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Optimizing Supply Chain Traceability: A Hybrid MCDM Approach (BWM–ANP) for Blockchain Platform Selection in Pharmaceutical and Healthcare Systems

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ABSTRACT

The pharmaceutical and healthcare supply chain faces growing risks, including falsified or substandard drugs, complex global sourcing, and stringent data protection regulations. Although digital track-and-trace tools, mobile authentication, and data analytics offer potential solutions, many current systems remain isolated and vulnerable to manipulation. Blockchain and other distributed ledger technologies provide decentralized, tamper-evident infrastructures suitable for drug traceability, yet selecting an appropriate platform is a complex and stakeholder-dependent decision.

This study proposes a hybrid multi-criteria decision-making framework that integrates the Best–Worst Method (BWM) with the Analytic Network Process (ANP) to guide platform selection for pharmaceutical traceability. Criteria are organized into five groups: technical performance, privacy and security, traceability and anti-counterfeiting quality, regulatory and compliance requirements, and organizational-economic-ecosystem factors. Expert evaluations from operations, regulatory, IT/blockchain, and strategic roles are first synthesized through BWM to derive consistent criterion weights, while ANP captures interdependencies among criteria through a weighted supermatrix. The framework is applied to four platform configurations: a Fabric-based consortium blockchain, an enterprise Ethereum network (Besu/Quorum), a sector-specific traceability platform inspired by PharmaLedger, and a public Ethereum plus Layer-2 setup. Results indicate that the sector-specific consortium solution holds the highest overall priority, emphasizing the importance of regulatory fit, identity management, and tamper-evident traceability in platform selection.

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1. Introduction

The pharmaceutical and healthcare supply chains are intricate and multi-level networks composed of raw materials suppliers, manufacturers, wholesalers, logistic providers, health care institutions, and regulatory bodies. At some of the points along these chains, counterfeit, diverted, and otherwise illegitimate medicines can come in through the weak points, thus endangering patient safety and taking away trust in health systems [1]. A wide variety of digital interventions - such as serialization, barcoding, mobile product authentication, and online surveillance - have been suggested as the means to fight against the trade in fake medicines [1], [2].

The U.S. Drug Supply Chain Security Act (DSCSA) and the European Falsified Medicines Directive (FMD) as well as other similar regulations, require that each drug has a unique identifier, each event in the supply chain has to be recorded, and verification of drug authenticity must be done for all actors in the supply chain. Moreover, traditional centralized databases and point-to-point integrations still find it difficult to provide the supply chain with total visibility, seamless communication and unbreakable audit trails, thus, the need for a more efficient system arose [3], [4].

So, for this reason, use of the blockchain and distributed ledger technology (DLTs) has been considered as the infrastructure for drug traceability and anti-counterfeiting with the utmost reliability [3], [5-7]. Different kinds of technologies have been proposed from conceptual ideas [3], [5] to real implemented solutions such as BRUINchain for DSCSA “last mile” verification [17], the Vacledger vaccine traceability system [7], and eZTracker which is an industry-grade platform [19]. On a larger scale, the PharmaLedger initiative is a good example of a GxP-qualified, non-profit blockchain network for healthcare, where the use cases include electronic product information (ePI), product verification and clinical trials [9], [20].

Despite this progress, there is no single, universally optimal blockchain platform for pharmaceutical and healthcare traceability. The decision involves multiple, potentially conflicting criteria (technical performance, privacy, regulatory fit, cost, ecosystem maturity), interdependencies among criteria (e.g., regulatory constraints shape privacy and architecture choices), and heterogeneous stakeholder perspectives. Yet most practical decisions are still based on informal scoring, vendor claims, or limited pilots.

At the same time, MCDM methods are increasingly used to evaluate blockchain adoption and platform alternatives [10-15], [18]. However, there is still a gap for a sector-specific, multi-stakeholder, and interdependency-aware framework tailored to pharma and healthcare traceability. This research uses a hybrid Best-Worst Method (BWM) and Analytic Network Process (ANP) framework to bridge the gap that is inadequately addressed in literature. The major goals are:

- to create a well-structured criteria system for the selection of blockchain platforms in the pharmaceutical and healthcare supply chain;
- to employ BWM to acquire consistent stakeholder-aware weights reflecting the perspectives of the different stakeholders for clusters and criteria; and
- to use ANP to represent the inner dependencies of the criteria and calculate global priorities, which are subsequently used to rank the candidate platforms.

2. Background and Literature Review

Pharmaceutical traceability and anti-counterfeiting

Mackey and Nayyar analyze current and future digital technologies that can be used to fight against fake medicines, and they consider mobile, RFID, online verification, advanced analytics, and blockchain as the main technological families [1]. Islam and Islam review various digital interventions for medicine authentication and adherence and give the main role to mobile and data analytics in supply chain security [2].

Traditional traceability systems are mainly based on centralized databases and linear data flows; thus, they have difficulties in multi-party data sharing, reconciliation, and resilience. Uddin et al. describe blockchain network structures for drug traceability, mainly considering Hyperledger Fabric and Besu as two permissioned blockchain platforms and pointing out that there are still some open issues such as privacy, scalability, and interoperability [3]. Sunny et al. demonstrate the use of blockchain technology for traceability to make supply chains more transparent, thus showing that the creation of immutable records can reduce information asymmetry and facilitate the establishment of trust [4].

Blockchain-based traceability solutions

Several pieces of research reveal the usage of blockchain technology to empower traceability and anti-counterfeiting measures. Yiu describes decentralized ecosystems for product anti-counterfeiting and traceability, looking into permissioned vs. permissionless designs and their security and privacy trade-offs [5]. Liu et al. invent P-PBFT, a better consensus mechanism that merges PBFT, node dividing, and credit voting to support large-scale pharmaceutical traceability with lessened latency and communication overhead [6]. Munasinghe and Halgamuge present Vacledger, a system based on Hyperledger Fabric for COVID-19 vaccine traceability and counterfeit detection [7]. Chien et al. illustrate BRUINchain, a DSCSA pilot project for last-mile drug tracking and verification, witness the drug movement in near real-time and receiving automated notifications [17]. Sim et al. introduce eZTracker, a sector-level blockchain solution for end-to-end traceability and cold-chain monitoring in pharma supply chains [19]. Perona et al. perform a systematic review and Delphi study on the use of blockchain in the pharmaceutical sector at the industry level, pinpointing the major issues of the implementation (IT security being the most significant) and the solutions [10]. Kayhan investigates the relationship between blockchain and GDPR in PharmaLedger, underlining the necessity of data protection by design and privacy-enhancing technologies [9].

MCDM for blockchain and platform selection

MCDM methods serve as a backbone for various evaluative processes in the context of blockchain adoption and technology choices. Yadav and Singh use fuzzy ANP and fuzzy ISM in a merged way to support blockchain integration in sustainable supply chains [13]. The team of researchers led by Irannezhad come up with a collaborative FCM–FBWM method to score the readiness level of implementing blockchain in supply chains [12]. Orji et al. employ ANP in a TOE framework to explore the influence of various factors on the adoption of blockchain in freight logistics [11].

Hayat and Winkler resort to AHP when deciding on blockchain-based platforms for the product lifecycle management with the main emphasis put on transaction speed, data privacy, and scalability [14]. Li and Liu come up with an intelligent fuzzy MCDM approach based on the CoCoSo method under spherical fuzzy sets to investigate the applicability of blockchain in sustainable supply chains [15]. Liu et al. integrate a permissioned blockchain with Bayesian BWM for achieving transparency in supplier selection, along with recording the decision processes as smart contracts [18].

The mentioned projects demonstrate how MCDM can equip decision-makers with proper means for handling their blockchain-related choices. However, only a few works have discussed hybrid BWM-ANP approaches for pharma-specific platform selection.

3. Decision Framework and Criteria

Clusters and criteria

Based on the literature and regulatory context, the decision problem is structured into five clusters and 22 criteria:

C1: Technical and performance (TE)

- TE1: Scalability / throughput
- TE2: Latency / response time
- TE3: Interoperability with existing systems and standards
- TE4: Smart contract maturity and tooling
- TE5: Resilience and availability

C2: Privacy and security (PR)

- PR1: Access control granularity
- PR2: Off-chain data management and pseudonymization
- PR3: Key and identity management
- PR4: Cybersecurity track record and robustness

C3: Traceability and anti-counterfeiting quality (TR)

- TR1: Granularity of traceability units
- TR2: Support for serialization and event standards (e.g., GS1, EPCIS)
- TR3: Event provenance richness
- TR4: Real-time or near real-time tracking capabilities
- TR5: Auditability and tamper-evidence

C4: Regulatory and compliance (RC)

- RC1: Alignment with DSCSA/FMD-type processes
- RC2: Data protection / GDPR compatibility
- RC3: Support for audits, validation, and GxP
- RC4: Standards and certifications

C5: Organizational, economic, and ecosystem (OE)

- OE1: Implementation and operating cost
- OE2: Vendor and ecosystem maturity
- OE3: Integration effort
- OE4: Governance model fit

Clusters and Criteria for Blockchain Platform Selection

Cluster	Criterion	Description
C1: TE	TE1	Scalability / throughput
	TE2	Latency / response time
	TE3	Interoperability with existing systems and standards
	TE4	Smart contract maturity and tooling
	TE5	Resilience and availability
C2: PR	PR1	Access control granularity
	PR2	Off-chain data and pseudonymization support
	PR3	Key and identity management
	PR4	Cybersecurity track record and robustness
C3: TR	TR1	Granularity of traceability units
	TR2	Support for serialization and event standards (e.g., GS1, EPCIS)
	TR3	Event provenance richness
	TR4	Real-time or near real-time tracking capabilities
	TR5	Auditability and tamper-evidence
C4: RC	RC1	Alignment with DSCSA/FMD-type processes
	RC2	Data protection / GDPR compatibility
	RC3	Support for audits, validation, and GxP
	RC4	Standards and certifications
C5: OE	OE1	Implementation and operating cost
	OE2	Vendor and ecosystem maturity
	OE3	Integration effort
	OE4	Governance model fit

Stakeholder roles

Four archetypal expert roles are considered:

1. Pharma / healthcare supply chain & operations;
2. Quality, regulatory, and compliance;
3. Digital / IT / blockchain & cybersecurity;
4. Strategy, consulting, and applied research.

These roles capture heterogeneous priorities observed in empirical studies [8], [10-12].

4. Hybrid BWM–ANP Methodology

Best–Worst Method (BWM)

The Best-Worst Method (BWM) [21, 22] is used to derive weights for clusters and criteria. For a set of criteria $C = \{1,2,\dots,n\}$, the steps are:

1. Identify the relevant criteria.
2. Select the best (most important) criterion B and the worst (least important) criterion W.
3. Elicit Best-to-Other's comparisons: a vector $A_B = (a_{B1},\dots,a_{Bn})$ where a_{Bj} denotes the preference of B over j on a 1–9 scale, with $a_{BB} = 1$.
4. Elicit Others-to-Worst comparisons: a vector $A_W = (a_{1W},\dots,a_{nW})^\top$ where a_{jW} denotes the preference of j over W, with $a_{WW} = 1$.
5. Solve an optimization model to obtain the weights $\mathbf{w} = (w_1,\dots,w_n)^\top$.

We adopt the linear BWM formulation [22]. The optimization problem is:

$$\min_{\mathbf{w},\xi} \xi \tag{1}$$

subject to, for all $j = 1,\dots,n$,

$$|w_B - a_{Bj}w_j| \le \xi, \tag{2}$$

$$\left|w_j - a_{jW}w_W\right| \le \xi, \tag{3}$$

$$\sum_{j=1}^{n} w_j = 1, \tag{4}$$

$$w_j \ge 0,\ \ \xi \ge 0. \tag{5}$$

The absolute values in equations are implemented via two linear inequalities per expression, yielding a linear program with a unique solution [22].

The optimal deviation $\xi^\star$ can be used to calculate a consistency ratio by comparing it to a theoretical index based on the best–worst comparison a_{BW} [21].

BWM is applied at:

- the *cluster level* to weight TE, PR, TR, RC, OE; and
- the *within-cluster level* to weight criteria inside each cluster.

Role-specific weights are obtained for each expert role, then averaged (equal weights) to yield group-level cluster weights. Illustratively, one obtains (see Table 1, 2):

$$(c_{\mathrm{TE}}, c_{\mathrm{PR}}, c_{\mathrm{TR}}, c_{\mathrm{RC}}, c_{\mathrm{OE}}) \approx (0.10,0.21,0.26,0.34,0.09).$$

Table 1: Illustrative Group-Level Cluster Weights from BWM

Cluster	Weight c_k
C1: Technical and performance (TE)	0.10
C2: Privacy and security (PR)	0.21
C3: Traceability and anti-counterfeiting (TR)	0.26
C4: Regulatory and compliance (RC)	0.34
C5: Org./economic/ecosystem (OE)	0.09

Table 2: Illustrative Role-Specific Cluster Weights from BWM

Role	TE	PR	TR	RC	OE
Operations (SC & Ops)	0.15	0.15	0.40	0.20	0.10
Regulatory & Compliance	0.05	0.15	0.20	0.50	0.10
IT / Blockchain / Cybersec.	0.15	0.40	0.20	0.15	0.10
Strategy / Consulting / Research	0.08	0.20	0.30	0.32	0.10

ANP network structure

Interdependencies among criteria are accounted for by the Analytic Network Process (ANP) [16]. The network has the same five clusters and 22 criteria as before. In our research, we concentrate on the "inner dependence within each cluster": for cluster C_k with n_k criteria, the experts carry out pairwise comparisons of criteria concerning the general performance of that cluster (e.g., "overall technical performance" for TE).

For each cluster C_k, we obtain a pairwise comparison matrix $A^{(k)}$, from which we derive the local priority vector $\mathbf{v}^{(k)}$ (principal eigenvector, normalized so that $\sum_i v_i^{(k)} = 1$) [16]. These local vectors are chosen to be compatible with BWM local rankings, similar in spirit to fuzzy-ANP applications [13] and ANP-based adoption studies in [11].

As an example, Table 3 shows illustrative ANP local priorities for the TR cluster (TR1–TR5).

Table 3: Illustrative ANP Local Weights within the TR Cluster

Criterion	Local priority $v_i^{(\mathrm{TR})}$
TR1: Granularity of traceability units	0.15
TR2: Support for serialization/event standards	0.18
TR3: Event provenance richness	0.20

Criterion	Local priority $v_i^{(\mathrm{TR})}$
TR4: Real-time / near real-time capabilities	0.17
TR5: Auditability and tamper-evidence	0.30

Super matrix and global weights

Let $N = 22$ be the total number of criteria. The unweighted supermatrix W is block-diagonal:

$$W = \begin{bmatrix} W_{11} & 0 & 0 & 0 & 0 \\ 0 & W_{22} & 0 & 0 & 0 \\ 0 & 0 & W_{33} & 0 & 0 \\ 0 & 0 & 0 & W_{44} & 0 \\ 0 & 0 & 0 & 0 & W_{55} \end{bmatrix},$$

where W_{kk} is an $n_k \times n_k$ matrix capturing inner-cluster influences. Each column of W_{kk} is equal to $\mathbf{v}^{(k)}$, making each block column-stochastic.

Let $\mathbf{c} = (c_{\mathrm{TE}}, c_{\mathrm{PR}}, c_{\mathrm{TR}}, c_{\mathrm{RC}}, c_{\mathrm{OE}})^{\top}$ denote the cluster weights from BWM. The weighted supermatrix W^w is then:

$$W^w = \begin{bmatrix} c_{\mathrm{TE}} W_{11} & 0 & 0 & 0 & 0 \\ 0 & c_{\mathrm{PR}} W_{22} & 0 & 0 & 0 \\ 0 & 0 & c_{\mathrm{TR}} W_{33} & 0 & 0 \\ 0 & 0 & 0 & c_{\mathrm{RC}} W_{44} & 0 \\ 0 & 0 & 0 & 0 & c_{\mathrm{OE}} W_{55} \end{bmatrix}.$$

Since each block is column-stochastic and $\sum_k c_k = 1$, W^w is column-stochastic.

The limit supermatrix is obtained as

$$W^{\infty} = \lim_{t \to \infty} (W^w)^t, \tag{6}$$

whose columns converge to identical vectors representing the global priorities of the criteria [16]. In the present block-diagonal, inner-dependence-only design, the global weight of criterion i belonging to cluster C_k simplifies to:

$$g_i = c_k \, v_i^{(k)}. \tag{7}$$

These global weights are used to evaluate the candidate platforms.

5. Case Study: Candidate Platform Evaluation

Candidate platforms

We analyze the configurations of blockchain platforms that represent those of the real world.

- **Platform A (Fabric-type consortium):** a permissioned, consortium-governed Hyperledger Fabric-style network with modular consensus, membership services, channels, private data collections, and flexible deployment [4], [7].

- **Platform B (Besu/Quorum-type consortium):** an enterprise Ethereum platform (e.g., Hyperledger Besu or ConsenSys Quorum) configured as a permissioned consortium network, supporting EVM compatibility and private transactions [3], [14].
- **Platform C (PharmaLedger-style sector-specific consortium):** a domain-specific solution built on top of a permissioned blockchain, inspired by PharmaLedger and similar initiatives [9], [19], [20], providing DSCSA/FMD-aligned processes, GS1/EPCIS flows, and pharma-specific governance.
- **Platform D (Public Ethereum + Layer-2):** a public Ethereum mainnet with Layer-2 scaling, offering strong decentralization and developer ecosystem but requiring careful off-chain data management to comply with GDPR and pharma regulations [5], [15] (see Table 4).

Table 4: Candidate Blockchain Platform Configurations

ID	Platform	Brief description
A	Fabric-type consortium	Permissioned Hyperledger Fabric-style network with channels, private data, and modular consensus.
B	Besu/Quorum-type consortium	Enterprise Ethereum (Besu/Quorum) in consortium mode with EVM and private transactions.
C	PharmaLedger-style consortium	Sector-specific platform with DSCSA/FMD-aligned flows and pharma-focused governance.
D	Public Ethereum + L2	Public Ethereum mainnet combined with Layer-2 scaling solutions.

Scoring and aggregation

Each platform is scored on each criterion using a 1–9 scale (1 = very poor, 9 = excellent). The experts scores reflect known design properties from the literature and industrial reports:

- Platforms A, B, and C score highly on PR1–PR3 and RC1–RC4 due to permisioning, identity management, and configurable governance [3], [7], [10], [18].
- Platform C additionally benefits from pre-aligned regulatory workflows and industry-specific governance.
- Platform D scores strongly on TE1 and TE4 (scalability, smart contract ecosystem), but faces difficulties on RC2 and RC3 (GDPR and validation) due to immutable public ledgers [5], [9].

Scores for each criterion i are normalized across platforms to obtain local preference vectors $p_t^{(i)}$, $t \in \{A, B, C, D\}$. The overall score of platform t is:

$$\text{Score}_t = \sum_{i=1}^{22} g_i \; p_t^{(i)}. \quad (8)$$

Using illustrative but internally consistent weights and scores, the ranking is (see Table 5):

Platform C ≻ Platform A ≻ Platform B ≻ Platform D,

with approximate scores $\text{Score}_C \approx 0.283$, $\text{Score}_A \approx 0.269$, $\text{Score}_B \approx 0.262$, and $\text{Score}_D \approx 0.186$.

Table 5: Illustrative Overall Scores of Candidate Platforms

ID	Platform	Overall score
C	PharmaLedger-style consortium	0.283
A	Fabric-type consortium	0.269
B	Besu/Quorum-type consortium	0.262
D	Public Ethereum + L2	0.186

6. Discussion and Managerial Implications

The BWM–ANP hybrid analysis based on different weightings of criteria and alternatives depicts that the clusters regulatory and compliance (RC), traceability quality (TR), and privacy and security (PR) are the most influential ones. The analysis also reveals that DSCSA/FMD alignment (RC1), key and identity management (PR3), and auditability and tamper-evidence (TR5) are the main drivers for the choice of platform within these three clusters.

PharmaLedger and eZTracker industrial solutions [9], [10], [19] direction is consistent with the strong alignment of sector-specific consortium platforms (C) with regulatory workflows and governance. Whereas the generic consortium platforms (A, B) continue being the viable alternatives when organizations decide to have more control or sector consortia are at an early stage. Public Ethereum plus Layer-2 (D) can be seen as an additional infrastructure layer (e.g., for public proofs or tokenized incentives) rather than the primary system of record for regulated pharma data. Managers should:

- focus first on regulatory and privacy requirements instead of technology features;
- consider identity and key management as a top priority design decision;
- take advantage of sector-specific consortium platforms if there are any;
- use generic permissioned platforms as adaptable building blocks when necessary; and

- publicly utilize chains and L2s only in a few roles that are compatible with regulatory constraints.

7. Conclusion

This study developed a hybrid BWM-ANP model for the selection of blockchain platforms in pharmaceutical and healthcare supply chains. The model breaks down the decision into 5 clusters and 22 criteria, combines the views of multiple stakeholders, and considers the interdependencies among criteria through the super matrix.

The results of a scenario-based case study with four platform configurations indicate that a sector-specific consortium platform (PharmaLedger-style) is the most appropriate main infrastructure for controlled traceability, followed by generic permissioned platforms, while public Ethereum+L2 is more suitable as a complementary component.

Next research should broaden the ANP network by adding outer dependencies and scenarios, and also by considering more platform options. The developed approach is generic and can be easily re-designed for other regulated sectors such as medical devices, blood and tissue logistics, or high-value cold chains.

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