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DESIGNING A BLOCKCHAIN-ENABLED SINGLE WINDOW (BESW) MODEL FOR SECURE AND TRANSPARENT CUSTOMS DATA EXCHANGE

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Abstract
This paper proposes a conceptual framework called the Blockchain-Enabled Single Window (BESW) to enhance the security, transparency, and interoperability of customs data exchange, particularly in the Delivery Order (DO) and Surat Penyerahan Petikemas (SP2) process. The model introduces four integrated layers: (1) an Infrastructure Layer using a permissioned blockchain network to connect customs, port, banking, and logistics stakeholders; (2) a Data and Smart Contract Layer for automated document validation and payment verification; (3) an Interoperability Layer harmonized with WCO Data Model 3.11, UN/CEFACT, and ISO 20022; and (4) an Application and Audit Layer offering real-time monitoring and immutable audit logs. BESW aims to complement Indonesia's National Single Window (INSW) and ASEAN Single Window (ASW) by establishing a distributed trust architecture that enhances efficiency and institutional accountability. The paper concludes by outlining future empirical validation to assess feasibility, governance adaptation, and scalability for ASEAN-wide customs digitalization.

Keywords: *Blockchain; Single Window; DO–SP2 Online; Digital Customs; Interoperability; ASEAN*

Abstrak
Makalah ini mengusulkan sebuah kerangka konseptual yang disebut *Blockchain-Enabled Single Window* (BESW) untuk meningkatkan keamanan, transparansi, dan interoperabilitas dalam pertukaran data kepabeanan, khususnya pada proses *Delivery Order* (DO) dan Surat Penyerahan Petikemas (SP2). Model ini memperkenalkan empat lapisan terintegrasi: (1) *Infrastructure Layer* yang menggunakan jaringan permissioned blockchain untuk menghubungkan pemangku kepentingan di bidang kepabeanan, pelabuhan, perbankan, dan logistik; (2) *Data and Smart Contract Layer* untuk otomatisasi validasi dokumen dan verifikasi pembayaran; (3) Interoperability Layer yang diselaraskan dengan WCO *Data Model* 3.11, UN/CEFACT, dan ISO 20022; serta (4) *Application and Audit Layer* yang menyediakan pemantauan real-time dan catatan audit yang tidak dapat diubah (*immutable)*. BESW bertujuan untuk melengkapi Indonesia *National Single Window* (INSW) dan ASEAN *Single Window* (ASW) dengan membangun arsitektur kepercayaan terdistribusi yang meningkatkan efisiensi dan akuntabilitas kelembagaan. Makalah ini diakhiri dengan rencana validasi empiris di masa depan untuk menilai kelayakan, adaptasi tata kelola, dan skalabilitas dalam konteks digitalisasi kepabeanan di kawasan ASEAN.

Kata Kunci*: Blockchain; Single Window*; DO-SP2 *Online*; *Kepabeanan Digital*; *Interoperabilitas*; *ASEAN*

INTRODUCTION

International trade has become increasingly complex, involving multiple regulatory bodies, logistics operators, and financial institutions that must coordinate to ensure the secure and efficient movement of goods across borders. In this context, customs administrations play a pivotal role in maintaining trade facilitation while ensuring compliance and revenue collection. However, the rapid expansion of trade volume and digital documentation has introduced new challenges related to data security, transparency, and interoperability among stakeholders.

In Indonesia, several digital initiatives, such as the Indonesia National Single Window (INSW), the Customs Excise Information System and Automation (CEISA), and various port

logistics platforms have improved operational efficiency. Yet, persistent issues remain within the Delivery Order (DO) and Surat Penyerahan Petikemas (SP2) workflow — critical stages in the cargo release process that require coordination between the Customs Authority, Shipping Lines, Terminal Operators, Banks, and Freight Forwarders. These interactions are often characterized by data fragmentation, manual verification, and limited cross-agency visibility, resulting in duplicated procedures, increased administrative costs, and prolonged clearance times.

Traditional customs systems rely heavily on centralized databases within each institution, which creates operational silos. This architecture poses three major problems. First, data integrity risks arise because document authentication trails are difficult to verify end-to-end, and asynchronous updates across systems may lead to inconsistencies. Second, transparency and auditability are constrained, since information access typically depends on manual exchange or scheduled synchronization. Third, duplicate verification occurs when each agency revalidates the same information independently, leading to inefficiency and potential discrepancies.

To address these limitations, emerging research and practice have highlighted the potential of blockchain technology as a trusted digital infrastructure for secure, traceable, and verifiable data exchange. Blockchain's inherent features - immutability, decentralized consensus, and cryptographic verification - provide a foundation for multi-stakeholder collaboration without relying on a single central authority. When combined with smart contracts, business rules in customs workflows such as document validation, cargo release, and payment confirmation can be executed automatically and transparently.

This study introduces the Blockchain - Enabled Single Window (BESW) as a conceptual model for secure and transparent customs data exchange. The BESW aims to complement existing systems like INSW and CEISA by providing a permissioned distributed ledger that records, validates, and synchronizes transactions across customs stakeholders. The model integrates key components: a blockchain infrastructure layer, a data and smart contract layer, an interoperability layer based on international data standards, and an application and audit layer for monitoring and analytics.

Unlike traditional centralized Single Window systems, BESW enables collective validation (consensus) instead of single-point control, ensuring that every change in data is cryptographically verified and permanently recorded. This creates a collaborative data-governance environment where trust is distributed rather than delegated, and compliance is transformed from post-facto inspection to automated pre-validation.

The main contributions of this study are fourfold. First, it develops a conceptual architecture of a blockchain-based Single Window that is suitable for customs and port logistics operations. Second, it identifies key functional mechanisms within the system, including the execution of smart contracts for document validation and payment verification. Third, it analyzes data standardization and interoperability frameworks that facilitate integration with both national and regional platforms such as the Indonesia National Single Window (INSW) and the ASEAN Single Window (ASW). Finally, it assesses the potential implications of the proposed model for governance, transparency, and institutional collaboration in the broader context of digital customs transformation.

Through these contributions, the BESW model seeks to advance the discourse on how blockchain can serve as a trust infrastructure for customs modernization and regional trade facilitation, in line with the World Customs Organization's (WCO) vision of transparency,

innovation, and digitalization in global trade. Accordingly, this study addresses the following research question: How can blockchain technology be integrated into the Single Window system to enhance data security, interoperability, and institutional trust in customs data exchange?

LITERATURE REVIEW

1. Concept and Evolution of the Single Window System

The Single Window (SW) concept was first introduced by the World Customs Organization (WCO) as a mechanism to simplify and harmonize trade-related information exchange between traders and government authorities. According to the WCO (2022), "A Single Window is a facility that allows parties involved in trade and transport to lodge standardized information and documents through a single-entry point to fulfill all import, export, and transit- related regulatory requirements."

Globally, Single Window systems have proven to be essential tools for trade facilitation, enabling efficiency through reduced processing time and administrative cost. Early adopters such as Singapore's TradeNet, Korea's uTradeHub, and Finland's PortNet demonstrated that digitalizing trade procedures could reduce document-processing time by 40–60% and lower operational costs by up to 20% (UNESCAP, 2021).

Nevertheless, despite these benefits, many national Single Window implementations still rely on centralized architectures, where data is stored and managed by a single coordinating agency. This creates potential bottlenecks in terms of data integrity, cybersecurity, and cross-agency trust. As trade becomes more complex and cross-border in nature, centralized systems struggle to provide real-time auditability, multi-stakeholder accountability, and resilience against cyberattacks.

In regional contexts, the ASEAN Single Window (ASW) has become a landmark initiative promoting data exchange among member states, particularly for electronic Certificates of Origin (e-Form D). However, studies (ASEAN Secretariat, 2023) show that ASW still faces interoperability challenges due to different data standards, inconsistent security mechanisms, and limited transparency between participating authorities. Hence, there is a growing need for a new trust-based and decentralized approach that can ensure secure and verifiable information exchange among customs administrations - an area where blockchain technology offers significant promise. This study also aligns with the ASEAN Digital Integration Framework (ASEAN, 2019), which highlights interoperability, data governance, and cross-border trust as essential enablers of digital trade integration. Incorporating blockchain within Single Window systems supports these pillars by ensuring verifiable and transparent customs data exchange among ASEAN member states.

2. Blockchain Technology in Trade Facilitation and Customs

Blockchain is a form of Distributed Ledger Technology (DLT) that maintains an immutable, cryptographically secured record of transactions shared among network participants. Unlike traditional centralized databases, blockchain achieves data integrity through consensus mechanisms - such as Proof of Work (PoW), Proof of Stake (PoS), or Proof of Authority (PoA) - which validate transactions collectively rather than through a single trusted intermediary (Kshetri, 2018).

In the context of international trade and customs, blockchain technology offers three primary advantages. First, it enhances data integrity and security, as each transaction is

cryptographically signed and linked within a chain of blocks, making any attempt at modification immediately detectable (Saberi et al., 2019). Second, it improves transparency and auditability by allowing authorized parties to trace the provenance of documents, verify digital signatures, and access immutable transaction records. Third, it increases process efficiency through the use of smart contracts, which automate the validation and approval of trade-related documents—such as customs declarations and import or export permits - thereby reducing manual intervention and administrative delays (Salah et al., 2019).

Several global initiatives illustrate blockchain's potential in customs modernization. TradeLens, developed by IBM and Maersk, has connected over 175 organizations and processed more than 30 million container shipments through blockchain-based documentation and event sharing (IBM, 2022). The Global Shipping Business Network (GSBN) also applies DLT to enable secure cross-border logistics data exchange among carriers, ports, and customs authorities. These projects demonstrate blockchain's ability to establish digital trust across multiple actors while ensuring data confidentiality and traceability.

3. Blockchain Applications in Customs Data Governance

The use of blockchain in customs systems has been explored across several functional domains, particularly focusing on document validation, data sharing, and audit mechanisms. Table 1 summarizes the comparative analysis between traditional Single Window systems and blockchain-based models.

Table 1. Comparative Analysis Between Traditional and Blockchain-Based Customs Systems

Customs Function	Traditional System Challenges	Blockchain-Based Solution
Data Exchange Between Agencies	Reliance on centralized servers; vulnerability to manipulation	Distributed ledger ensures integrity and synchronized updates
Document Verification	Manual validation and high redundancy	Smart contracts enable automatic rule enforcement
Audit and Transparency	Limited access to audit trails	Immutable transaction logs accessible to authorized parties
System Security	Single point of failure in centralized databases	Cryptographic consensus and decentralization increase cyber resilience
Inter-Agency Trust	Dependence on hierarchical authority	Shared ledger provides verifiable and equal data access

Empirical and conceptual research increasingly support blockchain's role as an enabler of data governance transformation in customs. For example, Hackius & Petersen (2020) emphasize blockchain's role in establishing *data provenance* and *tamper-proof audit trails*, while Yaren (2020) suggests that blockchain-based customs clearance systems can significantly enhance process integrity and reduce administrative overhead. However, these studies often focus on *technical feasibility* rather than *institutional governance integration*, which remains an underexplored dimension in public-sector contexts.

4. Research Gap

While numerous studies have examined blockchain applications in supply chains and financial services, relatively few have explored its potential in government-to-government (G2G) and business-to-government (B2G) data exchange frameworks—especially within Single Window customs ecosystems. Existing models primarily emphasize track-and-trace visibility or document notarization functions but rarely address how blockchain can facilitate cross-agency interoperability, standardized data governance, and policy-level transparency in customs operations (Mühlberger et al., 2020).

Furthermore, there remains a limited understanding of how blockchain could complement established systems like INSW and ASW without duplicating existing infrastructure, particularly in developing economies where technical capacity and regulatory readiness are uneven. Thus, there is a clear research opportunity to conceptualize a scalable, permissioned blockchain framework that aligns with international data standards while supporting multi-stakeholder customs collaboration.

5. Theoretical Framework

This research draws upon three theoretical foundations to design and evaluate the proposed Blockchain-Enabled Single Window (BESW) model. The first is Data Governance Theory, which emphasizes accountability, transparency, and consistency in data handling across institutional boundaries. Within the customs context, this theory underscores the importance of verifiable, auditable, and interoperable data flows. The second is Digital Trust Theory, which explains how trust can be established through cryptographic assurance and decentralized validation rather than relying on hierarchical institutional control. In this regard, blockchain serves as a trust infrastructure that embeds reliability directly into the system architecture. The third is the Technology Adoption Model (TAM), which provides a framework for assessing organizational readiness and perceived usefulness—two critical factors that influence the adoption of blockchain in public-sector environments. Collectively, these theoretical perspectives inform the conceptualization of BESW as a model that not only introduces technological innovation but also supports a paradigm shift in customs data governance, transitioning from centralized control to collaborative, consensus-based validation.

METHODS

1. Research Type and Design

This study adopts a conceptual–descriptive research design using a qualitative analytical approach. The purpose is not to implement a technical prototype but to conceptualize a model architecture for secure and transparent customs data exchange through blockchain technology. The study aims to synthesize theoretical and empirical findings from international literature, policy frameworks, and comparative practices in trade digitalization.

The research design combines two complementary approaches to ensure both analytical rigor and practical relevance. The first is a literature-based analysis, which aims to identify global trends, opportunities, and challenges associated with blockchain adoption in customs and trade facilitation systems. The second is a conceptual framework analysis, which focuses on developing the Blockchain-Enabled Single Window (BESW) model and comparing its characteristics with traditional centralized Single Window architectures. Together, these two approaches provide a

balanced foundation that integrates theoretical grounding with contextual relevance, supporting meaningful discussions on policy formulation and practical implementation.

2. Analytical Framework

The analysis was conducted through three structured phases to ensure logical coherence between literature synthesis, conceptual design, and model evaluation.

a. Phase 1: Literature and Policy Synthesis

A comprehensive review of international studies and policy guidelines was carried out to identify key variables influencing effective digital customs governance. The focus included:

- interoperability challenges among customs and logistics authorities;
- data integrity and transparency mechanisms;
- the role of automation and smart contracts in regulatory compliance; and
- cross-border information exchange mechanisms under the WCO and ASEAN frameworks.

b. Phase 2: Comparative Analysis

This phase compared centralized Single Window systems and blockchain-enabled frameworks using predefined evaluation dimensions:

- Data Security and Integrity (risk of manipulation, authentication traceability);
- Transparency and Auditability (access to verified records and audit logs);
- Process Efficiency (time reduction and automation potential);
- Cyber Resilience (fault tolerance and multi-node redundancy);
- Inter-Agency Trust and Governance (distribution of authority and data-sharing mechanisms); and
- Adoptability and Scalability (technical and institutional readiness).

The outcome of this comparison served as the analytical foundation for designing the BESW architecture.

Table 2. Evaluation Matrix of Centralized vs. Blockchain-Enabled Single Window (BESW)

Evaluation Dimension	Centralized Single Window	Blockchain-Enabled Single Window (BESW)	Expected Improvement
Security & Integrity	Prone to manipulation; single database	Distributed ledger; cryptographic verification	High
Process Efficiency	Manual validation; redundancy	Automated validation via smart contracts	High
Transparency & Auditability	Limited to manual reports	Real-time immutable logs	High
Institutional Trust	Hierarchical and centralized	Consensus-based distributed validation	Medium–High

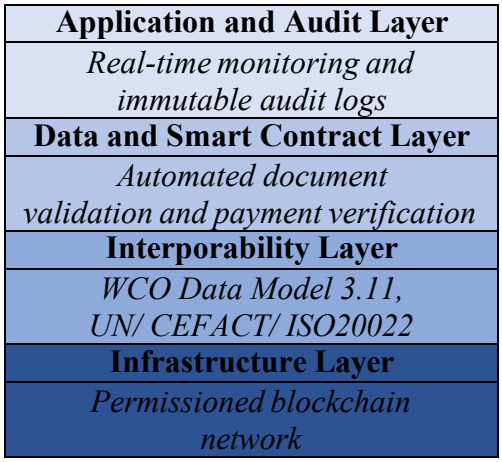
c. Phase 3: Conceptual Model Design

Based on the comparative insights, this research developed a four-layer architecture for the Blockchain-Enabled Single Window (BESW) model. The Infrastructure Layer defines the network topology, validator nodes, and consensus mechanisms, such as Proof of Authority, which ensure secure and efficient transaction validation across participating institutions. The Data and Smart Contract Layer manages encrypted document storage, metadata handling, and the automated

execution of business rules through smart contracts, enabling seamless validation and verification processes. The Interoperability Layer facilitates connection and data harmonization among customs, port, and banking systems by adhering to international standards, including the WCO Data Model 3.11, UN/CEFACT, and ISO 20022, thereby ensuring semantic and syntactic consistency. Finally, the Application and Audit Layer provides user interfaces, interactive dashboards, and immutable audit logs that support real-time decision-making and compliance monitoring, promoting transparency and accountability within the customs and logistics ecosystem.

This conceptual design emphasizes collaborative data governance by ensuring that every transaction or document exchange is validated by multiple authorized institutions through cryptographic consensus, thereby eliminating single points of failure and reducing dependency on central intermediaries. As shown in Figure 1, the proposed BESW architecture illustrates how data flows vertically through four functional layers, ensuring security, interoperability, and transparency. Figure 1 illustrates the proposed four-layer architecture of the Blockchain-Enabled Single Window (BESW), which depicts how data flows vertically from the infrastructure to the application layer. Each layer represents a distinct functional domain, ensuring security, automation, interoperability, and transparency in customs data exchange.

Figure 1. Conceptual architecture of the Blockchain-Enabled Single Window (BESW).



3. Summary of Research Stages

The research process was conducted in four sequential stages to ensure logical coherence between literature synthesis, conceptual design, and model evaluation. The first stage, Literature Review, involved reviewing academic publications and policy documents related to blockchain applications in customs and trade facilitation. This stage resulted in the identification of key variables, theoretical foundations, and emerging trends relevant to digital customs transformation. The second stage, Comparative Analysis, focused on evaluating the characteristics of centralized versus blockchain-based Single Window architectures. This analysis produced an analytical matrix highlighting the advantages, limitations, and potential areas for improvement in existing systems. The third stage, Model Design, developed the conceptual Blockchain-Enabled Single Window (BESW) architecture, which integrates four functional layers designed to enable secure and interoperable customs data exchange. Finally, the fourth stage, Conceptual Evaluation, assessed the potential benefits, risks, and feasibility of implementing the proposed BESW framework,

leading to policy and implementation recommendations that support future adoption and scalability within national and regional digital customs ecosystems.

4. Rationale for the Method

This conceptual–comparative methodology was selected for three main reasons. First, the field of blockchain adoption in customs is still in the exploratory stage, making a conceptual design approach an appropriate foundation for future pilot implementations. Second, empirical data from live blockchain projects within government systems remain limited; therefore, synthesizing existing literature and policy frameworks offers a reliable basis for analysis and model development. Third, this methodological approach enables the identification of both technical opportunities and institutional challenges, providing valuable insights to support evidence-based policy formulation for customs modernization and trade facilitation.

RESULTS AND DISCUSSION

1. Overview of the Blockchain-Enabled Single Window (BESW) Model

The proposed Blockchain-Enabled Single Window (BESW) represents a conceptual framework for strengthening data security, transparency, and interoperability in customs and trade operations. It envisions a national trusted data-exchange infrastructure connecting key actors within the logistics ecosystem - such as Customs (DJBC), the National Single Window Authority, Shipping Lines (S/L), Terminal Operators (TO), Banks, and Freight Forwarders (PPJK) - through a permissioned distributed ledger network.

Unlike conventional centralized Single Window systems that rely on a single coordinating database, BESW operates on the principle of distributed trust, ensuring that no single institution exclusively controls or validates trade data. Each participating institution acts as a validator node, maintaining synchronized and cryptographically verified copies of transaction records. Any data modification requires collective consensus, which significantly enhances traceability, non-repudiation, and auditability across agencies.

The conceptual goals of the Blockchain-Enabled Single Window (BESW) are fourfold. First, it aims to ensure data integrity through cryptographic commitment and consensus-based validation, preventing unauthorized alterations and ensuring trust in recorded transactions. Second, it seeks to enable automated rule enforcement by embedding smart contracts within trade processes, thereby reducing manual intervention and improving procedural efficiency. Third, it promotes interoperability by adopting standardized data formats and secure API integrations, ensuring seamless communication among customs, port, and banking systems. Finally, it enhances accountability and transparency by providing immutable, real-time audit trails that are accessible to authorized entities. Collectively, these objectives position BESW not only as a technological framework but also as a collaborative data governance model that redistributes trust and compliance responsibilities among multiple stakeholders.

2. System Architecture and Functional Mechanisms

The BESW architecture is structured into four functional layers, each representing a distinct operational domain - from infrastructure to application.

a. Infrastructure Layer

The Infrastructure Layer provides the backbone of the blockchain network, connecting

customs-related institutions within a permissioned blockchain environment (e.g., Hyperledger Fabric). Each participant operates a validator node, which performs transaction verification and block validation based on the Proof of Authority (PoA) consensus algorithm.

Table 3. Functional Roles of Validator Nodes in the Blockchain-Enabled Single Window (BESW) Network

Validator Node	Functional Role
National Single Window Authority	Network coordinator; manages node identities and digital certificates.
Customs Authority (DJBC)	Oversees trade documentation and regulatory compliance.
Shipping Line (S/L)	Issues Delivery Orders (DO) and validates bill-of-lading data.
Terminal Operator (TO)	Issues container delivery documents (SP2) and manages port status updates.
Bank / Payment Gateway	Confirms financial transactions and verifies Virtual Account (VA) payments.
Freight Forwarder / Cargo Owner (PPJK/CO)	Submits requests and provides digital documentation.

Key infrastructure characteristics include:

1) Mutual Transport Layer Security (mTLS) - All communication between validator nodes is encrypted using mTLS, providing both authentication and confidentiality for data-in-transit. In this mechanism, every node is equipped with its own cryptographic certificate issued by a trusted Certificate Authority (CA). Before any transaction or block propagation occurs, nodes authenticate each other's identity using these certificates, preventing impersonation, spoofing, or man-in-the-middle attacks. This dual-verification approach ensures that only verified institutions - such as Customs, Port Authorities, or Banking Nodes - can participate in the blockchain network, effectively establishing a zero-trust communication model at the infrastructure level.
2) Role-Based Access Control (RBAC) - To maintain institutional accountability and prevent unauthorized actions, BESW employs a granular RBAC framework. Each node and sub-user (e.g., customs officer, port clerk, or payment verifier) is assigned predefined roles that determine data access privileges - whether read, write, or endorse. Access rights are managed through blockchain-native policies enforced at the channel level within Hyperledger Fabric. For example, a Shipping Line node can write and endorse Delivery Order (DO) transactions but cannot alter payment or audit records. This separation of duties reflects real-world regulatory boundaries while reducing insider threat risks.
3) Crash Fault Tolerance and Redundancy - Given the criticality of customs operations, the system is designed for continuous uptime and data durability. Each validator node maintains a replicated copy of both the blockchain ledger and the world state database, distributed across multiple geographic locations or data centers. This design ensures that the network remains

functional even if one or more nodes fail unexpectedly - a property known as crash fault tolerance (CFT). Additionally, a dedicated Disaster Recovery (DR) Site continuously synchronizes ledger data to provide immediate failover capability in case of catastrophic system disruptions (e.g., data center outages or cyber incidents). Together, these features guarantee business continuity and compliance with international data availability standards.

4) Fast Finality (<3 seconds) - To support near-real-time customs clearance and trade facilitation, the BESW network employs a Proof of Authority (PoA) consensus mechanism, optimized for fast block finalization. Unlike energy-intensive protocols such as Proof of Work (PoW), PoA allows pre-approved validator nodes to commit transactions instantly after mutual validation. The average block confirmation time is maintained below three seconds, ensuring that updates such as DO approvals, payment confirmations, or SP2 issuances are reflected almost instantaneously across all institutional nodes. This low-latency characteristic is particularly important for high-volume port environments where document turnaround time directly affects logistics efficiency.

b. Data and Smart Contract Layer

The Data and Smart Contract Layer serves as the operational core of the Blockchain-Enabled Single Window (BESW). This layer is responsible for managing data storage, transaction validation, and the automated execution of business rules through smart contracts (chaincode). To ensure efficient processing and domain isolation, the system adopts a multi-channel architecture, in which each channel represents a distinct transactional scope: one channel handles Delivery Order (DO) requests and approvals, another governs SP2 submissions and payment verification, and a third supports audit and performance monitoring. This logical separation allows for clearer process governance and minimizes overlapping access among institutions involved in customs and port operations.

Each transaction recorded on the blockchain contains two main components: on-chain metadata and off-chain documents. The on-chain metadata includes cryptographic elements such as document hashes, transaction identifiers, timestamps, and digital signatures, which collectively ensure the authenticity and traceability of all records. Meanwhile, off-chain documents - typically PDF or XML files - are securely stored in trusted repositories or InterPlanetary File System (IPFS) nodes. They are linked to the ledger via hashed data pointers, providing a reference without exposing sensitive content. This hybrid approach preserves privacy, supports data minimization, and enhances the efficiency of storage management, all while maintaining the verifiability of transaction data.

Within this layer, several key smart contracts automate the customs clearance and logistics workflow. The first, the DO Validation Contract, verifies Bills of Lading and shipping documents submitted by freight forwarders. Upon validation by the Shipping Line, the contract records the cryptographic hash of the approved DO into the blockchain, ensuring permanent proof of authorization. The second, the SP2 Request Contract, facilitates container release requests to the Terminal Operator, automatically generates Proforma Invoices and Virtual Account (VA) numbers, and tracks payment statuses in real time. The third, the Payment Confirmation Contract, interacts directly with bank APIs to verify the authenticity of payments. Once a transaction is confirmed, it automatically updates the container status and triggers the release of the final SP2 document.

Every smart contract within BESW operates under specific endorsement policies, typically requiring digital signatures from multiple validators - such as three different institutions - before a transaction is approved and appended to the ledger. Additionally, each record is supported by Merkle proofs, which enable cryptographic verification of data integrity without revealing the full ledger contents. Through these mechanisms, the Data and Smart Contract Layer ensures that all activities are immutable, auditable, and verifiable without relying on centralized oversight. This design not only enhances procedural efficiency but also establishes a transparent, trustworthy, and tamper-resistant data exchange ecosystem among all participating customs stakeholders.

c. Interoperability Layer

The Interoperability Layer serves as the connective bridge between the Blockchain-Enabled Single Window (BESW) and a range of external systems operating at both the national and regional levels. It ensures that data can flow seamlessly between customs authorities, port operators, financial institutions, and other regulatory agencies while upholding stringent standards of privacy, data integrity, and compliance with international frameworks. In essence, this layer transforms the BESW from a closed blockchain network into an interoperable, standards-driven ecosystem capable of integrating with existing digital infrastructures without disrupting their operational autonomy.

At the domestic level, the interoperability layer facilitates direct integration with Indonesia's key digital trade systems to support end-to-end customs and logistics processes. The Indonesia National Single Window (INSW) Gateway acts as a central monitoring interface by publishing verified DO and SP2 transaction statuses, allowing external government agencies - such as the Ministry of Trade, the Quarantine Agency, or the Port Authority - to access and review shipment data in near real time. This integration enhances regulatory visibility and minimizes redundant manual reporting across agencies. The Customs Excise Information System and Automation (CEISA) is connected to the BESW through standardized APIs to synchronize data related to customs clearance, cargo manifests, inspection results, and declaration statuses. By using shared data identifiers and timestamps, CEISA and BESW maintain consistent and verified transaction records across institutional databases. The Inaportnet system, managed by the Port Authority, is synchronized with BESW to align physical port activities - such as gate-in and gate-out events - with digital SP2 status updates. This eliminates discrepancies between physical cargo movement and digital documentation, improving the accuracy of container release tracking. Integration with banking APIs allows the automated exchange of Virtual Account (VA) payment information through secure webhook connections. Payment confirmations are transmitted directly to the BESW ledger, ensuring that financial transactions are verified instantly and recorded immutably across all validator nodes.

Beyond national interoperability, the layer also ensures regional and international compatibility by adhering to globally recognized data standards.

- The WCO Data Model 3.11 provides a harmonized framework for structuring and interpreting customs-related data, ensuring semantic consistency in document exchange between national systems.
- The UN/CEFACT Core Component Library (CCL) defines standardized XML schemas for logistics and trade documentation, enabling syntactic interoperability across different IT platforms used by port authorities, logistics operators, and customs administrations.

- The ISO 20022 standard governs the format of financial messages, allowing uniform and secure payment verification processes between BESW and domestic or cross-border banking systems. This alignment with ISO standards also supports potential integration with fintech platforms and regional e-payment gateways in the future.

Each communication channel and API interface within this layer employs OAuth 2.0-based authentication and JSON Web Token (JWT) encryption to ensure that only authorized entities can initiate or retrieve data exchanges. These protocols enable fine-grained, auditable access control, ensuring accountability for every data transaction while maintaining compliance with privacy and data protection requirements.

Through this multi-layered integration framework, BESW achieves modular interoperability and cross-jurisdiction scalability. Nationally, it enables the seamless coordination of customs, logistics, and financial data flows within Indonesia's digital trade ecosystem. Regionally, it positions BESW as a ready-to-connect node for integration with the ASEAN Single Window (ASW) - facilitating trusted, secure, and standardized data exchange among ASEAN member states. In this way, the interoperability layer not only strengthens domestic coordination but also lays the groundwork for regional trade harmonization under a shared, blockchain-secured trust infrastructure.

d. Application and Audit Layer

The Application and Audit Layer acts as the main interaction point between users and the Blockchain-Enabled Single Window (BESW) system. It provides role-based access through dashboards and analytics tools for various stakeholders, ensuring that each participant – from freight forwarders to customs regulators - can monitor and verify transactions according to their institutional function.

Key components include the DO Online Portal, which allows freight forwarders and cargo owners to submit and track Delivery Order (DO) requests with digital signature verification; the SP2 Dashboard, enabling terminal operators to manage SP2 requests, issue invoices, and confirm payments; and the Bank Verification Console, which displays verified Virtual Account (VA) transactions and automatically updates payment records. Meanwhile, the Audit and Analytics Panel provides customs authorities and the National Single Window Agency with secure access to immutable transaction logs, filterable by container, vessel, or actor.

In addition, the layer integrates advanced monitoring tools such as real-time dashboards for cargo operations, AI-based anomaly detection to identify under-invoicing or data inconsistencies, and a policy simulation module for evaluating regulatory adjustments. Altogether, these features make BESW not only a data exchange platform but also an intelligent oversight system that supports predictive monitoring, operational transparency, and data-driven policy evaluation.

3. End-to-End Workflow

The complete BESW process integrates all participating entities into a synchronized, verifiable, and auditable sequence of operations:

a. Submission: A freight forwarder or cargo owner submits a DO request through the online portal.
b. Verification: The Shipping Line validates the documents and signs digitally; the approval hash is recorded on the blockchain.
c. SP2 Request: The same party submits an SP2 request to the Terminal Operator, which issues

a proforma invoice and a unique Virtual Account number.

d. Payment: The Bank node verifies payment automatically and triggers the smart contract to update the transaction status to "Paid."
e. Release: The Terminal Operator issues the final SP2, and the ledger updates the cargo status to "Released."
f. Audit and Monitoring: All events are logged immutably and can be accessed by customs officers and auditors in real time.

This workflow eliminates the need for repetitive document submissions and manual synchronization between agencies. Instead, a single shared ledger becomes the source of truth for all parties, improving coordination and reducing administrative overhead.

4. Comparative Evaluation: Traditional vs. BESW Systems

To further illustrate the comparative advantages of the proposed Blockchain-Enabled Single Window (BESW) model, a structured evaluation was conducted between traditional centralized Single Window systems and the BESW framework. The comparison focuses on key functional aspects such as data architecture, integrity, transparency, efficiency, resilience, interoperability, and institutional trust, as summarized in Table 4.

Table 4. Comparative Analysis of Functional Aspects in Single Window Architectures

Evaluation Aspect	Traditional Single Window (Centralized)	Blockchain-Enabled Single Window (BESW)
Data Architecture	Centralized databases managed per agency	Distributed ledger shared across institutions
Data Integrity	Vulnerable to modification or data loss	Immutable cryptographic records
Transparency	Limited, periodic reporting	Real-time visibility and auditability
Process Efficiency	Manual validation, redundant verification	Smart-contract automation of document and payment workflows
Cyber Resilience	Single point of failure	Decentralized, fault-tolerant network
Interoperability	Dependent on API integration per system	Harmonized through shared standards (WCO, UN/CEFACT, ISO 20022)
Institutional Trust	Based on hierarchical control	Based on distributed consensus and shared accountability

This comparison highlights that BESW offers structural advantages in security, transparency, and efficiency, providing a more resilient foundation for cross-agency and cross-border cooperation.

5. Adoption Challenges and Mitigation Strategies

While BESW offers a promising framework, several challenges must be addressed to ensure effective implementation.

Table 5. Implementation Challenges and Mitigation Strategies for the Blockchain-Enabled Single Window (BESW)

Challenge	Potential Impact	Mitigation Strategy
Regulatory Recognition	Absence of legal status for blockchain records	Establish an inter-agency legal framework recognizing blockchain data as admissible evidence
Technical Capacity	Uneven readiness among institutions	Conduct capacity-building programs and technical training; implement sandbox pilots
Data Privacy	Risk of exposing sensitive trade or pricing data	Implement permissioned blockchain architecture and zero-knowledge proof mechanisms
Institutional Resistance	Bureaucratic reluctance toward transparency	Adopt phased implementation, starting with major ports and early adopters
Infrastructure Cost	Initial investment for nodes and connectivity	Foster public–private partnerships and shared infrastructure models

These mitigation measures emphasize a phased and collaborative approach, where pilot deployments and regulatory adaptation occur in parallel with technological capacity development. Beyond technical barriers, institutional inertia remains a significant challenge in public-sector innovation. Resistance to organizational change, rigid bureaucratic structures, and limited cross-agency coordination can delay adoption. Overcoming these requires leadership commitment, regulatory incentives, and gradual cultural transformation toward data-driven governance.

6. Strategic and Policy Implications

The implementation of the Blockchain-Enabled Single Window (BESW) carries significant strategic and policy implications at national, regional, and global levels. For Indonesia, the BESW framework strengthens the integration of key digital systems such as the Indonesia National Single Window (INSW), Customs Excise Information System and Automation (CEISA), and Inaportnet into a unified, secure, and auditable data ecosystem. This integration supports the country's Digital Transformation Blueprint 2025–2030 and the broader National Logistics Ecosystem (NLE) initiative, both of which aim to enhance transparency, efficiency, and accountability in trade facilitation. By embedding blockchain into the customs infrastructure, Indonesia can establish a robust foundation for national digital trade policies that prioritize data integrity, interoperability, and institutional trust.

At the ASEAN regional level, the BESW framework can serve as a reference model for the development of an ASEAN Trusted Ledger for Customs and Trade Facilitation. Such a framework would complement the existing ASEAN Single Window (ASW) by introducing enhanced mechanisms for cross-border data validation, interoperability, and auditability. Through a shared blockchain-based infrastructure, ASEAN member states can achieve higher levels of transparency and harmonization in customs processes, while simultaneously strengthening regional collaboration and policy convergence.

At the global level, the BESW model contributes directly to the objectives of the World Customs Organization (WCO) SAFE Framework of Standards and the World Trade Organization (WTO) Trade Facilitation Agreement (TFA). It supports the advancement of data-driven governance, cyber-resilient infrastructure, and trusted digital documentation as cornerstones of

modern customs management. By demonstrating how blockchain can shift customs operations from traditional, manual compliance monitoring toward continuous, automated, and verifiable digital governance, BESW exemplifies the transformative role of distributed ledger technology in enhancing global trade transparency and operational integrity.

CONCLUSION AND RECOMMENDATIONS

1. Conclusion

This study proposed a conceptual framework for a Blockchain-Enabled Single Window (BESW) aimed at enhancing security, transparency, and interoperability in customs data exchange - particularly in the Delivery Order (DO) and Surat Penyerahan Petikemas (SP2) workflow that represents the critical path of cargo release in Indonesia's port operations.

The proposed BESW model integrates four functional layers - Infrastructure, Data & Smart Contract, Interoperability, and Application & Audit - to establish a permissioned blockchain network that connects customs authorities, port operators, shipping lines, banks, and logistics service providers. Through cryptographic verification, collective consensus, and smart-contract automation, BESW transforms document validation, payment verification, and status monitoring into secure, auditable, and real-time digital interactions.

The findings suggest that blockchain can serve not only as a technical innovation but also as a governance mechanism, embedding trust and accountability directly into the system architecture. By enabling transparent, immutable, and verifiable records, BESW shifts customs operations from post-facto compliance checking toward continuous, automated assurance. It represents a paradigm shift from centralized administrative control to distributed, data-driven governance, aligning with the WCO vision of transparency, innovation, and digitalization in global trade.

2. Limitations

Despite its conceptual comprehensiveness, this research remains theoretical and exploratory in nature. The proposed Blockchain-Enabled Single Window (BESW) framework has not yet been validated through a technical prototype or pilot implementation, meaning that empirical performance metrics such as throughput, latency, and transaction cost have not been tested. Furthermore, the legal recognition of blockchain-based records within customs administrative law requires additional research and regulatory harmonization to ensure compliance with existing legal frameworks. In addition, the level of institutional readiness among agencies to operate as blockchain validator nodes varies considerably, which may influence the scalability and effectiveness of implementation. These limitations, however, present promising opportunities for future research, particularly in the areas of empirical testing, regulatory integration, and the development of public–private pilot projects.

3. Recommendations

From a technical perspective, the study recommends initiating a pilot implementation of blockchain-based customs data exchange through a limited-scale proof-of-concept involving key stakeholders such as the Customs Authority, Port Operators, Shipping Lines, and Banks. The proposed BESW framework should be integrated with existing platforms - INSW, CEISA, and Inaportnet - through standardized APIs based on WCO Data Model 3.11, UN/CEFACT, and ISO 20022 to ensure interoperability.

To enhance security and privacy, it is essential to deploy a Public Key Infrastructure (PKI) for

digital signatures and adopt Zero-Knowledge Proof (ZKP) mechanisms to safeguard sensitive commercial information.

From a policy and institutional standpoint, governments should develop a regulatory framework recognizing blockchain transaction records as legally valid evidence in customs procedures, aligned with the Electronic Information and Transactions Law and international e-documentation standards. Strong public–private partnerships are needed to co-develop shared infrastructure, while continuous capacity building in blockchain governance, cybersecurity, and smart-contract auditing will ensure institutional readiness and long-term sustainability.

From a research and development perspective, future studies should simulate blockchain performance under real customs data conditions, explore advanced privacy-preserving technologies such as homomorphic encryption, and conduct comprehensive cost–benefit analyses to evaluate the economic feasibility of blockchain adoption in public-sector logistics systems.

In terms of policy implications, the BESW model provides a strategic foundation for integrating INSW, CEISA, and Inaportnet into a unified, secure, and interoperable digital ecosystem, in line with Indonesia's Digital Transformation Blueprint 2025–2030 and the National Logistics Ecosystem (NLE) agenda. At the regional level, BESW can serve as a reference model for establishing an ASEAN Trusted Ledger for Customs and Trade Facilitation, complementing the ASEAN Single Window (ASW) through verifiable and auditable data exchange across member states. Globally, BESW aligns with the principles of the WCO SAFE Framework of Standards and the WTO Trade Facilitation Agreement (TFA) by promoting data integrity, transparency, and risk-based compliance, enabling customs administrations to transition toward real-time, data-driven, and verifiable digital governance.

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