

A Blockchain-Integrated Digital Twin Framework for Supply Chain Visibility and Traceability

Sajjad Ali Memon ^{a, *}, Faheem Ahmed Abbasi ^b, Muhammad Ali Memon ^b, Muhammad Ali Nizamani ^b

^a Ph.D. Scholar Dr. A.H.S. Bukhari Post Graduate Centre of Information and Communication Technology, University of Sindh, Jamshoro

^b Department of Information Technology, University of Sindh, Jamshoro

* Corresponding author: sajjad.muet@gmail.com

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ABSTRACT

This research addresses the growing challenge of supply chain digitalization by emphasizing the importance of information exchange and cooperation. By extending the concept of digital twins, the study reviews, develops, and conceptualizes the emerging notion of Digital Supply Chain Twin (DSCT). While research on digital twin technology is continuous, data from many industry projects is easily accessible; its implementation within supply chains is growing as a multidisciplinary field, evolving from decades of advancements in supply chain digitization. While supply chains have employed digital twins, the idea of digitizing supply chains is still relatively emerging, with imprecise notions that go beyond important metaphors (such as visibility and provenance). The primary objective is to establish organizational and technological systems that enable supply chains to be monitored and controlled from integrated digital interfaces (such as a dashboard screen). Following an extensive literature review on the interactions between digital twins, digital supply chains, and digital technologies (such as blockchain), we propose a Digital Supply Chain Twin System (DSCTS) framework, specify an important gap (which we refer to as identifiability), and frame our findings in the absence of practical use cases. In the end, the proposed framework is applied to the expired medicine recycling of a simple reverse pharmaceutical supply chain.

1. Introduction

Digitalization refers to the use and integration of digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), and cloud computing into processes, operations, services, and existing systems to improve visibility, efficiency, decision-making, and overall performance. Today, digitalization has become a dominant paradigm in both societal and economic contexts. These technologies are revolutionizing modern industries by transforming conventional processes into data-driven intelligent systems [1]. Similar to industries such as finance, healthcare, and manufacturing, supply chain management (SCM) is also transforming its supply

chain (SC) networks to connect, visualize, monitor, and optimize its (SC) processes and services. While organizations are widely using these technologies for information sharing and collaboration among all SC stakeholders—the foundation of effective SC operations—there still remains a significant reliance on labour-intensive activities, including manual search for vendors, tracking of products and components, or planning overseas shipping [2]. Stakeholders in an SC often have limited visibility regarding their primary suppliers or customers [3]. Despite notable advancements in SCs, the notion of digital SCs is still an imprecise and evolving concept [4], we describe it as having the ability to use digital technologies to

visualize, monitor, and optimize SC processes in real time. The next evolution toward achieving complete SC digitalization is the use of digital twin (DT) technology. Leading companies such as Microsoft, IBM, and Amazon have made significant investments in the deployment of digital twins (DTs) due to their several benefits in a variety of applications, such as virtually monitoring and analysing physical processes and systems, forecasting product failures, analysing waste and raw material utilization, etc. [5]. For example, in Singapore, DHL (Dalsey, Hillblom, and Lynn) has built DTs of Tetra Pak's warehouse as part of their SCM system [6]. However, this research differs from previous research in that it focuses on the DT of SCs instead of the application of DT in SCs. To phrase it simply, we simulate the SC activities rather than how the DT of the physical SC can enhance SC performance. We emphasize that our approach goes much beyond limited IT system integrations between SC entities (such as manufacturers and customers), such as an email or e-commerce platforms. Our approach views an SC from the perspective of networks of computers and services. Here, we employ a distributed network of digital and physical entities to model the entire SC. By entities, we refer to products, parts, materials, as well as data, financial flows, workers, related documents, events, etc. Similar to IoT, in which an electronic device (such as a remote-controlled robot) sends and receives data. We study the idea that each entity in the SC has a corresponding virtual replica, based on its type. This aligns with the concept of the DT paradigm, where physical objects or processes have their corresponding digital representations (the DTs). The notion of DT technology can also be applied to non-physical activities, such as those that rely on human interaction and extend beyond a single business organization. This multiple organizational perspective gives rise to the concept of Digital Supply Chain Twin System (DSCTS), the main objective of this study. A DSCTS is an integrated system of systems that virtually models the entire SC instead of individual processes.

While the concept of DTs is not entirely new, it remains a developing field that requires further research and systematic organization. The current body of research remains at early conceptual stages (e.g., [7], [8], [9]), with few applications focusing on product-level DTs. As mentioned, SC automation is only feasible to a certain extent, and many processes still rely on human intervention. For example, when pharmaceutical products such as medicines are supplied from a distant supplier, both physical transport and a signature are necessary. Once the medicines are distributed to the final destination, it is difficult to track them down after consumption or

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return them for disposal, a well-known problem in expired medicine recycling [10]. One significant but often overlooked issue is that entities in a generic SC, such as products, parts, data, financial flows, etc., must be computer-addressable, much like a server on the Internet. The fundamental idea is that in a global network such as the SC, a medicine has its own unique address and the medicine can be queried and actuated on with this unique address. In general, the use of unique identification numbers for products, parts, activities, etc., and their interfaces with humans represents an important aspect of DSCTS, and we refer to this as the identifiability requirement, which is defined as the ability to uniquely identify and track each product throughout its lifecycle. We argue that the integration of DTs, DSCT, and blockchain-integrated SC identifiability can significantly facilitate long-term objectives, including determining product provenance and taking immediate action during disruptions.

Motivated by the rapid evolution of the DT technology and recognizing its importance within SCs, this study has the following main goals:

- 1) Generalize the concept of DT for SC applications and review key enabling technologies that support this integration,
- 2) determine and articulate gaps, especially those that come under the category of identifiability, and
- 3) propose a generic DSCTS framework.

This study proposes the DSCTS framework in a general context applicable to any SC; the example of expired medicine recycling is employed to demonstrate its application. This is for two primary reasons. First, this application is highly relevant to society; it is among the best examples of circularity being actively studied, which will make the SC more accurate and generic. The second significant challenge is obtaining product-specific information at the recycling point, where the idea of Digital Product Passports (DPPs) is being investigated. Since DPPs communicate unique identities of items (making them addressable), we directly relate this to the identifiability requirement.

The rest of the article is organized in the following manner. Section II presents a review of the concepts of digital SCs and DTs. In Section III, key technologies that support the development of DSCTS are reviewed. Section IV presents the proposed architectural framework for DSCTS and describes the identifiability requirement, followed by its application to the expired medicine recycling case. In Section V, simulation results and their implications are presented.

Section VI presents the main conclusions and provides recommendations for future research.

2. Digital Twins in Supply Chain Systems

This section looks at the SCs from a computer systems and networks perspective, and compares them to decentralized and distributed systems, such as the Internet.

2.1. Supply Chain Management (SCM)

SCM has become a dominant and widely studied concept. Modern SCs are very resilient and agile; this has created complications, as demonstrated by the ripple effect [11], in which any delay in an SC has an impact on inventories, downstream parties (i.e., end users), and upstream parties (i.e., material producers). Fig. 1 shows a generic view of a circular supply chain

(CSC) from the perspective of functional roles and material flows. The example illustrates the life cycle of an expired medicine, beginning with raw material extraction to product use and return flows. Suppliers supply essential raw materials (such as Active Pharmaceutical Ingredients, APIs), which are then shipped to manufacturers so they may produce finished products (i.e., medicines). The final products are delivered to retailers and end customers via logistics networks. Products can be recycled, refurbished, or reused at collection sites after the use phase, closing the loop, and facilitating the restorative and regenerative processes that characterize CSC [12].

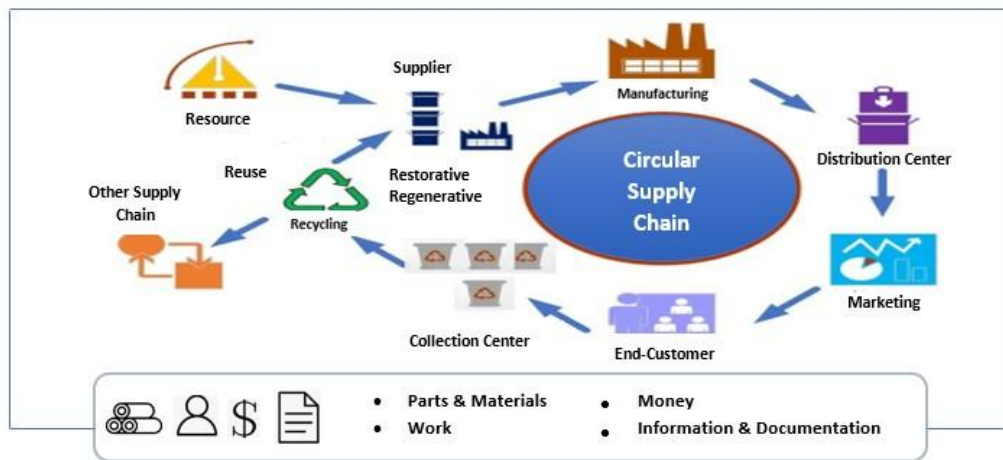


Fig. 1. Circular Supply Chain Model

Each stage of the supply chain involves four basic flows, as shown at the bottom of Fig. 1: (1) parts, materials, and goods; (2) work (such as identifying and inspecting expired medicines); (3) money and financial transactions; and (4) information and documentation. These are frequently the main causes of inefficiencies and disruptions in the supply chain operations [13].

2.2. Supply Chains as Multi-Party Networks

From a computer systems perspective, an SC can be visualized as a mathematical graph or network, in which the nodes represent entities (such as manufacturers, distributors, suppliers, etc.) and the edges for the links or interactions between them. All participants simultaneously seek to achieve specific goals, such as monetary benefits [14]. From this viewpoint, the primary challenge facing modern SCs could be described as establishing and managing a distributed, decentralized network involving multiple parties [15].

1) Distributed because individuals (within a role) are interchangeable (to differing degrees), and the graph is subject to change at any time [16].

2) Decentralized since no global entity is in charge of coordination [17].

3) Open and many-party since there are a lot of participants and they frequently come and go from the graph at random [14].

From the perspective of operations management, and especially in the context of digital SCs, digital technologies should be used to solve and improve the following essential requirements:

Lean: In SC operations, the idea of lean places a strong emphasis on transparency, sustainability, interoperability, and efficiency [18].

Agile: Another key feature of digital SC is agility, which is defined as being resilient, responsive, visualizable, and able to facilitate communication in nearly real-time [19].

Trust: Ensuring trust involves several needs, including being transparent [20], [21], measurable [22], auditable [23] and safe against malicious actors [24].

2.3. Computational and Operational Perspectives

The properties obtained from computer network principles should now be in line with the operations

management needs that were previously established (Fig. 2). However, the requirements of a digital SC originate from the characteristics of the physical SC it replicates, they became more complicated due to several limitations, including a substantial number of participants within a particular SC and the inherently distributed and decentralized network. We argue that the collection of these limitations is what instantly appeals to blockchain technology. As it serves as a central coordination point, blockchains are inherently distributed, decentralized, and able to handle several parties.

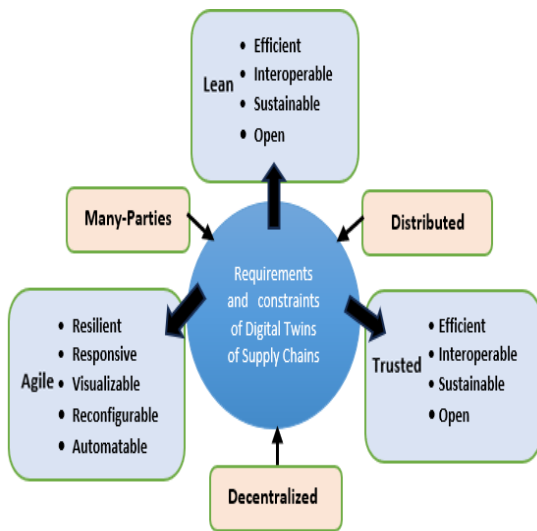


Fig. 2. SC Network and Operational Perspective

3. Technologies For Digital Supply Chains

For over a decade, the topic of digital SCs has been studied; however, much of the existing work remains narrow in scope—for example, focusing on online interaction between consumers or nearby SC teams [25], Enterprise Resource Planning (ERP) systems locally used [26], or sector-specific applications (e.g., automotive [25]). It has a direct connection to the evolution of the fundamental idea of DT, but it also requires particular revisions, generalizations, and modifications.

This study examines three important technical aspects. First is the use of blockchains, which have been widely discussed in the literature, in conjunction with technological integrations. Second is the specific configurations of DT and digital SCs, as well as how they intersect. Third, data models, which are essential to the formation of DSCTS.

3.1. Blockchain Technology

With the emergence of blockchain technology, SCM has increasingly recognized its potential to solve persistent issues, especially those related to traceability and visibility. Its applications have been increasingly evident to researchers and practitioners over the last decade, resulting in more sophisticated

and useful implementations, while there are still many questions and misconceptions that need to be addressed [27]. The increasing number of new journals and publishing trends indicates a significant increase in research activity since 2018 [28], [29], [30]. Although blockchain-based applications and services are highly sophisticated technically, the general idea is simple. In Fig. 3, two SC collaboration models are compared: a blockchain and a general internet-based electronic data interchange (EDI) model.

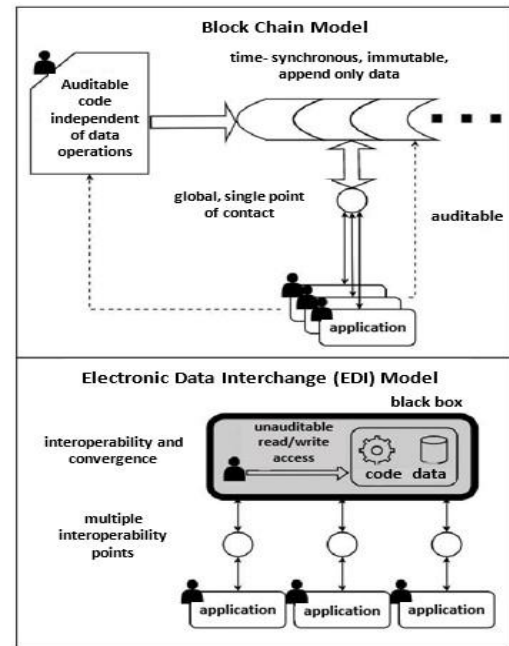


Fig. 3. Blockchain and EDI SC Models Comparison [31]

From this perspective, blockchain can be viewed as a single, globally public replica of a digital ledger that mainly serves as a record for data entry. Additionally, by using cryptographic methods and a wide range of decentralized participants (like Ethereum 2.0 validators or Bitcoin miners), blockchain guarantees that information is practically immutable [32]. Each time a new data entry is recorded on the blockchain, it becomes visible to all participants. Therefore, it serves as a central interaction point with end-to-end visibility. The combination of these two characteristics enables blockchain technology to be used as a form of digital currencies, such as Bitcoin, which maintains a basic two-column ledger mapping addresses to their corresponding balances. Bitcoin effectively resolves the double-spending problem that, before its introduction, had no viable solution [33]. With Ethereum, the data saved exceeds a straightforward two-column ledger and enables the implementation of logic (such as computations or testing of criteria). Usually, the state (such as program variables) and the code of the particular application are both publicly auditable, allowing for easy cooperation and accessibility [33].

On the other hand, an EDI-based strategy entails that each party finds others before working together to identify compatible interface points. This essentially involves a mediator party that creates code and functions (such as a collaborative platform) to manage collaborative data; additionally, this almost always functions as a black box and thus is not auditable. Because of its direct reliance on just one or fewer entities running a shared platform, its security architecture is consequently far weaker, especially with regard to data integrity [34].

Three inherent characteristics of blockchain (1) end-to-end visibility and auditing; (2) a common interaction point; and (3) tamper-proof data entries, make it suitable for collaborative environments that require trustless operations, transparency, provenance, traceability, and trackability [32]. Provenance deals with determining the quality of products; tracking delivers real-time visibility of the products' movement, and tracing reveals their previous handling. Enabling inter-party operational synchronization is another major benefit of blockchain technology, which permits smooth coordination as items move through the SC [35]. From the perspective of digital SCs, the existing literature on blockchain applications can be categorized into two main areas 1) use cases and potential, and (2) technology integration.

Use-Cases and Potential: Recently, there has been a significant amount of research published, including both use-case applications and literature reviews. Despite specific challenges [36], [37], and [38]. Nearly every industry reports advantages when implementing blockchain technology. Table. 1 provides an overview of the reported impact, mapping the literature to application areas.

Table 1

Applications of Blockchain

Area & Benefits	Examples
Logistics visibility, control, and finance.	Track shipments, monitor flows, automate trade, and crypto documents.
Food, Agriculture, Fishing Safety, communication	Provenance tracking, ingredient/cold chain monitoring
Manufacturing Inventory, quality	Track parts, prevent counterfeiting
Pharmaceuticals Compliance, security	Clinical trial data protection
Construction Resource management, accountability	Real-time resource tracking, project scheduling

3.2. Blockchain Key Enabling Technologies

Blockchains address only specific requirements within SCs, while other technologies are often discussed alongside them in a complementary or supplementary role. There are two primary subject areas in the literature. First is to acquire reliable data for blockchain input. However, transferring data onto blockchain can create security risks that threaten authenticity, as illustrated in Fig. 3. As our focus is on products, which are typically just packages of components, the challenge lies in reporting on the appropriate object, preferably automatically. A key role is played by two complementary technologies. The first is the IoT [39], which links sensors, actuators, and services—all necessary to fully realize blockchain's potential in automated environments like factories or transportation hubs. Second entails using barcodes or Quick Response (QR) codes to tag products as low-cost passive techniques, or more sophisticated Radio Frequency Identification (RFID) tags that actively transmit unique identification information in response to signals [40].

The second related technology is the integration of blockchain with existing digital systems, commonly known as ERP systems. These systems facilitate collaboration between suppliers and the allocation of resources. Because blockchain functions as an underlying technology, manufacturer planners and other users communicate with it via ERP interfaces. Therefore, blockchain integration must be aligned with existing IT systems, and ERP capabilities should be expanded to leverage blockchain's potential for improved visibility and cooperation [41]. It is important to remember that blockchain technology is merely a technical building block whose features must be mapped to well-defined needs, even while it is unique in solving some technical challenges that no other technology can. Also, the general context in which the technology is used—where and how it is used is equally essential.

3.3. Digital Twin concept

Although the concept of DTs has been around for over a decade, and continuously evolving in both theory and practice. The idea of DTs has been correlated with creating virtual replicas of physical assets and processes. The idea has gained traction in both industry and academia, broadening its applications to include current standardization projects like ISO/IEC 30173 (work in progress) [43]. The initially proposed concept of DT focused on data (from sensors) and simulation, which resulted in real-time visualization. Fig. 4 shows a basic model that we used as a foundation for our own, which was modified from [44]. A physical entity such as a machine, vehicle, warehouse, or production line has a corresponding

digital representation (i.e., DT), with varying fidelity. A DT operates by means of continuous transmission of data between physical and digital worlds. Real-time data from physical assets or processes is collected by sensors and IoT devices, and the DT uses models and simulations to analyze it. These insights are then used to enhance the performance of the physical system. The core components of a DT typically include:

Physical asset or process: The real-world objects or systems being replicated.

Sensors and connectivity: Devices that collect data from the physical entity.

Data storage and processing: Systems that manage and analyze the collected information.

Visualization and interface: Tools that present insights and enable interaction with the DT.

Analytics and AI: Capabilities that transform data into actionable insights and predictions

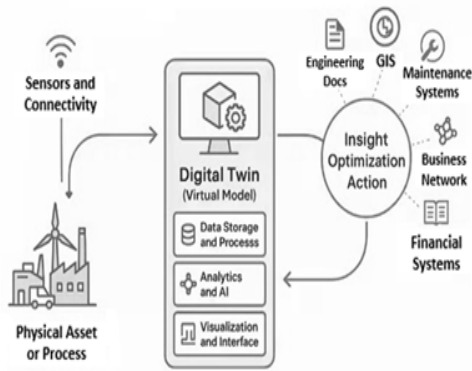


Fig. 4. Simplified DT model

The development of DTs is based on modern technologies such as IoT, virtual reality, big data, cloud computing, and blockchains [45]. However, integrating these technologies also presents a number of technological challenges, those must be resolved. From a simple Physical-Virtual modelling perspective many challenges arise, such as maintaining the accuracy between the DT and its physical counterpart, ensuring proper data and state synchronization, model reuse, and adaptability for various systems or products, and achieving precise calibration, accurate data, and control [46], etc. The complexities increase dramatically when considering systems from a systems perspective (such as a smart city or farm). The challenges arise with modelling approaches (physical, as well as in terms of visual representation and human interaction) [47], real-time data integration and related granularity [48], adapting to networked control and data management, [49], interoperability (including twin-to-twin communication [47]), and addressing cybersecurity challenges [50], etc. Since DTs in many application domains present different challenges, some of which are even use-case specific (e.g., compare vertical farming to modelling an airplane engine), developing a general digital twin conceptualization is not simple,

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given these various technological and situational challenges.

3.4. Digital Supply Chain Twin (DSCT)

In addition to modelling physical environments, an emerging area of study focuses on creating DTs for on-physical environments (or a combination of them), such as logistics, circularity, or entire SCs. While in the literature, the phrase digital twins of supply chains has been used [44]; however, in this study, we prefer to use the term Digital Supply Chain Twin (DSCT). The concept goes beyond the conventional notion of digitized SCs. A DSCTS is a data-driven, real-time digital representation of the entire SC (which includes manufacturers, suppliers, warehouses, transportation, etc.), data flows, financial flows, SC activities, etc. It is updated continuously by sensors, IoT devices, and information systems. It enables organizations to visualize, monitor, predict, and optimize SC operations, simulate scenarios, detect disruptions, and support informed decision-making. Besides traditional DT, which replicates individual entities and processes, the proposed DSCT replicates the entire SC (i.e., all the stakeholders, data streams, and flows). In the current literature, only a few practical examples of DTs for SCM have been implemented. For example, in a study [51], a conceptual DT framework for a circular meat SC has been developed, where DT facilitates the use of food waste for composted production and the planning and administration of surplus distribution between sponsors and receivers. In a research work [52], a DT-based resilient SC emergency decision cost and profit model has been proposed for mitigating losses and for enhancing SC visibility of protective medical masks. In a study [6], a blockchain-based framework has been proposed for supply chain visibility and traceability. However, the framework lacks predictive analytics, proactive decision support, and evidence of real-world implementation.

This research work proposes the DSCTS framework for enhancing SC visibility and control. The framework virtually models the entire SC, including SC entities and SC activities, providing real-time visualization, optimization, monitoring, and control in domains such as inventory management. Furthermore, it also ensures security and trust by integrating blockchain technology, and provides support for circularity by promoting the reuse of resources throughout the SC. The predictive analytics capabilities of DSCTS assist SC managers in recognizing, assessing, and controlling the likelihood of future risks at different stages of service delivery. Eventually, blockchain-enabled tracking and tracing make it possible to identify anomalies well before they create disruptions, especially when integrated with AI. The existing literature on the adoption of DSCTS

identifies three key challenges: (1) How to make reliable connections between the physical and the virtual worlds (i.e., DT). To address this gap, IoT-enabled sensors, along with connectivity technologies such as Zigbee, Bluetooth, RFID, and smart sensors, play a vital role; (2) the second challenge relates to adaptability, meaning that DSCTS need to be just as adaptable and volatile as the SCs; and (3) interoperability and integration present a third challenge. In terms of functionality, DSCTS can be thought of as a generational update of ERPs, but with full real-time response and visualization, as well as interaction with modules for analytics and optimization, and prediction. We contend, collaboration presents a fourth challenge: Considering that SCs are collaborative, distributed systems, DSCTS requires efficient technical cooperation approaches to be realized. As an example, there must be a framework that enables several SC operators to find the technological interfaces necessary for their

distributed and unintegrated systems to function together seamlessly. In this case, blockchain technology can be relatively useful.

4. Methodology

This section presents our proposed synthesized DSCTS framework. As we elaborate on this, we also highlight a crucial gap that limits the visibility and actionability of SCs, which is the identifiability requirement.

4.1. Architecture of DSCTS

Fig. 5 illustrates the proposed DSCTS framework, which comprises five interconnected layers. The architecture follows a bottom-up approach starting from the physical layer, followed by the data acquisition and processing layer, communication layer, digital twin layer, and finally, the proactive and decision support layer.

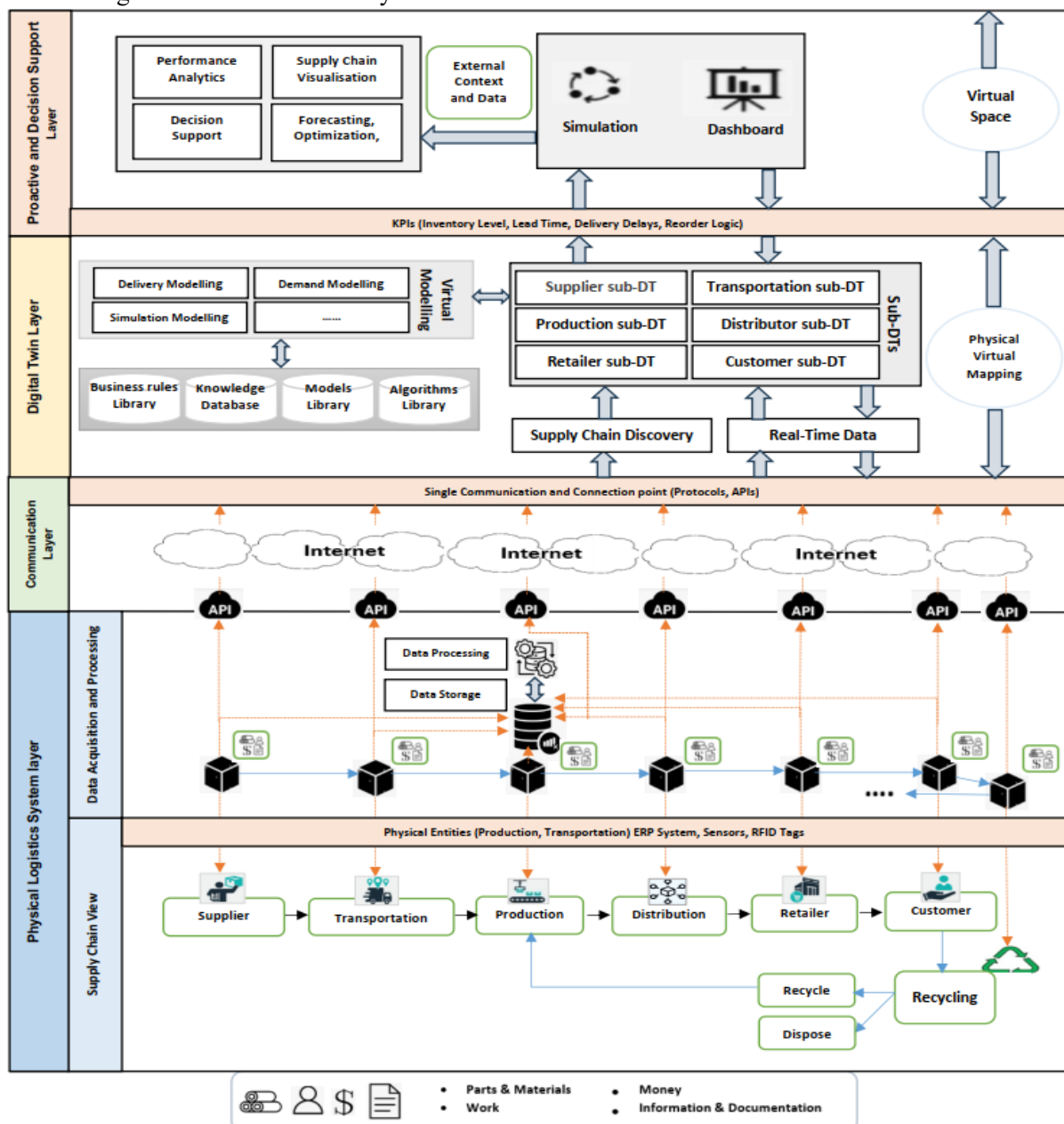


Fig. 5. Proposed Architecture of DSCTS

Physical Logistics System Layer: This layer forms the foundation of the DSCTS, representing the real-world SC entities and processes that the DT replicates. It consists of two sub-layers. The SC view at the bottom encompasses all the parties of an SC, including suppliers, transport fleets, manufacturing facilities, warehouses, retailers, and customers, that depend on the specific SC. The data acquisition and processing sublayer serves as the bridge between the physical SC and its virtual twin, ensuring that raw data from the physical SC is captured, standardized, and made ready for digital use. Several components types collaborate to generate data and drive SC operations inside this layer. From the SC perspective, we acquire data about the involved parties, while from the product perspective we acquire data about the product. Generally, four components flow into each product—parts and materials, work and labour, capital, and information compliance—are annotated at each stage. There must be a means for this data to be pulled into the higher layers. The concept of application programming interface (API) is an important concept in computer science, plays a vital role at this stage. Connectors and adapters integrate enterprise systems such as ERP through APIs or database connectors (e.g., REST, SOAP, or DB), while communication protocols (e.g., MQTT, CoAP) ensure interoperability across devices and systems. Before transmitting data to higher layers, preprocessing modules ensure the quality of data by filtering noise, removing duplicates, synchronizing timestamps, aggregating values, and encrypting sensitive information. This process ensures that only clean and contextualized data advances to the subsequent layer of the DSCTS architecture. In addition to SC visibility, we also anticipate actionability, often known as control; with these two general requirements in place, high degrees of automation, simulation, and forecasting can be achieved. For complete global visibility and actionability, it is specifically necessary for every step and every party to be uniquely identified. This idea—which we refer to as the identifiability requirement—has not been adequately addressed.

Identifiability in this study is conceptualized beyond the traditional barcode or RFID-based tagging mechanisms. The proposed DSCTS stipulates that every SC entity has a unique, computer-addressable digital identity. This identity is integrated within organizations and tied to a permissioned blockchain to provide validation and immutability.

Communication layer: This layer serves as the central integration hub that enables seamless interaction between the physical SC, enterprise applications, and the DT environment. In order to manage the scope and diversity of systems, multiple local systems, which

tend to be closed or proprietary, are depicted as distinct (while) clouds (Fig. 5). With open and interoperable interfaces, these systems interact to a higher-level global platform that integrates data and interactions from all parties involved. This aspect, which is a direct reflection of Fig. 3, is the ideal location at which blockchain could be applied. A blockchain, instead of transmitting data on its own, could be viewed as an intersection for a single, reliable, trustless point of discovery that can further facilitate actionability. Slightly delving into the technical details, the endpoints of the API (such as addresses) provided by the subsequent levels are here reconciled. It supports abstraction and mediation, preserving interoperability across many lower-layer implementations through standardized interfaces.

Digital Twin Layer: This layer creates a living, virtual replica of the physical SC, reflecting the state and behaviour of suppliers, transportation, production, distribution, retailers, and customers, and then uses simulation to fast-forward time, test scenarios, and quantify impacts before actions are taken in the real world. Two aspects are virtualized by the DT layer. First, it virtualizes the SC itself with its stakeholders. Second is the digitization of the particular SC instance with two routes: downward, actuating on the product (e.g., to change the number of orders given external events), and upward, querying the product's real-time status throughout its journey for visibility.

The DT model layer follows a Twin-of-Twins architecture, where the entire SC is broken down into several modular sub-twins. Together, these sub-twins form an integrated digital ecosystem that replicates the entire SC. Each sub-DT models the activities of its corresponding physical twin. For example, the supplier's sub-DT simulates the supplier's capacity, delivery lead times, and related risks, while the manufacturer's sub-DT models production facilities with daily production capacity, utilization of resources. The retailer's sub-DT replicated an SC retailer with inventory levels, order fulfilment rate, and reorder logic, while the warehouse's sub-DT models warehouse facilities with storage and inventory levels.

Ultimately, the customer's sub-DT simulates customer order behaviour and overall service experience, while the transport sub-twin keeps track of travel routes, anticipated arrival times. In addition to twin-of-twins architecture, this layer contains various libraries and a knowledge database.

Models Library: Comprises various industry-specific reusable simulation models for creating virtual replicas of various SC elements—such as production facility visualization, demand prediction, and other what-if scenarios testing (e.g., supplier shutdowns).

Business Rules Library: contains a well-defined set of rules that govern SC operations.

Algorithms Library: Encompasses AI and various algorithms for prediction, scheduling, and route optimization, etc.

Knowledge Database: Includes historical operational data, case studies, and best practices from the past to help with decision-making.

Proactive and Decision Support Layer: It is the uppermost layer, transforming DT from just being a visualization model into a decision support system. It enables managers to effectively assess the SC's performance by providing a visual depiction of key performance indicators (KPIs), including lead times, stock levels, delays in delivery, and reordering logic. SC managers can perform what-if scenario testing before implementation, which minimizes uncertainties. It should be noted that the functions provided in this layer (Fig. 5) serve as only examples; their implementation may differ based on the particular circumstances and goals related to the SC application. Potential functions include both proactive and reactive ones, such as risk forecasting, inventory planning, and fast modification of orders [53], or mass customization using Industry 4.0/5.0 [54]. These functions can be enhanced by integrating external data with internal systems, such as ERP and Customer Relationship Management (CRM).

The hybrid distributed topology is used in the proposed architecture, consisting of: (1) IoT-enabled edge devices (2) a cloud-based integration layer, and (3) a permissioned blockchain network that ensures authorized SC members have immutable transaction records.

4.2. Case Study: Recycling of Expired Medicines

4.2.1. Overview

This case study illustrates how the proposed DSCTS framework can be applied to the recycling and reverse logistics of specific recyclable pharmaceutical products (medicines) that are collected from consumers and retailers (pharmacies). Not all medicines can be recycled because of chemical instabilities, contamination hazards, and strict regulatory restrictions. Thus, this study focuses on stable compositions that maintain recoverable ingredients after their expiration, like biologics, medication for injection. The data assumptions used in this study are derived from peer-reviewed literature on DT technology, pharmaceutical reverse logistics, and blockchain-enabled SCs. ([55]-[59]). Since many pharmaceutical companies do not publicly release their internal recycling or reverse logistics data, this study uses data trends from recent studies to

synthesize important operational characteristics such as the number of batches, delivery times, stock levels, and recycling rates. The derived parameters represent actual industrial values while maintaining generality for simulation and framework evaluation. Such assumptions offer a controlled environment for simulation suitable for demonstrating the DSCTS framework's functionality.

To enhance the conceptual understanding, a qualitative walkthrough of the reverse pharmaceutical process of logistics has been developed first, and then the quantitative outcomes of the simulation are given to demonstrate the results. In this case, eight key entities—API supplier, manufacturer, distributor, pharmacy, customer, collection and inspection centre, and recycling and disposal facility of a mid-sized pharmaceutical company are represented as shown in Fig. 6.

The physical layer at the bottom represents the physical view of the SC, representing how the medicines move between the SC entities. In order to record data on medicine movement, expiration dates, and return rates, the entities are equipped with IoT sensors and RFID tags. Important data, such as medicines' unique IDs, batch numbers, returned quantities, and expiration dates, is collected and stored in local storage for further processing. From the product perspective, this layer represents the product-centric view of the SC, provides the lifecycle status of medicines. The medicines can be visualized, tracked, queried to store their current status and relevant data (e.g., batch numbers, returned quantities, and expiration dates, compliance records, and provenance), and actuated at any point throughout their lifecycle.

Predictive analytics is also possible if appropriate data is collected at regular intervals (see top of Fig. 6) and throughout the SC, which enables medicine expiration prediction, return forecasting, and compliance monitoring. This is achieved by employing blockchain-integrated RFID tags and assigning unique identification numbers to medicines, batches, and recording them in the globally accessible system (DPP), and we refer to this as the identifiability requirement, a well-known issue in pharmaceutical reverse logistics. All transactions (e.g., medicine returns, inspection findings, and recycling information) are timestamped and saved on the blockchain permanently. This approach ensures provenance, batch authenticity, and expiration traceability. Furthermore, SC managers can evaluate various KPIs, inspect manufacturing and expiration dates, quantity, origin (e.g., lab manufacturing), compliance attestation, provenance, and ownership data from blockchain. These insights assist in timely

decisions regarding medicine disposal and recycling, ensuring both visibility and traceability across the SC.

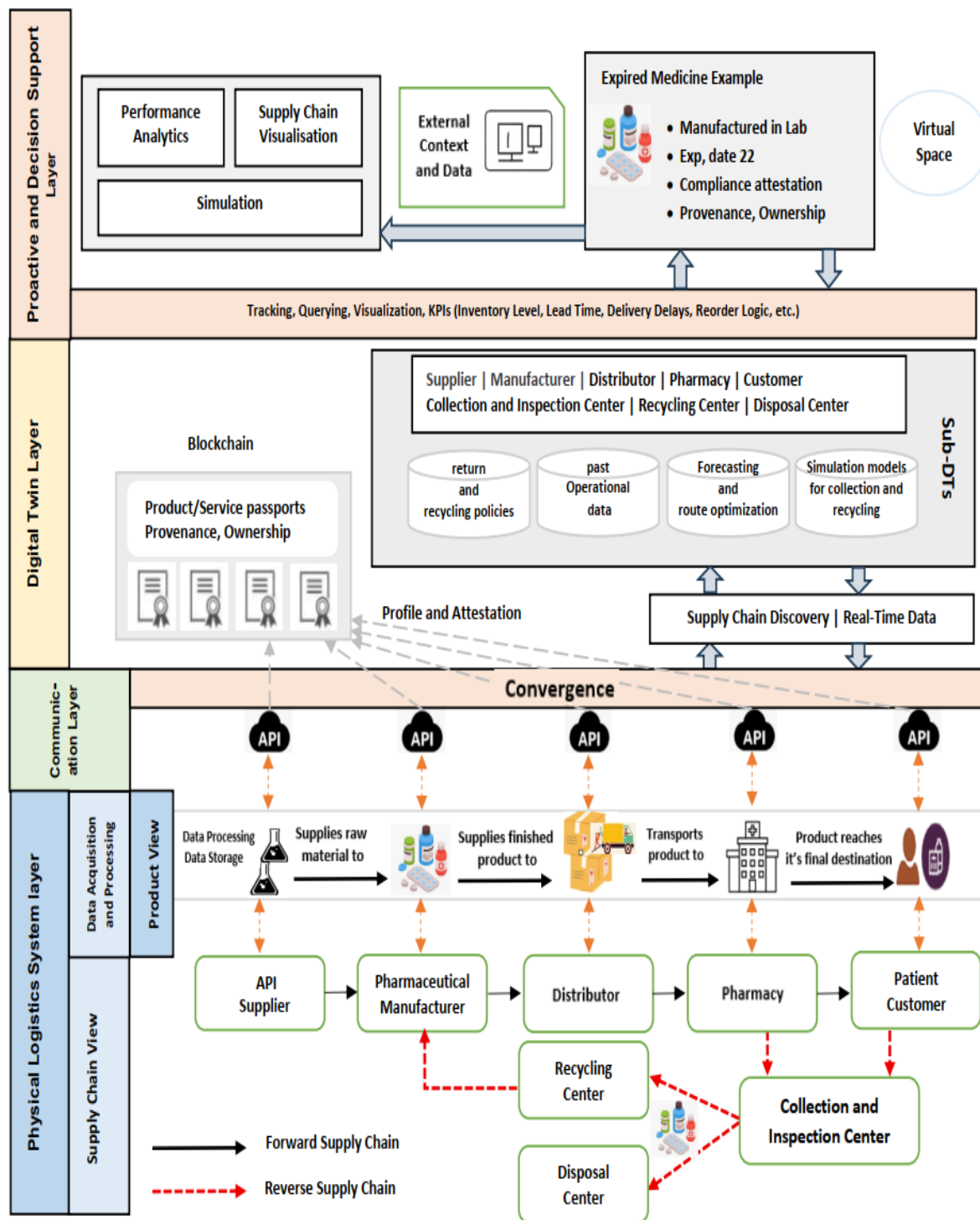


Fig. 6. Recycling and Reverse Logistics of expired pharmaceutical products (medicines)

Table 2 describes the key SC entities along with their functions, data flow, and related blockchain data attributes. It emphasizes how stakeholders in the SC provide operational and data inputs required to create an accurate DSCTS model for SC visibility and

proactive decision support. This organization also ensures precise modelling of blockchain-based identifiability and traceability throughout the entire SC.

Table 2

Supply Chain Entities, Functions, and Blockchain Data Attributes

Sr.	Entity / Functions	Blockchain-connected data attributes
1	API Supplier: Supplies API to manufacturers.	material IDs, supplier certificate, delivery date, quantity delivered
2	Manufacturer: Produces medicines, assigns blockchain-connected batch IDs, and uploads production date.	batch IDs, quantity manufactured, manufacturing date, expiration date, and digital signature
3	Distributor: Handles the transfer of medicines between pharmacies and manufacturers, updates shipping and distribution logs.	stock level, vehicle IDs, delivery IDs, delivery route, and delivery status
4	Retailer/Pharmacy: supplies patients with medicines and records outdated returns on the blockchain for provenance.	product ID, timestamp, expiration information, sales volume, and return quantity
5	Customer/Patient: uses medicines and returns them to pharmacies or collection facilities when they expire.	date of purchase, medicine used log, and return verification
6	Collection & Inspection Centre: collects and examines expired medicines and categorizes them for disposal or recycling.	collection frequency, examination report, and sorting decision
7	Recycling/Disposal Centre: uses blockchain records to recycle usable items or safely dispose of harmful waste	rate of recycling, quantity disposed of

5. Results and Discussion

5.1. Data Assumptions

As described, the data assumptions and parameters used in this study are derived from validated empirical findings reported in peer-reviewed literature on pharmaceutical logistics and reverse logistics SCs. These parameter values define key factors like lead

times, recycling effectiveness, medicine expiration rates, return rates, and blockchain efficiency, which all have a direct impact on the reliability and responsiveness of the pharmaceutical reverse logistics system. Table 3 summarizes the chosen parameter range values, along with their sources, descriptions, and relevance to the DSCTS case study configuration.

Table 3

Data Parameters and Literature-Based Justifications for DSCTS Case Study

Sr.	Parameter	Description	Use of range in the Case Study	Literature Source	Case Study Relevance
1	Rate of medicine expiration:	Quantity of medicines that expire before being consumed.	4–8% of all medicines supplied	[55], [56]	Represents the average amount of waste medicines found in SCs
2	Expired medicines return rate	Quantity of expired medicines returned by pharmacies/customers	35–55%	[55], [57]	Represents the efficiency of reverse flow in medicine recovery systems.
3	Average collection lead time	The interval between a medicine's expiration and retrieval.	15–20 days	[55]	demonstrates the typical delay between return and expiry determination.
4	Recycling efficiency	Percentage of accumulated medicines that can be recycled.	20–30%	[57]	evaluates material recovery to determine the percentage of medications that can be recycled.
5	Blockchain data transfer latency	Data transfer delay in blockchain-enabled communication.	3–6 seconds	[58]	evaluates the communication performance of the IoT-blockchain system.
6	Blockchain consensus latency	Time needed for block validation.	12 seconds	[58], [59]	Average verification time for logistics-related permissioned blockchain

5.2. DSCTS Simulation Setup

Table 4 summarizes the key input parameters used in the model. These inputs demonstrate how products move through various supply chain entities daily, as well as the KPIs related to returns, inspection, recycling, and disposal activities. These empirical parameters ensure that the system functionality and evaluation align with the real-world SC scenarios.

Interpretation of values

API Supplier: Supplies 6,000 units daily; no returns or recycling at this stage.

Pharmaceutical manufacturer: Total 6,000 units are produced daily, with a 4% return rate.

Return Rate: The return rate can be calculated by using the following formula:

$$\text{Return Units} = 6000 \times \frac{4}{100} = 240$$

So, 240 units are returned.

Table 4

Pharmaceutical Reverse Logistics Metrics

Sr.	Entity	Volume of Data	Expired Medicine Return Rate	Inspection Success Rate	Medicine Recycling Rate	Medicine Disposal Rate
1	API Supplier	6,000	–	–	–	–
2	Pharmaceutical Manufacturer	6,000	4%	90%	–	–
3	Distributor	5,650	3%	95%	–	–
4	Pharmacy	5,550	6%	80%	30%	70%
5	Collection Center	–	–	85%	35%	65%
6	Recycling Center	–	–	–		90%

The pharmaceutical SC reverse logistics system for expired medicines recycling was evaluated through a simulation using blockchain-enabled data traceability and the DSCTS framework as a reference. To ensure an accurate system representation, the parameters of the model were taken from previously conducted empirical research findings. The overall SC performance was compared before DSCTS implementation and after the blockchain-integrated DSCTS to assess improvements in SC visibility and identifiability. The system performance prior to and following the implementation of the DSCTS is compared in Table 5.

The simulation results (Table 5) demonstrate significant improvements in SC performance across

Inspection Pass Rate: Denotes the percent of returned units that pass inspection and are suitable for recycling, reuse, or resale. It can be calculated as:

$$\text{Inspection Pass Rate} = 240 \times \frac{90}{100} = 216$$

Thus, 90% of examined units pass inspection for quality.

Distributor: Manages 5,650 units/day; 3% of returns occur, and 95% of inspections are passed.

Pharmacy: Handles 5,550 units daily, 6% of returns are made, 30% of returned medicines are recycled, and 70% are disposed of.

Collection Center: It emphasizes returned medicines, where 85% pass inspection, 35% are recycled, and 65% are disposed of.

Recycling Center: 90% of processed material that cannot be recycled is disposed of at the final stage.

all tested KPIs. SC end-to-end visibility enhanced from 50% to 75%, reflecting a 25% increase in overall SC visibility. Blockchain-integrated unique medicine IDs ensure medicine traceability, resulting in a 20% improvement in tracking accuracy. Reverse SC logistics processes (e.g., expired medicines collection and inspection) were also accelerated.

Predictive analytics is also feasible if relevant data is gathered throughout the SC, which allows early identification of medicine expiry patterns, leading to a 12% improvement in operational efficiency. There is a 66% improvement in the repose time of the SC reverse logistics flow, as it was decreased from 15 days to 5 days.

Moreover, the system reduced operational costs per returned unit by 25% by eliminating redundant manual processes and enhancing cooperation between supply chain entities (suppliers and recyclers). The cost per returned product (medicine) is reduced by 25% by improving coordination among SC entities (such as manufacturers and recyclers) and minimizing repetitive manual SC processes. The average lead time is improved by 35%.

Eventually, blockchain integration guarantees that data is practically immutable and enables

decentralized transaction verification, thereby increasing data integrity by 30%. This improvement is crucial for regulatory compliance, audit readiness, and overall trust in reverse logistics processes.

The simulation results revealed the fact that the proposed blockchain-integrated DSCTS significantly enhanced the overall SC performance by improving end-to-end visibility, traceability, and recycling efficiency, while at the same time reducing response time, return-related costs, and average lead time.

Table 5

Simulation Results

Sr.	Key Performance Indicators	Before DT implementation	After DT & Blockchain Implementation	Improvements
1	Product Visibility	50%	75%	+25%
2	Traceability Accuracy	60%	80%	+20%
3	Recycling Efficiency	30%	42%	+12%
4	Reverse Flow Response Time	15 days	5 days	-66%
5	Cost per returned product	\$2.60	\$1.30	-25%
6	Average Lead Time	12 days	8.5 days	35%
7	Compliance & Audit Readiness	Manual	Automated	--
8	Data Integrity	60%	90%	30%

Conclusion and Future Work

This study proposes a blockchain-integrated Digital Supply Chain Twin System (DSCTS) by conducting an extensive literature review on digital supply chains, digital twin, and blockchain technology and its application to digital SCs, through which a conceptual system architecture has been derived. The findings revealed that technological integration and effective coordination among multiple stakeholders are necessary for the successful implementation of DSCTS. To demonstrate its potential and usefulness in real-world scenarios, a case study illustrates how the proposed DSCTS framework can be applied to the recycling and reverse logistics of specific recyclable pharmaceutical products (medicines). The DSCTS provides a road map for improving end-to-end visibility, traceability, and predictive analytics while integrating with blockchain technology. A key contribution of this study is the identification of the identifiability requirement; addressing this requirement is crucial for end-to-end visibility and traceability.

Future research could be to develop a functional prototype of DSCTS for complex industries such as fragile product logistics, to evaluate the system for real-time data integration and predictive analytics in real-world scenarios.

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