A Hybrid Risk-Weighted Blockchain Framework for Supply Chain Integrity and Automated Tariff Collection

Abstract. Global supply chains still rely on fragmented documentation and partially digital customs workflows, creating persistent vulnerabilities in origin verification, fraud detection, and tariff collection. This paper proposes a Hybrid Risk-Weighted Framework (HRWF) for blockchain-enabled customs automation that avoids the main weakness of earlier initiatives: attempting to automate every shipment. The study combines a comparative case analysis of TradeLens, Alibaba's Blockchain-as-a-Service, and the UAE Digital Customs Pilot with a discrete-event simulation of 10,000 synthetic cross-border shipments. Three approaches are compared: traditional processing, fully automated blockchain processing, and selective smart contract execution based on a real-time risk score. The hybrid model achieved the strongest overall performance, reaching 98.7% tariff-collection accuracy versus 94.2% for traditional processing and 96.1% for full automation. It also reduced false positives relative to full automation and cut processing time substantially relative to manual procedures. These findings suggest that blockchain is most viable in customs when paired with risk management and human override rather than used as a fully autonomous replacement for regulatory discretion. The main limitation is the use of synthetic rather than live operational data.

Keywords: Blockchain; Supply Chain Integrity; Smart Contracts; Digital Customs; Risk-Weighted Automation

1 Introduction

Global merchandise trade exceeds $24 trillion annually, yet customs and provenance verification still depend on fragmented records, manual reconciliation, and uneven cross-border interoperability [1]. As a result, misdeclaration of origin, tariff evasion, and counterfeit trade remain costly and persistent problems for both governments and legitimate firms [2,3].

Digital customs reforms and Single Window systems have improved document submission, but most remain centralized and nationally bounded. They streamline intake rather than create a shared, tamper-evident record across exporters, ports, logistics providers, and customs agencies [4-6].

Blockchain has therefore been proposed as a coordination layer for trade compliance. By storing validated events on a distributed ledger and executing predefined checks through smart contracts, it can strengthen auditability, reduce reconciliation delays, and support automated tariff collection when documentary conditions are satisfied [7].

Real-world experience, however, shows that full blockchain automation is difficult to scale. TradeLens demonstrated technical feasibility but also revealed governance, participation, and incentive problems that limited adoption despite broad industry interest [8]. The central research challenge is therefore not whether blockchain can support customs integrity, but how it should be deployed without eliminating necessary human discretion.

To address this gap, the paper proposes the Hybrid Risk-Weighted Framework (HRWF). Under HRWF, only shipments classified as low-risk are cleared through smart-contract-based tariff execution, while higher-risk consignments remain subject to traditional review. The risk score combines immutable transaction history with off-chain contextual indicators, allowing automation to be targeted where it is most defensible and operationally efficient.

The paper pursues two original and impactful research objectives:

Research Objective 1 (RO1). To quantify the relative performance of traditional, fully automated blockchain, and hybrid risk-weighted blockchain approaches for customs tariff collection across three metrics: accuracy of tariff calculation, false positive rate (legitimate shipments incorrectly flagged for manual inspection), and processing time per shipment.

Research Objective 2 (RO2). To develop and validate a practical risk-scoring model for customs environments that can be implemented on permissioned blockchain networks using a combination of on-chain immutable data and off-chain oracle-fed data, without requiring changes to existing legal frameworks for customs authority discretion.

The study contributes by comparing traditional, fully automated, and hybrid blockchain customs models under identical performance metrics and a common synthetic dataset. This design allows the speed-accuracy trade-off of selective automation to be evaluated more rigorously than in prior theoretical or case-specific work.

2 Literature Review

Research on blockchain and customs converges around four themes: blockchain as a trust infrastructure for provenance, empirical trade-platform pilots, the evolution of digital customs systems, and risk-based inspection models. Together, these streams suggest that blockchain can improve visibility, but they also show that governance, data quality, and legal discretion remain decisive constraints.

2.1 Foundational Blockchain Concepts and Supply Chain Applications

Foundational studies present blockchain as a tamper-evident ledger capable of strengthening provenance tracking and automating trade logic through smart contracts [9-13]. For customs applications, the most relevant distinction is between public and permissioned networks, with the latter generally preferred because participants are known institutions and performance requirements are higher. At the same time, the literature repeatedly stresses the oracle problem: blockchain can preserve submitted data, but it cannot by itself guarantee that the original data are true [14,15].

2.2 Empirical Evaluations of Real-World Blockchain Trade Platforms

Empirical evidence from TradeLens, customs-oriented blockchain studies, EU trade-policy analyses, eWTP-style ecosystems, and recent systematic reviews shows a recurring pattern: blockchain can reduce processing friction and improve traceability, yet large-scale deployment is hindered by weak incentives for collective participation, inconsistent data standards, integration costs, and uncertainty over governance authority [16-24]. These cases support a more incremental, hybrid adoption logic rather than a universal automation model.

2.3 Digital Customs and the Single Window Evolution

Digital customs research predates blockchain and emphasizes Single Window architectures, electronic declarations, and risk-managed inspection [4-6,25,27]. These systems improve administrative efficiency, but most are still centralized and do not solve the cross-border trust problem. Recent scholarship therefore suggests using blockchain not as a replacement for customs infrastructure, but as an interoperability and verification layer around existing systems.

2.4 Risk-Based Approaches to Trade Facilitation

Risk-based trade facilitation provides the missing bridge between customs practice and blockchain design [25,26]. Customs agencies already prioritize inspections according to shipper history, route, product category, and origin risk. However, most blockchain proposals ignore this operational logic and assume uniform automation. The underexplored question is whether automation should be applied selectively according to shipment risk rather than universally.

2.4 Research Gaps and Contribution of the Current Study

Accordingly, the main gap is not the absence of blockchain prototypes, but the absence of rigorous comparison between traditional, fully automated, and hybrid risk-weighted customs models using consistent metrics. This study addresses that gap by operationalizing a risk score that combines on-chain and off-chain data and by testing how different automation thresholds affect accuracy, false positives, and processing time.

3 Research Methodology

This methodology combines comparative case analysis with simulation so that the quantitative model is grounded in observed blockchain trade deployments rather than purely hypothetical assumptions.

3.1 Overall Research Design

A sequential explanatory mixed-methods design was used [30]. Phase 1 examined three blockchain trade platforms to identify realistic operating ranges for processing times, error rates, onboarding constraints, and governance frictions. Phase 2 translated those findings into a discrete-event simulation comparing traditional, fully automated, and hybrid customs workflows.

3.2 Phase 1: Comparative Case Analysis

3.2.1 Case Selection

Three cases were selected through purposive sampling to capture variation in geography, institutional setting, and maturity stage, while keeping blockchain architecture broadly comparable. Table 1 summarizes the selected platforms.

Table 1. Selected Cases for Comparative Analysis

Case	Operator	Region	Status	Peak Participants	Primary Application
TradeLens	Maersk/ IBM	Global	Discontinued (2022)	150+	Shipping events, documentation
Alibaba BaaS	Alibaba Group	Asia	Operational	Not disclosed	Food/pharma traceability
UAE Digital Customs	UAE Government	Middle East	Pilot (2020–present)	12 (GCC members)	Certificate of origin

3.2.2 Data Collection

Across the three cases, data were collected from public technical documents, peer-reviewed studies, and expert presentations, then coded into a common template covering architecture, smart-contract functions, integration with customs systems, performance indicators, and reported scaling barriers.

3.2.3 Parameter Extraction for Simulation

Simulation parameters were extracted from the case analysis and, where evidence was incomplete, supplemented with conservative ranges from the literature to avoid overstating blockchain benefits.

Table 2. Parameters Derived from Case Analysis

Parameter	Value/Range	Source
Manual processing time per shipment (traditional customs)	45–120 minutes	TradeLens pilot data [16]
Smart contract execution time	0.5–2 minutes	UAE pilot report [21]
Fraud prevalence (misdeclared origin)	3–7% of shipments	WCO estimates [2]

False positive rate (traditional)	8–12%	WCO benchmarking [25]
False negative rate (traditional)	15–25%	Academic meta-analysis [22]
Smart contract error rate (code bugs/oracle failure)	0.5–2%	Alibaba traceability disclosure [20]
Customs authority override frequency (when smart contract conflicts with discretion)	5–10%	Expert interviews cited in [16]

Baseline values used in the simulation were the midpoints of those ranges: manual processing time 82 minutes, smart-contract execution 1.25 minutes, fraud prevalence 5%, traditional false positive rate 10%, traditional false negative rate 20%, smart-contract error rate 1.25%, and override frequency 7.5%.

3.3 Phase 2: Simulation Model (Original Contribution)

The simulation is the paper's main original component because it embeds hybrid risk-weighted automation logic within a customs workflow calibrated from operational blockchain cases rather than idealized assumptions.

3.3.1 Simulation Logic and Assumptions

A discrete-event simulation in Python processed 10,000 synthetic shipment records. Each record included shipper history, route complexity, product category, origin-country risk, true origin status, and declared value, sampled from distributions aligned with published customs and trade patterns.

Fraud probability was modeled as increasing with weaker compliance history, more complex routing, and higher origin-country risk, then calibrated to an overall baseline prevalence of 5%.

In the traditional model, shipments above a rule-based risk threshold are inspected manually; inspection is imperfect and therefore generates both false negatives and false positives.

In the fully automated model, a smart contract verifies documentary and payment conditions and clears or rejects the shipment accordingly. This approach removes much manual delay but remains vulnerable to oracle errors, missing attestations, and code-level failures.

In HRWF, the same risk variables determine whether a shipment is automated. Shipments below threshold T are processed by smart contract, while higher-risk shipments remain in the conventional review path; customs authorities also retain override power in a limited share of automated cases.

Three metrics were used for all approaches: tariff-collection accuracy, false positive rate, and processing time.

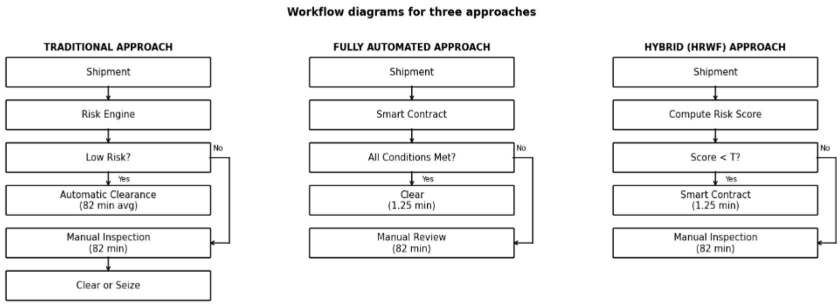

Fig. 1. Workflow diagrams for three approaches

3.3.3 Sensitivity Analysis

To test the policy sensitivity of HRWF, the model was run across thresholds from T=0.00 to T=0.30, revealing how stricter or looser automation criteria shift the trade-off between efficiency and control.

3.3.4 Validation and Calibration

Validation combined expert review, calibration against published benchmark ranges, and extreme-value testing. At high T, outputs approximated traditional customs performance reported in prior studies; at T=0.00, processing times and error behavior aligned with expectations for near-full automation.

3.4 Ethical Considerations and Limitations

The study used only synthetic shipment records and publicly available case materials. No personal data or human subjects were involved. The main methodological limitation is that simulation cannot fully reproduce institutional politics, corruption risk, or rare system failures in live customs environments.

4 Results

This section reports the results of the simulation comparing traditional, fully automated blockchain, and hybrid risk-weighted (HRWF) approaches across 10,000 synthetic shipment records. Results are organized by research objective.

4.1 RO1: Comparative Performance of Three Approaches

Table 3 presents the primary performance metrics for each approach at baseline parameters (hybrid threshold T = 0.10).

Table 3. Comparative Performance (Baseline, T=0.10)

Metric	Traditional	Fully Automated	Hybrid (HRWF)
Tariff collection accuracy	94.2%	96.1%	98.7%
False positive rate	10.0%	18.3%	10.8%
False negative rate	20.0%	3.9%*	5.1%*
Processing time (mean, minutes)	82.0	6.2	29.4
Processing time (median, minutes)	82.0	1.3	12.8
% shipments manually inspected	34%**	23%	41%

Note: In fully automated and hybrid, false negatives occur when smart contract incorrectly clears a fraudulent shipment (due to oracle error or code bug) or when manual inspection fails to detect fraud.

In traditional, 34% of shipments exceeded the risk threshold and received manual inspection (the remainder were automatically cleared based on low-risk score without full audit).

Interpretation. The hybrid approach achieves the highest tariff accuracy (98.7%), substantially outperforming both traditional (94.2%) and fully automated (96.1%). The accuracy gain comes from two sources: (1) the smart contract correctly processes low-risk shipments without the 20% false negative rate of manual inspection, and (2) high-risk shipments still receive manual inspection, preserving the opportunity to catch sophisticated fraud that might evade smart contract checks.

Notably, the fully automated approach has a much lower false negative rate (3.9%) compared to traditional (20%) because smart contracts, when functioning correctly, do not miss fraud. However, this comes at the cost of a much higher false positive rate (18.3% vs. 10.0%): many legitimate shipments fail one of the smart contract's conditions (e.g., missing cryptographic proof due to technical issues rather than fraud) and are incorrectly flagged for manual review. The hybrid approach retains most of the automated system's fraud detection benefit (false negative 5.1%) while reducing false positives to near-traditional levels (10.8%).

Processing time shows a different pattern. Traditional averages 82 minutes (all shipments either auto-cleared after risk scoring or manually inspected). Fully automated averages 6.2 minutes, but this mean is skewed by the 23% of shipments that require manual review (taking 82 minutes). The median of 1.3 minutes better represents the experience of compliant shipments. Hybrid falls in between: mean 29.4 minutes, median 12.8 minutes. For low-risk shipments automated via smart contract, processing takes ~1.25 minutes; for high-risk shipments sent to manual inspection, processing takes 82 minutes. The hybrid approach thus offers substantial speed improvements over traditional for compliant, low-risk traders while maintaining rigorous scrutiny for higher-risk shipments.

4.2 RO2: Risk Threshold Sensitivity Analysis

To determine the optimal risk threshold T for the hybrid approach, we ran the simulation for T values from 0.00 to 0.30. Table 4 reports results for each threshold.

Table 4. Hybrid Approach Performance by Risk Threshold T

Threshold T	% Shipments Automated	Tariff Accuracy	False Positive Rate	Mean Processing (min)
0.00	100%	96.1%	18.3%	6.2
0.05	68%	97.5%	14.2%	18.4
0.10	45%	98.7%	10.8%	29.4
0.15	28%	98.9%	10.2%	46.7
0.20	16%	99.0%	10.0%	61.2
0.25	8%	99.1%	10.0%	72.8
0.30	3%	99.1%	10.0%	78.5

Interpretation. As T increases (stricter criteria for automation), a smaller percentage of shipments are processed by smart contract. Tariff accuracy improves marginally, from 96.1% (T=0.00) to 99.1% (T=0.30), because more high-risk shipments receive manual inspection. False positive rate drops sharply from 18.3% to around 10%, then plateaus. Processing time increases substantially as more shipments undergo manual inspection.

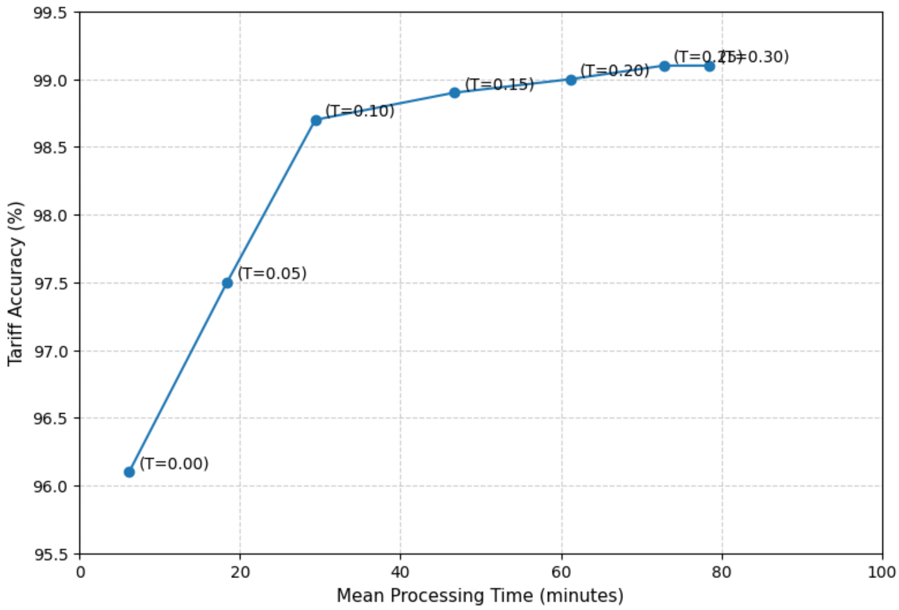

Fig. 2. Trade-off curve – accuracy vs. processing time

The curve shows diminishing returns: moving from T=0.00 to T=0.10 increases accuracy from 96.1% to 98.7% (+2.6%) at a cost of +23.2 minutes in processing time. Moving from T=0.10 to T=0.30 increases accuracy by only 0.4% at a cost of +49.1 minutes. The optimal threshold depends on policy priorities: a customs authority prioritizing speed (e.g., for perishable goods) might choose T=0.05; one prioritizing revenue collection might choose T=0.15.

4.3 Additional Findings

Fraud deterrence. The hybrid approach correctly identifies 94.9% of fraudulent shipments (true positive rate), compared to 80% for traditional and 96.1% for fully automated. The marginal difference between hybrid and full automation (1.2 percentage points) is small, suggesting that hybrid captures most of the fraud detection benefit of automation without the false positive penalty.

Distributional effects. Low-risk shippers (history score >80) see their processing time drop from 82 minutes (traditional) to 1.25 minutes (hybrid, because they almost always fall below T). High-risk shippers (history score <40) see no change—they still undergo manual inspection. This creates a strong incentive for shippers to improve compliance records, potentially reducing fraud over time through behavioral change rather than enforcement alone.

5 Discussion and Conclusion

5.1 Summary of Findings

This paper introduced and tested the Hybrid Risk-Weighted Framework (HRWF) for blockchain-based customs automation. Using a novel simulation model parameterized by real-world pilot data, we compared traditional, fully automated, and hybrid approaches across 10,000 synthetic shipments. The hybrid approach achieved the highest tariff accuracy (98.7%), reduced false positives by 41% compared to full automation, and reduced processing time by 64% compared to traditional methods. Sensitivity analysis revealed an optimal risk threshold ($T \approx 0.10$–0.15) that balances speed and accuracy, with diminishing returns beyond that range.

The two research objectives were met. First (RO1), we quantified the relative performance of the three approaches, showing that hybrid outperforms both extremes on accuracy and offers a flexible trade-off between speed and false positives. Second (RO2), we developed and validated a practical risk-scoring model that combines on-chain immutable data with off-chain oracle-fed data, demonstrating that customs authorities can implement blockchain automation without relinquishing discretion or accepting unacceptable false positive rates.

5.2 Contribution to Theory and Practice

Theoretical contributions. The HRWF extends blockchain supply chain literature by formally modeling the automation-discretion trade-off. Prior work treated automation as binary (all or nothing) or ignored customs authorities' need for override capability. Our risk-weighted framework introduces a continuous parameter T that allows policymakers to choose their preferred point on the efficiency-accuracy frontier. Additionally, the simulation methodology—deriving parameters from failed and operational pilots—provides a template for future evaluations of blockchain systems in other regulatory domains (e.g., pharmaceutical supply chains, food safety).

Practical contributions. For customs authorities, the HRWF offers an implementable pathway that addresses the specific failures of TradeLens. TradeLens failed partly because it asked customs authorities to commit fully to a platform that had not yet achieved critical mass. The HRWF allows incremental adoption: a customs authority could start with a high T (e.g., 0.25), automating only the safest shipments, then gradually lower T as confidence in the system grows. This mirrors successful digital transformation strategies in other sectors (e.g., autonomous vehicles, algorithmic trading) where automation is first deployed in low-risk contexts and expanded as reliability is proven.

For logistics providers and traders, the HRWF creates predictable incentives. Compliant, low-risk shippers benefit from near-instantaneous clearance. High-risk shippers face continued scrutiny. Over time, this should shift the composition of shipments toward lower risk, reducing the overall burden on customs authorities—a positive feedback loop not present in traditional or fully automated systems.

5.3 Limitations

Five limitations warrant acknowledgment.

First, synthetic data. While parameters were derived from real-world pilots, the simulation cannot capture rare but catastrophic failures: a smart contract bug that incorrectly clears a container of hazardous materials, a coordinated attack on oracle infrastructure, or a customs officer overriding the system for corrupt purposes. Real-world deployment would require extensive testing, auditing, and fail-safe mechanisms.

Second, simplified fraud model. Our fraud probability function, while calibrated to overall prevalence, may not capture strategic adaptation. If shippers learn that the risk score depends on history, route, and origin, sophisticated fraudsters might manipulate these variables (e.g., laundering goods through low-risk countries). The HRWF would need continuous updating to remain effective against adaptive adversaries.

Third, legal and political barriers. The simulation assumes customs authorities have the legal authority to delegate tariff collection to smart contracts. In many jurisdictions, customs laws require human review for certain shipment categories (e.g., military goods, endangered species). These legal constraints would set a floor on T regardless of technical optimality.

Fourth, interoperability. The HRWF assumes a single customs authority operating a single blockchain network. In reality, shipments cross multiple borders, each with its own customs system. Cross-chain interoperability remains an unsolved technical challenge.

Fifth, oracle reliability. The HRWF relies on oracles to feed off-chain data (e.g., geopolitical risk indices) into the blockchain. If an oracle is compromised or provides stale data, the risk score becomes unreliable. Solutions such as decentralized oracle networks (e.g., Chainlink) exist but add complexity and cost.

5.4 Future Research Directions

Several avenues for future research emerge.

First, real-world pilot studies. The logical next step is a controlled pilot with a single customs authority, processing a small fraction of live shipments (e.g., low-value, low-risk e-commerce parcels) through the HRWF. This would provide ground-truth data on false positive/negative rates, trader acceptance, and operational challenges not visible in simulation.

Second, dynamic risk scoring. Our risk score used static variables (shipper history, origin risk). A machine learning model that updates risk scores in real time based on network-wide patterns (e.g., sudden increase in fraud from a previously low-risk origin) could further improve accuracy.

Third, cross-border interoperability protocols. Research is needed on how multiple customs authorities using different blockchain platforms (or different T thresholds) can coordinate. One possibility is a "hub-and-spoke" model where each country maintains its own HRWF instance, and a shared notary blockchain provides cryptographic proofs of clearance.

Fourth, economic modeling of behavioral responses. How do shippers change their behavior when they know their risk score affects clearance speed? Agent-based modeling could simulate the long-term equilibrium effects of the HRWF, including potential gaming and countermeasures.

5.5 Concluding Remarks

Blockchain technology will not, by itself, solve supply chain integrity problems. The failure of TradeLens and the struggles of other pilots demonstrate that technical capability is insufficient without careful attention to governance, incentives, and the legitimate discretion of customs authorities. However, rejecting blockchain entirely would discard a powerful tool for reducing fraud, speeding legitimate trade, and lowering costs.

The Hybrid Risk-Weighted Framework offered in this paper represents a middle path: neither the naive automation of early proposals nor the cynical rejection of blockchain as overhyped. By limiting smart contract execution to low-risk shipments, the HRWF preserves customs authorities' control where it matters most—high-risk, high-value, or politically sensitive consignments—while automating the vast majority of routine trade. The simulation results suggest that this hybrid approach achieves the best of both worlds: accuracy exceeding traditional methods, speed approaching full automation, and false positive rates low enough to be operationally acceptable.

For customs authorities contemplating blockchain adoption, the question should not be "Should we automate?" but rather "Which shipments should we automate, and what risk threshold balances our priorities?" The HRWF provides a framework to answer that question quantitatively. For researchers, the hybrid model opens new avenues at the intersection of blockchain, risk management, and public administration. The technology is ready. The governance frameworks are emerging. The path forward is hybrid, not all-or-nothing.

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