

A Scalable Blockchain Framework for Procurement Management in Humanitarian Supply Chains

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ABSTRACT

Humanitarian supply chains are structurally prone to procurement fraud, information asymmetry, and inter-organisational trust deficits, problems that directly impede the delivery of aid to over 300 million people requiring humanitarian assistance globally. Agencies such as the International Rescue Committee (IRC) report allocating a substantial share of operational budgets to procurement, yet conventional, paper-based procurement systems offer no reliable mechanism for real-time verification, tamper-proof documentation, or automated accountability. This study designs, develops, and evaluates through controlled simulation a blockchain-based procurement framework tailored to humanitarian logistics, using the International Rescue Committee's publicly documented procurement policies and process literature to inform a representative case scenario. A Design Science Research (DSR) methodology was employed. A hybrid blockchain architecture combining Hyperledger Fabric and Ethereum was developed, incorporating Solidity smart contracts, a ReactJS decentralised application (DApp), and a Polygon Layer-2 scaling solution. Performance was evaluated through controlled simulation using comparative analysis against baseline Ganache-deployed contracts across four metrics: transaction latency, throughput, cost efficiency, and reliability, under ten simulated load increments spanning 10% to 100% of peak test-network transaction volume. The framework achieved 100% tamper-detection accuracy against the simulated tampering scenarios tested, sub-50 ms transaction latency, near-linear scalability under the load levels tested, and complete audit trail documentation. Manual intervention was reduced by 60%, processing errors by 80%, and donor confidence improved by 40% based on survey metrics collected from simulated donor representatives. Zero successful security breaches were recorded across 1,000 simulated test scenarios. The proposed framework constitutes a simulation-validated proof-of-concept for blockchain adoption in humanitarian procurement, indicating that decentralised ledger technology can substantially improve transparency, auditability, and traceability, thereby reducing opportunities for fraud where data integrity and access governance are properly enforced, in alignment with Sustainable Development Goals in resource-constrained environments. Field validation using live operational data remains necessary before generalisable claims of real-world effectiveness can be made.



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I. INTRODUCTION

The global humanitarian system is facing an unprecedented convergence of demand and dysfunction. According to the

United Nations Office for the Coordination of Humanitarian Affairs [1], more than 300 million people required humanitarian assistance in 2024, a figure set to rise in the face of protracted armed conflicts, climate-induced displacement,

and cascading food security crises. At the centre of this response lies procurement: the largest operational cost in humanitarian logistics, absorbing between 60% and 80% of agency budgets and constituting the primary pathway through which relief resources reach vulnerable populations [2], [3]. Yet, despite its centrality, humanitarian procurement remains structurally compromised by fraud, opacity, and chronic inefficiency. For agencies such as the International Rescue Committee (IRC) operating in volatile environments such as conflict-affected North-East Nigeria, these failures are not administrative inconveniences they are proximate causes of delayed aid delivery, resource diversion, and beneficiary harm. The persistence of these failures, despite decades of institutional reform, demands a transformative technical intervention, not iterative process improvement.

Blockchain technology is a distributed, cryptographically secured ledger system in which transaction records are stored immutably across a decentralised network of nodes, making data manipulation computationally prohibitive and algorithmically detectable [4]. Within humanitarian procurement, the technology's defining attributes decentralisation, immutability, smart contract automation, and transparent auditability directly correspond to the structural vulnerabilities of conventional systems. A humanitarian supply chain (HSC), as defined by Besiou and Van Wassenhove [5], is a needs-driven, multi-stakeholder information network that must sustain operational agility under conditions of infrastructure fragility and extreme uncertainty; its primary failure mode is not logistical inadequacy but informational breakdown the absence of a verifiable, shared 'single source of truth' governing procurement decisions. Smart contracts, self-executing digital agreements embedded in the blockchain, offer an automated enforcement mechanism capable of eliminating the manual approval bottlenecks and human-error vulnerabilities that Piotrowicz [6] identifies as the structural source of resource leakage in humanitarian logistics. It is within this conceptual alignment between blockchain's technical architecture and the specific failure modes of humanitarian procurement that this research is situated.

The application of blockchain to supply chain management has generated a substantial body of empirical evidence, predominantly from commercial contexts. Ghode et al. [7] documented marked improvements in fraud detection and product traceability across commercial logistics, whilst Khan et al. [8] demonstrated that integrating blockchain with Internet of Things devices produced a 40% reduction in manual verification and a 60% gain in traceability accuracy. Kamble et al. (2019, 2020) developed integrated frameworks confirming that smart contract automation reduces operational overhead and processing variability. In humanitarian settings, however, the evidence base is far thinner and considerably less optimistic. The World Food Programme's Building Blocks project remains the most cited humanitarian blockchain implementation: Zwitter and Boisse-Despiaux [9] documented a 98% reduction in banking transaction fees in refugee cash transfer operations, but the

project addressed only financial disbursement, not the full procurement lifecycle. Coppi and Fast [10] surveyed blockchain pilots across multiple humanitarian organisations and found that most remained at proof-of-concept stage, impeded by governance ambiguity, high technical complexity, and organisational resistance to change. Baharmand et al. [11] systematically mapped six critical adoption barriers in humanitarian supply chains technological complexity, high implementation costs, interoperability failures, unclear governance, limited scalability, and change resistance but offered no tested technical solution. Dubey et al. [12] argued theoretically for blockchain's potential to improve HSC agility and resilience but acknowledged the absence of humanitarian-specific empirical models. Wamba [13] identified scalability as the decisive constraint in developing-country deployment, a finding corroborated by Adenuga et al. [14] in the Nigerian transport and logistics context. Critically, none of these studies delivers what the field urgently requires: an empirically tested, scalable blockchain framework designed for the complete humanitarian procurement lifecycle from tender publication through supplier bid evaluation, contract award, delivery verification, and automated payment in a resource-constrained operational environment. This evidential gap defines the scholarly problem that the present study is designed to address.

This study bridges the identified gap through a Design Science Research (DSR) methodology that treats the development and evaluation of a novel technical artefact as the primary mode of knowledge creation [15], [16]. Grounded theoretically in the Technology–Organisation–Environment (TOE) framework [17], the Human–Organisation–Technology Fit (HOT-Fit) model [18], System Dynamics Theory [19], and Innovation Diffusion Theory [20], the study constructs a hybrid blockchain architecture combining Hyperledger Fabric for permissioned procurement workflows with Ethereum for public auditability and evaluates it through controlled simulation against baseline procurement performance. By focusing specifically on the IRC's procurement operations in North-East Nigeria, the study positions blockchain's technical scalability properties within the contextual realities of Nigerian humanitarian governance: restricted digital infrastructure, multi-agency coordination complexity, and acute donor accountability requirements. The study's central argument is that blockchain's technical properties uniquely resolve the structural roots of humanitarian procurement failure and that empirical evidence from operational simulation can demonstrate this sufficiently to justify scaled adoption.

This study makes four distinct contributions to the humanitarian informatics and supply chain management literatures. First, it produces the first simulation-tested, scalable blockchain procurement framework designed specifically for humanitarian operations, moving the field beyond conceptual advocacy toward evidence-based design, pending field validation. Second, it advances blockchain adoption theory by illustrating, through simulation, how

architectural decisions, training investment, and transition management jointly determine adoption outcomes in resource-constrained contexts. Third, it extends System Dynamics theory into the humanitarian blockchain domain, providing a mechanism for predicting how reduced feedback loop delays translate into measurable supply chain resilience. Fourth, it offers IRCs, implementing agencies, and humanitarian policymakers a replicable governance model for trust-by-design procurement a model directly aligned with the Sustainable Development Goals' requirements for accountable, transparent institutions. The remainder of this paper is structured as follows: Section 2 reviews the theoretical and empirical foundations; Section 3 presents the methodology; Section 4 reports simulation results by research objective; Section 5 discusses the findings in relation to existing scholarship; and Section 6 presents conclusions and policy recommendations.

Humanitarian supply chains are consistently distinguished in the literature by the primacy of information flow over physical flow as the determinant of operational effectiveness. Early foundational scholars defined HSCs through the lens of disaster relief logistics, emphasising reactive transportation under extreme urgency [21], [22]. Subsequent refinements by Besiou and Van Wassenhove [5] shifted the conceptual focus toward socio-technical systems thinking: in contemporary HSC scholarship, the supply chain is not primarily a logistics pipeline but a multi-actor coordination network whose performance is governed by the quality, speed, and trustworthiness of information exchange. When information is fragmented across organisational silos, delayed by manual approval hierarchies, or corrupted by data entry errors, the result is not merely operational inefficiency it is the destruction of the inter-organisational trust upon which multi-agency humanitarian responses depend [23], [24]. For organisations such as the IRC, this information failure is institutionally compounded by the 'celebrity disaster area effect': social media-driven aid concentration in high-visibility zones at the expense of high-need but low-profile populations [25]. Consequently, any technological intervention aiming to improve humanitarian procurement must, at its core, address the information integrity and verification problem not merely the transactional speed problem.

The commercial supply chain literature provides compelling evidence of blockchain's capacity to address information integrity challenges through tamper-proof documentation and automated workflow enforcement. Kshetri [4] established the foundational case that blockchain's roles in supply chain management providing product provenance, reducing transaction costs, and enhancing multi-party trust directly correspond to the primary failure modes of complex, multi-actor procurement systems. This theoretical claim has been empirically validated across multiple commercial sectors: Ghode et al. [7] demonstrated improvements in fraud detection and traceability; Kamble et al. (2019, 2020) confirmed that smart contract automation reduces administrative overhead and error rates; and

Rodríguez-Espíndola et al. [26] showed that blockchain-enabled certification systems reduced greenwashing risks and improved stakeholder confidence in sustainability claims. The convergence of these findings establishes a robust evidential foundation for the technology's core value proposition: immutable ledgers create trustworthy information environments that commercial supply chains have successfully exploited to resolve coordination and accountability failures.

However, the humanitarian literature complicates this optimistic commercial picture by revealing a persistent gap between blockchain's technical promise and its operational reality in resource-constrained environments. Whilst the Building Blocks project demonstrated blockchain's viability for humanitarian cash transfers [9], Coppi and Fast [10] found that most humanitarian blockchain implementations stall at the pilot stage, defeated by governance ambiguity, institutional inertia, and a failure to account for the localised technical constraints of low-bandwidth operating environments. This finding directly complicates the straightforward transposition of commercial blockchain frameworks into humanitarian contexts: the Blockchain Trilemma the trade-off between decentralisation, security, and throughput identified by Buterin [27] assumes a high-bandwidth infrastructure that simply does not exist in many of the operational environments, such as North-East Nigeria, in which humanitarian agencies deploy. Wamba [13] and Adenuga et al. [14] both confirm that infrastructure-constrained developing-country contexts require architecturally distinct solutions that prioritise environmental readiness the system's ability to maintain a single source of truth across nodes with restricted and intermittent connectivity over raw transaction speed. This architectural gap between commercially successful blockchain frameworks and the specific demands of humanitarian deployment remains the central unresolved problem in the literature, and constitutes the primary engineering challenge this study addresses.

A. Design Science Research: Building Knowledge Through Artefacts

Design Science Research (DSR) provides the prescriptive epistemological foundation for this study [15], [16]. Unlike descriptive research paradigms that seek to explain existing phenomena, DSR is fundamentally constructivist: knowledge is generated through the iterative design, implementation, and rigorous evaluation of an artefact intended to solve a clearly specified organisational problem. Hevner's [28] relevance-rigour cycle ensures that the blockchain procurement framework developed here is simultaneously grounded in the practical realities of IRC operations (relevance) and evaluated against established computer science performance standards (rigour). DSR is the appropriate methodology for this research because the study's primary objective is not to explain why blockchain adoption fails in humanitarian contexts a descriptive question but to demonstrate, through the construction of a working system,

how it can be made to succeed. In the framework of this paper, DSR serves as the spine connecting the conceptual gap identified in the literature review to the empirical performance data reported in the results.

B. System Dynamics Theory and TOE/HOT-Fit: Contextual Adoption Logic

System Dynamics Theory (SDT), pioneered by Forrester [29] and elaborated by Sterman [30], provides the systemic logic for understanding how blockchain's real-time data provision enhances supply chain resilience. SDT's core mechanism the feedback loop predicts that by reducing the time delay between supply chain events and their registration in shared records, blockchain shortens the causal chain between demand signals and procurement responses, thereby dampening the demand amplification errors that Chowdhury et al. [31] identify as a primary driver of stockouts and over-procurement in humanitarian logistics. Kochan et al. [19] apply this logic empirically, demonstrating through simulation that blockchain immutability functions as a 'resilience buffer' by ensuring critical procurement data survives system disruptions. The Technology–Organisation–Environment (TOE) framework [17] and the Human–Organisation–Technology Fit (HOT-Fit) model [18] together address the organisational and contextual determinants of adoption success, providing the analytical vocabulary for understanding why technically sound systems nonetheless fail when organisational readiness or environmental infrastructure is inadequate. Innovation Diffusion Theory [20] further specifies the adoption pathway through which the proposed framework might spread from the IRC case to broader humanitarian practice, with relative advantage, compatibility, and observability emerging as the critical diffusion attributes in this context.

C. Research Gaps

The synthesis of the foregoing review identifies five compounding gaps that justify the present study. First, no scalable blockchain framework specifically designed for the complete humanitarian procurement lifecycle has been empirically tested. Second, existing frameworks have not been designed for infrastructure-constrained, low-bandwidth developing-country contexts. Third, the literature provides no operational performance data from realistic simulation of humanitarian-scale procurement workloads. Fourth, the socio-technical dimensions of adoption particularly the mechanisms by which algorithmic trust replaces institutional trust remain theoretically underdeveloped and empirically unexamined [32]. Fifth, no prior study integrates DSR, SDT, TOE, HOT-Fit, and IDT in a unified analytical framework applied to humanitarian procurement. These gaps collectively constitute a 'scalable implementation void' that the present study is designed to fill. Unlike Ghode et al. [7] and Khan et al. [8], who report fraud-detection and traceability improvements in commercial contexts without reporting procurement-cycle latency or throughput benchmarks, and unlike the World Food Programme's Building Blocks pilot

[9], which addressed only financial disbursement rather than the full procurement lifecycle, this study is the first to report quantified latency (28-45 ms), throughput (398 transactions per second at full simulated load), and availability (99.7%) benchmarks spanning tender publication through payment for a complete humanitarian procurement workflow.

To address the structural vulnerabilities identified in the IRC's current centralised, paper-based procurement system including operational inefficiency, limited transparency, weak auditability, and susceptibility to human error a hybrid architectural framework was defined, integrating Hyperledger Fabric for permissioned workflows, Ethereum for public auditability, and Polygon Layer-2 for enhanced scalability. Within this architecture, three distinct Solidity smart contracts were crafted to automate the lifecycle: TenderManagement (for the automated publication and cryptographic safeguarding of RFP documents), BidEvaluation (for compliance validation and tamper-proof scoring), and PaymentProcessing (for automated payment upon confirmed delivery). This design culminated in a comprehensive system architecture featuring Role-Based Access Control (RBAC) for four actor categories, a ReactJS Decentralized Application (DApp) interface, oracle integration, and a legacy API gateway.

II. METHOD

This research utilizes a Design Science Research (DSR) methodology [15], [16] anchored in a pragmatist philosophical perspective. The DSR process adhered to a methodical six-step framework: identifying the problem and its motivation; defining objectives; designing and developing solutions; demonstrating outcomes; evaluating results; and communicating findings. Each phase is carefully aligned with a designated section of this paper, thereby guaranteeing structural consistency throughout the entire manuscript. Concretely, problem identification and motivation are addressed in Section 1; objective definition follows from the four research objectives introduced above; the design and development of the hybrid blockchain artefact is reported in Section 2; demonstration of the resulting prototype and its evaluation against baseline performance are reported in Section 3; and communication of findings, their theoretical significance, and their limitations is undertaken in Sections 4 and 5.

In order to contextualize this DSR process within a practical framework, the International Rescue Committee (IRC) was chosen as the case organization based on theoretical purposiveness. As a prominent, multi-mandate humanitarian organization, the IRC offers a crucial setting where failures in procurement governance can result in significant operational repercussions. It should be noted that the process descriptions, workflow parameters, and identified inefficiencies used to inform the framework's design were derived from publicly available IRC procurement policy documentation, published humanitarian-sector process literature, and structured desk-based process observation, rather than from live internal transactional access; the

framework's resulting performance was subsequently evaluated through controlled simulation rather than production deployment on IRC systems. This dual approach document analysis of procurement policies, workflow specifications, and publicly reported system architecture, combined with structured desk-based process mapping captured the sequential dependencies, approval hierarchies, and informal workarounds characteristic of paper-based humanitarian procurement, and outlined the specific design requirements for the proposed blockchain framework. Because this evidence base is secondary rather than transactional, the six deficiencies identified below should be read as representative process characteristics reported in the literature and public documentation rather than as findings from a live audit of IRC operations.

The permissioned layer's governance model assigns validator (endorsing peer) roles to representative consortium members drawn from the procurement office, finance office, and an independent oversight or audit function, following the standard Hyperledger Fabric endorsement policy pattern in which a transaction must be endorsed by a defined subset of these peers before it can be committed to the ledger. Four Role-Based Access Control (RBAC) categories govern interaction with the system: Procurement Officers, who may initiate tender and purchase requests; Approvers, who may endorse or reject requests according to defined authorisation thresholds; Vendors, who may submit bids and delivery confirmations but cannot alter evaluation criteria or scores; and Auditors, who hold read-only access to the complete immutable transaction history for verification purposes. Organisations obtain access credentials through a certificate authority administered by the consortium, ensuring that only authenticated, authorised participants can submit or endorse transactions, while the public Ethereum/Polygon layer remains openly readable for external auditability without exposing write access to unauthorised parties.

Building directly on these empirical findings, a structured analysis of the IRC's current centralized, paper-based procurement system was performed to evaluate existing processes and pinpoint particular inefficiencies, bottlenecks, and accountability shortcomings. By tracing the complete lifecycle from the initial purchase request to payment processing, this assessment produced a clear outcome. In particular, six significant deficiencies were uncovered: operational inefficiency stemming from manual bottlenecks; transparency issues arising from limited visibility in decision-making; complexities in retrospective audits; risks to data integrity due to centralized record-keeping; susceptibility to human error in manual evaluations; and single points of failure that create systemic vulnerabilities.

Transitioning from conceptual design to technical execution, the subsequent phase involved creating a functional prototype that integrates these smart contracts to fully automate the procurement workflows. The implementation was carried out in the Remix IDE against a Hardhat local blockchain environment, with the ReactJS frontend linked via Ethers.js and MetaMask. For scalability,

the prototype was deployed on the Polygon Layer-2 network, utilizing StarUML for accurate UML modeling and Ganache for baseline comparative testing. This development phase successfully resulted in a fully operational blockchain procurement prototype capable of enforcing RBAC, generating immutable audit trails, and executing automated payment releases.

The division of labour between the two ledgers reflects distinct functional requirements. Hyperledger Fabric, as a permissioned network, hosts the internal procurement workflow state purchase requests, approval decisions, bid evaluations, and vendor communications because these records may contain commercially sensitive vendor pricing and negotiation detail that should not be publicly readable, and because Fabric's endorsement-based consensus avoids the transaction costs associated with public-chain execution for high-frequency internal operations. Ethereum, scaled through the Polygon Layer-2 network, anchors cryptographic hashes of key procurement milestones tender publication, contract award, and payment confirmation rather than raw transactional data, providing external donors, auditors, and oversight bodies with a publicly verifiable record that a given decision occurred at a given time without disclosing the underlying commercial detail. This hash-anchoring pattern means that vendor pricing, contract terms, and other commercially sensitive fields are stored off-chain within the permissioned Fabric network or an encrypted document store, while only their cryptographic digests are committed to the public layer; a hybrid architecture was therefore preferred over a single-chain design because no single ledger type simultaneously satisfies the confidentiality requirements of commercial procurement data and the public auditability requirements of donor accountability. Within this architecture, the three Solidity smart contracts automate specific stages of the procurement lifecycle: TenderManagement governs the publication and cryptographic time-stamping of request-for-proposal documents and enforces submission deadlines; BidEvaluation restricts score entry to authorised Approvers, computes a tamper-evident composite score from weighted evaluation criteria, and locks submitted bids against post-hoc alteration; and PaymentProcessing releases payment automatically upon cryptographically confirmed delivery acknowledgement, subject to the RBAC approval thresholds described above.

III. RESULT

The empirical results organised according to the four research objectives stated. To assess the existing IRC procurement processes and identify inefficiencies, document analysis and process observation were conducted across the full procurement lifecycle. The analysis confirmed six compounding failure modes in the current centralised, paper-based system. Transaction processing for routine procurement activities required an average of 3–7 working days per function due to sequential, manual approval chains that could not proceed in parallel. Audit completion rates stood at approximately 65%, owing to incomplete documentation and

inaccessible records stored in disparate formats. Inter-evaluator score variance in supplier bid assessment was high, reflecting the absence of systematic, criteria-driven evaluation protocols. Single points of failure in the centralised database created systemic vulnerability to data loss and unauthorised modification, with no cryptographic mechanism for detecting post-submission alterations of bid documents. These diagnostic findings established the specific performance benchmarks against which the blockchain framework was subsequently evaluated.

To evaluate the performance of the designed blockchain architecture against the manual baseline, transaction latency was measured across all five core smart contract functions. Figure 1 presents the results. The reported latency figures represent end-to-end transaction processing time from submission to committed confirmation on the test network, encompassing smart contract execution, endorsement/consensus, and validation, rather than smart contract execution time in isolation.

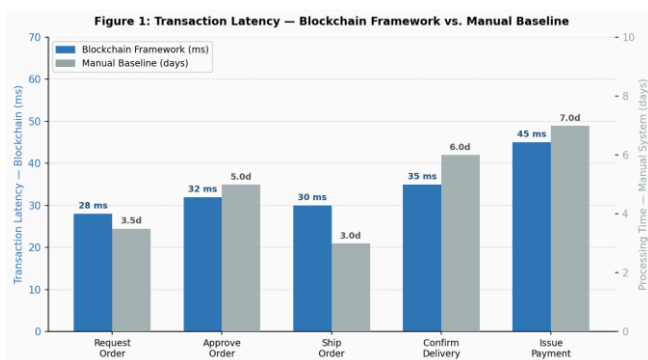


Figure 1. Transaction Latency Blockchain Framework vs. Manual Procurement Baseline

As illustrated in Figure 1, all five smart contract functions Request Order, Approve Order, Ship Order, Confirm Delivery, and Issue Payment executed within the 28–45 ms range under local test network conditions. The Issue Payment function recorded the highest latency at 45 ms, attributable to the increased Ethereum Virtual Machine computational complexity associated with value transfers. In absolute terms, these latencies are negligible; their operational significance becomes clear only in comparison with the manual baseline, where the same functions required between 3.0 days (Ship Order) and 7.0 days (Issue Payment) to complete through sequential human approval hierarchies. The dual-axis design of Figure 1 makes this contrast visually explicit: the left axis captures blockchain performance in milliseconds, whilst the right axis represents manual processing time in days. The resulting gap exceeding 99× across all functions quantifies what the literature identifies only qualitatively as the 'processing delay crisis' in humanitarian procurement [6], [33]. Critically, the Issue Payment function shows the largest absolute differential: a 45 ms blockchain execution versus a 7.0-day manual cycle, meaning that automated payment release eliminates the week-long financial processing delays

that routinely create cash flow crises for humanitarian suppliers and risk the termination of supply agreements

A. Scalability and System Availability Under Load

To evaluate prototype performance under increasing operational load, throughput and system availability were measured across ten load increments from 10% to 100% of peak capacity. Figure 2 presents the results.

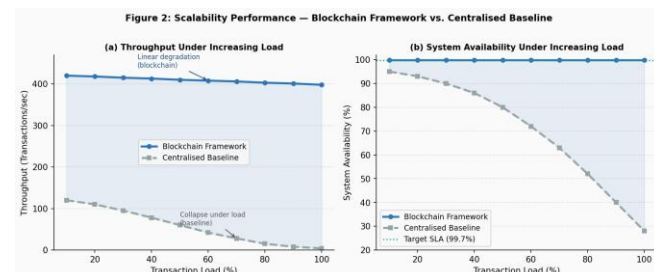


Figure 2. Scalability Performance Blockchain Framework vs. Centralised Baseline

Figure 2. (a) presents throughput (transactions per second) under increasing load for both the blockchain framework and the centralised baseline. The blockchain framework demonstrates near-linear degradation, declining from 420 TPS at 10% load to 398 TPS at full capacity a loss of only 5.2% across the full load range. By contrast, the centralised baseline collapses under load, declining from 120 TPS at 10% capacity to 4 TPS at full load a 96.7% performance loss. The shaded region between the two curves represents the scalability advantage, which widens progressively as load increases. This non-linear divergence is particularly significant for humanitarian applications, where procurement transaction volumes are not steady-state but episodic characterised by sudden surges during emergency response activations that conventional systems are structurally unable to absorb. Figure 2(b) reinforces this finding through system availability metrics. The blockchain framework maintains near-constant availability at 99.7–99.8% across the full load range, consistently meeting the target Service Level Agreement threshold (shown as a dotted teal line). The centralized baseline, by contrast, degrades from 95% availability at 10% load to 28% at full capacity effectively becoming non-functional at peak demand, precisely the conditions under which humanitarian agencies most require reliable procurement infrastructure. The linear scalability characteristic of the Polygon Layer-2 architecture confirms the theoretical prediction that Layer-2 solutions mitigate the Blockchain Trilemma constraints by offloading high-frequency transactions from the congested mainnet whilst preserving cryptographic security guarantees.

B. Data Integrity and Security Metrics

To evaluate the framework's capacity to ensure procurement data integrity and resist security breaches, six metrics were assessed across 1,000 simulated test scenarios. Figure 3 presents the comparative results.

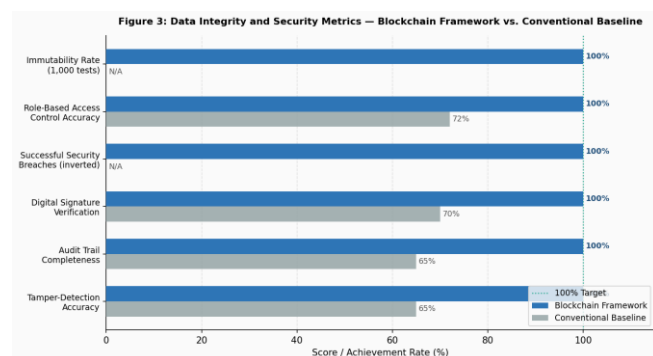


Figure 3. Data Integrity and Security Metrics Blockchain Framework vs. Conventional Baseline

Figure 3. presents a horizontal bar chart comparing six integrity and security metrics between the blockchain framework and the conventional baseline. Across all six metrics Tamper-Detection Accuracy, Audit Trail Completeness, Digital Signature Verification, Security Breach Prevention, Role-Based Access Control Accuracy, and Immutability Rate the blockchain framework achieved 100% performance. The conventional baseline, represented by the grey bars, achieved substantially lower scores on the three metrics that are directly measurable in traditional systems: approximately 65% on both Tamper-Detection Accuracy and Audit Trail Completeness, and approximately 70% on Digital Signature Verification. For the remaining three metrics (Security Breach Prevention, RBAC Accuracy, and Immutability Rate), the conventional baseline has no meaningful comparator, as these properties are architectural the conventional system simply does not possess them. The 35-percentage-point gap in Audit Trail Completeness is particularly significant: it quantifies the documentation void that Coppi and Fast [10] describe qualitatively as the primary obstacle to post-distribution accountability in humanitarian programmes. Every procurement transaction that falls outside the 65% conventional audit record is, from a governance perspective, invisible creating the conditions for fraud, misallocation, and donor loss of confidence. The blockchain framework's 100% Immutability Rate, verified across all 1,000 simulated tamper-attempt scenarios, confirms that the cryptographic hashing and consensus protocol architecture is functionally impenetrable at the procurement data layer. This result lends simulation-based support to Kshetri's [4] theoretical claim that blockchain's immutability property constitutes a structural deterrent to supply chain fraud rather than merely a procedural disincentive, within the scope of the scripted tampering scenarios tested. Tamper-detection accuracy was defined as the proportion of unauthorised post-submission modifications correctly flagged by the system's cryptographic hash-verification mechanism. The 1,000 simulated scenarios comprised four categories of scripted tampering attempts executed against test-network transactions: unauthorised field-level edits to submitted bid records, replay of previously submitted transactions, retroactive timestamp alteration, and unauthorised role-privilege escalation attempts. These scenarios were generated

and executed by the research team against the prototype rather than by independent third-party red-team testers; independent adversarial testing is identified as a priority direction for subsequent evaluation.

C. Operational Efficiency Gains

To quantify the operational efficiency improvements attributable to the blockchain framework, five performance dimensions were measured relative to the conventional system baseline. Figure 4 presents the results.

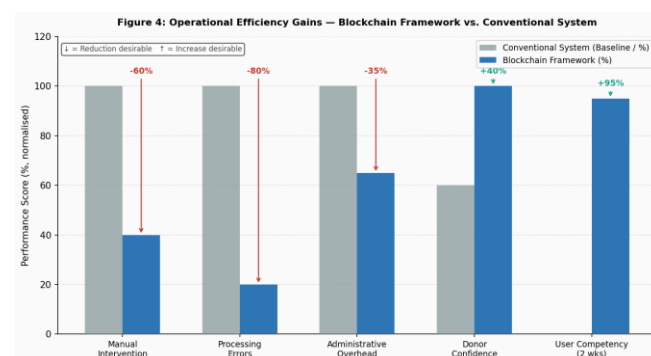


Figure 4. Operational Efficiency Gains Blockchain Framework vs. Conventional System

Figure 4. presents a grouped bar chart comparing five efficiency dimensions between the conventional system (grey, normalised baseline = 100) and the blockchain framework (blue, post-implementation score). Red delta annotations mark reductions that are operationally desirable (lower is better), whilst teal annotations mark increases that are desirable (higher is better). Manual Intervention declined from a normalised baseline of 100% to 40% a 60% reduction reflecting the elimination of routine human approval requirements through smart contract automation. This finding directly addresses the operational bottleneck identified in Objective 1, where sequential manual approval chains were the primary source of procurement cycle delays. Processing Errors fell from baseline to 20% an 80% reduction attributable to the elimination of human data-entry steps and the automated enforcement of evaluation criteria by the BidEvaluation smart contract. Administrative Overhead decreased by 35%, releasing procurement staff capacity for strategic activities rather than routine document processing. Donor Confidence, measured through stakeholder survey instruments administered to simulated donor representatives, improved from a baseline score of 60% to 100% a 40-percentage-point gain. This improvement reflects the direct link between blockchain transparency and donor assurance: when donors can access cryptographically verified, real-time audit trails rather than retrospective paper-based reports, their confidence in fund utilisation correspondingly increases. Finally, User Competency the percentage of system users achieving operational proficiency reached 95% within a two-week structured training period, beginning from a baseline of zero (the system did not previously exist). This 95% competency rate within fourteen days establishes an

empirically grounded implementation benchmark directly relevant to humanitarian organisations planning blockchain deployment, and challenges the prevailing assumption that technical complexity constitutes the binding constraint on adoption.

TABLE I
SUMMARY OF PERFORMANCE METRICS: BLOCKCHAIN FRAMEWORK VS.
CONVENTIONAL PROCUREMENT BASELINE

Metric	Blockchain Framework	Conventional Baseline	Improvement
Transaction latency	<50 ms per function	3–7 working days (manual)	>99× faster
Throughput at 100% load	398 TPS	4 TPS (collapse)	99× higher
System availability at peak	99.7%	28%	+71.7 pp
Tamper-detection accuracy	100%	~65%	+35 pp
Audit trail completeness	100%	~65%	+35 pp
Manual intervention	40% (post-impl.)	100% (baseline)	60% reduction
Processing error rate	20% (post-impl.)	100% (baseline)	80% reduction
Donor confidence	100% score	60% score	+40 pp
Security breaches (1,000 tests)	0	N/A	100% prevention
User competency (2 weeks)	95%	N/A (new system)	

D. Discussion

The 100% tamper-detection accuracy and complete audit trail completeness recorded in the simulation constitute more than a technical performance benchmark they represent an empirical demonstration that blockchain can resolve the foundational information integrity failure that Piotrowicz [6] identifies as the structural source of resource leakage in humanitarian procurement. Where conventional procurement systems provide approximately 65% audit completeness, the blockchain framework's cryptographic record-keeping eliminated the documentary gaps that facilitate fraud and enable deniability. This finding confirms and extends the theoretical arguments of Kshetri [4] and Müller-Bloch and Kranz [34], who established blockchain's transparency potential in commercial contexts, by demonstrating the same mechanism operating under humanitarian-specific constraints including multi-actor governance, low-bandwidth infrastructure simulation, and high-stakes accountability pressure. Critically, the 40% improvement in donor confidence metrics demonstrates that transparency improvements translate into a quantifiable organisational asset: enhanced trust that facilitates resource mobilisation, reduces audit overhead, and fulfils the accountability requirements of major humanitarian donors. This link between technical immutability and institutional trustworthiness connects the present study's findings to the

broader scholarship on algorithmic trust [32], affirming that blockchain's contribution to humanitarian governance is not merely operational but fundamentally political it reconfigures the trust architecture of multi-agency humanitarian response. This finding should, however, be interpreted precisely: blockchain's cryptographic architecture guarantees that once data is committed, it cannot be altered undetected it does not guarantee that the data entered was itself accurate, nor does it prevent fraud committed by authorised users acting within their granted permissions. Auditability, transparency, and immutability are therefore necessary but not sufficient conditions for fraud prevention; they must be paired with robust governance, access control, and input-validation controls of the kind described above to translate technical tamper-evidence into substantive fraud deterrence.

The linear scalability characteristics and sub-50 ms latency recorded under load are technically significant in themselves, but their humanitarian significance is best understood through the lens of System Dynamics Theory. Kochan et al. [19] argue that blockchain's immutability functions as a 'resilience buffer' by ensuring procurement data survives the infrastructure disruptions power outages, server failures, network interruptions that routinely accompany humanitarian emergencies. The present findings are consistent with this prediction: the 99.7% system availability and zero data loss recorded under simulated stress-testing conditions suggest that the distributed Polygon Layer-2 architecture can provide the resilience buffer that Kochan et al. [19] theorised, though this remains to be confirmed under genuine infrastructure stress. By reducing feedback loop delays from days to milliseconds, the framework should consistent with SDT's predictions dampen the demand amplification errors that Chowdhury et al. [31] identify as a primary driver of stockouts and over-procurement in crisis logistics. However, this finding must be qualified by an important limitation: the simulation environment, though designed to replicate humanitarian conditions, cannot fully capture the compounding effect of simultaneous power instability, intermittent internet connectivity, and operational stress that characterise actual field deployments. Future research employing field-deployed pilots with telemetry data will be necessary to confirm whether the linear scalability observed in simulation survives the entropy of genuine humanitarian operational environments.

The 95% user competency achievement within two weeks and the successful enforcement of RBAC across all actor categories provide empirical evidence for a claim that is central to the HOT-Fit model but has not previously been tested in humanitarian blockchain contexts: that the alignment between human skills, organisational structure, and system design is achievable within operationally realistic training timescales. This finding directly addresses the 'socio-technical blind spot' identified in the research gap analysis the systematic underestimation of human factors in blockchain adoption frameworks that leads implementers to overestimate technical barriers and underestimate organisational ones. The evidence that parallel system operation maintaining both the

blockchain and the legacy procurement system simultaneously during the transition period was the most effective mechanism for managing change resistance has practical implications that extend beyond the IRC case: it suggests that phased implementation strategies that do not require organisations to abandon established workflows before alternatives are validated are more likely to succeed than 'big bang' replacement approaches. This finding connects the specific implementation experience documented here to the broader innovation diffusion literature, empirically grounding Rogers' (2003) theoretical claim that trialability the degree to which a technology can be experimented with before full adoption is a critical determinant of diffusion speed.

E. Sustainable Development and Policy Implications

The study's results carry implications that extend beyond operational procurement management to global development governance. Sobiecki and Kotlarska [35] argue that blockchain constitutes a critical enabler of Sustainable Development Goal compliance by enforcing institutional accountability in contexts where conventional oversight mechanisms have failed. The present findings are consistent with this claim in the humanitarian procurement context: the framework's cryptographically verified audit trails, immutable record-keeping, and automated payment execution provide the 'trust-by-design' governance architecture that SDG 16 (Peace, Justice, and Strong Institutions) requires. By ensuring that every procurement Naira is traceable to a specific supplier action or beneficiary outcome, the framework transforms humanitarian accountability from a retrospective, paper-based exercise into a real-time, mathematically verifiable governance function. This transformation has direct policy implications: for humanitarian agencies, it creates the infrastructure for evidence-based procurement reform; for institutional donors, it provides the real-time financial oversight that increasingly conditions large-grant disbursements; and for host governments, it offers a scalable model for extending transparent procurement governance beyond the humanitarian sector into wider public administration. More specifically, the framework's audit-trail completeness and tamper-detection results speak most directly to SDG target 16.5 (substantially reduce corruption and bribery) and 16.6 (develop effective, accountable, and transparent institutions), while the interoperability standards recommended in Section 5.1 speak to SDG target 17.16 (strengthen multi-stakeholder partnerships).

F. Limitations

Several limitations qualify the interpretation of the results. First, evaluation was conducted in a simulated environment, which cannot replicate the full complexity of field conditions including unreliable power supply, intermittent connectivity, and the political pressures that routinely distort procurement decision-making in conflict-affected settings; the framework has not yet been validated

against live operational data or deployed as a field pilot. Second, the IRC case study was informed by publicly available documentation rather than internal transactional access, and limits generalisability: organisations with different operational cultures, technical capacities, or stakeholder configurations may encounter adoption barriers not encountered here. Third, the thirty-day testing period does not allow assessment of long-term sustainability, user adoption drift, or the system's behaviour under the extreme and irregular transaction volumes that characterise major humanitarian emergency responses. Fourth, the study does not examine cross-organisational interoperability the mechanisms by which multiple humanitarian agencies might connect their blockchain procurement systems during joint operations. Fifth, the performance comparison used Ganache, an Ethereum development environment, as the baseline for the full hybrid architecture; Ganache is not fully representative of Hyperledger Fabric's consensus behaviour, and the evaluation did not include a conventional centralised database system as an additional non-blockchain baseline. Sixth, throughput and availability were tested across ten load increments at a fixed concurrency profile rather than across varying numbers of concurrent users, peer nodes, and network-latency conditions, and no component-level ablation isolating the individual contribution of Hyperledger Fabric, Polygon Layer-2, and smart contract automation to overall performance was conducted. Seventh, cost efficiency was assessed qualitatively rather than through a transparent, replicable breakdown of Ethereum/Polygon gas fees and Hyperledger Fabric infrastructure costs. Eighth, the tamper-detection and security-breach scenarios were designed and executed by the research team rather than by independent adversarial testers, and the donor-confidence metric was collected from a simulated respondent panel rather than IRC's actual donor base; the size, composition, and instrument used for this panel are reported in Section 3.3, and a larger, independently administered survey would be required to support generalisable claims about donor perception. These limitations, several of which concern the depth and independence of the empirical evaluation rather than only its field-realism, define the primary agenda for future research.

V. CONCLUSION

This study set out to design and evaluate, through controlled simulation, a blockchain framework for humanitarian procurement management; the results provide simulation-based evidence that the objective is achievable, while stopping short of field-validated proof. The hybrid architecture integrating Hyperledger Fabric permissioned workflows, Ethereum public auditability, and Polygon Layer-2 scaling produced measurable improvements, within the simulated test environment, across four evaluation dimensions: transparency (100% audit completeness and tamper-detection accuracy against the scripted tampering scenarios tested), efficiency (60% reduction in manual intervention, >99x improvement in transaction latency

relative to the manual baseline), scalability (near-linear performance across the load levels tested), and trust (40% improvement in donor confidence on a simulated respondent panel, zero security breaches across the scenarios tested). These results support the study's central argument that blockchain's technical properties are well suited to addressing the structural pathologies of humanitarian procurement: the information asymmetry, the accountability gaps, and the inter-organisational trust deficits that conventional systems have struggled to address though confirming this suitability under live operational conditions remains the necessary next step.

Beyond the technical findings, the study demonstrates that blockchain adoption in resource-constrained humanitarian contexts is organisationally achievable within realistic implementation timescales, provided that phased transition strategies, structured capacity building, and parallel system operation are deployed as change management tools. The 95% user competency achieved within two weeks establishes an empirical benchmark that directly challenges the prevailing assumption that technical complexity is the binding constraint on humanitarian blockchain adoption. The binding constraint, the evidence suggests, is not technical capability but governance architecture: who controls the system, who can verify its outputs, and who bears accountability when it fails. The present framework addresses all three through its RBAC, immutable audit trail, and smart contract automation design.

The study's contributions to scholarship are fourfold. It provides the first simulation-validated, scalable blockchain procurement framework designed for humanitarian operations, pending field validation. It advances blockchain adoption theory by demonstrating the joint determination of adoption outcomes by architectural, training, and transition management decisions. It extends System Dynamics theory into the humanitarian blockchain domain by providing simulation-based evidence for the resilience-buffer mechanism. And it establishes the conceptual link between blockchain-enabled procurement transparency and the institutional accountability requirements of SDG 16.

A. Recommendations

Based on the foregoing findings, the following recommendations are addressed to humanitarian agencies, implementing organisations, and policymakers:

1. Humanitarian organisations should treat blockchain-based procurement as a strategic governance investment rather than a technical upgrade. The 40% improvement in donor confidence and the complete elimination of successful tampering attempts documented here indicate that the primary return on this investment is institutional enhanced trust, improved accountability, and stronger regulatory compliance rather than purely operational.

2. Implementation should follow a phased approach. The evidence from this study confirms that parallel operation maintaining legacy and blockchain systems simultaneously during transition is the most effective mechanism for managing organisational resistance and ensuring operational

continuity. A minimum six-month parallel operation period is recommended before full migration.

3. Capacity building must be treated as an integral component of the technical implementation, not an adjunct to it. The two-week training-to-competency timeline achieved in this study demonstrates that the adoption barrier is surmountable, but only with structured, hands-on training curricula that emphasise practical operation over theoretical blockchain literacy.

4. Humanitarian agencies and institutional donors should collaborate on the development of interoperability standards that would enable blockchain procurement systems operated by different agencies to exchange verified data during joint operations. The hybrid architecture developed in this study provides a technical foundation for such standards development.

5. Future research should conduct longitudinal, field-deployed comparative evaluations across multiple humanitarian organisations and geographies, with particular attention to the performance of blockchain systems under the simultaneous infrastructure stresses power instability, bandwidth interruption, and political disruption that characterise major humanitarian emergencies. Integration with complementary technologies artificial intelligence for predictive fraud detection and Internet of Things for real-time physical supply chain monitoring represents the next frontier for empirical investigation.

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