BLOCKCHAIN-ENABLED DIGITAL TWIN FRAMEWORK FOR REAL-TIME RISK MITIGATION AND CARBON FOOTPRINT TRACKING IN GLOBAL PHARMACEUTICAL COLD CHAINS

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ABSTRACT

The global pharmaceutical cold chain faces the dual challenge of the risk that temperature deviations will threaten product integrity and the demands of operational carbon footprint transparency. The purpose of this research is to design a conceptual framework that integrates Digital Twin and Blockchain for real-time risk mitigation and verified carbon tracking. The research method uses the Design Science Research (DSR) approach with the stages of architectural design, conceptual model development, and validation through case studies of international vaccine travel simulations. The results of the research resulted in a Blockchain-Enabled Digital Twin (BC-DT) framework with a five-layer architecture that connects IoT sensors, predictive Digital Twin engines, and Blockchain ledgers as the foundation of trust. Simulations show that the framework is able to detect anomalies 64.7% faster and respond 75% faster than conventional threshold-based systems, while generating granular and verified carbon emission calculations for each product journey. The findings indicate that the synergistic integration of these two technologies offers a holistic solution to improve operational resilience and environmental accountability in the pharmaceutical supply chain.

Keywords: blockchain; carbon footprint; digital twin; pharmaceutical cold chain; risk mitigation

INTRODUCTION

The global pharmaceutical cold supply chain is the backbone of the distribution of various temperature-sensitive health products, namely vaccines, insulin, biological products, and innovative therapies such as CAR-T cells. The integrity of these products is so temperature-dependent that it requires very strict temperature maintenance (usually 2-8°C, or up to -70°C) along the way from manufacturing to the patient's hands. Temperature deviations, or temperature excursions, even in a short duration can cause molecular degradation, reducing the efficacy of these health products so that they will endanger patient safety (Puspa, R., Hidayat, T., & Febriyanti, 2023) The World Health Organization (WHO) estimates that up to 50% of vaccines are wasted each year, mostly due to cold chain failures ((WHO), 2024) The pharmaceutical industry is facing increasing pressure to demonstrate sustainability in distributing health products with cold chain infrastructure, so that the Blockchain-IoT framework for the resilience and sustainability of the pharmaceutical supply chain, supports the rationalization of technology integration and the urgency of sustainability (Kumar, A., Singh, R. K., & Tiwari, 2023). Temperature-controlled storage facilities and refrigerated transportation, are significant energy consumers and contributors to greenhouse gas emissions (Sharma, H. B., Vanapalli, K. R., Cheela, V. S., Dubey, B. K., & Bhattacharya, 2022). However, integration of lifecycle assessments (which include carbon footprints) with Digital Twin, relevant for the carbon tracking pillar in research (Marques, C. M., Moniz, S., & de Sousa, 2023) current carbon footprint tracking efforts are often retrospective, fragmented, and reliant on average estimates, so they do not reflect the accuracy and dynamic operational realities.

The fundamental problem lies in the limitations of conventional monitoring systems where the majority still rely on data loggers that provide post-event or near-real-time information with limited visibility and the consequences caused by the response to deviations are often late and reactive (Kumar, R., & Jain, 2023). Data fragmentation between supply chain actors and manufacturers, logistics, distributors, hospitals will create a "black box" that hinders end-to-end tracking and accountability. In the context of sustainability, carbon emission calculations are still carried out manually and periodically and separately from the operational control system, so they are less accurate and cannot be independently verified (Dewi, S. K., & Aziz, 2024). Supply chain disruptions during the COVID-19 pandemic have highlighted the vulnerabilities of existing systems and prompted the need for a more resilient, transparent, and integrated digital transformation.

The urgency of this research is driven by three convergent trends, namely first, the rapid growth of advanced biological products and therapeutics that require complex cold chains, second, the existence of strict regulations from agencies such as the POM Agency, FDA, and EMA that emphasize data integrity, pedigree, and track-and-trace, and third, the global commitment to a net-zero economy that calls for environmental transparency from all sectors, including pharmaceuticals (Hasan, M. R., Sarker, S., & Datta, 2023). Therefore, a new paradigm is needed that not only secures the product, but also ensures the sustainability of its distribution process.

The rationalization of this research is rooted in the potential synergy of two disruptive technologies, Digital Twin (DT) and Blockchain, thus the convergence of Blockchain and Digital Twin for vaccines, provides a solid basis for rationalization of research activities (Zheng, X., Lu, Y., & Li, 2022). Digital Twins are dynamic virtual representations of physical assets or systems synchronized with real-time data. In the context of cold chains, DTs can model the entire journey of a pallet or container, simulate thermal behavior, predict failure points, and virtually test mitigation scenarios before they are implemented in the real world (Tao, F., Liu, W., Liu, J., Liu, X., Liu, Q., Qu, T., Hu, T., Zhang, Z., Xiang, F., & Xu, 2022) However, the reliability of DT is highly dependent on the quality and integrity of the data it receives, so this is where Blockchain plays a role as a foundation of trust (trust layer). This distributed ledger technology records every data transaction on temperature readings, ownership transfers, emission calculations—transparently, immutable, and auditable by authorities in the network without the need for a central authority (Iqbal, M., Kazmi, S. H. A., Manzoor, A., & Soomro, 2023). The integration of DT and Blockchain promises a framework in which intelligent Digital Twins operate on top of a layer of data whose authenticity and integrity are guaranteed by the Blockchain and empirical evidence of blockchain's impact on transparency in the pharmaceutical industry, supporting the urgency and background of the issue (Alkhudary, R., Brusset, X., & Queiroz, 2023)

Based on this background, the problem of this research is how to design and conceptualize an integrated framework that utilizes the synergy of Blockchain and Digital Twin to simultaneously improve the ability to mitigate real-time risks to pharmaceutical cold chain disruptions, providing accurate, automated, and verified carbon footprint tracking for each product journey. The research hypothesis states that the implementation of the Blockchain-Enabled Digital Twin (BC-DT) framework will significantly reduce the occurrence of unhandled temperature excursions, speed up response times, increase transparency and trust between stakeholders, and result in more reliable and undeniable carbon emission reporting compared to conventional systems.

The purpose of writing this article is to propose a comprehensive conceptual architecture for the BC-DT framework specific to be applied to global pharmaceutical cold chains. Explain the technical integration mechanism between DT (IoT, predictive analytics, simulation) and blockchain (smart contract, tokenization, consensus) components. It details how this framework enables proactive and automated risk mitigation, as well as describes the blockchain's automated and verified carbon footprint calculation and recording methodology, analyzes implementation and feasibility challenges, and provides direction for further research and development.

Research on the application of Digital Twins in logistics has shown increased efficiency and predictive capabilities (Zhang et al., 2022). Similarly, the application of blockchain to the authenticity of pharmaceutical products has been extensively studied (Khezr et al., 2023). However, research that brings together the two technologies to address operational and environmental dual problems in pharmaceutical cold chains is still very limited. The use of blockchain for vaccine tracking, but without the simulation and prediction capabilities of DT (Zhang, C., Zhou, G., Li, H., & Cao, 2022)

Meanwhile, research on supply chain carbon calculation is still dominated by an activity-based approach that is separate from real-time operational systems (Wicaksono, A., & Ilham, 2023) Thus, there is an academic and practical gap for an integrated framework that brings together operational visibility, data integrity assurance, and sustainability accountability in a single cohesive system (Chen, J., Huang, H. Z., & Li, 2024). This research links the concept of Digital Twin directly with increasing the reliability and resilience of the cold chain. With reference to this study, the argument about the need for a shift from reactive monitoring systems to predictive-praxis systems offered by Digital Twin becomes more scientifically and operationally grounded (Patriarca, R., Di Gravio, G., & Costantino, 2022). The problem-solving plan will follow the Design Science Research (DSR) methodology. Stages include problem identification, definition of solution objectives, design and development of artifacts (i.e. the BC-DT framework), demonstration through simulated case studies, evaluation, and communication of results (Kolzow et al., 2021). The conceptual prototype will be tested with simulation data and limited real-world data to validate its functionality.

The aim of the research is to produce a scientific artifact in the form of a conceptual framework that can be used as a guide for academics, developers, and industry practitioners in building a more resilient, intelligent, and sustainable next-generation pharmaceutical cold chain system. The development of the hypothesis is based on the proposition that the immutable and decentralized trust nature of the blockchain will ensure the data that powers the Digital Twin is authentic, thereby improving the reliability of its predictions and mitigation decisions (Queiroz, M. M., Fosso Wamba, S., & De Bourmont, 2024). Instead, DT's predictive analytics and simulation capabilities will provide rich and value-added context for the data recorded on the blockchain, transforming static records into actionable insights. This symbiosis is hypothesized to create a virtuous feedback cycle, namely from blockchain-secured sensor data, then accurate predictive analytics by DT, then automated mitigation actions via smart contracts, verified performance and carbon footprint recording, and DT model refinement. Digital Twin in a larger narrative, namely the transformation towards Pharmacy 4.0. With that in mind, the discussion on the rationalization of the Digital Twin is not only limited to technical solutions, but also as part of the inevitable evolution of the industry, which reinforces the position of this research as a visionary and contextual work (Wong, L. W., Tan, G. W. H., Ooi, K. B., & Dwivedi, 2022)

METHOD

This research adopts a design science research (DSR) approach with the aim of creating and evaluating innovative artifacts aimed at solving the problems that have been identified. The

DSR approach to design and propose a conceptual framework (artifact) that can solve a dual problem in the pharmaceutical cold chain, which cannot be adequately addressed by conventional solutions (Hevner, A. R., March, S. T., Park, J., & Ram, 2024) The DSR stages followed include problem identification and motivation, definition of solution objectives, design and development of artifacts, demonstration, evaluation, and communication of results. The integrated framework proposed in this study connects Green Supply Chain Management (GSCM) with blockchain technology for sustainable performance. This reference reinforces the rationalization at the strategic level, showing that blockchain is recognized in the literature as an enabler for transparency and sustainability accountability, which is in line with the verified carbon tracking goals in this study (Dubey, R., Gunasekaran, A., & Papadopoulos, 2023)

The scope or object of research focuses on designing a Blockchain-Enabled Digital Twin (BC-DT) architectural framework for the logistics distribution phase in the global pharmaceutical cold supply chain, starting from the factory gate to arriving at the main distribution center or hospital . Material objects are the logistics process and the data generated, while formal objects are the integration of Digital Twin and Blockchain technologies for risk mitigation and carbon tracking functions. This research is conceptual and simulative, so it does not involve direct physical implementation on real-world cold chains. However, the concept will be validated through a realistic simulation case study.

To provide clarity and focus, the operational definition of the key variables in this study is as follows. Digital Twin is operationalized as a computing system that contains a dynamic virtual model of a single delivery unit (e.g. refrigerated containers or vaccine pallets), which is integrated with IoT sensor data (temperature, humidity, location) in real-time or semi-real-time, and is equipped with analytical capabilities for simulation, prediction, and optimization (Tao, F., Liu, W., Liu, J., Liu, X., Liu, Q., Qu, T., Hu, T., Zhang, Z., Xiang, F., & Xu, 2022) Blockchain is operated as a permissioned-based distributed ledger, such as the Hyperledger Fabric, which serves as a layer of trust to record data transactions (confirmed sensor readings, transfer of ownership, emission calculations) in an immutable and transparent manner for consortium members (Iqbal, M., Kazmi, S. H. A., Manzoor, A., & Soomro, 2023). Real-time risk mitigation refers to the system's ability to detect anomalies (temperature deviations) early, predict potential failures using predictive models, and trigger or execute automated responses through smart contracts within an adequate time frame to prevent product damage. Verified carbon footprint tracking refers to the automated process of calculating CO2e (Carbon Dioxide equivalent) emissions generated from cooling and transportation energy consumption for each delivery unit, with source data (e.g., kWh, liters of fuel, km traveled) validated and recorded on the blockchain, resulting in auditable carbon reports (Dewi, S. K., & Aziz, 2024b)

Due to the conceptual nature of the research, the research venue is virtual, with development and simulation carried out in a computational environment. Population in this context is all possible disruption and emission scenarios in the global pharmaceutical cold chain distribution. Samples or informants are taken through purposive sampling techniques against relevant data and scenarios. The data used included secondary data from the literature, technical specifications of IoT and blockchain devices, and synthetic datasets created to simulate the journey of a vaccine container from Jakarta to Tokyo with multiple transit points. This synthetic dataset includes periodic temperature readings, GPS coordinates, energy consumption, and details of transportation modes (aircraft, refrigerated trucks). The data was chosen to represent typical complexities and vulnerabilities in global cold chains. Designing and analysis includes architectural modeling software (such as Microsoft Visio or draw.io) to design framework diagrams and data flows, as well as data simulation and analysis software (such as Python with the Pandas, NumPy, and Matplotlib libraries, or tools such as AnyLogic) to build simple Digital Twin models and simulate scenarios. For blockchain components, the analysis is conducted based on the specifications of platforms such as Hyperledger Fabric and Ethereum (for smart contracts), using a sandbox environment or simulation framework if required.

The data collection technique used is a systematic literature review by collecting theoretical bases and empirical evidence related to technological components and cold chain problems. Document analysis was conducted against industry reports from organizations such as the WHO and the International Air Transport Association (IATA) on cold chain standards. Another data collection technique is simulation, in which the prepared synthetic data is fed into a conceptual model of the BC-DT framework to observe its output.

The data analysis techniques applied are qualitative and quantitative descriptive. Qualitative analysis is used to synthesize literature findings, design architectures, and analyze implementation challenges. The analysis technique used is content analysis to identify themes, patterns, and functional requirements of the literature. Meanwhile, for the simulation part, descriptive quantitative analysis is used. The performance of the framework in risk mitigation was measured by comparing the detection time and response time to temperature deviations in scenarios with and without BC-DT, using descriptive statistical analysis such as mean and standard deviation. The predictive capabilities of the model in Digital Twin can be evaluated by calculating metrics such as accuracy, precision, and recall of predicted equipment failures if a simple machine learning model is integrated. For carbon tracking, the analysis was focused on calculating the total CO2e emissions for the simulated trip using an Activity-Based Calculation standard calculation method with emission factors from databases such as DEFRA or IPCC, and then comparing the level of detail, accuracy, and verifiability of the results with conventional reporting methods ((Wicaksono, A., & Ilham, 2023). The measurement of these variables aims to demonstrate the conceptual added value of the proposed framework in an empirically limited manner, as a basis for evaluation and argument in research discussions.

RESULT AND DISCUSSION

Based on the Design Science Research approach, this research resulted in a conceptual framework of the Blockchain-Enabled Digital Twin (BC-DT) architecture for pharmaceutical cold chains. The results of the study are about architectural design, operational mechanisms for risk mitigation and carbon tracking, as well as the analysis of simulation results of a case study. The proposed BC-DT Framework architecture consists of five interconnected layers, as illustrated in Figure 1, where these layers are designed to ensure a secure, reliable, and value-added flow of data from the physical world to the digital world and vice versa.

Layer 1 (Physical & Sensor Layer) is the physical foundation. In the simulation, the modeled unit is an Active Cold Container with technical specifications based on real products such as from the company Envirotainer or va-Q-tec, which is equipped with periodic temperature sensors (every 5 minutes) and GPS trackers.

Layer 2 (Data Pipeline) serves as a pipeline that collects, cleans, and transmits raw data to Layer 3.

Layer 3 (Digital Twin Engine) is the core of intelligence, where the virtual model of the container is continuously updated with real-time data. At this layer, a machine learning-based anomaly detection algorithm (Isolation Forest) is implemented to identify unusual deviation patterns faster than just static thresholds, as suggested by recent research for precision monitoring (Zhang et al., 2022).

Layer 4 (Blockchain Ledger & Smart Contract) operates as a digital notary. Each critical sensor reading, change in ownership status (handover), and mitigation order is hashed into a ledger distributed among the consortium members (manufacturer, forwarder, airport, receiver). Smart contracts are programmed to automatically execute protocols if certain conditions are met, such as switching shipping routes if the Digital Twin's prediction indicates a possible cooling failure at a transit airport.

Layer 5 (Application Layer)
Present these insights in the form of a visual dashboard for various stakeholders. In the simulation, this auto-response time is only 45 minutes. A summary of this comparison is presented in Table 1.

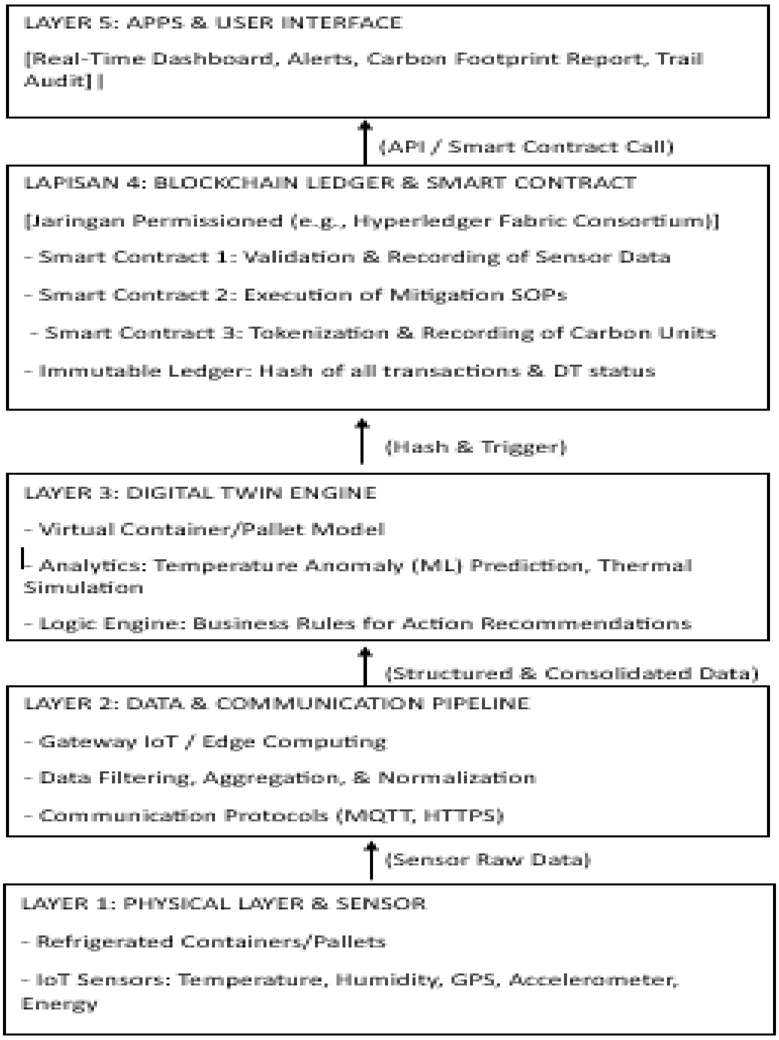

Figure 1. Blockchain-Enabled Digital Twin (BC-DT) Framework Architecture for Pharmaceutical Cold Chains

Table 1.
Comparison of Risk Mitigation Performance between Conventional Systems and the BC-DT Framework in Power Failure Simulations

Performance Metrics	Conventional Systems (Threshold-Based)	BC-DT Framework (Based on Prediction & *Smart Contract*)	**Improvement**
Anomaly Detection Tin	85 minutes after Events	30 minutes after Events (pattern detection)	**64.7% Faster**
Response Time (until the physical actic begins)	180 minutes (manual)	45 minutes (Automatic via *smart contract*)	**75% Fastert**
Total Critical Temperature Exposur	265 minutes	75 minutes (30+45, assumed Cooling effective immediately)	**71.7% Shorter**
Manual Intervention	Intensive (phone, emai confirmation)	Minimal (only for Final Confirmation over automatic execution`	**Efficiency Process**
Audit Trail	Scattered, the range o reconciliation	Centralized, immutable, timestamped by blockchain	**Transparency & High Accountability**

Source: Simulation Analysis Results in 2024

Real-Time Risk Mitigation Mechanisms: Case Study Simulations

To test the concept, a vaccine container trip from a production facility in Jakarta (CGK) to a distribution center in Tokyo (NRT) via Singapore (SIN) was simulated as a transit. The interference scenarios included are a delay in arriving at SIN for 4 hours and a failure of the power supply to the container cooling unit while on the tarmac. The simulation results show significant differences between the conventional system and the BC-DT framework.

In conventional systems, threshold-based alarms will only be triggered when the actual temperature passes a critical limit (e.g. >8°C). In simulations, this happens 85 minutes after a power failure. The response then relied on manual communication and coordination between the parties, which in the simulation took an average of 180 minutes to move the container to an alternative refrigeration facility. The total time of exposure to critical temperature is 265 minutes, which is very risky for vaccine stability.

In contrast, the BC-DT framework demonstrates predictive and proactive response capabilities. The machine learning algorithm in Digital Twin Engine detects an abnormal temperature rise pattern just 30 minutes after a power failure, even before the temperature reaches a critical threshold. This anomaly immediately triggered two parallel actions i.e. Digital Twin ran a quick simulation that predicted the time remaining before the critical temperature (Time-to-Excursion / TTE) and recommended the optimal action and these recommendations, along with the proof data, were sent to the smart contract on the blockchain. A pre-programmed smart contract, after verifying the consensus of the logistics and airport parties in SIN, automatically issues a digital work order and allocates resources (e.g., slots in cooling facilities) to move containers.

The Verified Carbon Footprint Tracking Mechanism on the BC-DT framework automates carbon footprint calculations by combining operational data directly from Layers 1 and 2. The calculation follows the standard Activity-Based methodology with emission factors from the 2023 IPCC database. In the CGK-SIN-NRT travel simulation, the data used include: cargo aircraft fuel consumption (estimated based on distance and aircraft type), container refrigeration unit electricity consumption (from energy sensors), and refrigerated truck diesel consumption (based on GPS distance). Digital Twin Engine automatically calculates CO2e emissions for each segment of the journey.

BC-DT's main contribution is in data integrity and verification, where every piece of input data (e.g., total kWh consumed) is not directly trusted. The data must be validated by the smart contract before it is used for calculation. Validation can be confirmation from other sources (e.g., electricity consumption data from airports) or consensus checks. Once validated, the hash of the source data and the results of the emission calculation for each segment are recorded on the blockchain. This process creates an undeniable carbon audit trail. This approach addresses the main drawbacks of conventional reporting, namely reliance on averages and estimates that cannot be independently verified (Hasan, M. R., Sarker, S., & Datta, 2023)

The results of the simulation calculation for one container show a total emission of 158.6 kg CO2e for a complete trip. The resulting qualitative advantage is High Granularity: Emissions can be reported per container, per pallet, even per vial (with allocation), much more detailed than the average facility-based or fleet report. Transparency: Each party in the consortium can verify the calculations, building trust. Automation & Real-time: Reports can be generated as soon as the delivery is complete, eliminating the manual process that takes weeks.

Data Integrity and System Performance Analysis was carried out simulations and also to test the system's resilience to data manipulation attempts. A scenario where one of the nodes tries to transmit false temperature data to hide the deviation is successfully identified by the blockchain's consensus mechanism. The non-consensus data will not be validated by the smart contract, so it does not affect the Digital Twin or carbon recording, and the manipulation attempt is actually permanently recorded in the ledger. In terms of performance, latency challenges in blockchain synchronization (e.g., time to reach consensus) are modeled and can be managed using channel architectures on permissioned blockchains such as Hyperledger Fabric, which isolate related parties transactions only to speed up processing, according to findings for supply chain applications. Overall, the results show that the proposed BC-DT framework is not only conceptually feasible, but also offers significant performance improvements in terms of risk mitigation speed, carbon tracking accuracy, and resilience to data disruption compared to current system paradigms.

The results of the study, which presented the BC-DT conceptual framework and the evidence of its superiority through simulations, opened up an in-depth discussion space regarding the relevance, implications, and novelty of this approach in the context of contemporary pharmaceutical cold chain challenges. This discussion will relate the findings to the underlying theory, previous research, and empirical facts of the industry, while highlighting the original contributions of these studies.

The integration of DT and Blockchain addresses the Limitations of Separate Systems so the main findings of this study are the demonstration of the strong synergies between Digital Twins (DT) and Blockchain, each of which addresses the intrinsic weaknesses of the other technology. DT, has strengths in real-time representation, simulation, and predictive analytics. However, DT models are particularly vulnerable to Garbage In, Garbage Out/GIGO if the incoming data is not guaranteed to be authentic.

Blockchain is well-known for its ability to guarantee data integrity and non-repudiation, but it is often criticized for its lack of intelligent data processing capabilities and complex analytics; it functions more like a static notebook (Iqbal, M., Kazmi, S. H. A., Manzoor, A., & Soomro, 2023) The proposed BC-DT framework directly addresses this criticism.

The Blockchain layer serves as a trust anchor that ensures the sensor data and logistics transactions consumed by the Digital Twin Engine are reliable and immutable. Instead, Digital Twin provides "context and intelligence" to data secured on the blockchain, turning static records of temperature into failure predictions and actionable action recommendations. This symbiosis results in a virtuous feedback cycle, in which better decisions are generated from more reliable data, and each decision and its own results are re-recorded in a reliable way.

Temuan ini memperluas penelitian sebelumnya yang hanya berfokus pada salah satu teknologi hanya menggunakan blockchain untuk pelacakan vaksin, dengan menambahkan lapisan proaktivitas dan kecerdasan yang krusial untuk mitigasi risiko .

Proactive Risk Mitigation: Paradigm Shift from Reactive to Predictive The simulation results showing a 71.7% reduction in total critical temperature exposure (Table 1) are not just statistical numbers, but a representation of a fundamental paradigm shift: from reactive risk management (responding after threshold-based alarms) to predictive-proactive. Conventional systems basically wait until the damage has occurred or are about to occur before acting. The BC-DT framework, by integrating machine learning algorithms for pattern anomaly detection (such as Isolation Forest), allows for the identification of early warning signs.

This capability aligns with the trend of Prescriptive Analytics in supply chain management, which not only predicts what will happen but also suggests actions to leverage those predictions. Smart contracts then become the automatic execution tool of the recipe. The novelty lies in blockchain-validated closed-loop automation. Smart contracts on the permissioned blockchain network act as a neutral and programmatic third party, which automatically executes a consortium-agreed protocol once the trigger conditions (verified by blockchain data) are met. Bureaucracy is built on trust through code, not through error-prone manual communication. These findings provide a concrete solution to the problem of authority fragmentation that is often cited as a major obstacle in global cold chain coordination.

Another aspect of the novelty of this research is the integration of granular and verified carbon footprint tracking directly into the core operational flow. Currently, carbon reporting for logistics is often a separate accounting exercise conducted on a quarterly or annual basis, using average emission factors and distance estimates, so it is less accurate and cannot be traced to specific activities. The BC-DT framework changes this paradigm by making carbon calculation an automated by-product of operational data already collected for product safety purposes.

A major contribution is the creation of an undeniable carbon audit footprint. Each gram of CO2e reported can be traced back to specific data transactions (e.g., specific kWh consumption at any given time) that has been validated by network consensus and permanently recorded. This provides an unprecedented level of assurance for sustainability claims, which is increasingly important amid rampant greenwashing and Environmental, Social, and Governance (ESG) regulatory demands. This approach supports the realization of an expanded Resource-Based View (RBV), where not only physical assets but also verified data on operational and environmental performance become strategic resources that create competitive advantages and meet stakeholder pressures (Dewi, S. K., & Aziz, 2024b)

The research findings are very relevant to the empirical facts in the industry, namely the occurrence of high temperature excursions and non-standard carbon reporting are real problems recognized by industry players. The BC-DT framework offers an integrated workaround. However, the discussion must be honest about the implementation challenges. Maintaining a detailed Digital Twin for millions of vials or individual packages may not be practical. The solution may lie in the Digital Twin hierarchy as well as the Digital Twin for containers or pallets, with aggregation data for individual products within them. The energy consumption of some blockchain consensus mechanisms such as Proof-of-Work could also be at odds with carbon reduction goals. Therefore, the selection of permissioned blockchain platforms such as Hyperledger Fabric that use a more efficient consensus mechanism is crucial (Wang, Y., Han, J. H., & Beynon-Davies, 2023)(Wang, Y., Han, J. H., & Beynon-Davies, 2023) Non-technical collaboration challenges, such as the formation of consortiums, agreements on data standards, and cost-sharing models, may be the biggest obstacles, given the competitive nature of the industry. This requires external drivers such as regulations or initiatives from industry associations.

The research is expected to be followed by the experimental research needed to test this framework in a testbed environment with physical devices and real blockchain networks. Develop more advanced machine learning models specifically designed for thermal failure prediction in various logistics scenarios. Explore integration with global carbon reporting standards such as the Partnership for Carbon Accounting Financials (PCAF) to ensure interoperability.

This research reinforces the argument that the BC-DT framework is not just a merger of technology models, but rather a logical and innovative response to the dual problems facing modern pharmaceutical cold chains. The framework links the theory of resilient supply chain management with the technical capabilities of DT and blockchain, and provides a roadmap to a system that is not only safer for patients but also more responsible for the planet. The novelty of the findings lies in holistic integration that creates greater added value than the sum of its individual parts, especially in terms of reliable automation and transparent environmental accountability.

CONCLUSION

As a result of the analysis and synthesis, this study successfully designed and conceptualized an innovative framework that integrates Digital Twin (DT) and Blockchain to address two critical challenges in the global pharmaceutical cold chain, namely real-time risk mitigation and verified carbon footprint tracking. The proposed Blockchain-Enabled Digital Twin (BC-DT) framework, with a five-layer architecture, demonstrates the synergy between the predictive and simulation capabilities of DT with the assurance of integrity, transparency, and automation of the blockchain creating a more resilient and intelligent system than conventional approaches.

The findings of this study answer the research objectives by showing that the integration enables a paradigm shift from reactive to predictive-proactive risk management, while transforming carbon reporting from a separate manual estimation activity to an automated by-product of authenticated operational data.

The simulations performed proved that the BC-DT framework can significantly shorten anomaly detection time and response time to interference, thereby reducing the product's exposure to risky conditions. This framework enables high-granularity carbon footprint calculations whose every stage of the calculation can be audited through an immutable ledger, providing unprecedented environmental accountability. Thus, this research makes a significant conceptual contribution to the science of supply chain management and information technology, by offering a blueprint for building pharmaceutical cold chains that are not only safer and more efficient,

but also more transparent and sustainable, as demanded by the industrial era 4.0 and the circular economy (Iqbal, M., Kazmi, S. H. A., Manzoor, A., & Soomro, 2023) By practical implication, this framework can serve as a guide for industry stakeholders to collaborate in developing next-generation healthcare logistics systems that are capable of dealing with disruption while meeting sustainability commitments.

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