Edelweiss Applied Science and Technology
ISSN: 2576-8484
Vol. 9, No. 7, 1218-1234
2025
Publisher: Learning Gate
DOI: 10.55214/25768484.v9i7.8863

Blockchain-enabled digital twin integration for supply chain transparency enhancement in large-scale engineering project optimization

Yuejun Liu[1,2*], Faizatul Akmar Abdul Nifa[1,3], Lim Kong Teong[1]
[1]School of Technology Management & Logistics, UUM College of Business, Universiti Utara Malaysia, Kedah Darul Aman, 06010, Malaysia; lyj20082005@163.com (Y.L.).
[2]Hebei University of Architecture, Zhangjiakou, 075000, China.
[3]Disaster Management Institute, Universiti Utara Malaysia, Kedah Darul Aman, 06010, Malaysia.

Abstract: In large-scale engineering projects, managing complex supply chains effectively is essential to ensure timely delivery, cost efficiency, and quality assurance. Traditional methods often fail to address key challenges in transparency, traceability, and security, leading to inefficiencies and vulnerabilities. To overcome these limitations, this research proposes the Blockchain-Integrated Digital Twin MBA Optimization Framework (BDT-MBA), which combines advanced blockchain security, digital twins (DT), and optimization techniques to improve supply chain management. Blockchain technology provides a decentralized and immutable system for secure data sharing, ensuring data integrity, transparency, and trust among stakeholders. Real-time updates are enabled through IoT sensors, which synchronize DTs with the physical state of assets, facilitating cyber-physical systems security. The DT framework delivers real-time insights into asset performance, forming the basis for optimized decision-making. The MBA analyzes data to optimize logistics, resource allocation, and system efficiency, aligning with the needs of internet services for adaptive and scalable supply chain operations. This framework mitigates cybersecurity threats, ensures privacy, and enhances the efficiency of sanitization (98.4%) and restoration (98.8%). The proposed BDT-MBA framework represents a robust and transformative approach for secure and transparent supply chain optimization in complex engineering projects. Integrating blockchain, IoT, and DTs demonstrates significant advancements in traceability, secure data management, and real-time decision-making for modern supply chain systems.

Keywords: *Blockchain, Digital twin, Supply chain transparency, Large-scale engineering projects, Multi-behavior bat algorithm (MBA).*

1. Introduction

Blockchain technology is a distributed, decentralized ledger that permanently, securely, and transparently records transactions [1]. Blockchain has been widely used in several areas, including healthcare, finance, logistics, and security and privacy concerns in cloud computing, due to its capacity to reduce intermediaries, minimize fraud, improve traceability, and support security modeling and analysis. A DT is a computerized model of a real asset, procedure, or system that is modified in real-time using information from sensors, IoT devices, cloud computing, and other sources [2].

Supply chain transparency tracks every phase of a product's journey, beginning with obtaining raw materials and ending with delivering them to the final consumer [3]. Incorporating security modeling and analysis into the process helps safeguard sensitive information and detect vulnerabilities, ensuring data integrity and confidentiality throughout the supply chain [4]. Many industries, such as electronics, food & beverage, retail, manufacturing, and medicine, require a transparent supply chain. Transparency, when combined with cloud computing, security modeling, and analysis, helps track product origins in the food industry and keeps them safe from fraud and contamination [5].

History: Received: 6 May 2025; Revised: 18 June 2025; Accepted: 23 June 2025; Published: 15 July 2025
* Correspondence: lyj20082005@163.com

In the past, organizations managed supply chain transparency by handling everything manually, using paper documentation, and conducting regular audits. These techniques involve adding barcodes or RFID tags to packages, verifying vendor data, and leveraging ERP systems and cloud computing for integrated supply chain data management, often enhanced by security modeling and analysis to assess vulnerabilities [6]. Figure 1 shows the process of supply chain transparency enhancement.

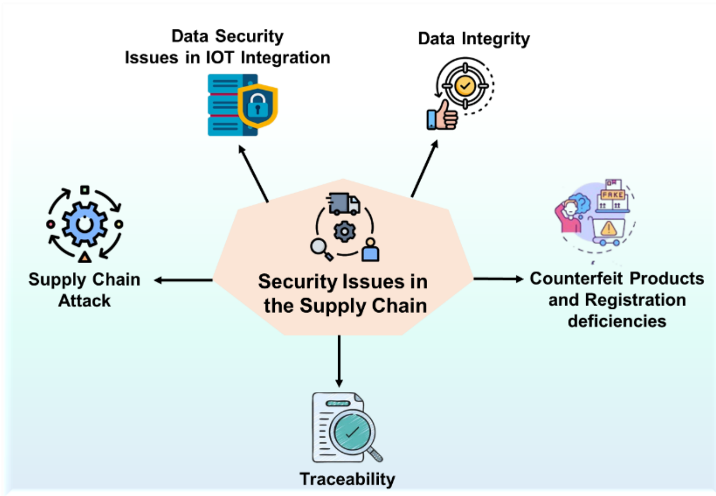

Figure 1.
Supply chain transparency enhancement process.

Several traditional techniques, such as cryptographic hashing for data integrity and DLT, are commonly used for supply chain management forecasting [7]. Consensus techniques such as PoW, PBFT, and smart contracts are applied to address disruptions in supply chain data [8]. Traditional methods are time-consuming, often make errors, and do not provide real-time access to data for complicated, cross-border supply chains. Cloud computing can help address some of these issues, but data availability and the quality of that information can vary between suppliers, leading to potential inaccuracies in models [9].

The research presents a new BDT-MBA method that focuses on improved supply chain transparency, security, and traceability in complex engineering projects. This system aims to provide secure data transmission, detailed real-time asset monitoring, and better use of resources and logistics by using DTs, blockchain technology, and optimization techniques that increase effective operations and enhance stakeholder trust.

2. Related Works

Lalitha, et al. [10] investigated how combining blockchain technology with simulations and optimization techniques can increase supply chain operations' transparency. Findings show that their approach can be used to identify inefficiencies, reduce risks, and enhance supply chain effectiveness overall. Morgan, et al. [11] presented the basis for further supply chain transparency investigations in two distinct ways. The principle of supply chain transparency was conceptually expanded by their evaluation, which connects theories from several fields and offers recommendations for combining those concepts to tackle intricate new problems. The combination of blockchain technology, AI, and data analytics to improve business processes was examined by Ahmad [12] with a specific focus on supply chain transparency and employee efficiency management. A framework based on the dynamic capability concept was developed by Li, et al. [13] which also examines the impact on company efficiency of the relationships between the three categories of SCV and the two kinds of SCT. The results showed that

SCT and SCV were integrated to improve excellent company performance. A novel method for efficiently identifying fake products that combines QR codes, blockchain technology, and ML was presented by Pandey and Singh [14]. A unique FR-ROA was proposed by Liu and Han [15] and offered a method of protecting privacy in supply chain systems that use blockchain technology. The results showed that it was more effective than traditional methods in enhancing supply chain security. The use of blockchain technology in supply chain management could be examined by Chen [16] along the way, it improved effectiveness and visibility. The conceptual structure that outlined how blockchain technology and smart contracts can improve supply chain transparency was created by Kumar, et al. [17]. The adoption of the structure has several benefits, such as improved compliance with regulations, enhanced accuracy in data management, and increased processing capacity for various operations.

The growing complexity, dangers, and inefficiencies in contemporary supply networks frequently make it difficult for conventional strategies to improve supply chain transparency [10]. Conventional methods for protecting privacy in supply chains are often less effective, exposing sensitive data vulnerable and restricting stakeholders' ability to share information securely [15]. The suggested BDT-MBA system addresses constraints by combining digital twins for real-time model, blockchain for secure transparency, and MBA optimization to improve supply chain durability, efficiency, and decision-making.

3. Methodology

The supply chain data was obtained from the Kaggle source. The data are preprocessed by employing the data cleaning and Z-score normalization approaches. A novel BDT-MBA approach was introduced, which uses improved blockchain security, DTs, and optimization approaches to enhance supply chain management. The flow of the BDT-MBA model is depicted in Figure 2.

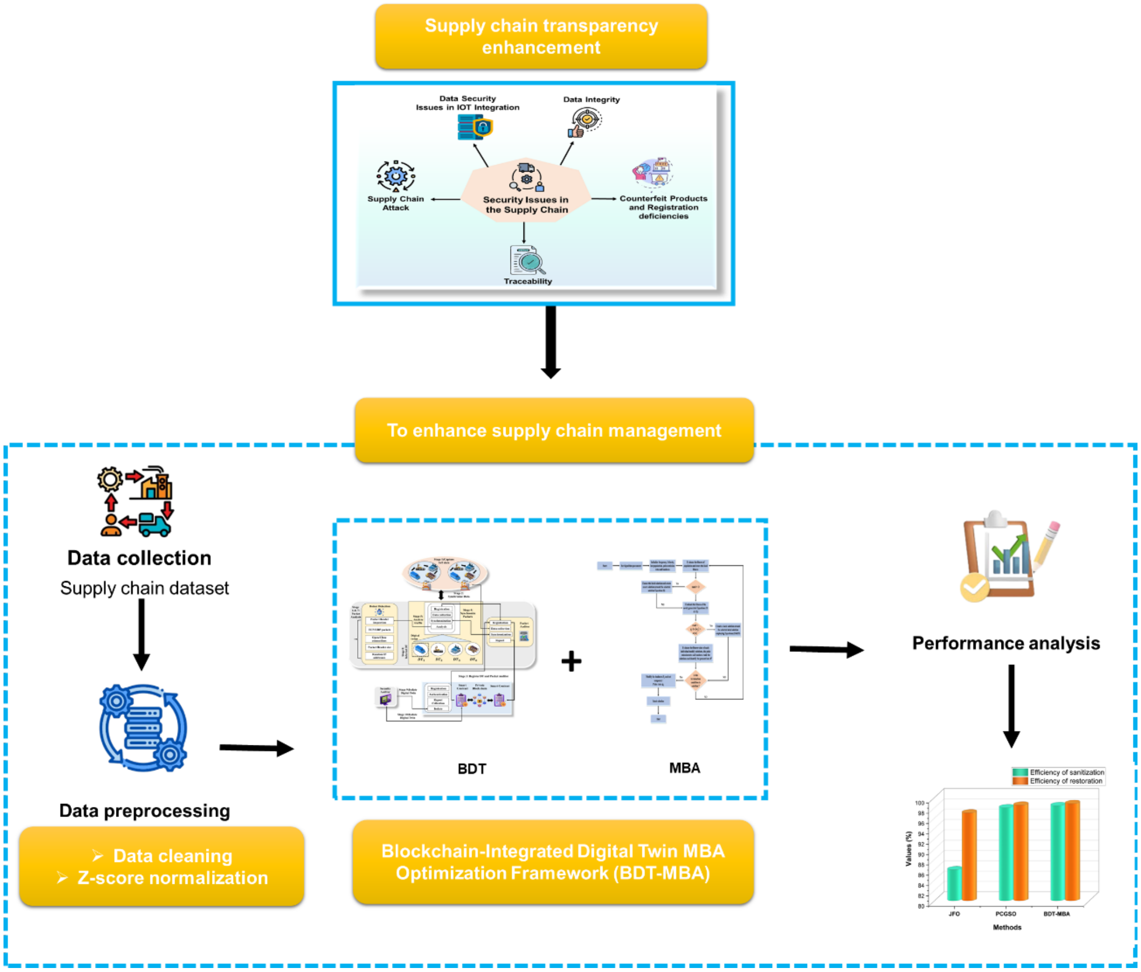

Figure 2.
Overview of the suggested BDT-MBA approach.
Source: [https://www.kaggle.com/datasets/ziya07/bdt-mba-supply-chain-dataset/data.](https://www.kaggle.com/datasets/ziya07/bdt-mba-supply-chain-dataset/data)

3.1. Data Collection

The supply chain dataset was gathered from Kaggle. This data can be used to model supply chain activities for large-scale engineering tasks. It incorporates accurate data from DTs, blockchain-enabled tracking systems, and IoT sensors covering the period from 2023 to 2024. Using sophisticated analytics, this dataset is intended to support research in supply chain transparency, resource optimization, maintenance forecasting, and secure data exchange.

3.2. Data Cleaning

To clean the data, first, verify and handle missing values using imputation or removal techniques. Column names should be standardized for clarity and consistency. Eliminate duplicate data and unnecessary columns that don't add to the analysis. Date fields should be converted to datetime format, and the assignment of numerical data types should be verified. Ensure that blockchain entries and sensor data are scaled consistently. Track and manage outliers, particularly with IoT and tracking data. Check that categorical variables are properly encoded. Evaluate the accuracy of the data by comparing IDs, timestamps, and locations. Figure 3 displays the features obtained after data cleaning.

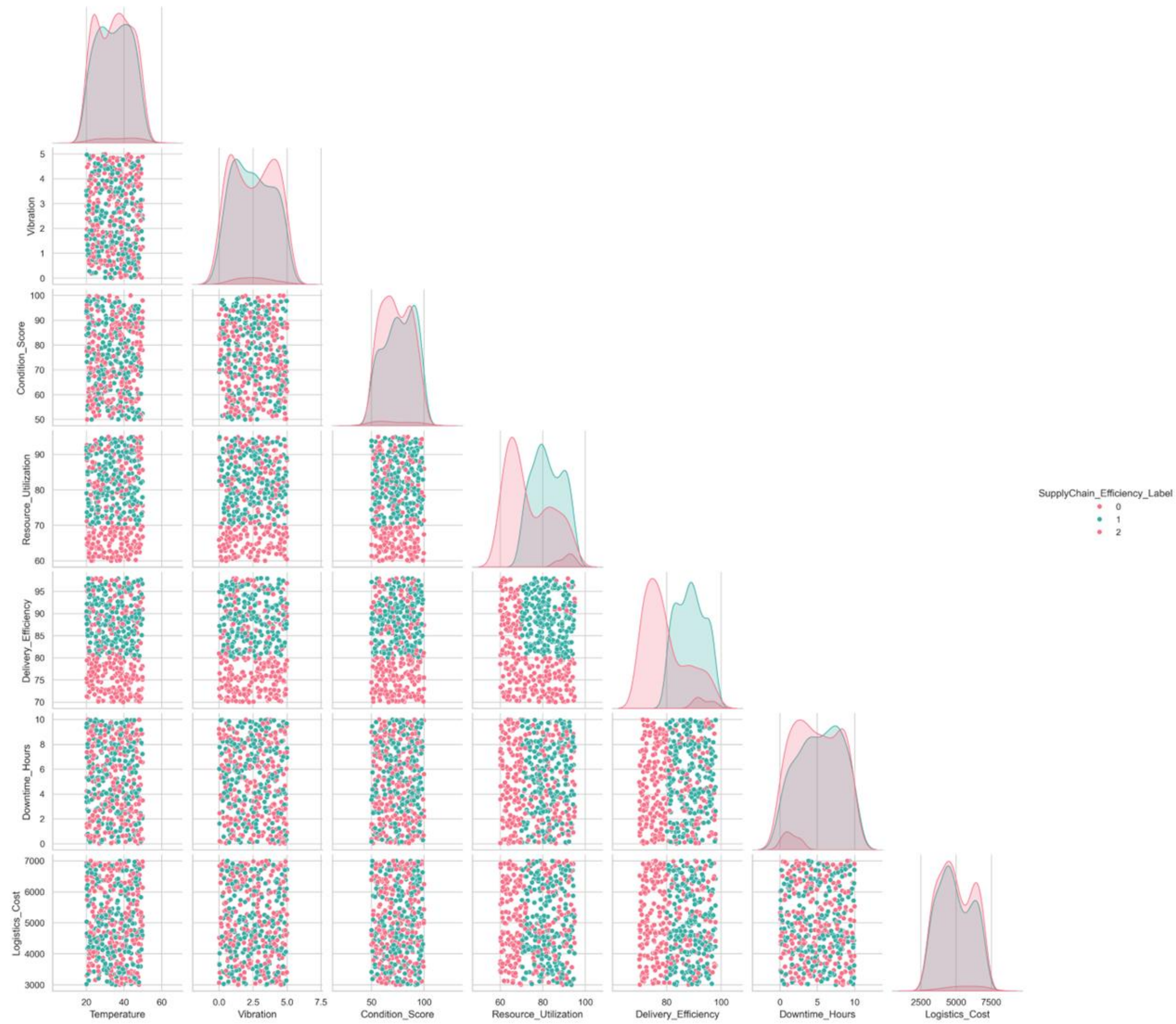

Figure 3.
Supply chain dataset features obtained after data cleaning.

3.3. Z-Score Normalization

Z-score normalization standardizes data by transforming values to standard deviation from the mean, allowing for more accurate comparisons, eliminating bias, and enhancing the efficiency of analytical or forecasting models. Z-score normalization is a method based on the mean and standard deviation (SD) of the data. This approach is particularly helpful when the data's actual maximum and minimum values are unknown. The calculation for Z-score normalization is shown in Equation (1). Figure 4 displays the outcome of the distribution of the supply chain dataset (a) delivery efficiency, (b) downtime hours, (c) logistic cost, and (d) resource utilization.

$$Y_{new} = \frac{Y - \mu}{\sigma} \tag{1}$$

Where, Y – Old value, Y_{new} - The modified value derived from the normalized outcomes, σ – SD value, and μ – Population mean.

Edelweiss Applied Science and Technology
ISSN: 2576-8484
Vol. 9, No. 7: 1218-1234, 2025
DOI: 10.55214/25768484.v9i7.8863

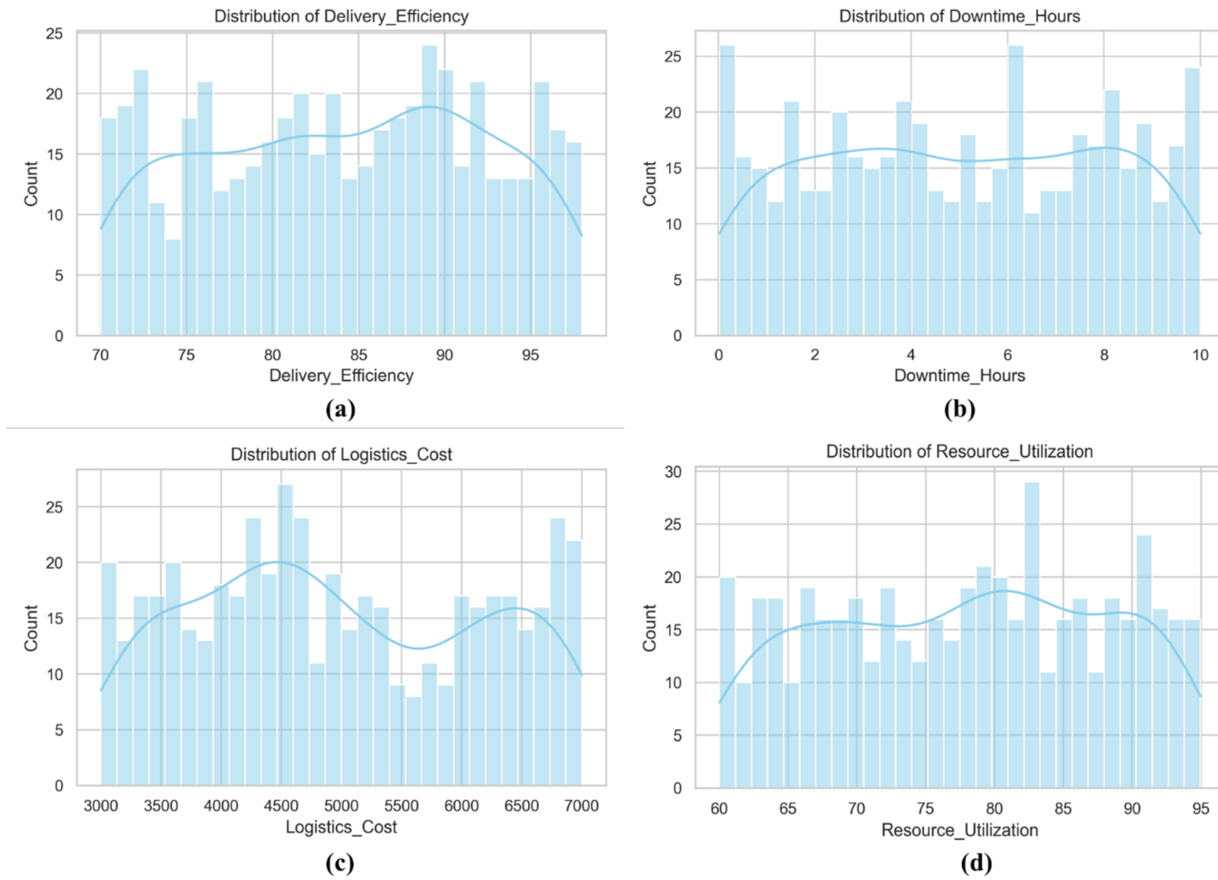

Figure 4.
Distribution of supply chain dataset (a) delivery efficiency, (b) downtime hours, (c) logistic cost, and (d) resource utilization.

3.4. BDT-MBA

A novel strategy called the BDT-MBA combines modern technologies to improve supply chain transparency management. This system uses DTs, which are virtual copies of physical supply chain resources, to offer precise, real-time operational visibility. Through the use of blockchain technology, all supply chain interactions are guaranteed to be stable, decentralized, and transparent, which reduces fraud and increases stakeholder trust.

The main optimization algorithm uses an MBA, which was inspired by bats' echolocation behavior, to effectively handle challenging supply chain issues like demand forecasting, inventory control, and route optimization. The DT offers real-time data, blockchain protects the integrity of the data, and MBA enhances decision-making. This combination provides more transparency, tracking, and more responsive, robust supply chain management. The BDT-MBA methodology helps organizations optimize their supply chains for sustainability, reliability, and efficiency. BDT-MBA optimizes supply chains by using BDT for real-time monitoring, secure data, and enhanced decision-making through MBA, improving transparency, efficiency, and sustainability in operations

3.5. Blockchain-Integrated Digital Twin

The methodology for enhancing supply chain transparency management enabled by DTs was introduced. The device layer is made up of several physical assets with embedded sensors, including warehouses, logistics hubs, and delivery vehicles that independently operate to collect and transmit real-time information to cloud computing platforms. A blockchain-integrated digital twin improves supply chain transparency by offering secure, continuous monitoring of activities and products. Blockchain offers a decentralized, secure record that permanently captures all supply chain transactions. Through the automated performance of smart contracts, validated and secure data, and the capacity to track products, it increases transparency, reduces fraud, and fosters stakeholder trust. A DT is a digital representation of a supply chain's physical assets or operations. Figure 5 depicts the architecture of the Blockchain-Integrated Digital Twin.

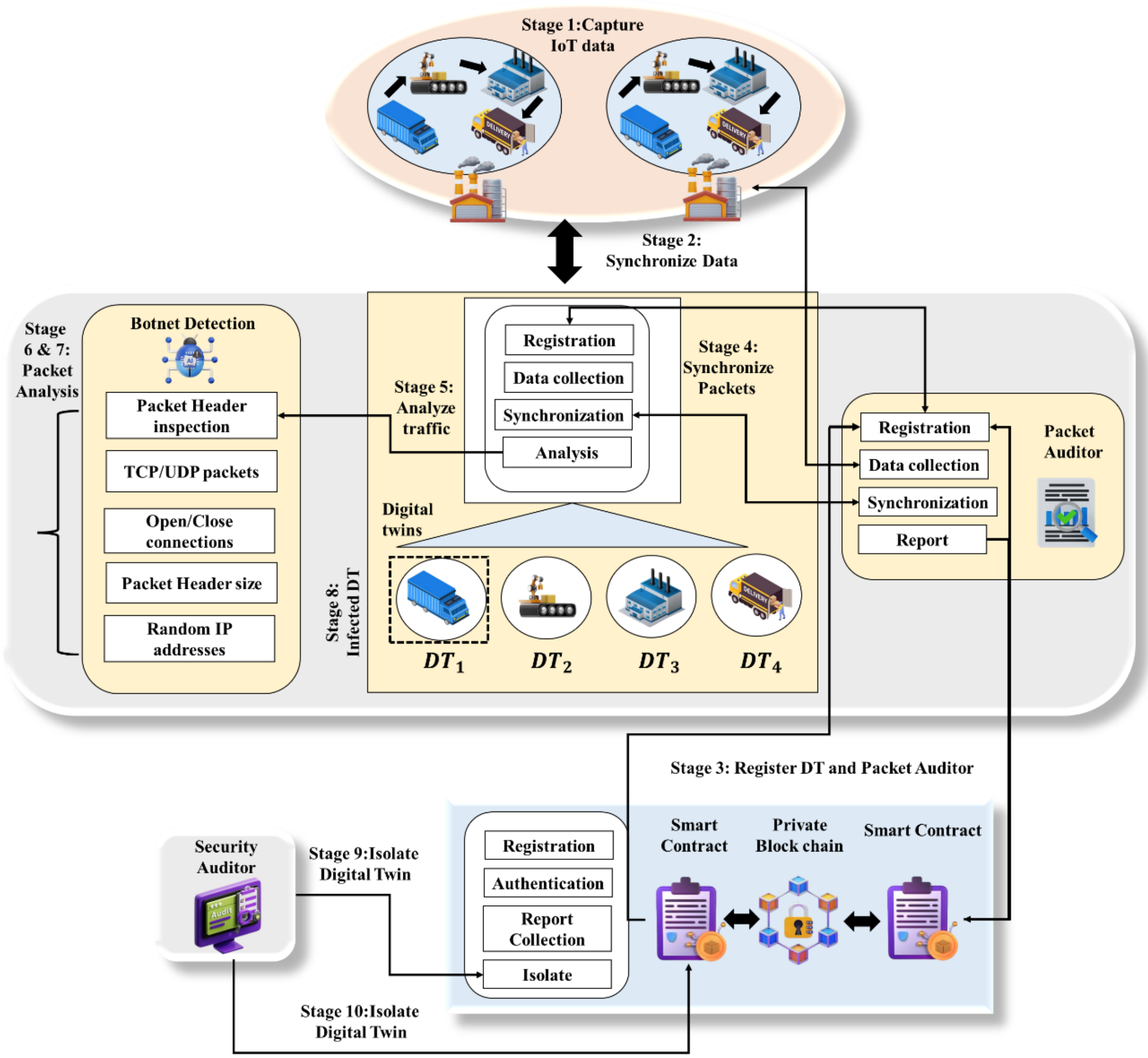

Figure 5.
Blockchain-Integrated Digital Twin Architecture.

Stage 1: DT systems in factories capture information from machines and transmit it to the edge for calculation and analysis.

Stage 2: DTs at the edge layer synchronize data with their divisions, including the production floor (DT_1), raw-materials management (DT_2), assembly line (DT_3), and packaging and warehousing (DT_4).

Applications that gather unprocessed data from DT systems and provide it to the edge are used to represent each department. All information collected from sensors used in the production and use of products is gathered on the production floor.

Stage 3: Provided that only authorized DTs can communicate data, they are recorded on the private blockchain. The registration of a distinct Packet Auditor (PA) makes it easier for the DT and IoT devices to synchronize their data.

Stage 4: To prevent unauthorized entities from intercepting industrial traffic, DT and the PA synchronize data. The DT gathers data that is utilized to train the model for botnet identification and needs to be protected from man-in-the-middle attacks.

Stage 5: DTs are representations of the network's topology, traffic volume, and both malicious and benign traffic. At this stage, information is gathered to examine and detect botnet activities.

Stage 6: To examine unencrypted packet information, TCP/UDP packet headers are gathered. Because the Secure Socket Layer (SSL) encrypts IP packets, such as those used in Hypertext Transfer Protocol Secure (HTTPS), botnet identification using packet headers examines both HTTP and HTTPS traffic.

Stage 7: The DTs that contain both UDP and TCP packets are used for collecting features. The IP addresses used, open or closed associations, and packet arrival time are gathered for analysis.

Stage 8: DT_1 introduces malicious packet traffic to stimulate botnet detection. The benign virtual cluster of systems known as $DT_2, DT_3, and\ DT_4$ could become the focus of increasing botnet activity.

Stage 9: The security provider begins preventing the increasing botnet activity after successfully classifying DT_1 exhibiting botnet activity. It stops the spread of botnet activities by isolating all traffic from the compromised device DT, preventing it from interacting with systems from the benign DTs. While all systems and local gateway connection points, including routers, are included in each DT, no outgoing traffic is allowed at DT_1 is not allowed to send packets to $DT_2, DT_3, and\ DT_4$.

Stage 10: To preserve the chain of assets during assessments of the origin of attacks and device safety firmware management, each Smart Contract is documented on the Blockchain.

3.6. Bat Algorithm (BA)

The BA optimizes the selection of suppliers and logistics, increasing supply chain visibility by improving reliability, reducing delays, and guaranteeing accurate information through adaptive, swarm-based solutions for exploration and exploitation. The BA is a metaheuristic technique that was inspired by microbat echolocation, which occurs at frequencies between 25 and 150 kHz over short spans. The following principles can be used to generalize these microbat echolocation behaviors:

- All bats use echolocation to identify distance and possess an exceptional ability to discriminate between environmental barriers and products/materials.
- To find products, the bats travel randomly to a location w_i with velocity u_i, constant frequency e_{min}, and variable loudness B_0 and wavelength λ. The wavelength of their transmitted pulses can be changed, and the velocity of pulse emission $q \in [0.1]$ can be tuned according to the proximity of their target.
- Although there are several ways in which the volume can change, consider that it will shift from a high initial value (B_0) to a constant, lowest value (B_{min}),

In a c-dimensional search area, $u_i\ and\ w_i$ represent the velocity and location of each bat (i). To produce unique solutions, the modified location and velocity at the time step s, $u_i^s, and\ w_i^s$ are represented as follows in Equations (2 - 4),

$$e_j = B_{min} + (B_{max} - B_{min}) \times \alpha \quad (2)$$

$$u_i^s = u_i^{s_1} + \left(w_i^{s-1} - w^*\right) \times e_i \quad (3)$$

$$w_i^s = w_i^{s-1} + u_i^s \quad (4)$$

ISSN: 2576-8484
Vol. 9, No. 7: 1218-1234, 2025
DOI: 10.55214/25768484.v9i7.8863

At the present iteration, all m bats are compared to get the current global ideal position, denoted by w^*. Within the boundaries of $[0,1]$, α denotes an arbitrary vector selected from a uniform distribution. This velocity increment is derived from the product of $\lambda_j\ and\ e_j$. One can alter the other factor by either $e_j(or\ \lambda_j)$ to modify the velocity variation. Each bat is associated with a frequency that is arbitrarily selected from a uniform distribution between $e_{min}\ and\ e_{max}$ to execute the procedure shown in Equation (5).

$$w_{new} = w_{old} + \varepsilon B^s \tag{5}$$

The average volume of all bats at a specific time step can be expressed as, $B^s = < B_i^s >$, where ε is a random value within the interval $[0,1]$. The range $[B^0\ B_{min}] = [1.0]$ is an effective strategy for selecting loudness, where $B_{min} = 0$ indicates that a bat has successfully captured its products and has stopped making any noise. Equation (6) provides a formula for expressing the loudness and pulse emission rate.

$$\begin{cases} q_i^{s+1} = q_i^0[1 - \exp(-\gamma s)] \\ B_i^{s+1} = \beta B_i^s \end{cases} \tag{6}$$

According to the simulated annealing approach, β is comparable to the cooling component of a cooling strategy for any γ larger than 0 and a value of β from $0\ to\ 1$, where $\beta\ and\ \gamma$ are constants as shown in Equation (7).

$$\begin{cases} B_i^s \to 0 \\ q_i^s \to q_i^0 \cdot as \\ s \to \infty \end{cases} \tag{7}$$

It can decide that $\beta\ and\ \gamma$ are equal. The typical range for $\beta\ and\ \gamma$ in the traditional Bat method is $0.9\ to\ 0.975$.

3.7. Multi-Behavior Bat (MBA) Algorithm

The Multi-Behavior Bat Algorithm improves supply chain transparency by modeling adaptive echolocation behaviors, resulting in better continuous monitoring, data reliability and decision-making across intricate, multi-tier networks.

The NBA is an expansion of the traditional BA that includes the following operators.

3.7.1. Habitat Selection

The choice of the bats' habitat is influenced by several random occurrences, and for simplicity, it is represented as an advanced decision. The selection threshold is represented by $O \in [0.1]$. Bats must choose the QB to forage in a wide variety of habitats if an arbitrary number Q within $[0, 1]$ is insignificant against O; must choose the mechanical behavior to access supply chain products in a restricted number of habitats.

3.7.2. Bats with QB

The virtual bats that exhibit QB can forage in a wide range of environments. If one bat finds the product source, others should immediately seek forage from it. Therefore, Equation (8) can be used to determine their locations.

$$w_{i,j}^{s+1} = \begin{cases} h_i^s + \theta \times \left|mean_i^s - w_{i,j}^s\right| \times In\left(\frac{1}{v_{j.i}}\right) \forall\ rand_j(0,1) < 0.5 \\ h_i^s - \theta \times \left|mean_i^s - w_{i,j}^s\right| \times In\left(\frac{1}{v_{j.i}}\right)\ Otherwsie \end{cases} \tag{8}$$

3.7.3. Bats With Mechanical Behavior

The calculations for the updated offspring at time step s differ significantly from the corresponding sections in the traditional BA due to the Doppler Effect.

Initially, the frequency calculation is divided into three sections. Except for the random selection from the range $[e_{min}, e_{max}]$, the frequency is based on the bats' Doppler Effect and compensation rates. Bats move towards their target as they attempt to flee. It can be considered that both have the same global ideal solution (h_i^s).

The frequency e_j determines the bats' speed increment, $\lambda_j e_j$, which influences their distance to the product. Bats fly forward if their position is smaller than h_i^s and compensate flexibly in echoes for the Doppler Effects. If $w_{j.i}^s$ improves, they can slow down and catch products by negatively compensating. Compensation rates change depending on the individual. Therefore, using the NBA, Equations (2 - 4) can be expressed as follows in Equations (9-12),

$$e_j = e_{min} + (e_{max} - e_{min}) + \alpha \tag{9}$$

$$e_{j.i} = \frac{\left(d + u_{j.i}^s\right)}{d + u_{h.i}^s} + e_{j.i} \times \left(1 + D_j \times \frac{\left(h_i^s - w_{j.i}^s\right)}{\left|h_i^s - w_{j.i}^s\right| + \varepsilon}\right) \tag{10}$$

$$u_{j.i}^{s+1} = x \times u_{j.i}^s \times \left(h_i^s - w_{j.i}^s\right) \times e_{j.i} \tag{11}$$

$$w_{j.i}^{s+1} = w_{j.i}^s + u_{j.i}^s \tag{12}$$

Where, ε is the lowest constant in this case, when $x \in [0.1]$. $D \in [0.1]$. d is in $[0,1]$. $u_{h.i}^s$ is the speed that corresponds to the global ideal location, and $c = 340\ m/s$ is the velocity in the air.

3.7.4. Local Search

Bats approach products in silence by increasing the pace at which they emit pulses and decreasing their noise level. Taking into account the natural loudness of bats and other animals, loudness increases the possibility of capturing products. In Equation (13), each bat's new location is created as follows:

$$\begin{cases} w_{j.i}^{s+1} = h_i^s \times \left(1 - randn(0.\sigma^2)\right), & if\ (rand(0,1) > q_j \\ \sigma^2 = \left|B_j^s - B_{mean}^s\right| + \varepsilon, & end\ if \end{cases} \tag{13}$$

Where $randn(0.\sigma^2)$ displays the GD with a mean of 0 and an SD of σ^2.

3.7.5. Chaotic maps (CMs)

The use of CMs is an effective method for addressing initial convergence and modifying static variables in metaheuristic processes. Chaos was incorporated into the standard NBA to avoid local optima. The Chaotic NBA (CNBA) is a hybrid method that combines the NBA with chaotic sequences to improve global convergence. The most significant benefit of CMs is the seamless transition between exploitation and exploration; it will select for their excellent efficiency in choosing the ideal solutions and offering good algorithm behavior. The various kinds of CMs are described by the following,

- Logistic map,
- Gaussian map,
- Piecewise map, and
- Iterative map.

An expression for the iterative map with limitless collapses can be identified in Equation (14). However, Equation (15) can provide the Gaussian map. Furthermore, Equations (16 & 17), which demonstrate logistic and piecewise linear maps, are provided. Figure 6 shows the flow chart for the Multi-Behavior Bat Algorithm.

$$w_{l+1} = \sin\left(\frac{\gamma\pi}{w_l}\right) \tag{14}$$

$$w_{l+1} = \begin{cases} 0\ \forall_{wl} = 0 \\ \dfrac{1}{w_l mod(1)}, Otherwise \end{cases} \tag{15}$$

$$w_{l+1} = b.w_l(1 - w_l) \tag{16}$$

$$w_{l+1} = \begin{cases} \dfrac{wl}{O} 0 \leq w_l < O \\ \dfrac{w_l - O}{0.5} O \leq w_l < \dfrac{1}{2} \\ \dfrac{\frac{1-O-w_l}{0.5-O} 1}{2} \leq w_l < 1 - O \\ \dfrac{1 - w_l}{O} 1 - O \leq w_l < 1 \end{cases} \tag{17}$$

Where, w_l - Value between $0\ and\ 1$, O - Control variable in the range of $[0, 0.5]$, b - Favorable variable between $0\ and\ 1$, and $\gamma\ =\ 4$ - Suitable parameter.

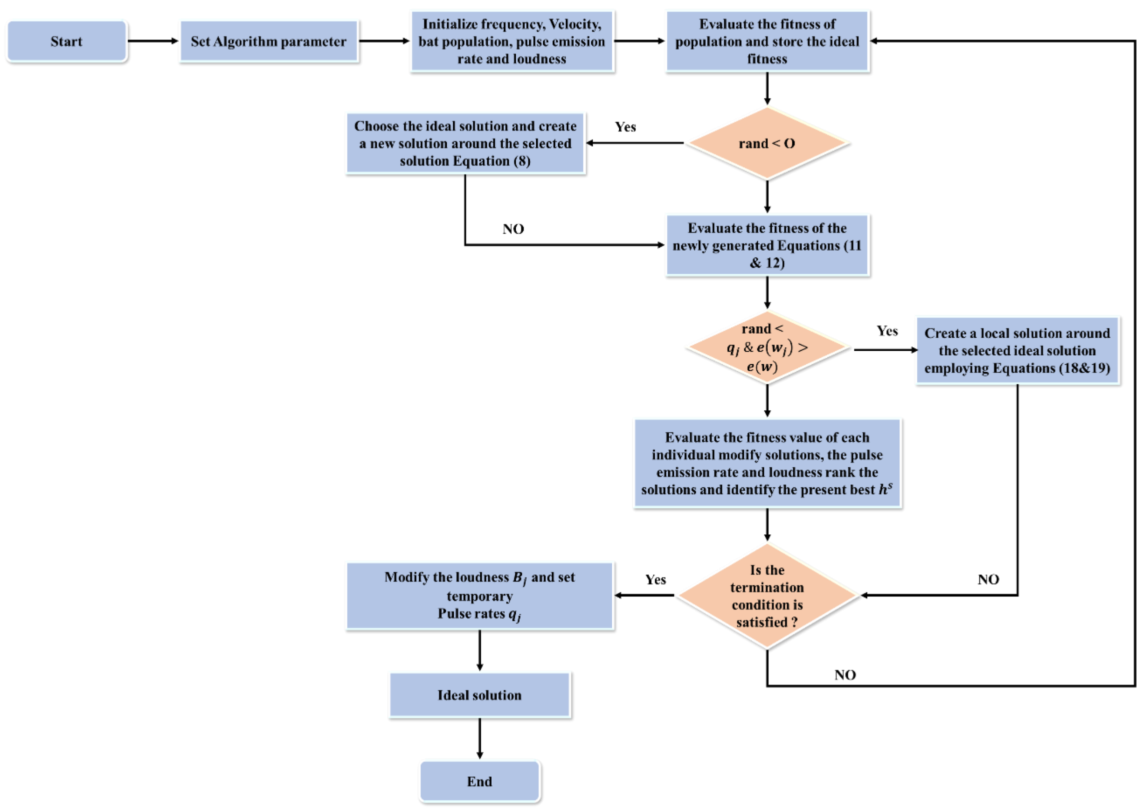

Figure 6.
Flowchart of Multi-Behavior Bat Algorithm.

CMs have been used in place of the variable in the original frequency equation, and Equation (9) was changed as follows in Equation (18),

$$e_j = e_{min} + (e_{max} - e_{min}) \times DN \tag{18}$$

Additionally, CM replaces the frequency equation's compensating rates, and Equation (10) has been modified as follows in Equation (19).

ISSN: 2576-8484
Vol. 9, No. 7: 1218-1234, 2025
DOI: 10.55214/25768484.v9i7.8863

$$e_{j,i} = \frac{\left(d + u_{j,i}^{s}\right)}{d + u_{h,i}^{s}} \times e_{j,i}\left(1 + DN_j \times \frac{\left(h_i^s - w_{j,i}^{s}\right)}{\left|h_i^s - w_{i,j}^{s}\right| + \varepsilon}\right) \quad (19)$$

Through the traditional NBA, d_j falls inside $[0.1]$, while α and ρ are arbitrary numbers in the $[0.1]$ range.

4. Results

The Python platform was used to evaluate the proposed BDT-MBA approach. The performance of the suggested method was evaluated with traditional methods such as jellyfish optimization (JFO) [18] and perceptual craving game search optimization (PCGSO) [18].

4.1. Supply Chain Transparency Assessment Using the BDT-MBA Approach

The performance indicators highlight critical aspects of improving supply chain transparency under the BDT-MBA approach, as shown in Figure 7. Continuous monitoring across processes can be achieved by a 40% reduction in supply chain processing time, indicating faster activities. Resource Utilization Performance at 15% and Logistics Effectiveness at 20% indicate modest improvements in operational efficiency and asset utilization. The overall integrity and adaptability of the supply chain network are strengthened by increased transparency, which makes it possible to respond to disruptions more quickly, achieve better coordination, and enhance accountability.

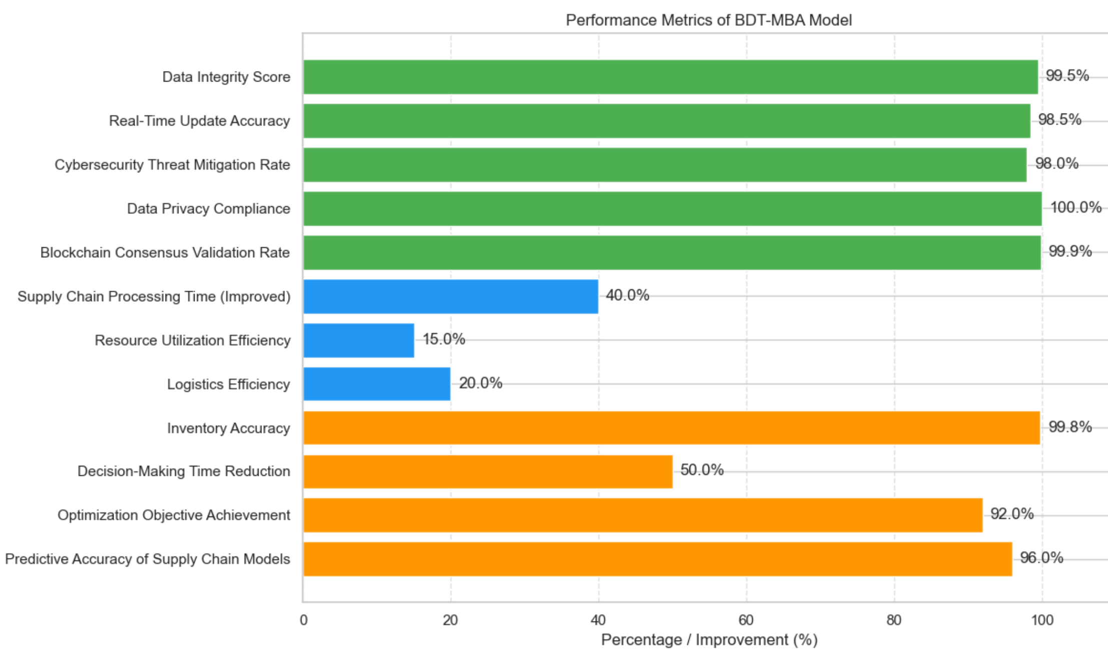

Figure 7.
Enhanced supply chain transparency through BDT-MBA model performance improvements.

4.2. Daily Changes in Resource Utilization From 2023 To 2025

Resource usage from the beginning of 2023 to 2025 is depicted in Figure 8. Utilization rates exhibit frequent and sudden peaks and troughs, with a wide range of 60% to 95%. This indicates a changing environment with shifting demand or performance levels, which could be impacted by changes in workloads, user behavior, or system performance. The data often shows fluctuating resource use, maintaining a high utilization level throughout the variations. The intense pattern of variances indicates frequent data collection or monitoring, possibly daily, which reflects thorough resource utilization monitoring and control over the observed period.

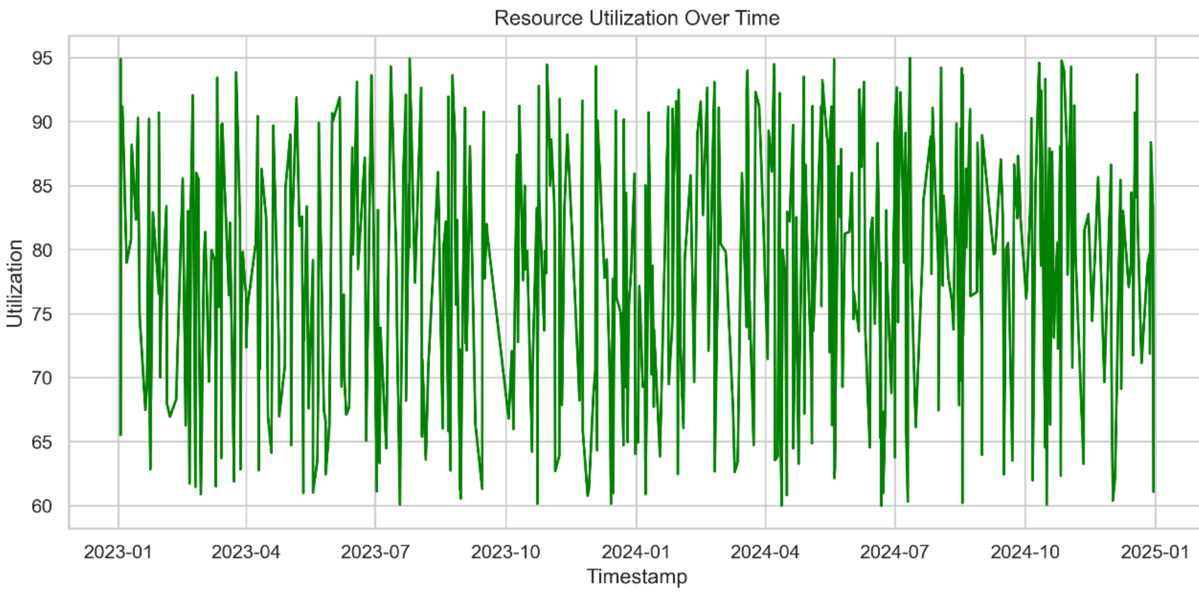

Figure 8.
Resource utilization trends detected using the suggested BDT-MBA approach from January 2023 to January 2025.

4.3. Tracking Supply Chain Efficiency Trends from 2023 to 2025

The supply chain efficiency rolling average from early 2023 to 2025 is shown in Figure 9. Efficiency values exhibit considerable change over time, ranging from 0 to 1. Additionally, peaks come close to 1.0, which denotes good efficiency, while close to 0 indicates poor performance. The frequent changes could be brought about by demand variations, irregular resource accessibility, or operational issues. This instability could be caused by irregular inventory control, delays in transportation, fluctuating demand, or logistical problems.

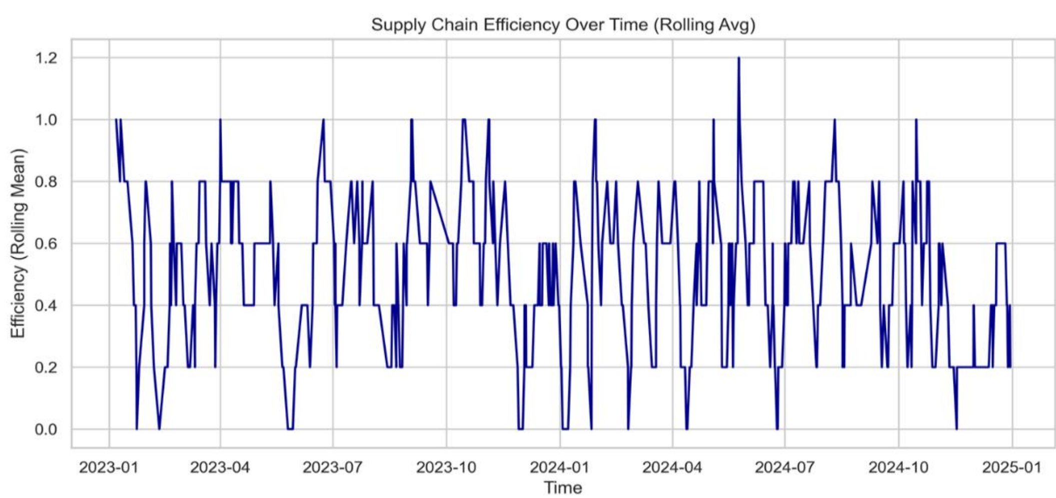

Figure 9.
Supply chain efficiency variation detected through the BDT-MBA approach.

Edelweiss Applied Science and Technology
ISSN: 2576-8484
Vol. 9, No. 7: 1218-1234, 2025
DOI: 10.55214/25768484.v9i7.8863

4.4. Performance Assessment of the Suggested BDT-MBA Approach using Different Metrics

The Efficiency of Sanitization assesses the efficacy of cleaning supply chain data by analyzing the speed, accuracy, and reliability of removing irregularities, leveraging cloud computing to provide accurate, accessible, and tamper-free data across all transactional interactions.

The Efficiency of Restoration evaluates how rapidly and successfully a supply chain regains transparency after delays, reducing information lag and re-establishing confidence through precise data exchange, cloud computing-enabled continuous monitoring, and swift clearing of transparency deficiencies for all stakeholders involved.

The suggested BDT-MBA technique for enhancing supply chain transparency was assessed using several performance metrics. The approach produced better outcomes with Efficiency of Sanitization (98.4%) and Efficiency of Restoration (98.8%).

5. Discussion

The exploration-exploitation balance of JFO [18] was susceptible to parameter adjustment, which could make it more difficult to achieve reliable results in dynamic supply chain settings. The movement patterns of the algorithm, which were inspired by nature, might not be able to adjust to sudden interruptions or real-time changes, which would make it less appropriate for highly unpredictable supply chains.

The PCGSO's Aljabhan and Obaidat [18] dependence on game-theoretic behavioral modeling provides a complexity that might interfere with the simplicity required in supply chains, while security modeling and analysis are other aspects to consider. Practical application was hampered by PCGSO's scaling issues and the potential need for thorough validation of decision-making and behavioral parameters. To address these issues, a unique BDT-MBA approach was presented to improve supply chain transparency management.

The proposed BDT-MBA method achieved an Efficiency of Restoration value of 98.8%, which outperforms the traditional JFO and PCGSO methods with Efficiency of Restoration values of 97% and 98.5%, as displayed in Figure 10. With an Efficiency of Sanitization value of 98.4%, the suggested BDT-MBA method outperformed the conventional JFO and PCGSO approaches, which had Efficiency of Sanitization values of 86% and 98%, as displayed in Figure 10. Table 1 presents the Efficiency of Restoration and the Efficiency of Sanitization values of all evaluated methods.

Table 1.
Comparative analysis of existing JFO and PCGSO, and the proposed method.

Methods	Efficiency of Sanitization (%)	Efficiency of Restoration (%)
JFO	86	97
PCGSO	98	98.5
BDT-MBA	98.4	98.8

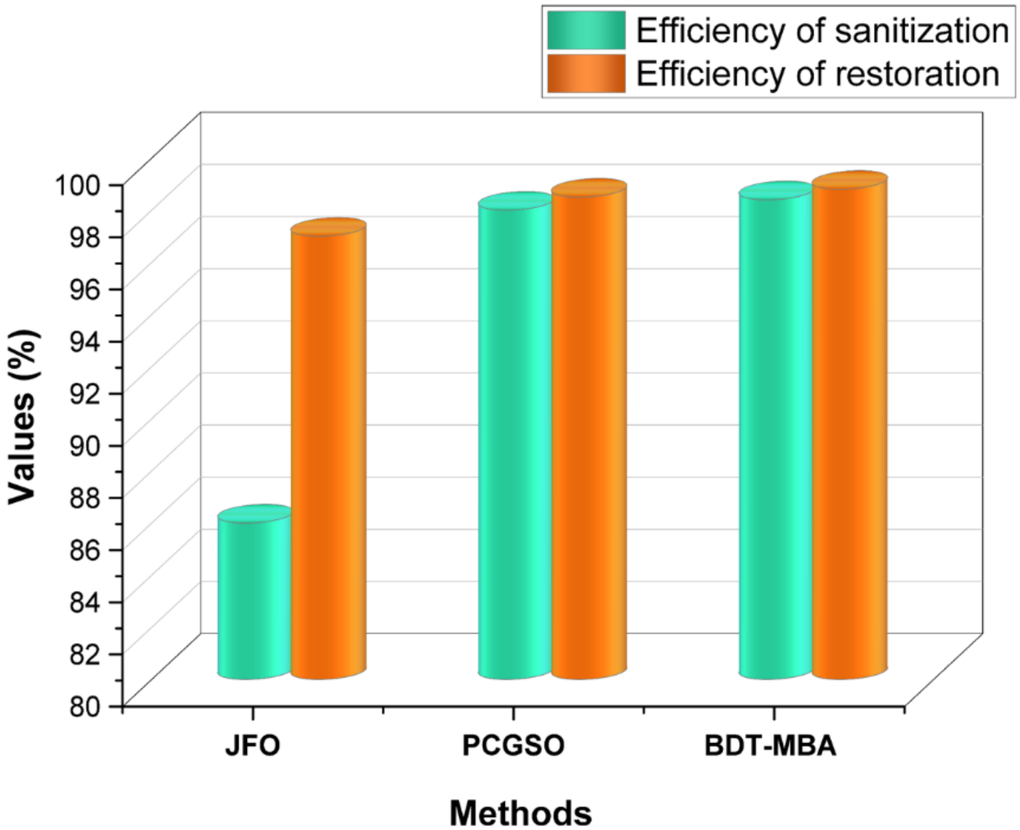

Figure 10.
Comparative assessment of the Efficiency of Restoration and the Efficiency of Sanitization of existing methods and BDT-MBA.

6. Conclusion

Supply chains have become increasingly complicated in today's highly interdependent and globalized commercial environment, involving several suppliers, countries, and systems. The supply chain data were gathered from the Kaggle platform. The data are preprocessed by employing the data cleaning and Z-score normalization strategies. An innovative BDT-MBA method was introduced to enhance supply chain management through DTs, enhanced blockchain security, and optimization techniques. The performance of the suggested BDT-MBA method was evaluated in terms of Efficiency of Sanitization (98.4%) and Efficiency of Restoration (98.8%). It could be limited by problems including high implementation costs, data privacy issues, stakeholder reluctance, technical challenges, and difficulties in verifying complex, multi-tier supplier data. Future scope involves improving stakeholder engagement, increasing data accuracy, promoting sustainable practices, integrating modern technologies like AI and cloud computing for real-time monitoring, and increasing transparency across international, multi-tier supply chains.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

References

[1] T. S. M. Toapanta *et al.*, "Blockchain-based security model to mitigate the risks of a database for a public organization," *Journal of Internet Services and Information Security*, vol. 14, pp. 78–98, 2024.

[2] B. Sindhusaranya, R. Yamini, M. Manimekalai, and K. Geetha, "Federated learning and blockchain-enabled privacy-preserving healthcare 5.0 system: A comprehensive approach to fraud prevention and security in iomt," *Journal of Internet Services and Information Security*, vol. 13, no. 4, pp. 199-209, 2023.

[3] D. M. Gligor *et al.*, "Utilizing blockchain technology for supply chain transparency: A resource orchestration perspective," *Journal of Business Logistics*, vol. 43, no. 1, pp. 140-159, 2022.

[4] M. S. Rahman *et al.*, "Enhancing supply chain transparency with blockchain: A data-driven analysis of distributed ledger applications," *Journal of Business and Management Studies*, vol. 7, no. 3, pp. 59-77, 2025. https://doi.org/10.32996/jbms.2025.7.3.7

[5] E. I. Vazquez Melendez, P. Bergey, and B. Smith, "Blockchain technology for supply chain provenance: Increasing supply chain efficiency and consumer trust," *Supply Chain Management: An International Journal*, vol. 29, no. 4, pp. 706-730, 2024. https://doi.org/10.1108/SCM-08-2023-0383

[6] H. A. Fattahi Bafghi, "Leveraging blockchain technology for sustainable, transparent and efficient supply chain management: An integrative exploration from an engineering management perspective," Master Thesis, Technische Universität Wien, 2024.

[7] M. M. Akkan, "Reshoring decisions in supply chains and industry 5.0 optimization: AI based sustainable decision support model," 2025. https://doi.org/10.21203/rs.3.rs-6252236/v1

[8] A. Bertila, K. Raghuveer, S. Chandhok, P. Parida, and P. Pirakatheeswari, "Leveraging reinforcement learning and blockchain technology for enhanced supply chain management efficiency and transparency," presented at the 2024 IEEE 2nd International Conference on Innovations in High Speed Communication and Signal Processing (IHCSP) (pp. 1–5). IEEE, 2024.

[9] Y. Cui and V. Gaur, *Supply chain transparency using blockchain: Benefits, challenges, and examples. In R. Gopalakrishnan & S. R. Narayanan (Eds.), Global logistics and supply chain strategies for the 2020s: Vital skills for the next generation.* Cham, Switzerland: Springer International Publishing, 2022.

[10] G. Lalitha, M. Gupta, S. J. Arul, Praveen, A. K. Parashar, and R. A. Hussien, "Blockchain-enabled simulation and optimization for supply chain transparency," *E3S Web of Conferences*, vol. 472, p. 02007, 2024. https://doi.org/10.1051/e3sconf/202447202007

[11] T. R. Morgan, C. B. Gabler, and P. S. Manhart, "Supply chain transparency: Theoretical perspectives for future research," *The International Journal of Logistics Management*, vol. 34, no. 5, pp. 1422-1445, 2023. https://doi.org/10.1108/IJLM-02-2021-0115

[12] N. Ahmad, "Synergizing business insights: Integrating data analytics, AI, and blockchain for enhanced performance and supply chain transparency," 2024. https://doi.org/10.13140/RG.2.2.20836.39041

[13] L. Li, Y. Liu, Y. Jin, T. C. E. Cheng, and X. Zhu, "The interplay between supply chain transparency and visibility: Implications for firm performance in manufacturing and service sectors," *Journal of Business Logistics*, vol. 46, no. 3, p. e70016, 2025. https://doi.org/10.1111/jbl.70016

[14] S. Pandey and A. K. Singh, "Blockchain-based fake product detection system: Enhancing supply chain transparency," presented at the 2024 First International Conference on Pioneering Developments in Computer Science & Digital Technologies (IC2SDT) (pp. 546–550). IEEE, 2024.

[15] A. Liu and Z. Han, "Blockchain-based supply chain management system: Framework design for achieving transparency and collaboration," *International Journal of High Speed Electronics and Systems*, vol. 0, no. 0, p. 2540241, 2025. https://doi.org/10.1142/s0129156425402414

[16] Y. Chen, "Transparency enhancement and trust mechanism construction of global supply chain based on blockchain technology," *Advances in Computer and Communication*, vol. 5, no. 3, pp. 195-199, 2024. http://dx.doi.org/10.26855/acc.2024.07.007

[17] R. Kumar, V. Mangaiyarkarasi, G. Ramesh, S. Arvind, and M. H. Fallah, "Boosting supply chain transparency with blockchain and smart contracts," presented at the 2024 International Conference on IoT, Communication and Automation Technology (ICICAT) (pp. 1351–1355). IEEE, 2024.

[18] B. Aljabhan and M. A. Obaidat, "Privacy-preserving blockchain framework for supply chain management: Perceptive craving game search optimization (PCGSO)," *Sustainability*, vol. 15, no. 8, p. 6905, 2023. https://doi.org/10.3390/su15086905

Appendix

PBFT	Practical Byzantine Fault Tolerance	DL	Deep learning
IoT	Internet of Things	PoW	Proof of Work
RFID	Radio Frequency Identification	SD	Standard deviation
AI	Artificial intelligence	DT	Digital Twin
QB	Quantum behavior	SCV	Supply chain visibility
DLT	Distributed ledger technology	MBA	Multi-Behavior Bat Algorithm
FR-ROA	Foraging Redefined Remora Optimization Algorithm	NBA	Novel Bat Algorithm
SCT	Supply chain transparency	BA	Bat algorithm
ML	Machine learning	GD	Gaussian distribution
RW	Random walk	ERP	Enterprise Resource Planning
QR	Quick Response		