia, industry, and politics with various functional hierarchies and backgrounds [59]. The experts were used to evaluate the blockchain technologies for the construction of DT. Figure 2 shows the overview of the proposed MCDM method in three layers. OWA and TOPSIS can be analyzed with methods and data in place, and details are presented in Sections 4.2.1 and 4.2.2. In this study, the experts' evaluations were modeled as quantitative results using neutrosophic theory [20]. The neutrosophic set can model the indeterminate cases in real-life situations into a substitute neutrosophic scale. The neutrosophic scale can express the criteria and alternatives in a descriptive form to reflect their importance and priority from an expert point of view in real-life situations. According to the current problem definition, this study adopted the triangular neutrosophic scale mentioned in [60].

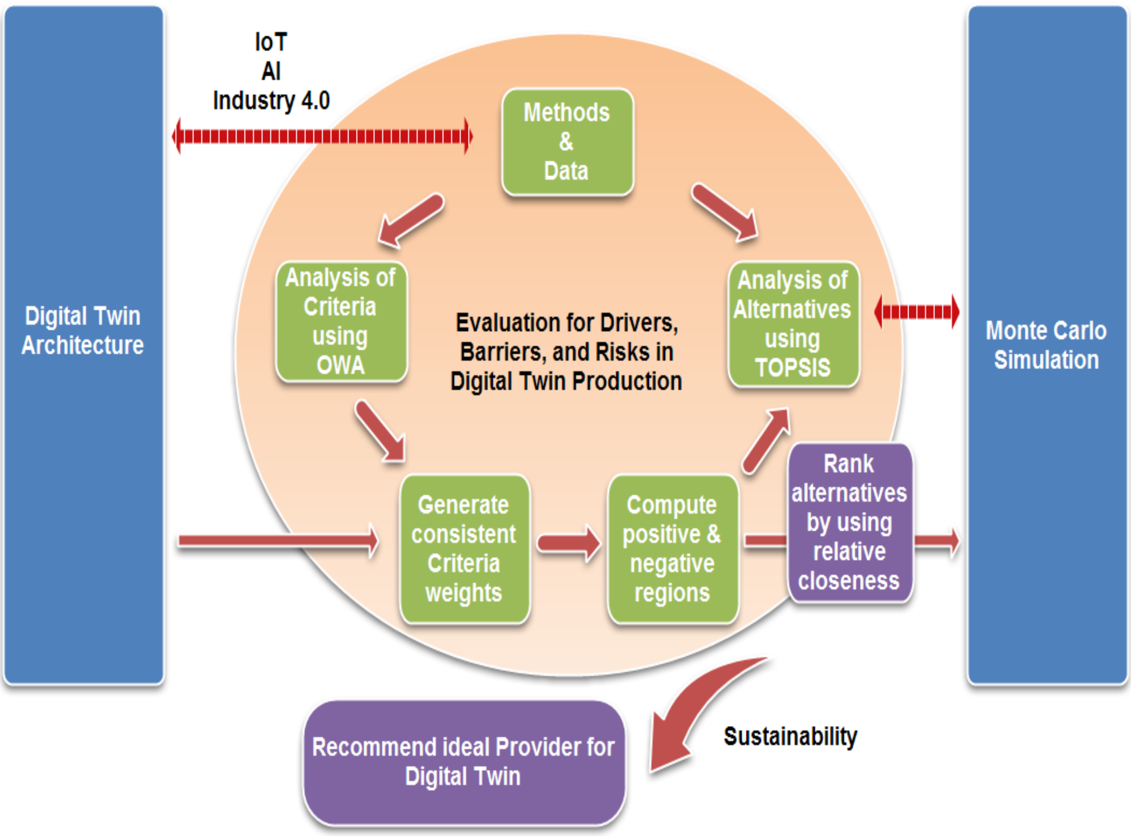

Figure 1. The model for ranking drivers, barriers, and risks for DT.

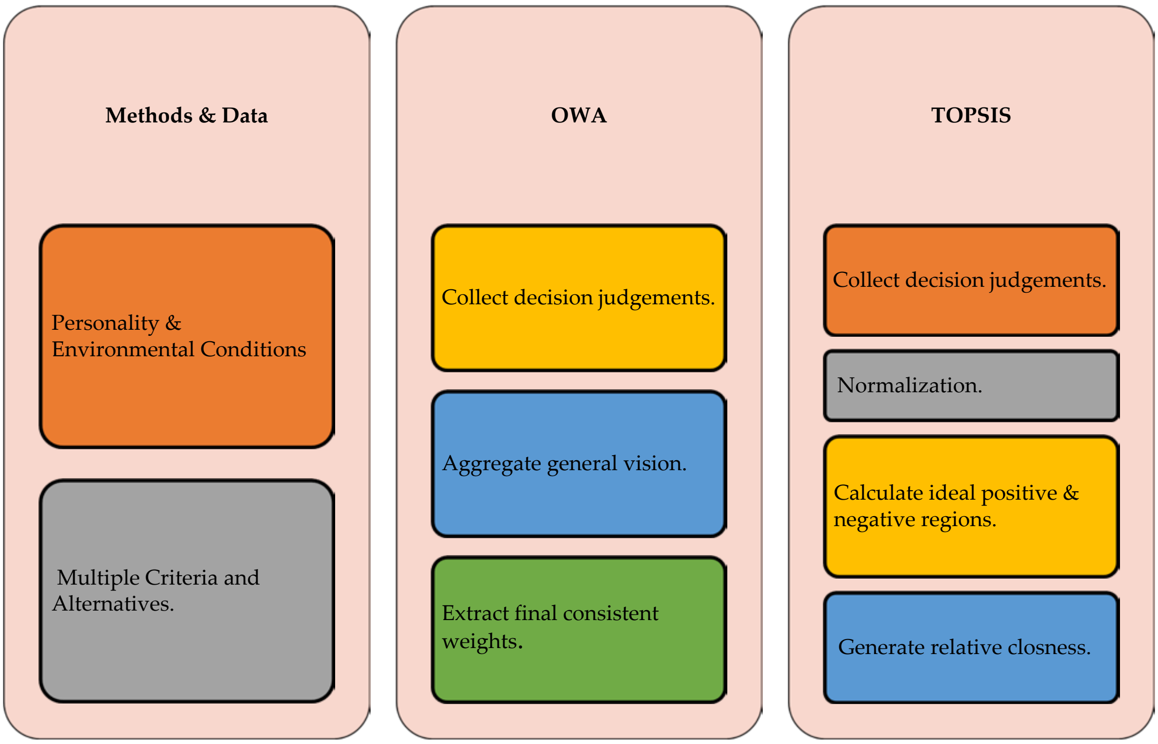

Figure 2. Overview of the proposed method.

4.2.1. Analysing Criteria Using OWA

The aggregation of experts' perspectives was applied using the OWA operator [61]. The OWA administers a general aspect of operators to diminish the effect of inconsistent decision judgments. Assume that there are q experts $D_1, D_2, \ldots, D_q$ who participate in a decision-making problem such that $1 \leq k \leq q$. The OWA is defined as follows:

Step 1: Create a matrix of decision-making DM_{ij}^{K} for experts D_k to model the experts' perspectives on blockchain technology as criteria; the DM_{ij}^{K} the matrix in Form (1) is in the form of a neutrosophic triangular scale [20] and is defined as follows [62]:

$$
\begin{array}{c} \quad x_1 \; x_2 \; x_m \end{array}
$$

$$
DM_{ij}^{K} = \begin{array}{c} f_1 \\ f_2 \\ \vdots \\ f_n \end{array} \begin{bmatrix} x_{11}^{k} & x_{12}^{k} & \cdots & x_{1m}^{k} \\ x_{21}^{k} & x_{22}^{k} & \cdots & x_{2m}^{k} \\ \vdots & \vdots & \vdots & \vdots \\ x_{n1}^{k} & x_{n2}^{k} & \cdots & x_{nm}^{k} \end{bmatrix} \tag{1}
$$

where ${x_{ij}}^{k}$ refers to the performance rating of the element of the i^{th} criterion with respect to $f_1, f_2, \ldots, f_j$ the j^{th} criterion $x_1, x_2, \ldots, x_j$ from the experts' perspective, D_k. Note that the type of ${x_{ij}}^{k}$ represents the experts' perspectives according to the neutrosophic scale.

Step 2: The values of the indeterminate case are detected in the uncertainty conditions for the three main factors of personality conditions, environmental conditions, and MCDM. In this step, the neutrosophic scale can be converted into real numbers using the score function presented in [18]. The values for the de-neutrosophic experts' perspective matrix DM_{ij}^{K} are shown, as follows, in Form (2):

$$
\begin{array}{c} \quad x_1 \; x_2 \; x_m \end{array}
$$

$$
DM_{ij}^{K} = \begin{array}{c} f_1 \\ f_2 \\ \vdots \\ f_n \end{array} \begin{bmatrix} x_{11}^{k} & x_{12}^{k} & \cdots & x_{1m}^{k} \\ x_{21}^{k} & x_{22}^{k} & \cdots & x_{2m}^{k} \\ \vdots & \vdots & \vdots & \vdots \\ x_{n1}^{k} & x_{n2}^{k} & \cdots & x_{nm}^{k} \end{bmatrix} \tag{2}
$$

Step 3: Provide general and aggregated managerial vision for experts for matrix DM_{ij}^{K} for all k = 1, 2, . . . , q to a DM_{ij} with OWA operators. The outcome result is presented as follows, in Form (3):

$$
\begin{array}{c} \quad x_1 \; x_2 \; x_m \end{array}
$$

$$
DM_{ij} = \begin{array}{c} f_1 \\ f_2 \\ \vdots \\ f_n \end{array} \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \tag{3}
$$

where x_{ij} refers to the value of f_i with respect to x_j in the group decision-making matrix DM_{ij}. The OWA operators are calculated x_{ij} as follows in Equation (4).

NB: The initial weights are assumed such that the summations for weights must be one equal to one.

$$
x_{ij} = \text{OWA}\left({x_{ij}}^{1}, {x_{ij}}^{2}, \ldots, {x_{ij}}^{q}\right) = \sum_{j=1}^{q} w_j s_{jl} \tag{4}
$$

where s_{jl} represents the l^{th} largest ${x_{ij}}^{k}$ such that $k = 1, 2, \ldots, q$ according to x_j.

The weights can be generated in Equation (5) by applying the following equation: [61]:

$$
w_j = \text{Q}(j/m) - \text{Q}((j-1)/m), \; \text{j} = 1, \, 2, \, \ldots, \, \text{m}. \tag{5}
$$

where Q(x) refers to a non-decreasing relative quantifier [29,63], such that

$$
\text{Q(x)} = \begin{cases} 0, & 0 \leq x < a, \\ \frac{x-a}{b-a} & a \leq x \leq b, \\ 1, & x > b \end{cases}
$$

The values of parameters a, b represent the degree of coverage analysis for the ordered parameters. The combination terms can be applied from the Saaty scale represented in [4], e.g., equally significant, slightly significant, very strongly significant, etc.

4.2.2. Analysing Alternatives Using TOPSIS

The MCDM methods are used to support decision-makers in complex problems with various criteria and alternatives. The TOPSIS method, illustrated in reference [64], is used to solve various problems. TOPSIS ranks proposed alternatives according to generated ideal solutions. Assume that there are p alternatives $O_1, O_2, \ldots, O_p$ as evaluated from m criteria $x_1, x_2, \ldots, x_m$. Assume that there are q experts $D_1, D_2, \ldots, D_q$ who participate in this decision-making problem, such that $1 \leq k \leq q$. Let $w_1, w_2, \ldots, w_m$ be the weighting vector of m criteria with $1 \leq j \leq m$, $w_j \geq 0$ and $\sum_{j=1}^{m} w_j = 1$.

Step 4: Create a matrix of decision-making Y_{ij}^{K} for experts D_k to model the experts' perspectives of blockchain technology as criteria and the effect on the production of DT, (the Y_{ij}^{K} the matrix in Form 6) and convert it into a numerical form by applying the score function mentioned in [20]:

x_1 x_2 x_m

$$Y_{rt}^{K} = \begin{matrix} O_1 \\ O_2 \\ \vdots \\ O_p \end{matrix} \begin{bmatrix} y_{11}^{k} & y_{12}^{k} & \cdots & y_{1m}^{k} \\ y_{21}^{k} & y_{22}^{k} & \cdots & y_{2m}^{k} \\ \vdots & \vdots & \vdots & \vdots \\ y_{p1}^{k} & y_{p2}^{k} & \cdots & y_{pm}^{k} \end{bmatrix} \tag{6}$$

where ${y_{rt}}^{k}$ refers to the performance rating of O_p with respect to x_t provided by expert D_k, $1 \leq r \leq p$, $1 \leq t \leq m$, and $1 \leq k \leq q$. Note that the type of ${y_{rt}}^{k}$ represents the experts' perspectives on the neutrosophic scale.

Step 4: The aggregation of decision-makers' judgments is achieved using the following Equation (7):

$$y_{rt} = \frac{\sum_{t=1}^{m}\left(y_{rt}^{k}\right)}{D_q} \tag{7}$$

where y_{rt} represents the decision-makers' judgments for alternatives and D_q refers to the number of decision-makers.

The outcome result is presented as follows in Form (3):

x_1 x_2 x_m

$$Y_{rt} = \begin{matrix} O_1 \\ O_2 \\ \vdots \\ O_p \end{matrix} \begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1m} \\ y_{21} & y_{22} & \cdots & y_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ y_{p1} & y_{p2} & \cdots & y_{pm} \end{bmatrix} \tag{8}$$

where y_{rt} refers to the performance rating of O_p with respect to x_t provided by expert D_k.

TOPSIS is based on three main steps: (1) normalization, (2) calculating the ideal solution in positive and negative regions, and (3) computing the relative distances between the generated positive and negative regions.

Step 5: The normalization is achieved as follows in Equation (9):

$$z_{rt} = w_j * \frac{y_{rt}}{\sqrt{\sum_{t=1}^{m} x_{rt}^{2}}}; r = 1,2,3\ldots p; t = 1,2,3\ldots m \tag{9}$$

where w_j refers to the weights of criteria to generate a normalized weighted z_{rt} matrix

Step 6: Compute the positive and negative regions, as follows, in Equations (10) and (11):

$$z_t^{+} = \left\{ \begin{matrix} \langle max(z_{rt}|r = 1,2,\ldots,p)|j \in j^{+}\rangle, \\ \langle min(z_{rt}|r = 1,2,\ldots,p)|j \in j^{-}\rangle \end{matrix} \right\} \tag{10}$$

$$z_t^- = \left\{ \begin{array}{l} \langle min(z_{rt} | r = 1, 2, \ldots, p) | j \in j^+ \rangle, \\ \langle max(z_{rt} | r = 1, 2, \ldots, p) | j \in j^- \rangle \end{array} \right\} \quad (11)$$

where j^+ and j^- refer to profit and cost criteria, respectively.

Step 7: Calculate the Euclidean distance between positive (d_r^+) and negative ideal solution (d_r^-) on study's alternatives in Equations (12) and (13) to achieve the two optimal regions of solutions:

$$d_r^+ = \sqrt{\sum_{t=1}^{m} (z_{rt} - z_t^+)^2}, r = 1, 2, \ldots, p \quad (12)$$

$$d_r^- = \sqrt{\sum_{t=1}^{m} (z_{rt} - z_t^-)^2}, \ r = 1, 2, \ldots, p \quad (13)$$

Step 8: Compute the relative closeness by aggregating the positive and negatives regions of the solutions to achieve ideal solutions, as mentioned in Equation (14):

$$c_r = \frac{d_r^-}{d_r^+ + d_r^-}; r = 1, 2, \ldots, p \quad (14)$$

Step 9: Recommend the ideal solutions according to the proposed model.

5. Empirical Study

An empirical study is illustrated here to show the applicability of the proposed model. The case study depends on the analysis of thirteen criteria about drivers, barriers, and risks, as mentioned in Table 2. The perspectives were collected according to a specialist in the application of blockchain technologies in the uncertain circumstances of real-life situations and modeled using Form (1). Decision-makers' judgments are modeled and expressed on a triangular neutrosophic scale [4] to convert qualitative expressions into quantitative values using Form (2). The triangular neutrosophic scale is converted into the numerical form using the score function [18] in order to be simpler and more readable for researchers. The general and aggregated form for decision-makers is modeled in Table 3.

Table 3. The initial aggregated decision-maker judgments for the driver, barrier, and risk criteria.

Criteria	D_1	D2	D3	D4	D5	B1	B2	B3	B4	R1	R2	R3	R4
D_1	1	1.843	1.85	2.03	1.85	1.388	1.848	1.85	1.843	2.03	1.388	1.843	2.03
D_2	0.542	1	1.85	1.843	2.03	1.85	1.843	2.03	1.848	1.85	1.85	1.843	1.85
D_3	0.539	0.542	1	1.848	1.843	1.843	2.03	1.85	1.843	2.03	1.85	2.03	1.848
D_4	0.491	0.542	0.541	1	1.85	1.848	1.85	2.03	1.85	2.03	1.843	2.03	1.388
D_5	0.539	0.491	0.542	0.539	1	2.03	2.03	1.848	1.85	1.843	1.388	1.843	1.85,
B_1	0.720	0.539	0.542	0.541	0.491	1	2.03	1.85	1.848	1.388	1.85	1.843	2.03
B_2	0.541	0.542	0.491	0.539	0.491	0.491	1	1.85	1.85	1.843	1.388	1.85	1.843
B_3	0.539	0.491	0.539	0.491	0.541	0.539	0.539	1	1.85	1.85	1.388	2.03	1.85
B_4	0.542	0.541	0.542	0.539	0.539	0.541	0.539	0.539	1	1.85	1.843	1.843	1.388
R_1	0.491	0.539	0.491	0.491	0.542	0.720	0.542	0.539	0.539	1	1.85	1.85	1.85
R_2	0.720	0.539	0.539	0.542	0.720	0.539	0.720	0.720	0.542	0.539	1	1.85	1.843
R_3	0.542	0.542	0.491	0.491	0.542	0.542	0.539	0.491	0.542	0.539	0.539	1	1.388
R_4	0.491	0.539	0.541	0.720	0.539	0.491	0.542	0.539	0.720	0.539	0.542	0.720	1

The graphical representation for aggregated decision-makers' judgments is illustrated in Figure 3. For applying OWA, the weights were assumed as mentioned in Table 4 and represented in Figure 4. Then, the OWA general and aggregated decision-makers' judgments were generated using Form (3) and Equation (4) and as mentioned in Table 5. Hence, the new and accurate weights calculated on the generated OWA decision-makers' judgments and results are depicted in Table 6.

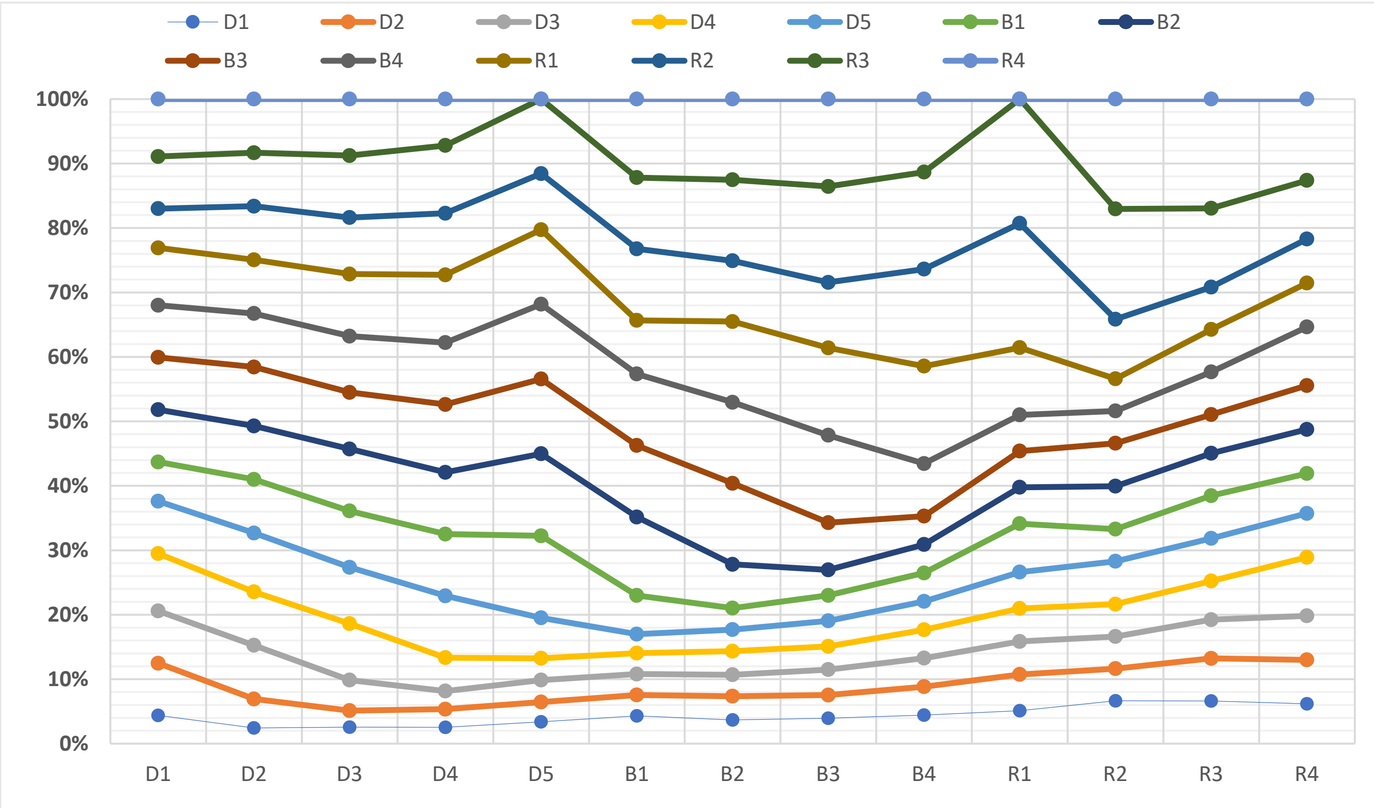

Figure 3. The graphical representation of initial experts' perspectives.

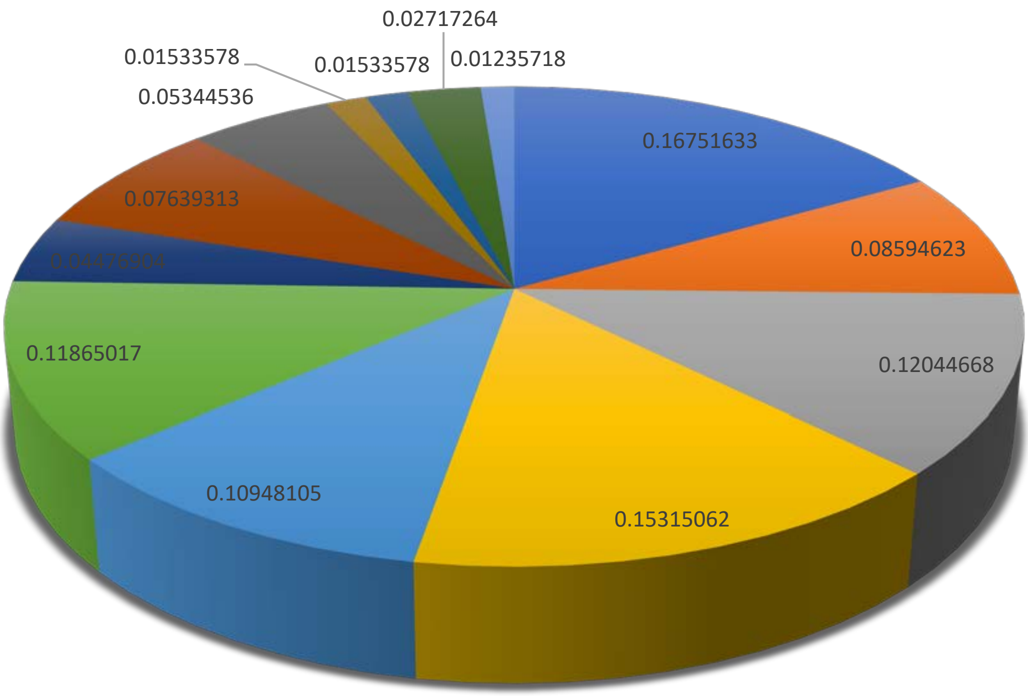

Figure 4. The weights representing decision-makers' perspectives.

Table 4. Assumed weights for the decision-maker judgments.

Criteria	Weights
D_1	0.159799
D_2	0.081987
D_3	0.114898
D_4	0.146095
D_5	0.104437
B_1	0.113184
B_2	0.047362
B_3	0.080273
B_4	0.056109
R_1	0.016165
R_2	0.016165
R_3	0.038615
R_4	0.024911

Table 5. The final generated matrix uses OWA for decision-maker judgments about driver, barrier, and risk criteria.

Criteria	D_1	D2	D3	D4	D5	B1	B2	B3	B4	R1	R2	R3	R4
D_1	0.325	0.325	0.325	0.325	0.325	0.325	0.325	0.325	0.325	0.325	0.325	0.325	0.325
D_2	0.166	0.166	0.166	0.166	0.166	0.166	0.166	0.166	0.166	0.166	0.166	0.166	0.166
D_3	0.233	0.233	0.233	0.233	0.233	0.233	0.233	0.233	0.233	0.233	0.233	0.233	0.233
D_4	0.297	0.297	0.297	0.297	0.297	0.297	0.297	0.297	0.297	0.297	0.297	0.297	0.297
D_5	0.212	0.212	0.212	0.212	0.212	0.212	0.212	0.212	0.212	0.212	0.212	0.212	0.212
B_1	0.230	0.230	0.230	0.230	0.230	0.230	0.230	0.230	0.230	0.230	0.230	0.230	0.230
B_2	0.086	0.086	0.086	0.086	0.086	0.086	0.086	0.086	0.086	0.086	0.086	0.086	0.086
B_3	0.148	0.148	0.148	0.148	0.148	0.148	0.148	0.148	0.148	0.148	0.148	0.148	0.148
B_4	0.103	0.103	0.103	0.103	0.103	0.103	0.103	0.103	0.103	0.103	0.103	0.103	0.103
R_1	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029
R_2	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029
R_3	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052
R_4	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024	0.024

Table 6. The final weights on the generated OWA decision-maker judgments.

Criteria	Weights
D_1	0.16751633
D_2	0.08594623
D_3	0.12044668
D_4	0.15315062
D_5	0.10948105
B_1	0.11865017
B_2	0.04476904
B_3	0.07639313
B_4	0.05344536
R_1	0.01533578
R_2	0.01533578
R_3	0.02717264
R_4	0.01235718

In order to aid the process of decision-makers in uncertain conditions, the case study adopts the application of TOPSIS on four different service providers for DT according to the final weights for criteria. The four alternatives are: (1) Azure Digital Twins; (2) IBM; (3) CISCO; and (4) Oracle. The judgments of decision-makers are collected in a triangular neutrosophic scale and converted into numerical values. The aggregated decision makers' judgments of alternatives for criteria are aggregated using Equation (7) and as mentioned in Table 7. Apply the three steps for TOPSIS as follows: normalization is applied using Equation (9); results are depicted in Table 8. The positive and negative regions are applied using Equations (10) and (11), with the results presented in Table 8. Compute negative and positive regions using Equations (12) and (13) to achieve the relative closeness using Equation (14), as mentioned in Table 9. Figure 5 shows the final ranking as follows: IBM, Azure DT, oracle, and CISCO. The final rankings can aid decision-makers to achieve ideal DT providers to achieve sustainability with respect to the challenges of IoT, AI, and industry 4.0 technologies.

Table 7. The aggregated decision-maker judgments for DT alternatives.

Alternatives/Criteria	D_1	D2	D3	D4	D5	B1	B2	B3	B4	R1	R2	R3	R4
Azure DT	2.101	1.843	1.388	2.03	1.85	1.38	1.848	1.85	1.843	2.03	1.388	1.843	2.03
IBM	1.85	1	1.85	1.843	2.03	1.85	1.843	2.03	1.848	1.85	1.85	1.843	1.85
CISCO	1.85	2.101	1	1.848	1.843	1.38	2.03	1.38	1.843	2.03	1.85	2.03	1.848
Oracle	1.388	1.388	2.101	1.388	1.85	1.848	1.85	2.03	1.85	2.03	1.843	2.03	1.388

Table 8. The normalization of alternatives with respect to criteria.

Alternatives/Criteria	D_1	D2	D3	D4	D5	B1	B2	B3	B4	R1	R2	R3	R4
Azure DT	0.092	0.046	0.048	0.090	0.058	0.047	0.026	0.045	0.031	0.010	0.006	0.021	0.015
IBM	0.081	0.025	0.064	0.082	0.064	0.063	0.026	0.049	0.031	0.009	0.009	0.021	0.014
CISCO	0.081	0.052	0.035	0.082	0.058	0.047	0.029	0.033	0.031	0.010	0.009	0.023	0.014
Oracle	0.060	0.034	0.073	0.061	0.058	0.063	0.026	0.049	0.031	0.010	0.009	0.023	0.010
z^+	0.092	0.052	0.073	0.090	0.064	0.063	0.029	0.049	0.031	0.010	0.009	0.023	0.015
z^-	0.060	0.025	0.035	0.061	0.058	0.047	0.026	0.033	0.031	0.009	0.006	0.021	0.010

Table 9. The final ranking of alternatives according to relative closeness.

Alternatives	d_r^+	d_r^-	c_r	Ranking
Azure DT	0.065811	0.112928	0.631803	2
IBM	0.063398	0.115341	0.645302	1
CISCO	0.097831	0.080908	0.452659	4
Oracle	0.092603	0.086136	0.481908	3

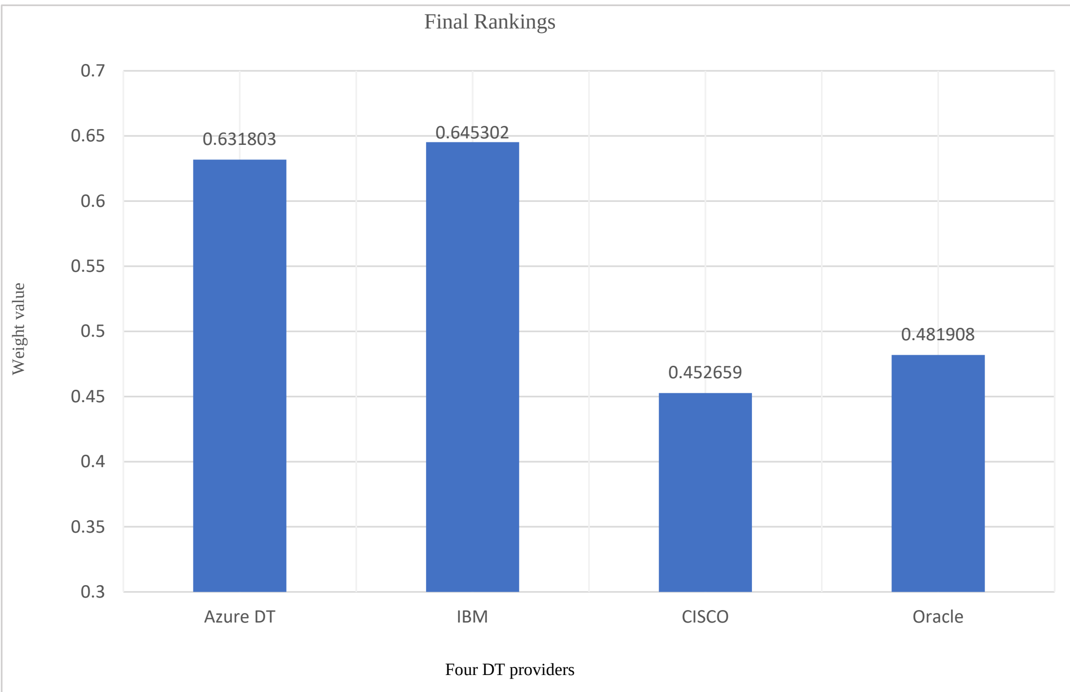

Figure 5. The final ranking for DT providers.

6. Model Simulation

Monte Carlo simulation is a model used in prediction and forecasting models under conditions of risk and uncertainty. The proposed model depends on the evaluation of the digital twin according to the weighted judgments of decision-makers. There are many ways to adjust weights, e.g., AHP, OWA, Neural Networks, etc. MCDM methods mainly depend on ranking alternatives according to certain criteria weights. The present study mainly works with the initial weights for criteria and then verifies these with OWA to reach final accurate weights. Therefore, the study focuses on the robustness of the recommended alternatives. Zhang et al. used Monte Carlo to make simulations for the robustness of results [65]. While considering the weights in the perturbation state, a random number is generated with uniform distribution. The random numbers are achieved by the use of the RAND ( ) function in business applications or computer packages. Consequently, normalization is applied to the series of random numbers considering the original sum of individual weights. The output of the normalization process refers to the relative importance of criteria. The simulation is applied for 4000 trials, which is efficiently a large number of trials concerning the number of study criteria and alternatives. The Monte Carlo simulation is mainly used to test whether the final ranking of alternatives relies on the weights of criteria to demonstrate the important priorities and weights of criteria, alternatives, and decision-makers' judgments, as mentioned in the results [18].

As a result, for the applied methods of OWA, TOPSIS, and Monte Carlo simulations, the robustness of decisions needs to take into consideration the estimation decision-makers' judgments of criteria and alternatives to prevent falling to local optimum. The applied methods present a final ranking according to the input of decision judgments and real-world situations. Any contradictions cannot be detected from the MCDM methods and must be fixed with decision-makers according to current real situations. In [60], a consistency rate for decision-makers' judgments is applied to check the consistency of decision-making judgments. The discrepancies and unbiases in decision judgments can be detected to be further edited and managed by decision-makers and experts according to real-life situations. Finally, the use of Monte Carlo showed that the perturbation of weights for criteria and alternatives directly impacts the robustness of the final rankings and recommendations such that the differences in weights as the input provided by decision-makers can change the ranking for recommendation results [18].

7. Conclusions

In this paper, blockchain technologies are regarded as a milestone for evaluating the challenges facing DTs. The model adopts the main drivers, barriers, and risks of blockchain technologies to be reflected and analyzed in DT production. As the novelty, uncertainty, and risk situations of DT technology should be handled and modeled with untraditional and intelligent methods. Our model collected decision-makers' judgments using neutrosophic theory to model the indeterminate cases. The model used OWA to achieve consistent weights for various challenge criteria for analysis. In addition, the model used TOPSIS to analyze alternatives to ranking the best solutions in terms of sustainability. Finally, a Monte Carlo simulation was applied to predict and forecast the outcomes in conditions of uncertainty and risk. Future work could include the use of additional technologies to analyze the challenges of DT manufacturing to attain sustainability.

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