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Smarttrace: An Ai-Assisted Blockchain Framework For Qr-Enabled E-Commerce Supply Chain Transparency

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Abstract: Contemporary e-commerce systems still have to struggle with issues of fake products, insufficient transparency of logistics and the inability to provide verifications of the authenticity of products on the level of consumers. The traditional supply chain systems are based on centralized databases, which can be manipulated, limited in the process of auditability, and cannot reliably provide end users with provenance information. The SmartTrace framework proposed presents a customer-centric and decentralized approach to solving the problem by incorporating the lifecycle tracking of products into the blockchain, the QR-enabled verification, and the AI-based narrative generation. Product events are safely stored in Ethereum-compatible smart contracts, which enable state transitions that are impossible to alter and are controlled by roles by different manufacturers, suppliers, distributors, and consumers. IPFS is also used to store sensitive metadata of products, images and tracking summaries to ensure scalability and data integrity. On-chain events in the form of structured event streams are also converted into product journey narratives that can be read by humans by a generative AI component to make usable and transparent to non-technical users. QR scanning allows consumers to verify products by accessing blockchain-based provenance and AI-generated provenance to obtain timelines via a Web3 interface. The introduced prototype proves to be reliable in traceability, tamper-resistant history information and better supply chain visibility, defining an effective way in advancing trust, transparency, and anti-counterfeiting aspects in the contemporary e-commerce settings.

Index Terms - Blockchain traceability, Supply chain transparency, QR verification, Generative AI, Smart contracts, IPFS.

I. INTRODUCTION

There has been a significant increase in the number of the e-commerce platforms enhancing accessibility and convenience to the purchasing of the products, however, this has brought its share of problems including fake products, lack of logistics visibility, and lack of mechanisms to check the product authenticity. The consumers normally rely on centralized tracking update and information that may be supplied by the sellers which may be incomplete and can be manipulated by the sellers thus it is hard to build trust and learn the full lifecycle of products among various supply chain stakeholders.

The traditional supply chain systems are highly centralized databases which do not possess the capability of being tamper resistant, provenance and independently auditable. This restriction makes resolving the dispute more complicated and transparency is lowered, whereas more manual work is involved to relay the information on product movement and status. Despite the fact that blockchain technology provides an immutable, secure record keeping, most of the current implementations are oriented towards the regime of the backend traceability and offer less utility to consumers who want to have a simple and trustworthy verification.

In an attempt to overcome such challenges, this paper will propose SmartTrace, an AI-powered blockchain system that empowers supply chain tracking that is transparent and accessible to consumers. It captures lifecycle events by smart contracts that are Ethereum-compatible, uses IPFS to store extended metadata so as to be scalable, and applies generative AI to convert blockchain recordings of events into readable tracking narratives. By enabling verification with the help of QRs, consumers can also view immutable provenance information on a Web3 interface to enhance transparency and increase trust in digital commerce settings.

II. Existing & Proposed System

Existing System

The existing e-commerce supply chain systems are based on central databases, which are operated by single organizations, which gives rise to fragmentation of tracking information and scanty end-to-end visibility. These systems can easily be subject to manipulation of data, can not be audited independently, and have little assistance in verifying the authenticity of the product. Consumers will usually use updates given by sellers which can be partial, which can translate to more risks of counterfeiting and a decrease in confidence.

Moreover, the communication between the supply chain participants is usually inefficient and delayed due to manual coordination of supply chain members. Even though QR-based tracking is occasionally employed, many implementations cite centralized storage where the data authenticity cannot be verified independently, therefore, restricting transparency and making the dispute resolution challenging.

Proposed System

The suggested SmartTrace system will present a decentralized architecture which will be based on blockchain lifecycle tracking, IPFS storage, narrative generation with the help of AI, and verification with the help of QRs. Smart contracts written in Ethereum are used to track the events of the products and execute transitions among the roles, which guarantee an immutable and provable provenance among supply chain members. IPFS stores product metadata and images thus ensuring scalability and integrity.

A generative AI model can convert the logs of events occurring on the blockchain into readable tracking stories that are easier to use by the consumer. Attaching QR codes to products means direct access to blockchain-supported provenance using a Web3 interface, which allows easy authentication of authenticity and increases transparency and manual coordination.

III. Related Works

Much research has been done on enhancing transparency and traceability in the systems of the supply chain with the help of digital technologies. The conventional supply chain management systems majorly depend on centralized databases and enterprise resource planning systems to track the product movement. Though these systems make the coordination of logistics easier, they do not typically have record keeping which is hard to tamper or independent verification of the records. Consequently, counterfeit products, data discrepancy, and lack of auditability are some of the problems, which persist as critical in the context of the modern e-commerce ecosystems.

The blockchain technology has become a potential remedy to increasing the visibility of supply chains as it offers decentralized and unalterable documentation of product life cycle events. Some of the researches show that verified provenance, minimized fraud, and multi-stakeholder collaboration can be enhanced with distributed ledgers without the involvement of an intermediary trusted by all stakeholders. The use of blockchain in agriculture, pharmaceutical, and retail industries implies that the technology can be effective in preventing the substitution of products and realizing trackable offers. However, much of the current implementation is concerned with the integrity of data at the backend and it does not effectively tackle the issue of usability as experienced by the end consumer in interpreting blockchain information.

The recent studies have further examined how artificial intelligence can be incorporated in supply chain to enhance demand forecasting, anomaly detection and operational decision making. Using AI-based systems, one can also analyze massive amounts of logistics data and produce actionable insights, but they tend to rely on centralized sources of data, which cannot be provenanced. Moreover, little has been done to explore using AI as an interpretability layer that can decode blockchain event logs, which are often complex, into a comprehensible story format to consumers and other stakeholders.

Moreover, the use of QR and other such identification systems have become extensive as the interface between tangible good and the online tracking data. Although QR-based traceability allows consumers to obtain the origin and logistics information by a simple scan, most implementations rely on centralized servers on which the authenticity of the data cannot be verified on its own. Even though there are studies that are a mix of blockchain and QR verification, the data there is often technical and uninterpretable by non-technical users. Thus, there is a still gap in the development of integrated solutions that involve blockchain-based

traceability, decentralized storage, QR-enabled verification, and AI-assisted explanation that would be integrated into one consumer-friendly system. SmartTrace system fills this gap by offering a complete architecture end-to-end that improves transparency, authenticity checks and usability in e-commerce supply chain.

IV. METHODOLOGY

The SmartTrace system that will be proposed is based on a modular and layered architecture that is aimed at delivering secure, transparent, and consumer-friendly supply chain traceability. The framework combines the registration of the products, decentralized storage, lifecycle tracking on the blockchain, AI-aided narrative generation, and the verification into a single workflow. A rest of the modules play a particular role in the system, which guarantees its ability to scale, maintain, and rely on each stakeholder to interact with the others some manufacturers, suppliers, distributors, and consumers. The layered architecture allows each component of the system to be improved individually without causing the data flow to slow or an unstable operational environment.

The system is split into sections that encompass project related financial analysis, project management and project's financial and non-financial performance evaluation. The system is divided into sections, which include project related financial analysis, project management and project financial and non-financial performance evaluation.

4.1 System Architecture Overview

SmartTrace architecture consists of several functional layers such as the registration of product, decentralized metadata storage, blockchain lifecycle management, AI narrative processing and consumer verification. Products are registered via a Web3 interface to which metadata and media assets are stored using decentralized storage. An encrypted hash of this data gets stored on the blockchain, such that the lifecycle cannot be spoiled. The stakeholders get updates on the products status in a role-restricted interaction with smart contracts and the consumers get access to the provenance information by verifying with QR-based interfaces.

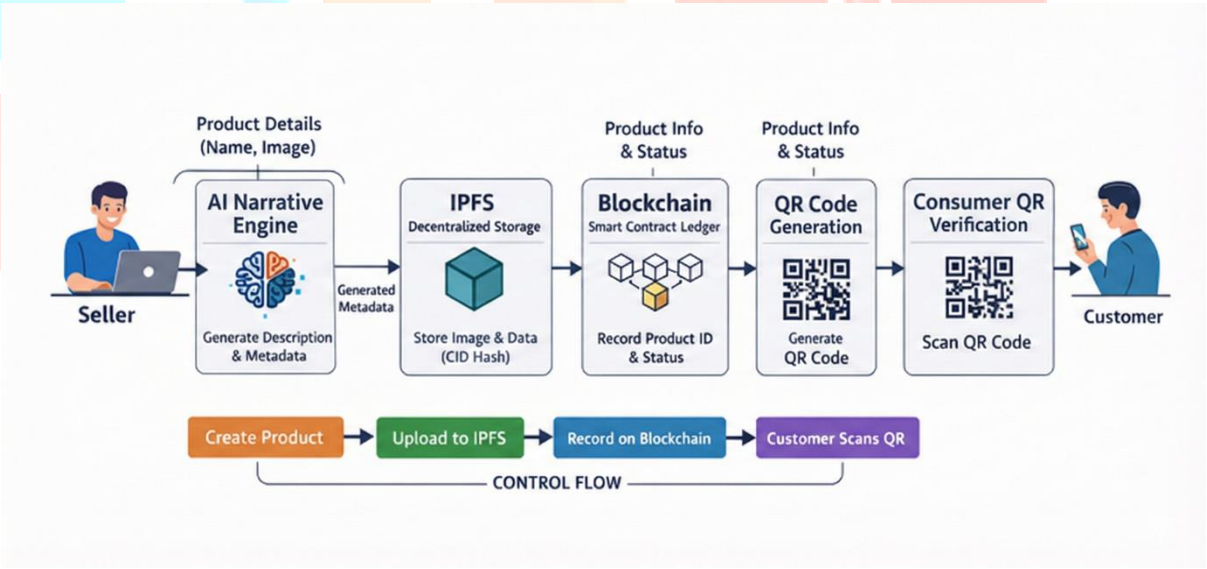

Figure 1: SmartTrace System Architecture

4.2 Product Registration and Metadata Module

This module is the entry point of the system whereby authorized stakeholders add products and post relevant metadata which includes description, images and identifiers. The module makes product information structured and validated prior to any further processing. Once registered, metadata is ready to be decentralized and connected to blockchain information, which allows the reliable retrieval and verification of metadata at later lifecycle phases.

4.3 Decentralized Storage and Metadata Management

Product metadata and media assets are stored in decentralized storage to achieve scalability and minimize overhead on the on-chain storage. This model maintains data integrity and enables the product information to be easily retrieved during the process of verification. The ensuing content identifiers are recorded in the smart contract and can be used by the stakeholders and consumers to confirm that the metadata retrieved is the same content uploaded in the first place.

4.4 Blockchain Lifecycle Management Module

This module handles secure event recording of product lifecycle with smart contracts that are compatible with Ethereum. The contract implement state transitions between manufacturers, suppliers, distributors and consumers predefining them and making role based access control and unauthorized updates impossible. Every lifecycle change leaves a cryptographically signed blockchain record containing timestamps, which creates a cryptographically verifiable tracking record of product movement throughout the supply chain.

4.5 AI-Assisted Tracking and Narrative Module

The AI module can take structured lifecycle events data and generate summaries of tracking readable to clarify the product movement and status. This module enhances the usability of technical event logs by converting them into narratives that are easy to understand to enable consumers to derive product history without needing technical knowledge of blockchain transactions.

4.6 QR-Based Verification Module

The module creates product-specific QR codes that connect the physical products to their provenance, which is supported by blockchain. The QR code contains the lifecycle events and metadata when scanned, which are retrieved via the application interface, and instant verification of their authenticity is possible. This process serves as an interface between the tangible supply chain resources and the decentralized digital information.

4.7 Algorithm

Procedure PRODUCT_TRACE_AND_VERIFY (Product P, Event E)

1. Create product P and upload assets.
2. Metadata is stored in decentralized storage and reference content is received.
3. Metadata reference of records product creation on blockchain.
4. To every event E of the lifecycle, ensure validation of role of stakeholders and update product state.
5. Emit provenance tracking blockchain event.
6. Create narrative using AI on the basis of recorded lifecycle events.
7. Design QR code which connects the identifier of the product and verification interface.
8. Upon scanning one can access lifecycle data and see tracking summary.
9. Provide end of life product provenance to the consumer.

End Procedure

V. Results & Discussion

A. System Workflow Evaluation

SmartTrace prototype was tested through the simulation of realistic supply chain interactions such as the registration of the product, lifecycle updates, distributor assignment and the confirmation of the delivery. Various roles of the participants were authenticated using wallet-based authentication to confirm the role-restricted functions. The system also ensured the lifecycle transitions were recorded on the blockchain with the same synchronization with the IPFS metadata showing effective provenance tracking across the workflows.

B. Role-based Dashboard validation

Role specific visibility and operational permissions were tested by testing various user dashboards. Each of the manufacturers, suppliers, distributors, and consumers could only access the capabilities bestowed upon them in their respective positions and this prevented any attempts of lifecycle manipulation that were not authorised and ensured better operational visibility within the system.

C. Product Registration and Metadata Integrity

The process of product creation was put through testing by uploading metadata and images and connecting them to blockchain records by IPFS references. The system was able to maintain metadata integrity through operations of retrieval and this ensured that product information would not be tampered with once registered.

D. QR-Verification and Traceability

QR-verification was tested by creating product specific codes associated with blockchain transactions. Based on scanning interfaces consumers could access immutable lifecycle history and tracking narratives, and this is evidence of the success of QR codes in facilitating the easy process of authenticity checking.

E. Contract Enforcement and Security

Attempts on incorrect participant roles were wilfully made to make unauthorized lifecycle updates. In every situation, the smart contract did not allow invalid operations, and that ensured safe state transition and provided an effective audit trail of the product events.

F. Tracking and Ordering of Events and Timeline

Evaluation of the product timeline interface was done to ensure that the lifecycle events were chronologically ordered. The blockchain time stamps allowed precise sequence of transitions in products enabling users to readily read the flow of products and detect delays in the chain of supply chain.

G. Performance Observations

The measurements of performance were completed based on the observation of the time of the transactions confirmation, metadata retrieval latency, and QR verification responsiveness. Operation tracking used to take a matter of seconds depending on the conditions of the network, and repeated metadata access was also supported by caching.

H. User Interaction and Usability Testing

The informal usability testing showed that QR-reading verification and AI-generated summaries enhanced the user vision of the product status more than a conventional tracking interface. The participants could make an interpretation of product movement without having technical knowledge about the blockchain data.

I. Comparison to the Traditional Tracking Systems

The SmartTrace system offers provenance accounting and decentralized certificate authentication in comparison to centralized tracking systems. Combining blockchain traceability with easy visualization improves transparency and minimizes the use of tracking information under the control of the platform.

VI. Figures and Tables

Table 1: Functional Validation of SmartTrace Workflow

ID	Scenario	Result
TC-01	Wallet connection via MetaMask and network selection	Pass
TC-02	Role detection for manufacturer dashboard	Pass
TC-03	Role detection for consumer dashboard	Pass
TC-04	Product registration and marketplace listing	Pass
TC-05	Order placement by consumer	Pass
TC-06	Material request by manufacturer	Pass
TC-07	Dispatch confirmation and status update	Pass
TC-08	Automatic distributor assignment after production	Pass
TC-09	Delivery confirmation by distributor	Pass
TC-10	AI narrative generation for full order history	Pass
TC-11	Unauthorized access blocked with error message	Pass

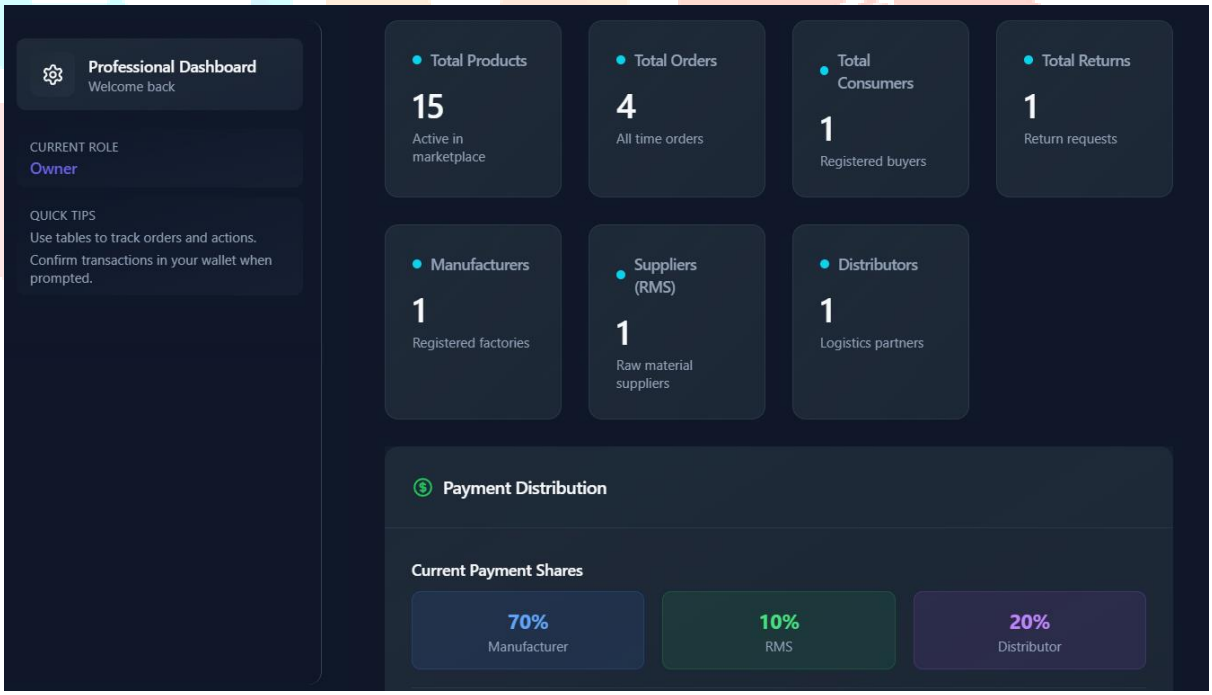

Figure 2: Owner dashboard summarizing products, participants, and payment distribution.

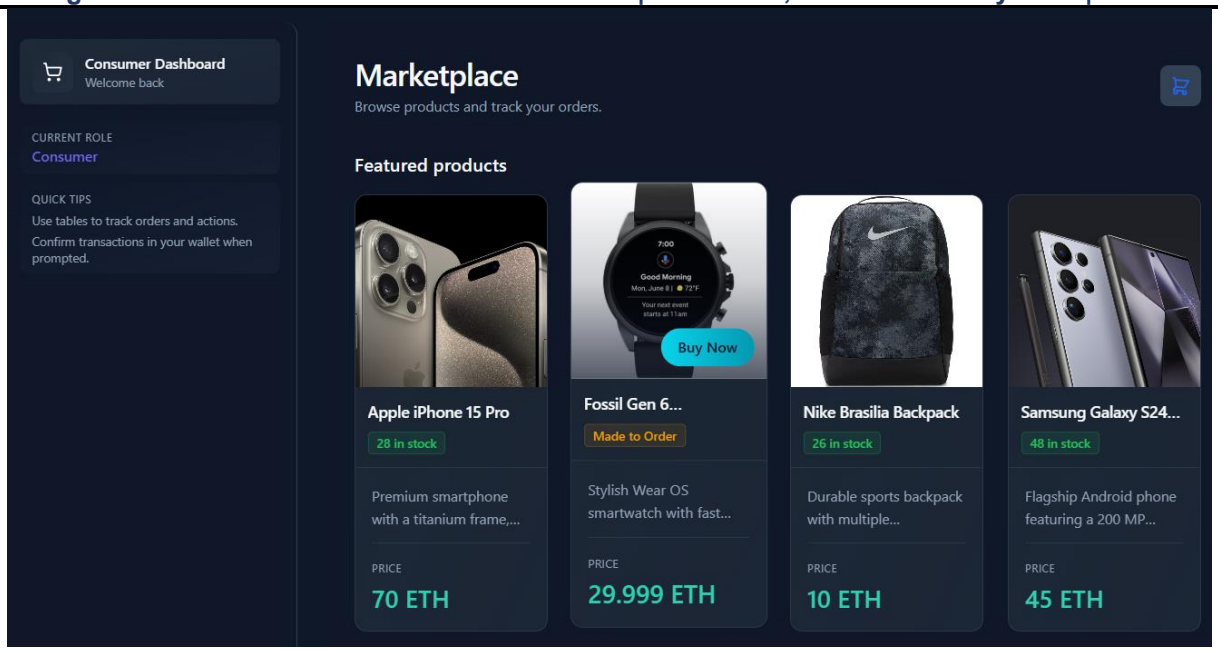

Figure 3: The consumer market with blockchain-registered products.

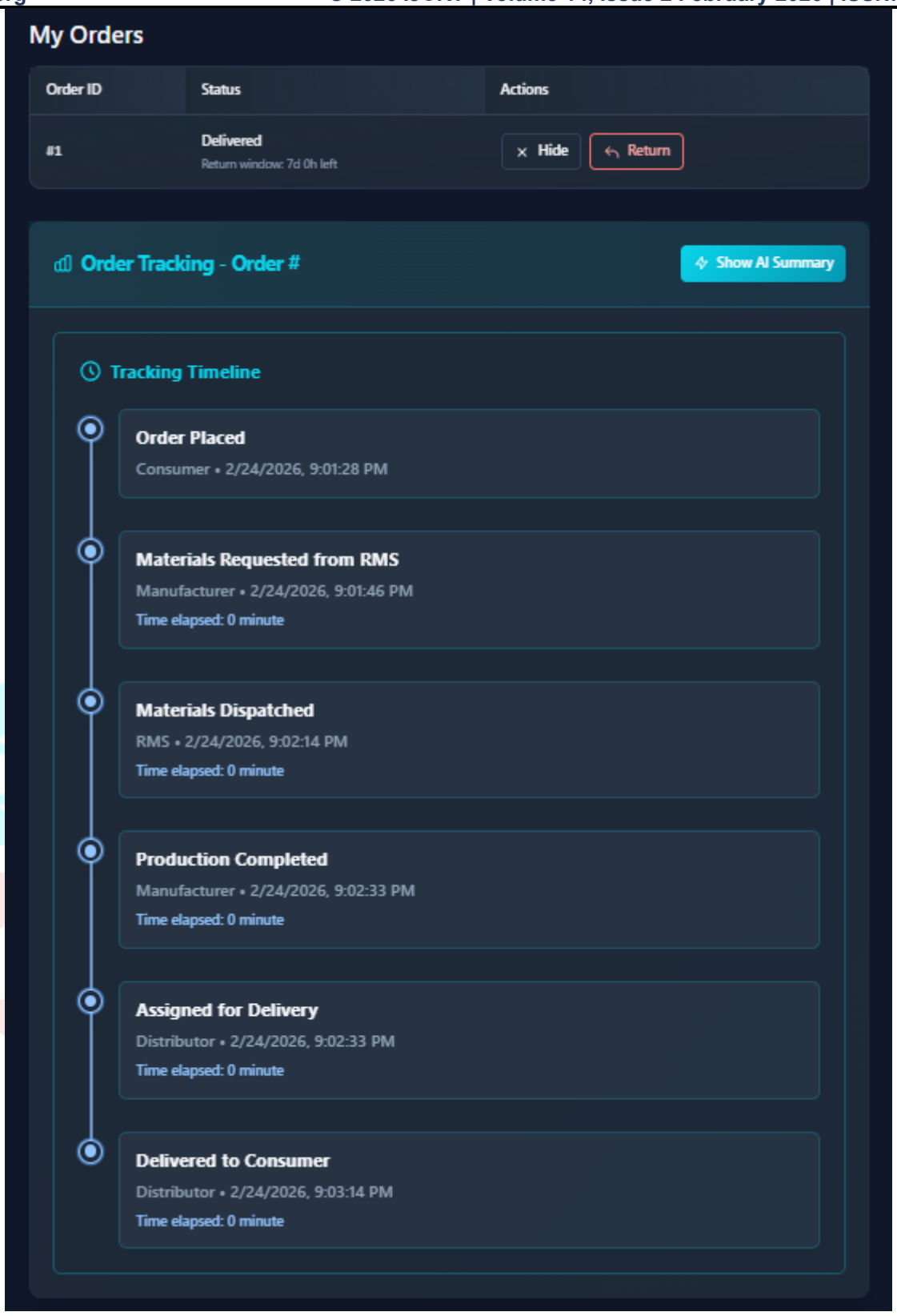

Figure 4: Timeline of order tracking with lifecycle events and time.

VII. Future Scope

The SmartTrace framework can offer a baseline on how to build transparency and authenticity checking on e-commerce supply chains; nevertheless, a number of enhancements can be made to scale and enable a wider adoption. Further labor can be devoted to the implementation of the system on Layer-2 blockchain networks to minimize the costs of transactions and increase the speed of their confirmation, which will make it possible to cover high-volume marketsplace conditions. An opportunity to integrate with IoT-based tracking devices to monitor the logistics can also be considered in order to automatize the lifecycle update and to reduce the manual intervention with the product movements.

Usability-wise, these issues can be mitigated by mobile-friendly interfaces and easier wallet onboarding processes to develop a more accessible interface to non-technical users and more consumers to participate in decentralized verification. Also, it is possible to add sophisticated analytics and anomaly detection systems to spot suspicious supply chain actions and possible counterfeit operations. The other relevant direction is that of interoperability with current e-commerce platforms and logistics APIs, through which, the decentralized traceability can be integrated with the off-the-shelf marketplace infrastructures in a seamless manner. These additions can make AI-aided blockchain traceability systems more viable, scalable, and adoptable in the digital trade environment in the future.

VIII. Conclusion

The paper has introduced SmartTrace, an AI-based blockchain architecture that enhances the supply chain transparency and authenticity check in e-commerce. Customer lifetime tracking based on smart contracts, decentralized storage of metadata via IPFS, and verification using QRs are combined in the system to deliver consumer-level visibility and proving resistant to tampering. The addition of generative AI also makes it easier to use, turning structured blockchain events into understandable product tracking stories.

The deployed prototype showed secure roles-based operations, sound lifecycle tracking as well as efficient consumer verification under simulated workflows. The proposed system has a better auditability, is decentralized and it provides better understanding of the product movement than the traditional centralized methods of tracking. On the whole, SmartTrace creates a sensible strategy of improving consumer trust and minimizing risks of counterfeit in the contemporary digital trade atmosphere.

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