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Empowering Global Supply Chains Through Blockchain-Based Platforms: New Evidence from the Coffee Industry

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Abstract: Global supply chains, especially in commodity trading, are plagued by fragmentation, lack of transparency, and trust deficits among participants. These issues lead to inefficiencies, increased costs, and an over-reliance on intermediaries. The present Communication describes a blockchain-based platform that leverages Self-Sovereign Identity (SSI) and Verifiable Credentials (VCs) to address these challenges in supply chain management. Developed in collaboration with coffee industry stakeholders, our approach proposes a platform with an integrated marketplace for seller discovery, enables precise order definition with detailed terms and conditions, and actively guides both buyers and sellers throughout the shipping process, managing financial guarantees and ensuring a secure transaction flow. The platform is compatible with both traditional banking infrastructure and modern crypto-based systems, enabling seamless financial transactions. In cases where disputes arise, we empower users to easily collect all communications and documents to present to legal authorities, expediting the resolution process. The platform is implemented using the Internet Computer Protocol (ICP) for secure, on-chain storage and application hosting, and is integrated with the Ethereum blockchain to leverage its extensive decentralized finance (DeFi) ecosystem, significant liquidity, and robust stablecoin infrastructure, thereby facilitating secure financial transactions. Moreover, we introduce an SSI-based authentication and authorization framework that spans across the entire platform, including both the Ethereum Virtual Machine (EVM) and Internet Computer Protocol (ICP), enabling unified role-based access control through verifiable credentials. A value-added of the present Communication, the framework is demonstrated by means of a detailed case study in the coffee industry, highlighting the technical challenges addressed during implementation. While quantitative efficiency metrics will be established through upcoming real-world testing with industry partners, the platform's design aims to streamline operations by reducing intermediary dependencies and automating key processes. Finally, the Communication provides insights into its adaptability to other industries facing comparable supply chain challenges, presenting an approach focused on enhancing trust and reducing reliance on intermediaries.

Keywords: blockchain-based platform; Ethereum; global supply chains; internet computer protocol (ICP); peer-to-peer negotiation; self-sovereign identity (SSI); verifiable credential (VC)

JEL Classification: E44; O32; O33

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1. Introduction

The present Communication aims at exploring an emerging topic that consists of potential blockchain-related solutions to foster global supply chains. In fact, after the COVID-19 pandemic and lockdowns, which have highlighted the precariousness of global value chains [1,2], there is an increasing need to find solutions based on new technologies to ensure the efficient functioning of the global supply chain even in economically uncertain times. Furthermore, while traditionally associated with cryptocurrencies, the blockchain, described as 'an open, distributed ledger that can record transactions between two parties efficiently and in a verifiable and permanent way' [3], also offers a versatile foundation to address the challenges of trust, coordination, and data management in various sectors.

The following Communication, therefore, contextualizes the topic of blockchain-related solutions for the global supply chain and provides a practical example to manage the transaction flows of one of the most highly demanded commodities worldwide, namely coffee and coffee-related products.

1.1. Global Supply Chain, Blockchain-Based Solutions and the Coffee Industry: A Literature Review

The scientific community began rather recently to analyze the potential use of blockchain to cope with the challenges posed by the global supply chain in an interconnected world economy. For example, Roy [4] highlights that 'Blockchain technology has found significant success in all fields, including the banking and finance sector, health, manufacturing, transportation, and many others', while Tiwari et al. [5] find that blockchain is particularly helpful whenever third-party logistics is involved. In fact, as Liu et al. [6] summed up, 'Blockchain technology can be used to record real data at various nodes in the supply chain and can achieve timely data sharing and full traceability of the entire life cycle of products in the supply chain'. The impact on 'supply chain capabilities and supply chain flexibility of firms' is also 'notable' [7]. In particular, its 'transparency' [8] and 'traceability' [9] are features that are particularly appreciated by its users.

The growing importance of blockchain solutions for supply chains mirrors the increasing importance of international trade in the global economy. As shown in Figure 1, since 1970, global imports and exports of goods and services have more than doubled as a percentage of the global GDP, growing from less than 13% to nearly 30% by 2023. This dramatic increase reflects the deepening interconnectedness of the global economy, where almost one-third of global GDP now depends on smooth-functioning supply chains [10]. The concept of the 'spatial division of labor', which implies the 'organization of certain production tasks in particular regions and geographical areas and/or concentration of certain economic sectors in particular' [11], has led to the creation of complex trade dependency networks. The COVID-19 pandemic starkly demonstrated the vulnerability of these networks, contributing to an unprecedented 2.9% decrease in global GDP in 2020—a decline that exceeded even the 1.4% drop during the global financial crisis of 2009 [12].

Multiple empirical studies indicate that blockchain promotes transparency, traceability and operational integrity, and can also improve product quality, optimize production costs, and reduce fraud [13–16]. In agriculture, for example, a hypothetical soybean trade from Jamestown (North Dakota) to China could yield savings of 2.3 cents per bushel—with a reference price of USD 3.56—while cutting the total shipping time by roughly 41% [17]. In particular, value-at-risk estimates show a further reduction of 2.6 cents per bushel. Beyond these direct operational gains, industry research suggests that blockchain helps minimize administrative overhead, fosters new business models, and supports revenue growth [18]. However, most of these projections are derived from early-stage implementations, leaving the full quantitative impact on supply chain efficiency and financial performance to be fully substantiated as technology matures [19].

Given the opportunities for technological advance embedded in the blockchain, the present Communication further assesses a potential additional solution to successfully cope with global supply chains and avoid unexpected disruptions.

Figure 1. Global imports and exports of goods and services (% of global GDP), 1970–2023; Own representation based on The World Bank [20,21].

If we further restrict the field of analysis to the coffee industry, which is interesting because it involves producing countries often particularly geographically far from the nations of destination, blockchain-based solutions have been identified in the economic literature to 'promote sustainability [. . .] through increased traceability and transparency' [22] and to 'support the ecological embeddedness of the coffee supply chain' [23]. Moreover, 'when applied to the coffee supply chain, blockchain allows everyone to know where their coffee came from and the conditions under which it was shipped and produced' [24].

As highlighted in Table 1, the top 10 of all countries producing coffee and coffee-related products belongs to low-income (Ethiopia, Uganda) and lower-middle-income economies (Honduras, India, Vietnam), while the remaining countries (Brazil, Colombia, Indonesia) are upper-middle-income nations [25]. Figure 2 further confirms the logistic complexity and economic interconnectedness of the trade flows involving coffee and coffee-related products.

Table 1. Coffee industry and top-producing countries *.

	% of Production	Total Production (2023/2024, 60 Kg Bags)
Brazil	39%	66.3 milion
Vietnam	17%	29.1 milion
Colombia	7%	12.2 milion
Ethiopia	5%	8.35 milion
Indonesia	5%	8.15 milion

Table 1. *Cont.*

	% of Production	Total Production (2023/2024, 60 Kg Bags)
Uganda	4%	6.4 milion
India	4%	6.1 milion
Honduras	3%	5.3 milion
Peru	2%	4 milion
Mexico	2%	3.87 milion

* Source: [26].

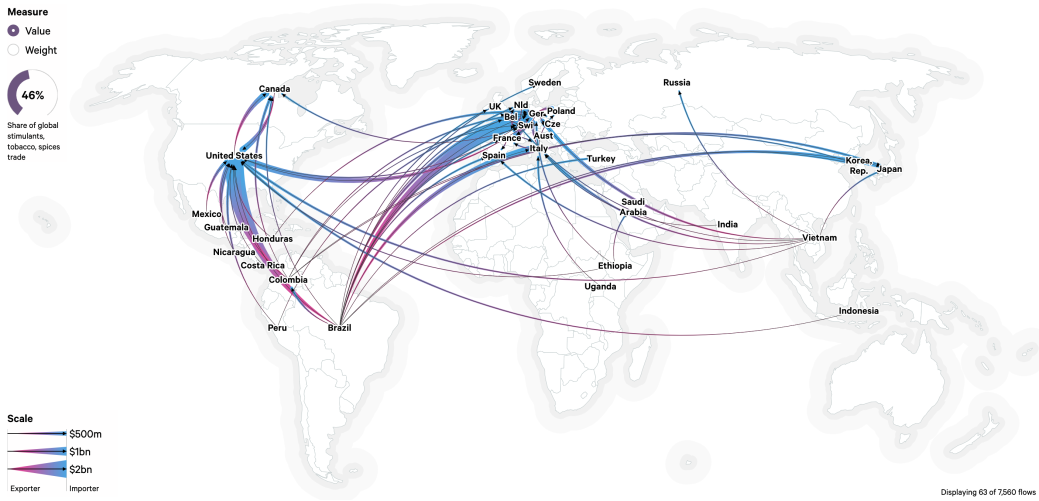

Figure 2. Value of trade flows of coffee-related products [27] (husks and skins; (not) roasted; (not) decaffeinated).

At the same time, the fact that these countries ranking the highest in the production of coffee and coffee-related products might be in particular need of diffuse access to non-traditional (i.e., non-banking) solutions due to having an account ownership rate below the global average (apart from Brazil and India) (Table 2) is another concrete explanation for the potential relevance of blockchain technology. The latter is indirectly confirmed by the share of the population in these nations—this being significantly higher than that in countries like Germany (12%) or the United States (15%) in 2022—that has been confirmed to own and/or use cryptocurrencies, which, notably, can be attributed to blockchain-related technological advances. Clearly enough, 'implementing blockchain throughout the coffee industry requires collaboration and industry-wide adoption, as a fragmented approach could limit its effectiveness' [28].

In the realm of global coffee trading, the application of cryptocurrencies extends beyond digital assets to function as effective trade currencies and contract facilitators. Using the intrinsic qualities of blockchain technology, cryptocurrencies enable direct peer-to-peer financial exchanges that bypass traditional banking intermediaries, significantly reducing transaction fees and improving the speed of cross-border payments [29]. This shift not only democratizes financial access for coffee producers, particularly in regions underserved by traditional banks [30], but also fosters greater economic stability by shielding them from local currency fluctuations [31]. Furthermore, the integration of smart contracts automates and enforces trade agreements transparently, ensuring that payments are released only after verified delivery and adherence to agreed standards, minimizing disputes and administrative overhead [32].

Table 2. Account ownership (% age 15+) and share of respondents having indicated they either owned or used cryptocurrencies [20,26,33].

	Account Ownership (% Age 15+)					Share of Respondents Having Indicated They Either Owned or Used Cryptocurrencies
	2011	**2014**	**2017**	**2021**	**2022**	**Latest Available Data (2021–2023)**
Brazil	55.9%	68.1%	70.0%	84.0%	-	7.8%
Vietnam	21.4%	31.0%	30.8%	-	56.3%	18.7%
Colombia	30.4%	39.0%	45.8%	59.7%	-	4.8%
Ethiopia	-	21.8%	34.8%	-	46.5%	1.8%
Indonesia	19.6%	36.1%	48.9%	51.8%	-	4.5%
Uganda	20.5%	44.5%	59.2%	65.9%	-	1.2%
India	35.2%	53.1%	79.9%	77.5%	-	7.1
Honduras	20.5%	31.5%	45.3%	37.9%	-	2.3%
Peru	20.5%	29.0%	42.6%	57.5%	-	3.7%
Mexico	27.4%	39.1%	36.9%	-	49.0%	6.6%
World	50.6%	61.9%	68.5%	76.2%	-	6.8%

The critical need for such technological improvements in the coffee supply chain is underscored by the observations of Alamsyah et al. [34], who note the difficulty consumers face in verifying coffee quality relative to price, due to the complexity and opacity of the supply chain. This challenge points to a broader issue of maintaining fair production standards and mitigating the risk of disruptions. Addressing these concerns, global IT players, such as IBM, have begun to implement blockchain solutions to create more efficient supply chains that improve the transparency and reliability of the coffee trade, contributing to a better ecosystem for the global coffee farming community [35]. These technological advances are pivotal in transforming traditional supply chain operations into more secure, efficient, and equitable systems, thereby improving the overall integrity of the coffee market.

1.2. Added Value and Contribution to the Economic Literature

The contribution of the present Communication to the existing economic literature encompasses several key aspects:

- Analysis of coffee supply chain processes: The research examines key challenges in the coffee supply chain based on the current literature and industry standards:
  - Documentation requirements;
  - Trust barriers between distant trading partners;
  - Manual processing inefficiencies;
  - Reliance on intermediaries.
- Technical solutions framework: This Communication develops practical, innovative solutions that directly address identified challenges:
  - Implementation of Self-Sovereign Identity (SSI) for secure participant authentication;
  - Smart contract automation for financial guarantees and compliance;
  - Decentralized documentation management;
  - Integration of traditional and blockchain-based payment systems;
  - Streamlined dispute resolution mechanisms.
- Industry-specific research contribution: This research advances the emerging stream of research exploring blockchain-based solutions in specific economic sectors, as discussed in Section 1.1, with a particular focus on the following:
  - Real-world implementation considerations;

   - Technical architecture specifications;
   - Cost–benefit analysis of the adoption.
- Practical implementation model: The framework specifically designed for the coffee industry carries out the following:
   - Addresses the challenges of coffee supply chains;
   - Considers the needs of both small producers and large traders;
   - Maintains compatibility with existing trading practices;
   - Offers scalability for future industry adoption.

This multifaceted contribution aims to enhance the efficiency and reliability of global trade operations. The proposed solutions, which combine technological innovation with practical applicability, contribute to building a more efficient, resilient, and flexible global economy [36–38].

2. Materials and Methods

The global coffee supply chain faces challenges in efficiency, transparency, and trust. We propose a platform that uses blockchain technology and self-sovereign identity (SSI) to address these issues.

Transparency and traceability problems arise from fragmentation and the absence of a unified tracking system, which obscures the origins of coffee beans and makes it difficult to verify authenticity, quality and sustainability [39]. This can potentially lead to frauds and a reduction in consumer trust. By recording every transaction, including all the documents and the money flows, on blockchain's immutable ledger, we enable participants to trace products from farm to cup, ensuring authenticity and compliance with standards.

Trust deficits and reliance on intermediaries are due to trust barriers caused by distance and cultural differences, which add costs and complexities, ultimately reducing profits and increasing prices [40]. Implementing SSI and Verifiable Credentials allows secure, authenticated identities. Trusted credentials verify legitimacy, enabling direct peer-to-peer transactions without intermediaries. Smart contracts automate negotiations and enforce agreements, improving efficiency.

Inefficient manual processes, such as paper documentation, cause errors and delays that slow down the supply chain [41,42]. By digitizing all documentation on the blockchain and implementing automated workflows, errors are minimized, and transactions are accelerated. Digital records improve efficiency and provide an auditable trail [43]. Dispute resolution is often hindered by the absence of transparent records: immutable blockchain records address this issue by providing a reliable and transparent basis for resolution. Authorized arbitrators can also access the necessary documentation, allowing for swift and equitable dispute resolution [44].

2.1. Coffee Trading Process Overview

The description of the trading process presented in this section is based on direct collaboration and structured interviews with key industry partners, specifically Alcomex SA, a Swiss-based coffee trading company, and their Brazilian partner JC Grossi & Fhilos. These companies have provided detailed information on their operational practices and requirements, ensuring that our understanding of the coffee trading process reflects current industry practices in the Brazil–Switzerland trade corridor. The information gathered through this direct engagement aligns and enriches the existing academic literature [45,46] on coffee trading processes. International coffee trading represents a complex ecosystem of transactions that involve multiple stakeholders on different continents. The process encompasses several structured phases, each critical to ensuring successful trade execution while managing the risks inherent in cross-border commodity transactions. We hereby review them in full detail.

2.1.1. Offer Publication and Discovery

The initial phase of coffee trading centers on market discovery, where sellers present their offerings to potential buyers. This process traditionally occurs through established channels, including trading houses, brokers, and industry-specific marketplaces [47]. Sellers, typically exporters or producer cooperatives, must provide comprehensive product information [47] including the following:

- Coffee origin and variety specification;
- Quality parameters and certifications;
- Available volume and minimum lot sizes;
- Indicative pricing structure;
- Possible delivery windows.

Figure 3 illustrates the typical flow of the coffee trading discovery process, highlighting the various channels through which buyers and sellers interact in the marketplace.

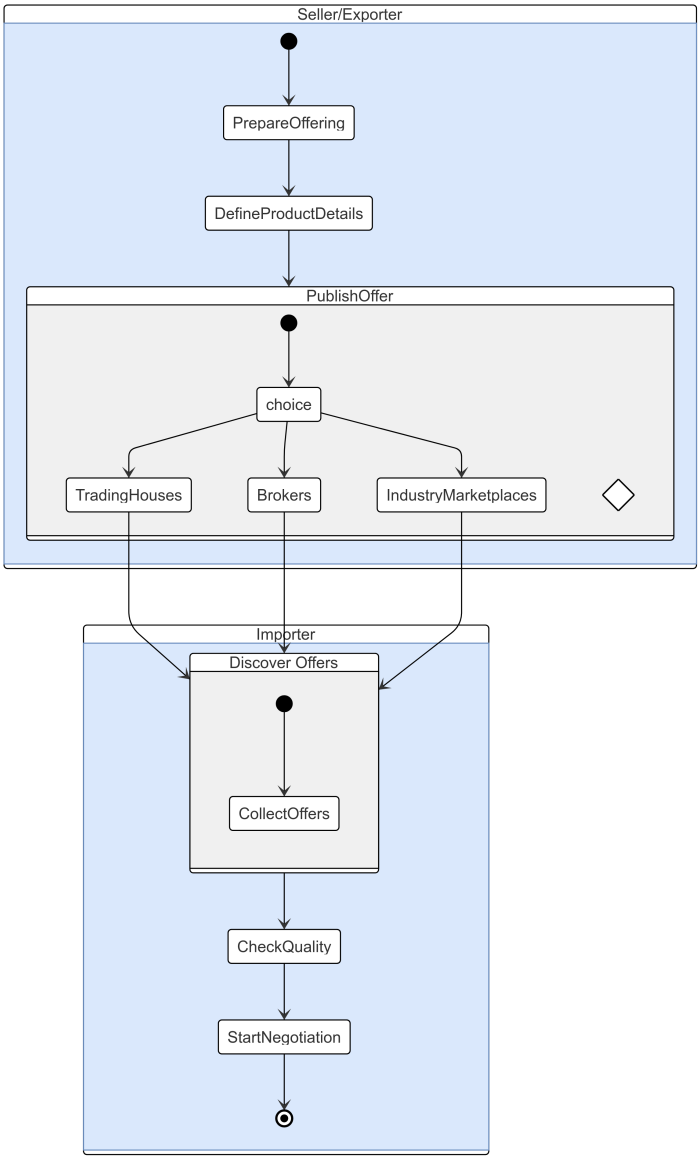

Figure 3. Coffee trading discovery process flowchart.

This discovery phase is crucial as it establishes the foundation for potential trading relationships and preliminary quality expectations. Buyers evaluate these offerings against their specific requirements, considering factors such as their blending needs, risk tolerance, and logistical capabilities.

2.1.2. Contract Negotiation

Upon establishing initial interest, parties enter into a structured negotiation process that involves multiple stages of increasing commitment. This phase is particularly critical, as it defines the legal and operational framework for the entire transaction. The coffee trading process is structured in three sequential phases depicted in Figures 4–6: Figure 4 shows the order definition phase where key terms are negotiated, Figure 5 illustrates the contract signature phase following the ESCC framework, and Figure 6 outlines the contract fulfillment phase with its documentation and payment execution requirements. Each stage necessitates specific documentation to proceed, creating a structured yet documentation-intensive workflow. Although this approach ensures proper risk management, it also introduces multiple points where operational efficiency could be improved through technological innovation.

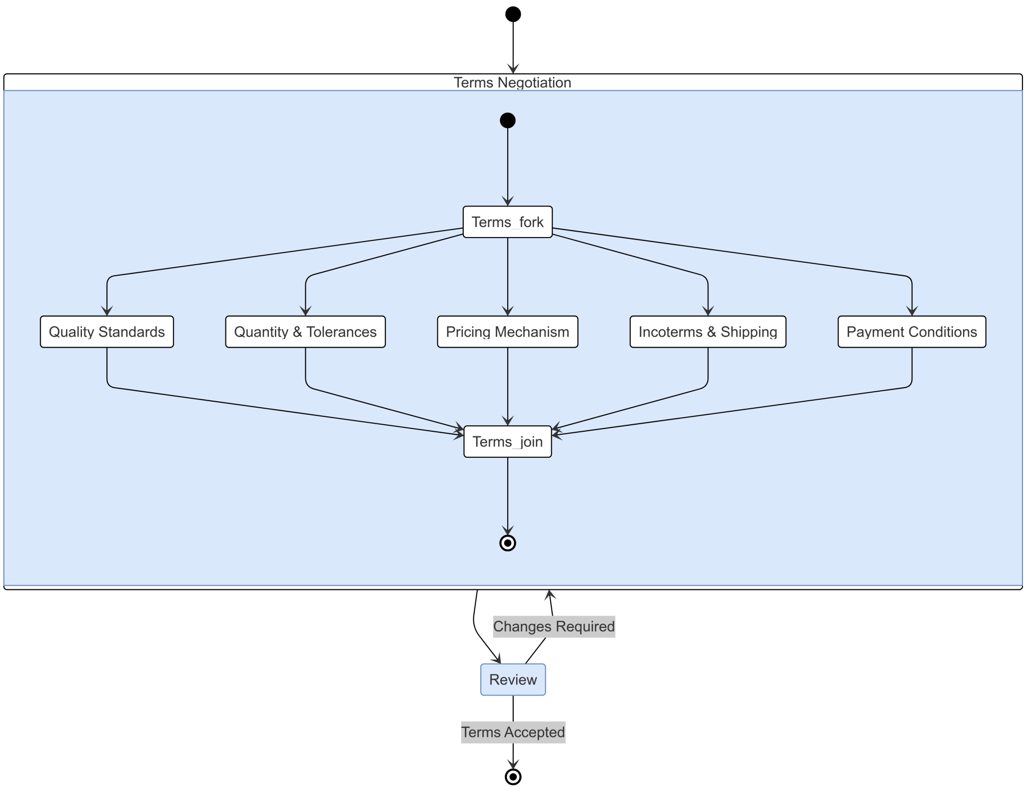

Figure 4. Order definition phase.

- Order definition: During this stage, parties must achieve alignment on fundamental transaction parameters [47]:
  - Precise quality specifications and standards;
  - Quantity commitments and tolerances;
  - Pricing mechanisms (fixed or differential);
  - Delivery terms and shipping windows;
  - Payment conditions and security requirements.

These elements require careful consideration, as they directly impact both parties' risk exposure and operational requirements. The selection of appropriate International

Commercial Terms Incoterms® proves particularly crucial as it delineates the transfer of costs, risks, and responsibilities between parties.

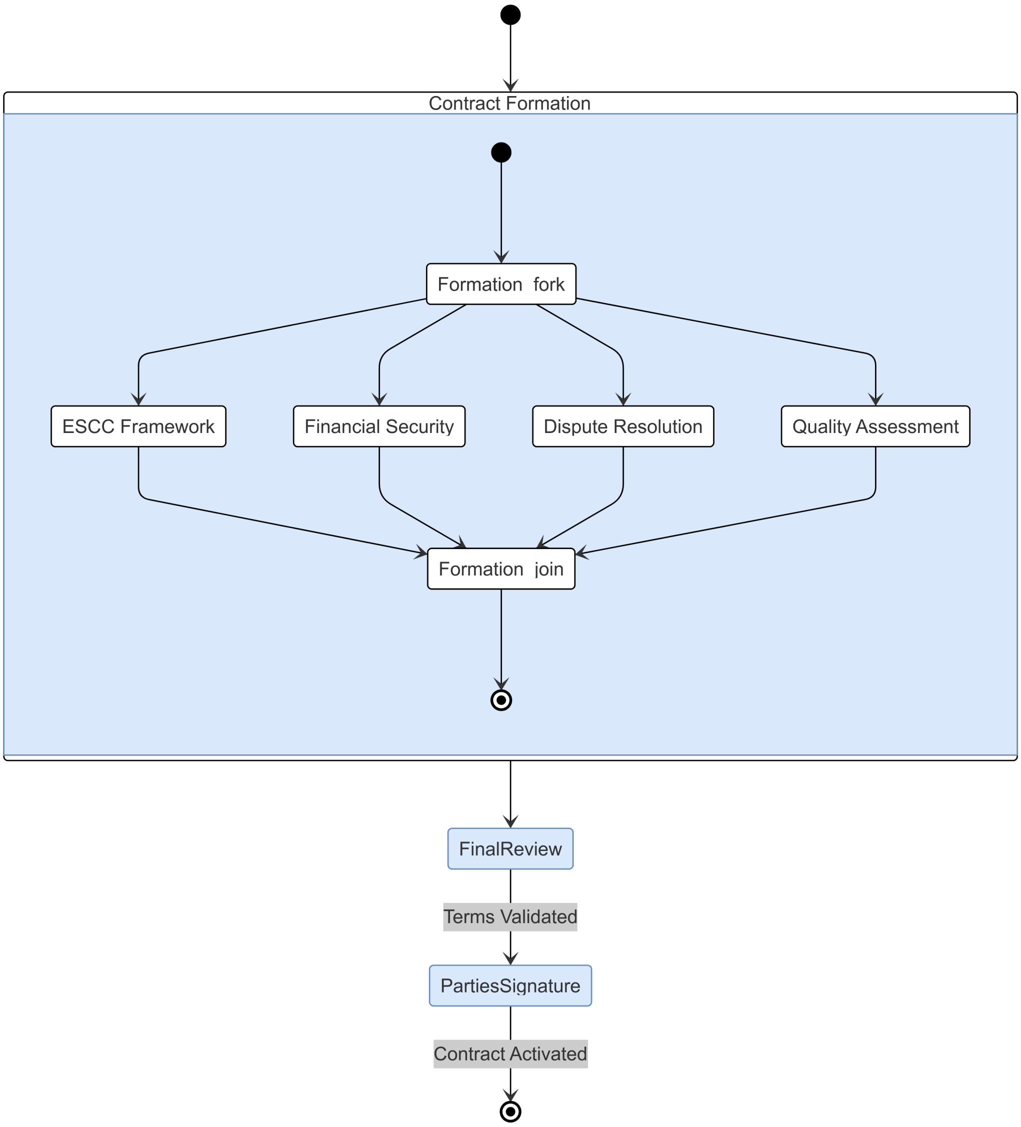

Figure 5. Contract signature phase.

- Order signature: Contract formation represents a critical milestone where parties formalize their commitments through legally binding agreements. Standard industry contracts, such as the European Standard Contract for Coffee (ESCC), provide the framework for these agreements [47], requiring the following:
  - Mutual agreement on all terms;
  - Financial security arrangements;
  - Dispute resolution mechanisms;
  - Quality assessment protocols.
- Contract fulfilment: The execution phase involves coordinated actions between multiple stakeholders to ensure the proper documentation and physical movement of goods. Essential documentation [47] includes the following:
  - Certificates of origin and quality;
  - Shipping documentation (bills of lading);
  - Insurance certificates;
  - Commercial documentation.

This documentation serves multiple purposes beyond mere compliance, as it facilitates payment processing, customs clearance, and quality verification.

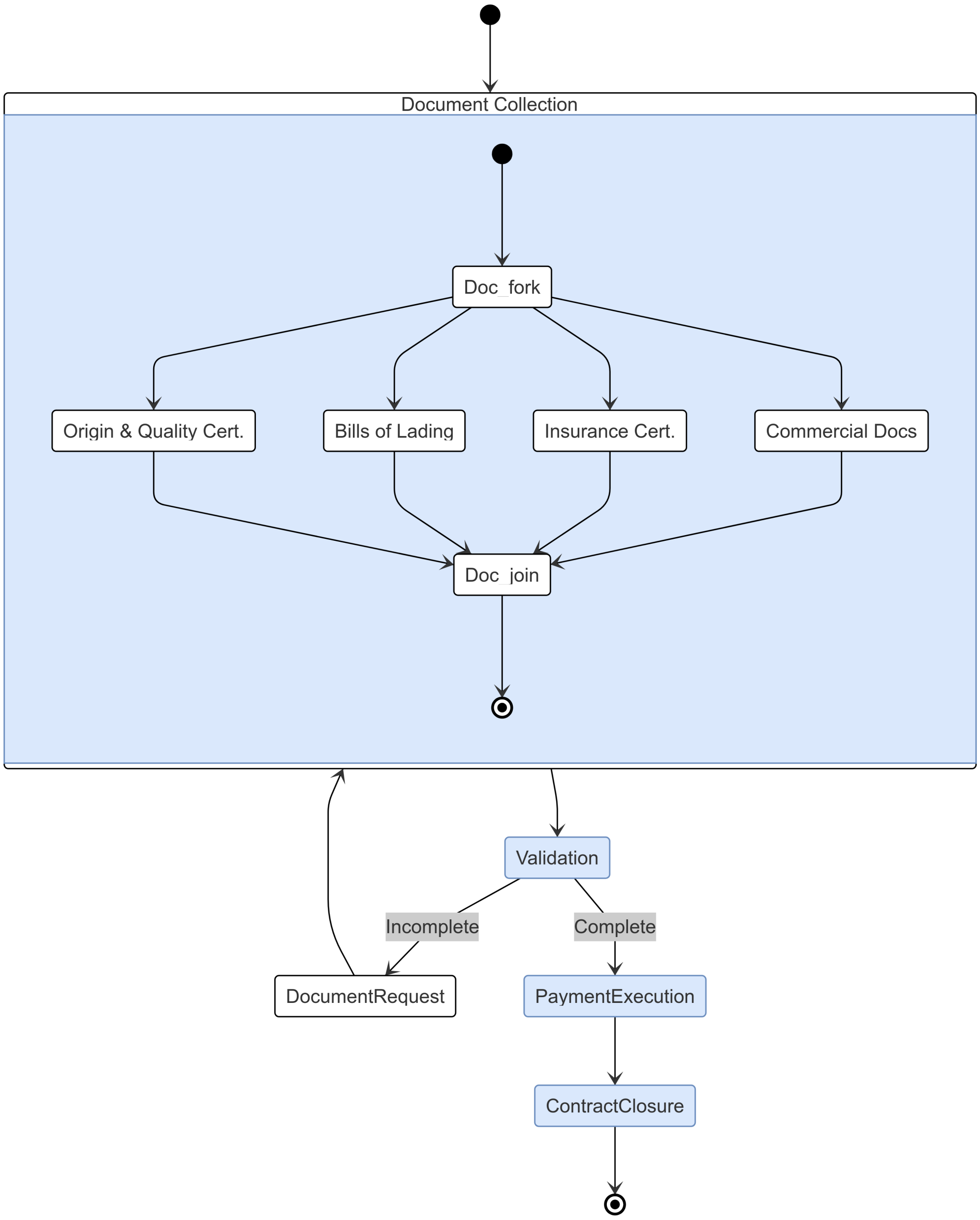

Figure 6. Contract fulfilment phase.

2.1.3. Dispute Management

The coffee industry has developed sophisticated mechanisms to handle disputes that may arise throughout the trading process. These mechanisms recognize the inherent challenges of cross-border trade and provide structured approaches to resolution. Figures 7–9 illustrate the structured approach to dispute resolution in coffee trading. More specifically, Figure 7 shows the initial phase of issue identification and classification, where problems are classified based on their nature (quality or other issues) and the corresponding time windows are assigned according to the ESCC guidelines [47]. Furthermore, Figure 8 details the evidence collection process, emphasizing the parallel collection of historical transaction data, supporting documentation, and communication records, all crucial elements for building a comprehensive claim. Finally, Figure 9 describes the resolution pathways, demonstrating how disputes can be resolved through amicable settlement or formal arbitration, the latter requiring detailed review of documents and expert analysis. This systematic approach ensures that all disputes are handled efficiently while maintaining transparency and fairness throughout the process.

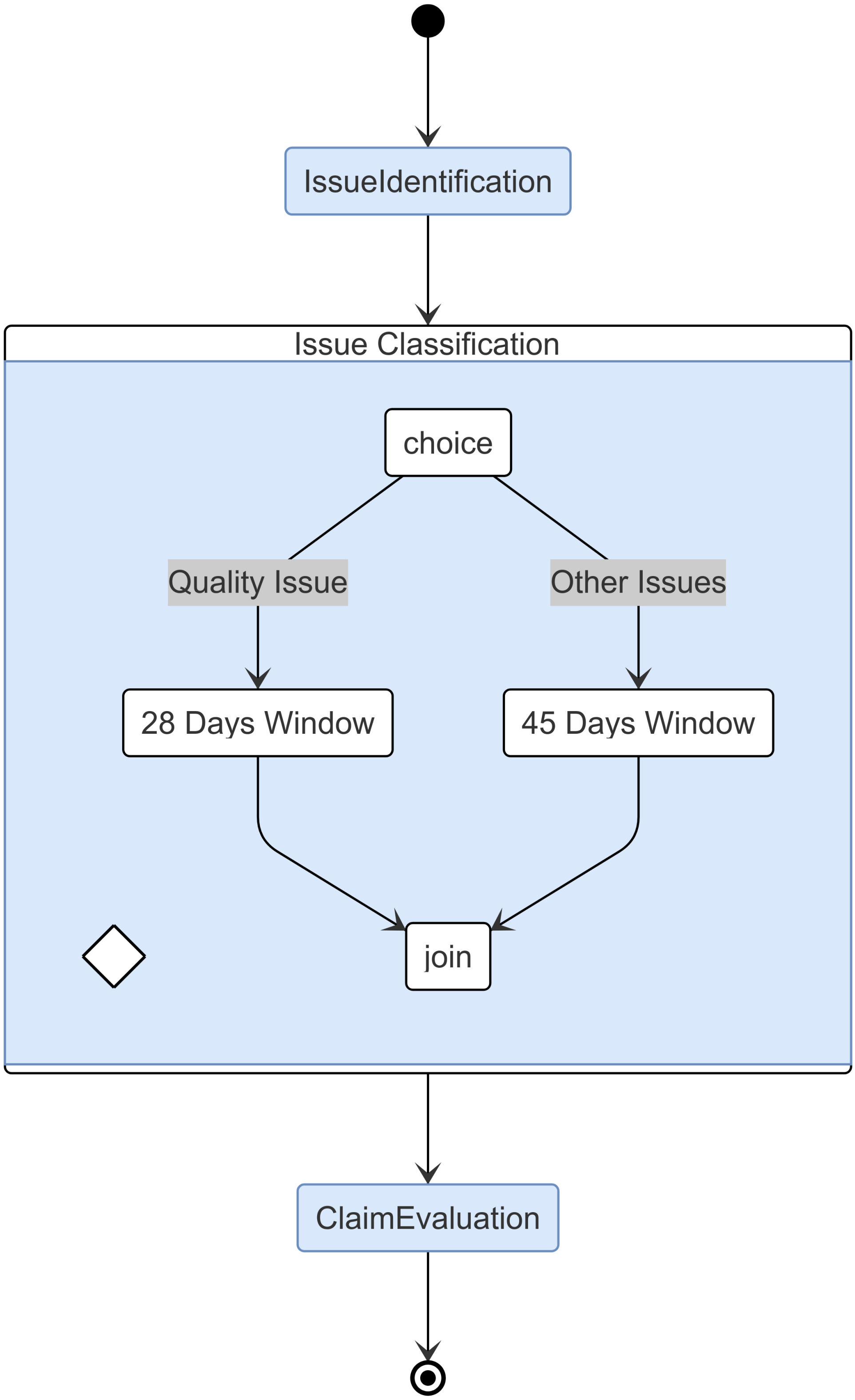

Figure 7. Issue identification.

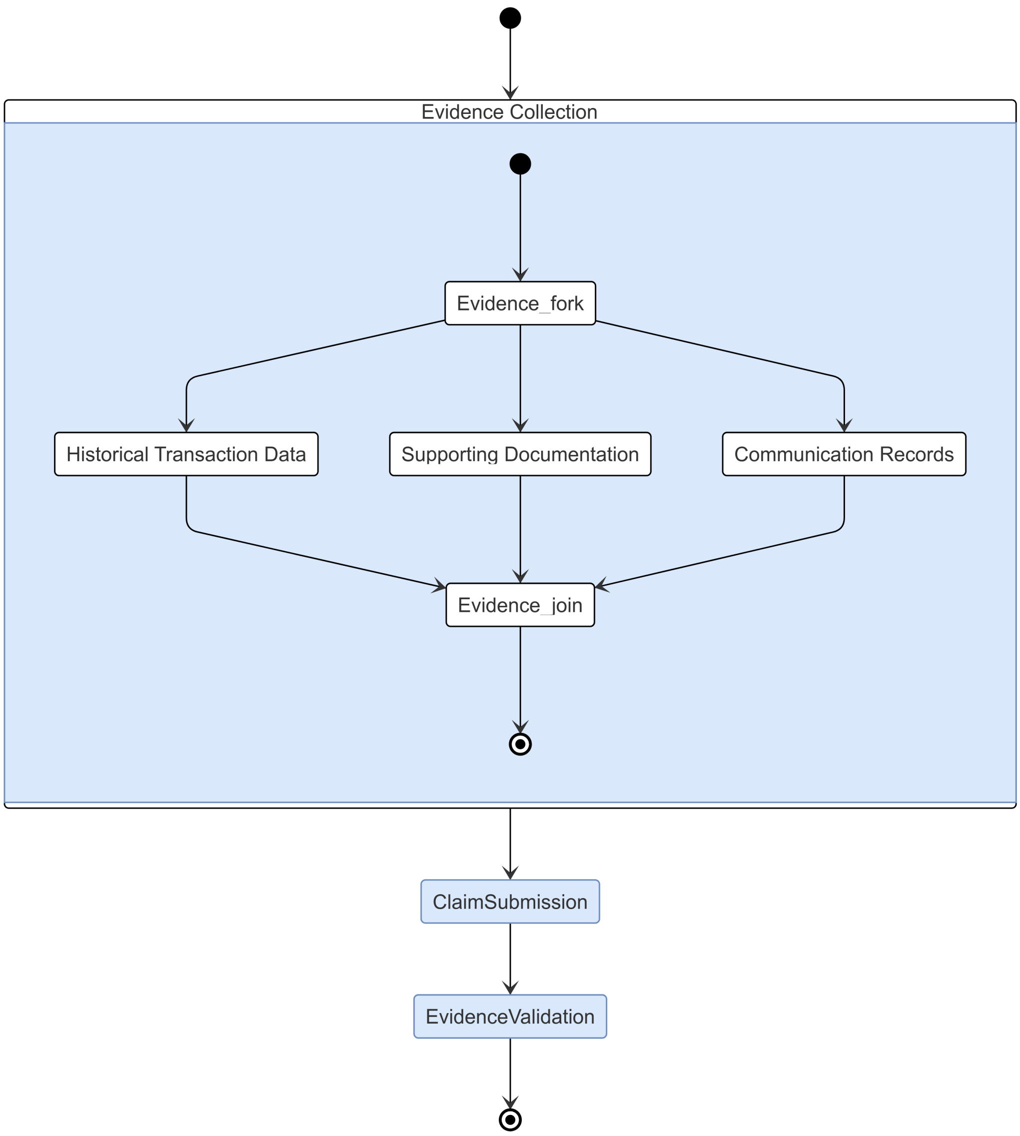

Figure 8. Evidence collection.

Common areas of dispute include the following:

- Quality variations from contracted specifications;
- Weight discrepancies beyond allowed tolerances;
- Shipping delays and logistics issues;
- Documentation discrepancies.

Industry standards establish specific time frames for claim submission, typically allowing 28 days for quality-related claims and 45 days for other issues. The resolution process often involves independent quality analysis and arbitration procedures, following established protocols under standard contracts like the ESCC [47].

This traditional trading framework, while comprehensive in its risk management approach, faces several operational challenges. The complex documentation requirements and sequential nature of document verification and approval processes can lead to delays and increased costs [48]. Moreover, the potential for documentation discrepancies or losses creates additional risks for trading parties, particularly in letter of credit transactions where strict compliance is required [49]. These challenges, coupled with the need for greater trust, transparency, and efficiency in the entire flow, highlight opportunities for technological innovation in the coffee trading ecosystem while maintaining the robust risk management framework that the industry requires.

The described processes have been empirically validated through collaboration with industry stakeholders. The practical insights gained from Alcomex SA and JC Grossi & Fhilos have confirmed the academic findings while providing additional context specific to the Brazil–Switzerland trade corridor. This combination of theoretical framework and practical validation ensures a comprehensive and accurate representation of contemporary coffee trading processes.

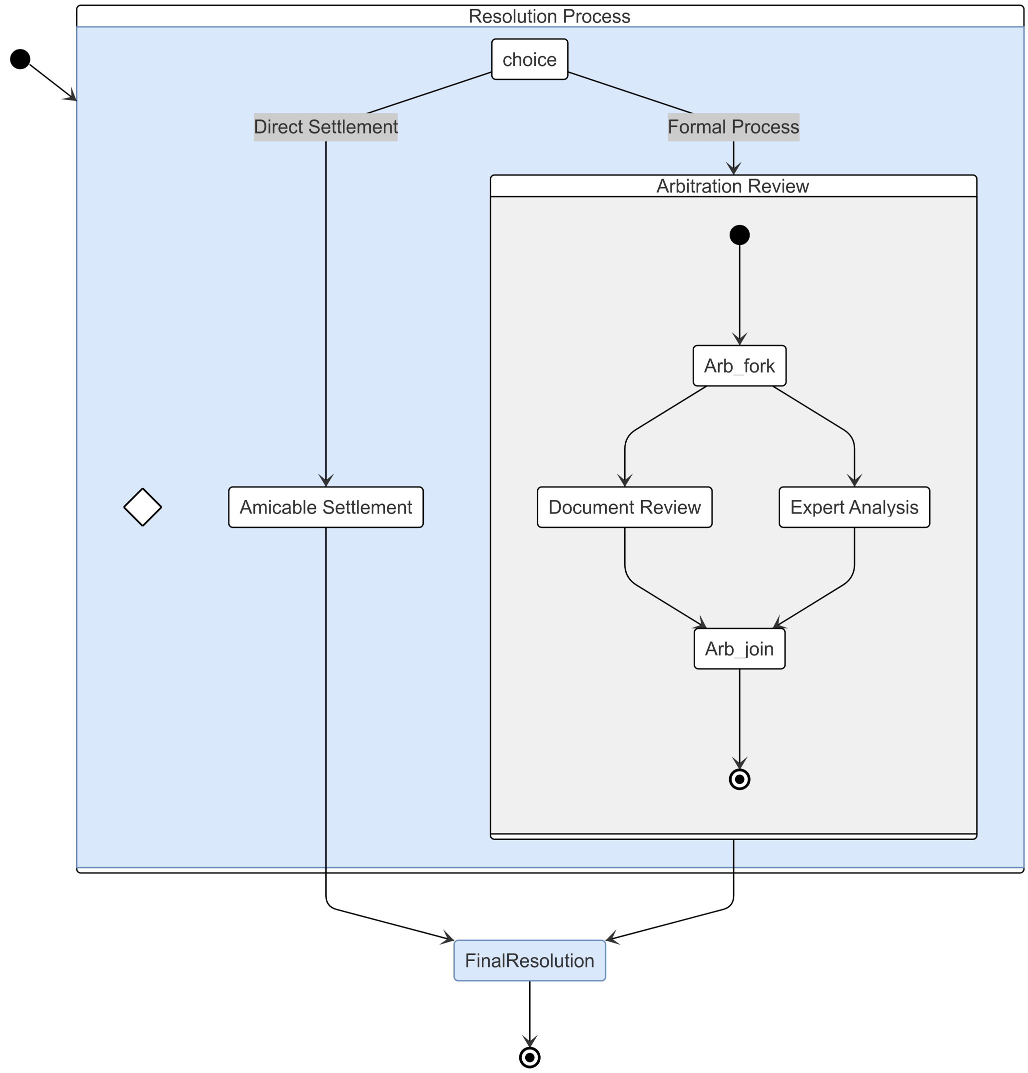

Figure 9. Dispute resolution.

2.2. Overview of the Proposed Framework

The framework requirements and design choices were informed by extensive consultation with our industry partners. Through a series of structured interviews and workshops with Alcomex SA and JC Grossi & Fhilos, we gathered detailed requirements about trading processes, documentation needs, and common challenges in the Brazil–Switzerland coffee trade corridor. This direct industry input ensured that our technical solutions address real-world needs and align with established trading practices. To directly address the challenges outlined in the coffee supply chain, we develop a framework that integrates blockchain technology with the principles of Self-Sovereign Identity (SSI). SSI has proven to be particularly effective for decentralized identification, especially when combined with blockchain systems [50,51]. Our platform empowers buyers and sellers to discover each other and negotiate terms directly, managing transactions with minimal reliance on third parties. Using the potential of blockchain to reduce the need for intermediaries in decentralized markets [52,53], we enhance trust and streamline operations within the supply chain. The platform implements comprehensive order execution protocols, facilitating end-to-end monitoring of logistics and quality assurance parameters according to contractual specifications. Its integrated financial infrastructure incorporates both conventional banking instruments and distributed ledger-based guarantee mechanisms, allowing frictionless transaction processing while maintaining operational flexibility in various financial frameworks [54]. Our framework also addresses the core processes of international coffee trading by providing technological solutions that enhance efficiency while maintaining compatibility with established industry practices:

- Marketplace: The traditional coffee marketplace is transformed through a decentralized infrastructure where participants establish their presence using verifiable digital identities. By implementing SSI principles, exporters can create verifiable offers with authenticated quality certifications, while importers can confidently evaluate potential trading partners through validated credentials. This approach significantly reduces the information asymmetry typically present in international trade while maintaining the flexibility needed for complex commodity transactions [55].
- Contract negotiation: The negotiation process is enhanced through smart contracts [56] that encode standard trading terms while maintaining the adaptability required for international coffee transactions. The system supports the complete trading lifecycle, from initial order specification through final settlement, with key innovations including the following:
  - Automated financial guarantee management;
  - Integration of quality verification protocols;
  - Secure document management;
  - Milestone-based payment release mechanisms.

This automation significantly reduces the operational overhead traditionally associated with international coffee trading while enhancing transparency and trust between parties.

- Dispute management: The framework provides comprehensive support for dispute resolution through an immutable record of all trading activities and communications. This transparent audit trail, combined with automated enforcement of claim submission time frames and structured access for arbitrators, enhances the efficiency of dispute resolution while maintaining alignment with established industry practices.

These core functionalities are implemented through a sophisticated technical architecture that combines Ethereum's smart contract capabilities with the Internet Computer Protocol's scalable infrastructure, as detailed in the following sections. The solution maintains compatibility with traditional banking systems while introducing new efficiencies through blockchain technology, allowing a gradual transition from existing processes to more automated, transparent operations.

2.3. System Architecture

The system architecture presented in this Communication was developed by the authors as part of a research project funded by Innosuisse (Project ID: 103.518.1 IP-ICT). The research project, conducted in collaboration between the University of Applied Sciences and Arts of Southern Switzerland (SUPSI) and Kraft Bio Chain SA, aimed to create a decentralized platform for agricultural supply chains, with a specific focus on the coffee industry. The platform was designed and implemented by our research team to address the challenges identified in Section 2, particularly those related to transparency, trust, and efficiency in international coffee trading.

The system architecture is organized into several interconnected layers, leveraging Ethereum and the Internet Computer Protocol (ICP) to provide a secure, efficient, and user-friendly platform. Ethereum supports robust transaction logic and financial operations through smart contracts, while ICP's decentralized infrastructure enables scalable application hosting without traditional servers, improving both security and performance [57]. The architecture comprises the following layers, each fulfilling a specific function within the application:

- Identity layer: It manages decentralized identities and verifiable credentials using Self Sovereign Identity (SSI) standards. Moreover, it ensures that only authenticated and authorized participants engage in transactions.
- Application layer: It hosts the front-end and back-end on the ICP blockchain, providing a decentralized and scalable infrastructure without the need for traditional servers.
- Smart contract layer: It contains smart contracts deployed on the Ethereum blockchain. These smart contracts handle SSI authentication and manage financial operations through down payment services.
- Integration layer: It facilitates communication between the ICP and Ethereum blockchains. Moreover, it includes protocols for identity derivation and secure transaction signing, ensuring seamless interoperability, which refers to the ability of different blockchain systems to communicate, exchange data, and execute cross-chain operations.

Figure 10 illustrates the system architecture, showing the interconnected layers and their respective components, along with the relationships that enable seamless functionality across the platform.

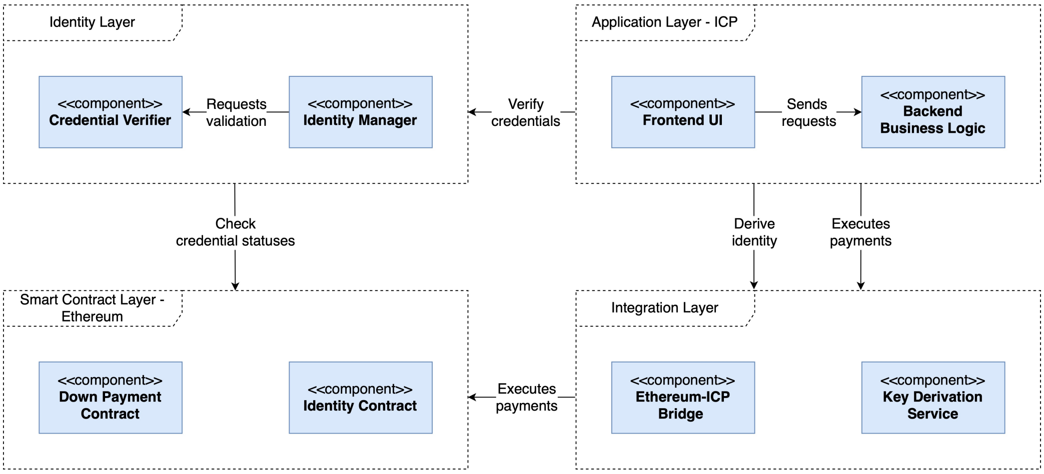

Figure 10. System architecture UML component diagram.

2.4. Roles and Participants

The platform also defines specific roles for participants in the supply chain, each with distinct responsibilities:

- Consortium: The platform operates under the oversight of an industry-specific consortium that manages member onboarding by evaluating and approving companies, issuing and revoking access credentials. This consortium not only oversees this specific platform but may supervise any service related to the management and exchange of goods.

- Exporter (seller): This person initiates trade offers, manages product listings, and completes shipment details. Exporters can be producers or suppliers looking to sell their commodities.
- Importer (buyer): This person engages with exporters, negotiates terms, approves, and supervises shipments. Importers are buyers seeking commodities for sale or processing.
- Certifier: This person verifies the credentials and authenticity of participants, certifies products and processes, ensuring compliance with industry standards and regulations. Certifiers play a crucial role in establishing trust within the platform.
- Arbiter: This person mediates disputes and facilitates resolution when disagreements arise. The arbitrator ensures that conflicts are resolved efficiently and fairly.

Each participant, identified through their role, accesses the platform using Verifiable Credentials (VCs), which grant them full control over their data while maintaining a decentralized structure. As shown in Figure 11, the "Triangle of Trust" model demonstrates how the consortium issues credentials, while only identifiers and cryptographic keys of participants are registered on the blockchain to preserve privacy [51]. The role of a "Participant" encompasses exporters, importers, certifiers, arbiters, and their respective employees, ensuring that all interactions align with the principles of self-sovereign identity and data autonomy. This structure eliminates intermediaries, reduces information asymmetries at the trade level [58] and ensures a secure, trust-based environment for all platform activities, aligning with current advancements in self-sovereign identity and data autonomy [59].

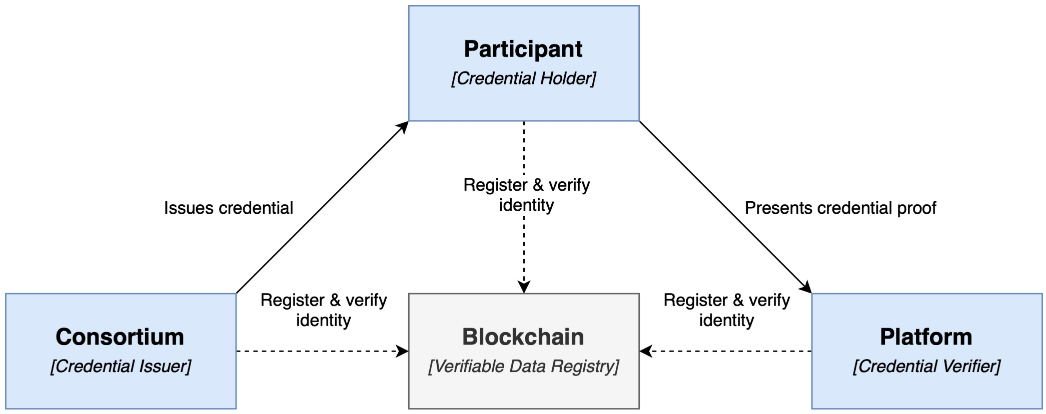

Figure 11. Triangle of trust.

2.5. Development Tools and Technologies

The platform leverages a combination of modern technologies to achieve its objectives:

- Programming languages:
  - Rust: This is used for developing some canisters (smart contracts) on the ICP blockchain. Rust provides safety and performance benefits, essential for secure blockchain applications.
  - TypeScript: This is used for developing some other canisters using the Azle Canister Development Kit (CDK), enabling flexible development on ICP with strong typing and ease of integration.
  - Solidity: This is used for writing smart contracts on the Ethereum blockchain. Solidity is the standard language for Ethereum development.
- Libraries and frameworks:
  - Identity management: The framework implements the W3C standards Decentralized Identifiers (DIDs) and Verifiable Credential (VCs) [59], ensuring inter-

operability and adherence to global identity management practices [60,61]. The Veramo library is utilized to manage identity functions, while protocols like DIDComm are adopted for secure messaging and credential exchange, enhancing the security and privacy of interactions on the platform;
  - Smart contracts: It utilizes OpenZeppelin's4 secure and community-vetted contract templates, providing a robust foundation for contract development.
  - Canister development: It uses Azle, a TypeScript-based Canister Development Kit (CDK), to write canisters on ICP, allowing for seamless TypeScript integration and expanded flexibility in canister development.
  - Wallet integration: It employs WalletConnect for secure communication between mobile wallets and decentralized applications, facilitating user-friendly interactions [62].
- Platforms:
  - Internet Computer Protocol: It provides a decentralized environment for hosting the application's front-end and back-end. In fact, ICP offers scalability and eliminates dependency on centralized servers [57];
  - Ethereum blockchain: This serves as the platform for executing smart contracts and handling financial transactions, benefiting from its mature ecosystem and widespread adoption. Additionally, Ethereum supports identity resolution through the DID method did:ethr, a recognized and widely adopted method within the SSI ecosystem, enabling decentralized and verifiable identity management [63].

2.6. Security Measures

Security is paramount in our platform, and several measures are implemented to protect users and their data:

- Private key management: Users' private keys are securely stored on user's smartphones, leveraging hardware security modules such as the Secure Enclave on iOS or the Trusted Execution Environment on Android. Biometric authentication adds an extra layer of security.
- Transaction signing: The "Sign-In with Ethereum" (SIWE) protocol enables secure interaction with ICP identities by signing a message using EVM keys. The signing operation is executed locally on the user's device, ensuring that private keys remain secure and are never transmitted or exposed to external entities [64].
- Data privacy: Sensitive data within Verifiable Credentials (VCs) are stored exclusively on the user's device. Only selected data, explicitly authorized by the user, are shared and stored to facilitate new commercial exchanges and allow participants to know their trading partners.
- Selective disclosure: The platform supports selective disclosure, allowing users to share only specific attributes within their Verifiable Credentials (VCs) while keeping other information private. This feature enables users to reveal only the necessary data for each interaction, enhancing privacy and maintaining control over personal information [51]. Future iterations of the platform will incorporate Zero Knowledge Proofs (ZKPs), enabling users to prove the validity of their credentials without revealing any underlying data. ZKPs represent a significant advancement in privacy-preserving technology, allowing parties to verify claims without exposing sensitive information [65]. Recent research demonstrates that ZKPs can be particularly effective in supply chain applications, allowing trust and verification while maintaining confidentiality of business-critical data [66]. Studies by Raikwar et al. [67] show that the integration of ZKP into blockchain-based trading platforms can reduce data exposure by up to 90% while maintaining the same level of verification certainty.

2.7. User Interface and Experience

The successful adoption of blockchain-based trading platforms in agricultural supply chains is highly dependent on their accessibility to users with varying levels of technological knowledge. This consideration is particularly crucial in the coffee industry, where many exporters are small-scale farmers or rural cooperatives that may have limited exposure to advanced digital technologies [68]. To address these challenges, our platform emphasizes simplicity and accessibility while maintaining the robust functionality required for international coffee trading. The following sections detail our approach to creating an inclusive user experience that accommodates varying levels of technological proficiency while ensuring secure and efficient trading operations. To ensure broad adoption, the platform is designed with user accessibility in mind:

- Mobile application: It functions as a digital wallet and identity manager. It allows users to manage credentials, approve transactions, and receive notifications in an intuitive way.
- Web application: It provides a comprehensive dashboard for managing negotiations, contracts, and supply chain operations. The user interface is designed to be intuitive and accommodating users with varying levels of technical expertise.
- Accessibility features: Multi-language support and guided workflows assist users in navigating complex processes. The platform emphasizes simplicity and clarity to reduce the learning curve.

3. Results

Before delving into the implementation details, it is essential to note that our research project concluded in its initial Proof-of-Concept (POC) phase, during which the core architectural components and fundamental functionalities of the platform were validated. The data and analysis presented in this section represent preliminary estimates derived from the POC implementation. To further validate the platform's effectiveness and gather comprehensive empirical data, collaborations with industry partners are scheduled for the coming months. These real-world implementations will enable thorough testing of the system's performance, scalability, and practical applicability in actual trading scenarios, providing valuable insights for future refinements and enhancements of the proposed solution.

3.1. Implementation Details

3.1.1. Decentralized Identity and Verifiable Credentials

We implement a decentralized identity system that empowers users with control over their digital identities:

- Credential issuance: Trusted authorities, such as industry consortia or certification bodies, issue verifiable credentials to companies. Companies, in turn, issue credentials to their employees, establishing a chain of trust.
- Credential storage: Credentials are securely stored on the user's mobile device or within the company's systems. This approach leverages SSI principles, ensuring portability and user sovereignty over credentials [69];
- Authentication process: Users authenticate by scanning QR codes and by approving requests within the mobile app. The platform acts as a verifier to validate credentials without storing or exposing sensitive information, thus maintaining privacy and security.

Figure 12 illustrates the credential issuance and verification process within the platform. The consortium generates and signs Verifiable Credentials (VCs) upon request from participants, who then store these credentials securely in their wallets. When participants request access to the platform, they present a Verifiable Presentation (VP), generated and signed using their VCs, which the platform validates by verifying signatures, temporal validity, and status. As explained, participants, such as companies, can issue credentials to their employees, extending the chain of trust and enabling secure delegation of responsibilities.

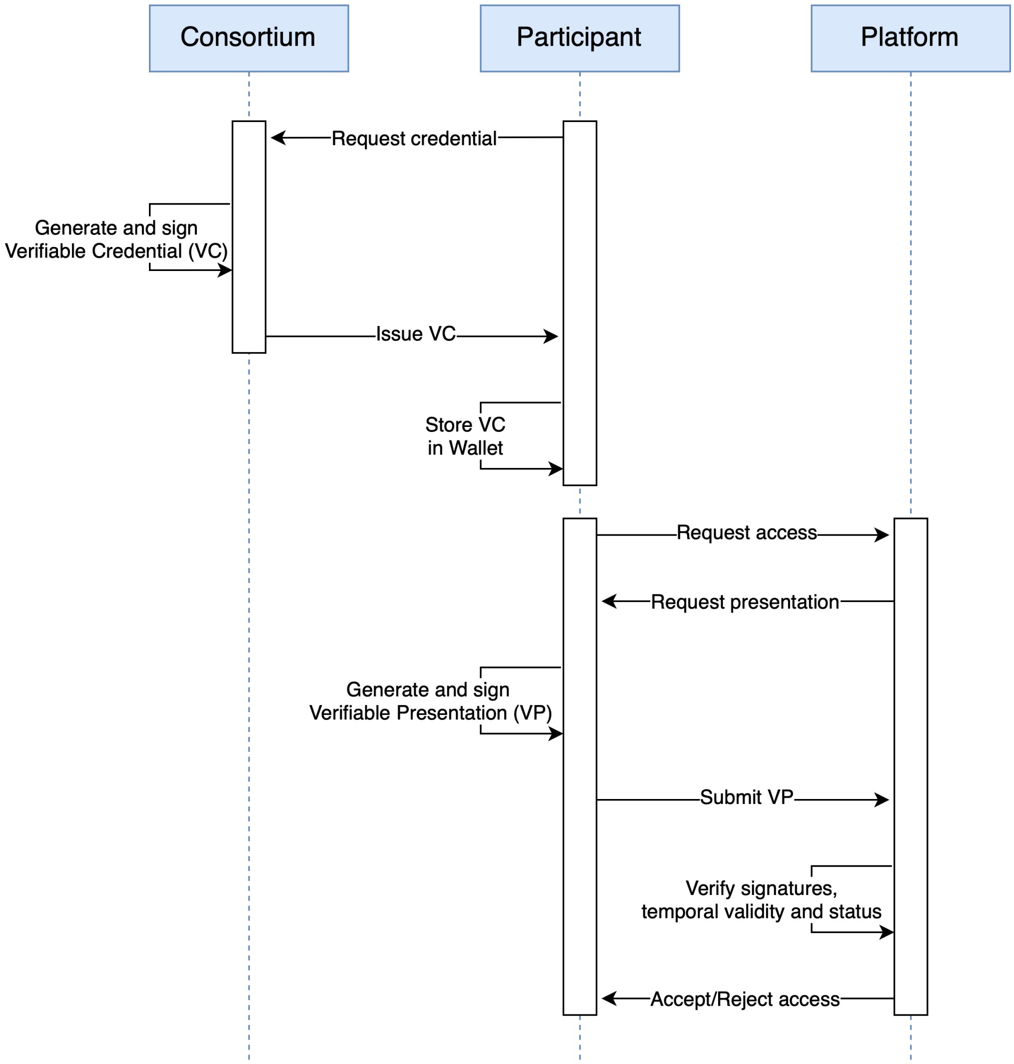

Figure 12. Verifiable Credential issuance and verification

3.1.2. Integration of ICP and Ethereum

Our platform seamlessly integrates the ICP and Ethereum blockchains:

- ICP deployment: The front-end and back-end services are hosted on ICP canisters, providing a decentralized and scalable infrastructure. Unlike Ethereum, data written to ICP are not inherently public [70], allowing the management of multiple privacy levels for data storage [71]. Furthermore, the ICP's reverse-gas model not only reduces transaction costs but also removes the need for users to manage funds for system usage, as the system itself covers transaction fees for user interactions, enhancing accessibility and ease of use [60].
- Ethereum interaction: The user interacts exclusively with their EVM-compatible keys, using them both for transactions on Ethereum and to derive an ICP identity via the SIWE protocol. This unified key usage streamlines the user experience, allowing seamless interaction across both blockchain platforms without requiring separate key management [65].

- Identity derivation protocol: We utilized the secure protocol provided by ICP to derive Ethereum-compatible keys from ICP identities. This ensures that private keys remain within the secure environment of the user's device, maintaining security across platforms [69].

3.1.3. SSI-Based Authentication Framework

We introduce an authentication and authorization framework designed to operate seamlessly across both the EVM and the ICP:

- Access modifiers: Custom access modifiers enforce role-based access control across the platform. In Solidity, we use modifiers to restrict function execution to authorized roles, while in ICP, decorators are applied to canister-related code to achieve similar access control. This ensures that only users with the appropriate SSI credentials can perform specific actions within smart contracts and canisters.
- Credential verification: Smart contracts and canisters verify cryptographic proofs provided by users. This process maintains the integrity of transactions and enforces business rules without compromising privacy.
- Role-based access control: Defined roles such as EXPORTER, IMPORTER, and CERTIFIER within smart contracts and canisters streamline the enforcement of business logic and compliance requirements. Certain platform functionalities are accessible only to specific roles, ensuring that each participant has the appropriate permissions to perform their designated actions securely and in accordance with their responsibilities.

3.1.4. User Experience Enhancements

We focus on enhancing the user experience to encourage adoption:

- Seamless authentication: Users authenticate through familiar actions, such as scanning QR codes and biometric verification, reducing barriers to entry.
- Notifications and alerts: Real-time notifications keep users informed of important events, such as contract updates or required approvals, maintaining engagement, and workflow continuity.
- Guided workflows: Step-by-step guides help users navigate complex processes, reduce the learning curve, and minimize errors.

3.2. Case Study

3.2.1. Scenario Overview

To demonstrate the practical application of our framework, we conduct a case study focusing on the coffee supply chain between Brazil and Switzerland. The case study presents the following characteristics:

- Participants: Small-scale coffee exporters in Brazil and importers in Switzerland.
- Challenges addressed:
  - Trust issues: Difficulty in establishing credibility due to geographical and informational gaps, leading to hesitance in direct transactions.
  - Intermediary costs: High fees charged by brokers and middlemen, reducing profit margins for producers, and increasing costs for buyers.
  - Bureaucracy: Time-consuming paperwork and manual processes, delaying transactions, and increasing the likelihood of errors.
  - Financial barriers: Complexities in setting up guarantees and down payment arrangements through traditional banking systems, which can be prohibitive for small exporters.

3.2.2. Trade Negotiation Process

The platform facilitates a streamlined trade negotiation process:

- Registration and verification: Upon registration, exporting and importing companies receive verifiable credentials issued by the consortium. The companies involved can then issue specific credentials to their employees, creating a chain of trust [69]. The platform can verify these employee credentials as needed, establishing a secure foundation for transactions.
- Offer creation: Exporters list coffee products with detailed specifications, including variety, quality, quantity, and pricing terms.
- Negotiation initiation: Importers express interest and initiate negotiations through the platform. Both parties can propose modifications to terms, facilitated by the platform's interactive interface.
- Contract formation: As illustrated in Figure 13, the platform ensures that when an agreement is reached, a new entity is created within an ICP canister to encapsulate the negotiated terms. This entity includes details such as shipment information, payment conditions, and dispute resolution mechanisms, securely storing and making them accessible within the platform.

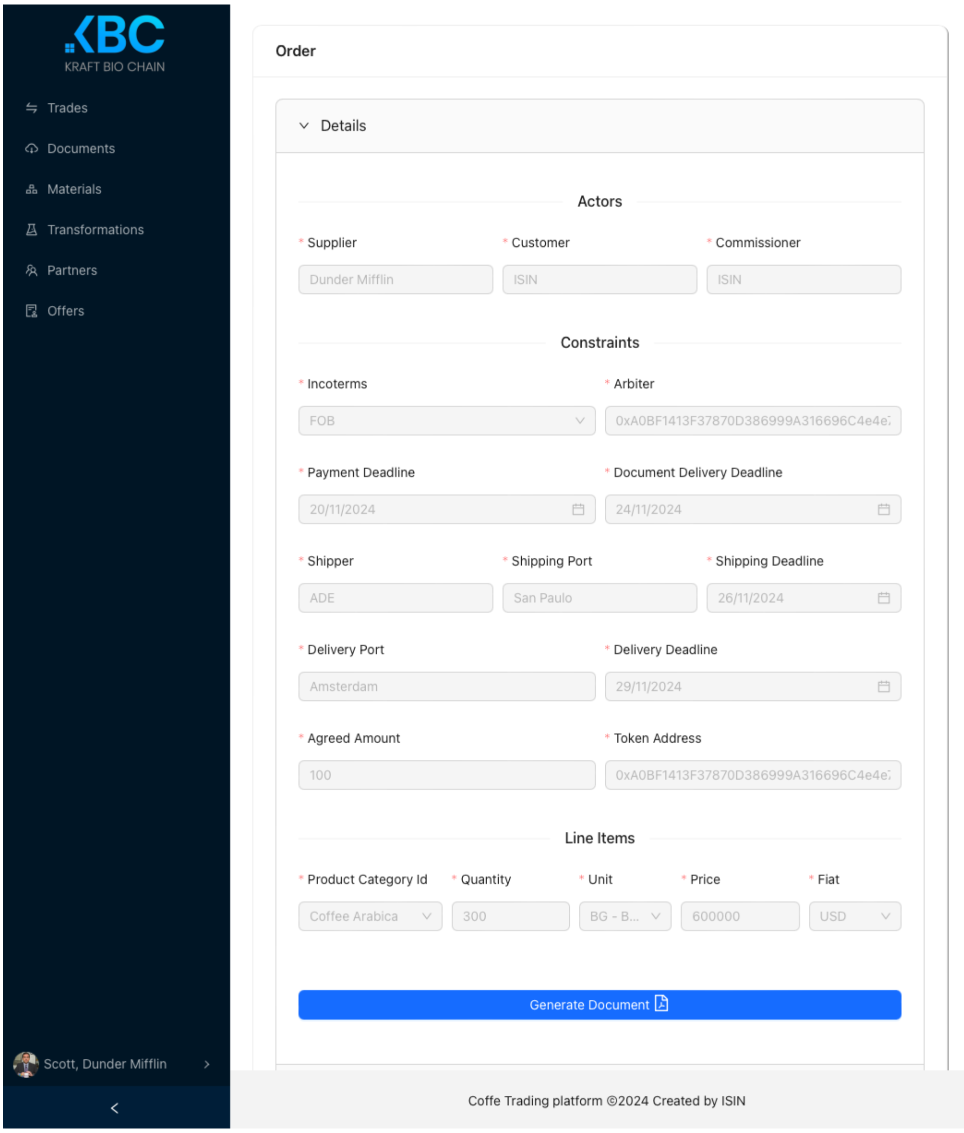

Figure 13. Platform negotiation page

3.2.3. Shipment and Payment Handling

As illustrated in Figure 14, our platform manages shipments and payment processes efficiently:

- Document management: Critical shipping-related documents such as bills of lading and certificates of origin are uploaded and securely stored on the ICP blockchain, ensuring both immutability and accessibility.
- Down payment services: Guarantees are secured through a down payment mechanism managed by the ICP canister. Funds are locked and released based on predefined conditions set in the previously signed contract, such as confirmation of shipment delivery, ensuring fairness and security for both parties.
- Transaction flow: The platform also orchestrates the transaction sequence, ensuring compliance with contractual obligations. Notifications prompt users to take the necessary actions, maintaining momentum in the supply chain.

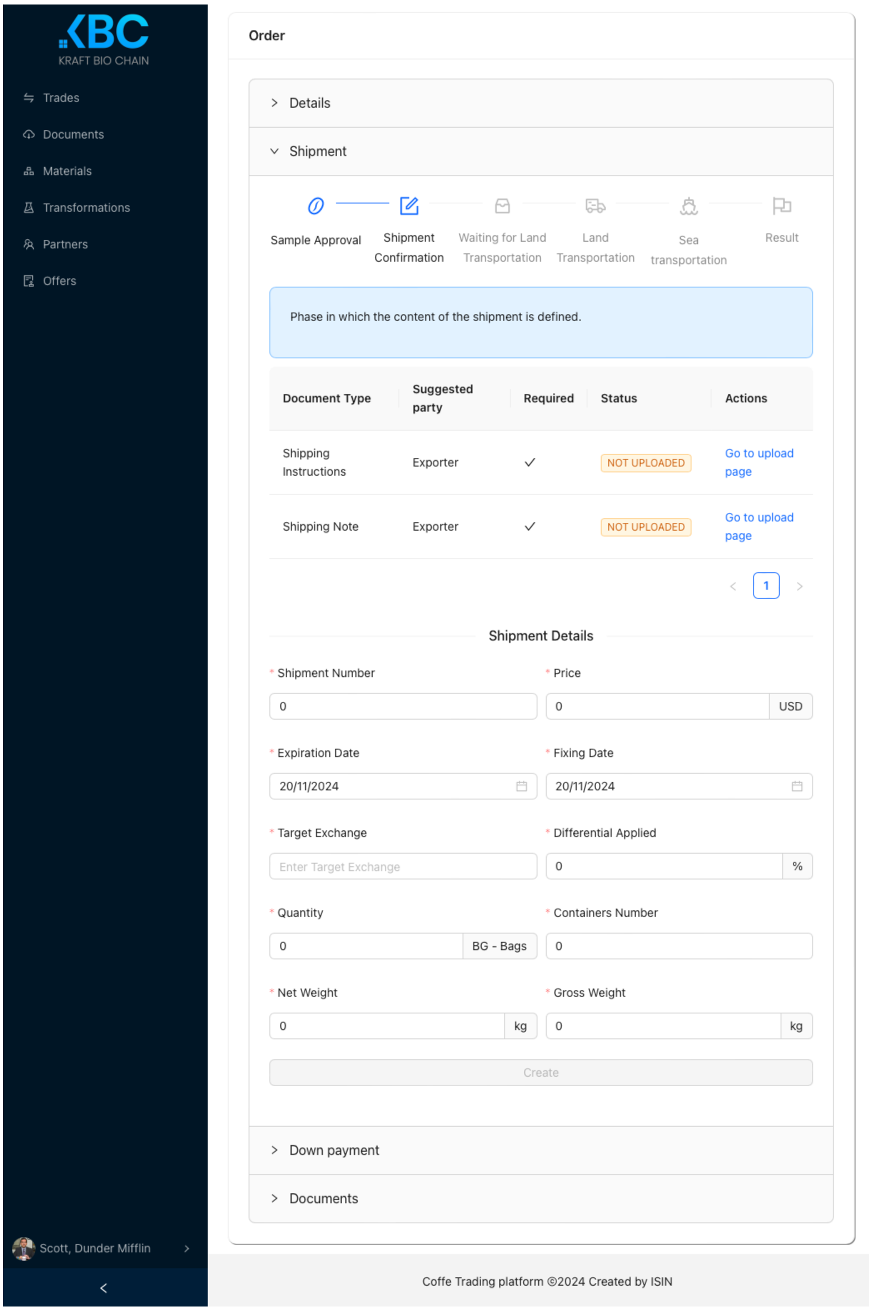

Figure 14. Platform shipment page

3.2.4. Dispute Resolution

In the event of disputes, the platform provides mechanisms for efficient resolution:

- Transparent logging: All interactions and document exchanges are immutably recorded. This provides a transparent audit trail that is invaluable for resolving disagreements.
- Arbitration mechanism: An arbiter can access relevant records to facilitate dispute resolution. The platform's logs serve as evidence, reducing ambiguity and expediting the process.
- Legal compliance: The generated records comply with legal standards, supporting enforcement if necessary. Users can easily collect all communications and documents to present to legal authorities, streamlining the path to resolution.

3.3. Technical Challenges and Solutions

We hereby address the potential challenges and their solutions that the proposed framework could effectively provide.

3.3.1. Identity Derivation and Management

- Challenge: Securely associating Ethereum addresses with ICP identities without compromising security.
- Solution: Instead of utilizing a standalone ICP identity, we derive one from an existing Ethereum account. This is achieved by implementing a SIWE mechanism using a canister developed by the ICP community. This approach maintains security while streamlining cross-platform interactions.

3.3.2. Unified Authentication Across Distinct Blockchain Networks

- Challenge: Implementing a unified authentication system across a platform that operates on different blockchains.
- Solution: We rely on the Ethereum SSI standard for identity management and perform RPC calls to the EVM network from ICP. This approach allows us to maintain a single coherent identity across both blockchains, enabling seamless authentication and authorization. Users can thus interact with different components of the platform through a unified identity, simplifying the experience while ensuring consistent access control across the platform.

3.3.3. Access Control

- Challenge: Enforcing role-based permissions in a decentralized and trustless environment.
- Solution: We implemented on-chain verification of off-chain credentials using cryptographic proofs. This approach ensures that only authorized users can execute specific smart contract and canister functions.

3.3.4. Data Privacy and Confidentiality

- Challenge: Balancing transparency with the need to protect sensitive business information.
- Solution: Sensitive documents are stored on the ICP blockchain, utilizing its capability to manage different levels of data access while ensuring immutability and security. This approach allows controlled visibility of data, preserving confidentiality without compromising the integrity and verifiability of transactions.

3.3.5. User Accessibility

- Challenge: Designing a user experience suitable for participants with limited technical expertise.

- Solution: We create intuitive interfaces with minimal technical jargon. Educational resources and support are provided within the platform to help users. The emphasis on a mobile-first design leverages the ubiquity of smartphones, making the platform accessible to a broad user base.

3.3.6. Interoperability

- Challenge: Facilitating seamless interaction between different blockchain platforms.
- Solution: APIs and middleware abstract the complexities of cross-chain interactions. Using standardized data formats and communication protocols, we ensure that the user experience remains consistent regardless of the underlying technologies.

3.4. Impact Analysis on Traditional Trading Processes

Before delving into the impact analysis, it is essential to note that the presented blockchain-based solution represents an initial Proof of Concept (POC). Although currently being tested by selected project participants, the platform has not yet been deployed on a scale. Therefore, the quantitative data and analysis presented in this section are based on preliminary estimates and calculations derived from the POC implementation. The actual values and impacts may vary as the solution evolves and achieves broader market adoption. However, the initial results provide valuable insight into the potential improvements in key trading processes compared to traditional methods. This section analyzes the estimated impacts on costs, processing times, and intermediary dependence for each major process phase based on the current implementation of the rPOC.

3.4.1. Offer Publication and Discovery

The initial phase of the traditional coffee supply chain, which involves partner discovery, is often a burden for small-scale producers. Obtaining market visibility requires substantial investments in trade fairs and intermediary services. This dependency on intermediaries for financing, logistics, and market access significantly impacts small-scale producer profitability. Participation in trade fairs can cost several thousand dollars annually, as highlighted in studies on barriers faced by new entrants into the system [72]. However, given the variability in resources and infrastructure among small-scale producers, it is challenging to provide an accurate estimate of the real costs involved. This discovery process, which often takes several months, remains a critical hurdle, particularly for those seeking to establish their first business relationships.

In contrast, the blockchain solution significantly reduces these discovery costs and time frames. The costs of creating ICP-based offers are less than USD 0.001 per publication, allowing exporters to instantly make their offerings visible to all participants in the platform. The built-in verification system and the credential mechanisms of the platform allow importers to evaluate the reliability of potential partners in hours rather than weeks and to make business more fair, as highlighted by [72], who reveals that the costs associated with intermediaries in the coffee supply chain can be substantial, with monthly interest rates on loans provided by intermediaries ranging from 10% to 20%. Direct partner discovery through the platform eliminates traditional broker fees, while the standardized digital interface reduces the initial relationship establishment period to approximately one week.

3.4.2. Contract Negotiation

The coffee supply chain, as in many commodity trading sectors, remains heavily dependent on manual processes based on paper. Research by researchers from The London School of Economics and Political Science [73] reveals the extent of this documentation burden: each trade transaction requires processing between 36 and 240 different documents, involving more than 30 different stakeholders. Most importantly, traditional contract negotiation processes typically take 2–3 weeks to complete. This complexity not only increases costs, but also introduces significant delays and potential failure points in the trading process. Traditional trading systems incur substantial costs through bank intermediation, particularly for letter of credit transactions, which generally cost about 2.5% of the transaction value [49].

The blockchain-based solution introduces significant efficiencies through smart contract automation. Due to the usage of ICP and Ethereum L2, the compute and storage costs related to document management are below USD 0.001 and hence completely negligible. This cost scales with the volume of documents managed by each company, making storage costs proportional to the trading activity and documentation needs of each participant. Based on preliminary estimates conducted with project partners during the POC phase, these operations could reduce the total processing time from weeks to 1–2 h, while enabling direct peer-to-peer interaction that eliminates the need for multiple intermediaries.

3.4.3. Dispute Management

Based on data shared by our implementation partners, in traditional systems, dispute resolution is a time-consuming process requiring 14–21 days for physical documentation retrieval alone. The process typically involves 6-8 different parties and spans 45–60 days on average. Legal intermediary costs vary significantly by jurisdiction, adding substantial uncertainty to the total transaction cost.

The blockchain platform provides immediate access to all relevant documentation through its immutable ledger. The system's transparent audit trails enable instant verification of all transaction details, while smart contract arbitration automates many aspects of the resolution process. This reduces the number of parties involved to 2–3 and, according to our estimates, shortens the average resolution time to 5–7 days.

These improvements are particularly significant for small and medium-sized traders, who traditionally face disproportionately higher costs and longer processing times due to their limited resources and market access. The blockchain solution effectively levels the playing field, enabling smaller participants to compete more effectively in the global coffee trade market.

4. Discussion

Our implementation framework demonstrates how the integration of blockchain technology with SSI principles effectively addresses trust and efficiency challenges in global supply chains. We hereby discuss its potential impact on the economy, as well as further concerns and future perspectives.

4.1. Impact on the Coffee Industry

The platform significantly impacts the coffee industry, namely our research target, via the following:

- Enhancing trust: Ensuring that only verified participants engage in transactions fosters a trustworthy environment. This reduces the risk of fraud and builds trust among participants.
- Reducing costs: By minimizing dependency on intermediaries, transaction costs are lowered. Producers can achieve better profit margins and buyers can access products at more competitive prices.
- Streamlining processes: Automating documentation and negotiation processes reduces delays and errors. More efficiency accelerates the supply chain, benefiting all stakeholders.

- Improving financial accessibility: Simplifying financial transactions using stablecoins and smart contracts bypasses traditional banking barriers. This is particularly beneficial for small exporters who may lack access to conventional financial services.

4.2. Generalization to Other Industries

The framework's modular and adaptable design allows it to be potentially applied to various industries facing similar challenges:

- Textiles: By ensuring ethical sourcing and authenticity of materials and by combating counterfeit goods.
- Pharmaceuticals: By tracking provenance and preventing counterfeit drugs as well as enhancing patient safety.
- Agriculture: By enhancing transparency and traceability in the supply chains of other commodities like cocoa and tea and by promoting fair trade practices.
- Minerals and metals: By verifying compliance with environmental and labor regulations and by supporting responsible sourcing.

4.3. Addressing Privacy Concerns

Our approach balances the need for transparency with privacy:

- Selective disclosure: Users share only the necessary information, maintaining confidentiality over sensitive data.
- Regulatory compliance: The platform can be configured to comply with data protection laws such as GDPR, ensuring legal adherence.
- User empowerment: Participants have control over their data, including the ability to revoke access when necessary, aligning with SSI principles.

4.4. Scalability and Performance Considerations

We consider scalability and performance to ensure that the platform can grow with demand:

- ICP Advantages: The Internet Computer Protocol offers high throughput and low latency, suitable for applications requiring real-time interactions. It scales horizontally, accommodating increasing user numbers [60].
- Ethereum challenges: We mitigated Ethereum's scalability issues using Layer 2 scaling solutions like rollups or sidechains. Transaction batching and gas optimization techniques reduce costs and improve performance [74].
- Prospects: Integration with other blockchain platforms that offer enhanced scalability and privacy features is planned, ensuring that the platform remains at the forefront of technological advancements.

4.5. Limitations and Future Perspectives

Although our platform offers significant benefits, there are certain limitations:

- Adoption hurdles: Resistance to new technology and lack of infrastructure in certain regions may slow adoption. Continued education and support are necessary to overcome these challenges.
- Regulatory landscape: Navigating different legal frameworks across jurisdictions requires adaptability. Monitoring and adjusting to regulatory changes are essential for compliance.
- Enhancements: Future work should include the integration of IoT devices for real-time tracking and monitoring, the application of artificial intelligence to demand forecasting, and the expansion of the SSI framework to support cross-chain identity solutions.

5. Conclusions

In this Communication, we have developed a universal blockchain-based platform that significantly enhances trust and efficiency in global supply chains, emphasizing the integration of Self-Sovereign Identity (SSI) and decentralized technologies. This integration not only facilitates secure and efficient interactions between stakeholders, but also revolutionizes traditional supply chain management.

Our platform pioneers a decentralized marketplace that empowers buyers and sellers to discover each other and negotiate directly, significantly reducing the dependency on intermediaries. This marketplace streamlines the contract formation process and manages the entire shipping trajectory, ensuring compliance and the timely delivery of commodities. In addition, it facilitates the secure handling of documentation and the management of financial guarantees. In the event of disputes, the platform's comprehensive record-keeping capabilities allow for easy collection and presentation of evidence to legal authorities, expediting resolution processes.

From a scientific perspective, our Communication introduces novel applications of blockchain and SSI technologies in supply chain management, particularly addressing the challenges of trust, transparency, and inefficiency that have long plagued global trade. By implementing these technologies, we demonstrate their potential to solve complex, systemic problems, providing a model that can be adapted to various industry contexts beyond the coffee industry.

From a practical and applied perspective, the significance of our work lies in its potential to transform global trade practices. The platform reduces transaction costs [75], shortens processing times, and minimizes the risks of fraud, making global trading more accessible. Furthermore, by automating the negotiation and enforcement of contracts, the platform ensures a higher level of compliance and security in international transactions.

Future perspectives include extending this platform to other industries such as textiles, pharmaceuticals, agriculture, and minerals, where there are similar supply chain challenges. Each industry can benefit from the increased transparency and efficiency that our platform offers, which could transform global supply chains into more sustainable, equitable, and resilient systems.

Finally, our work not only represents a significant technological innovation contributing to the literature on blockchain applications in supply chain management, but also provides a scalable and flexible solution with far-reaching implications for global economic practices. The adaptability and robustness of our platform suggest a promising future for the integration of blockchain technologies in improving the operational capabilities of supply chains worldwide.

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