

Article

Emergency Supply Chain Resilience Enhanced Through Blockchain and Digital Twin Technology

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Abstract: *Background:* Emergency scenarios present unprecedented challenges for supply chains worldwide, particularly in the management and distribution of critical supplies, where timely delivery and maintaining integrity are crucial. *Methods:* This article explores an innovative approach to enhance the emergency management of supply chains using blockchain technology and simulation-based modelling. The proposed methodology aims to tackle issues such as transparency, efficiency, and security, which are vital for managing logistics during crises. A case study involving a vaccine rollout is used to demonstrate how blockchain can optimise supply chain operations, reduce bottlenecks, and ensure better traceability and accountability throughout the process. The case study is specifically developed based on the distribution of COVID-19 vaccines in Italy. *Results:* The integration of blockchain technology not only enhances data integrity and security but also facilitates real-time monitoring and decision-making. *Conclusions:* The findings suggest that the proposed blockchain-based model can significantly improve supply chain resilience in emergency situations compared to traditional methods, thereby offering valuable insights for policymakers and supply chain managers facing future crises.

Keywords: emergency supply chain; blockchain; digital twin; COVID-19

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1. Introduction

Emergencies, such as pandemics, natural disasters, or other large-scale crises, present significant challenges for supply chains, often resulting in severe disruptions to the delivery of critical supplies. The effective distribution of essential goods, including vaccines and medical supplies, places extraordinary demands on supply chain networks. This often necessitates specialised logistics, particularly cold chain systems, to maintain product efficacy [1,2].

Managing such supply chains requires overcoming numerous logistical challenges, including securing adequate transportation, ensuring appropriate storage conditions, and implementing continuous monitoring to prevent spoilage. In this context, blockchain technology has emerged as a promising solution to enhance the transparency, efficiency, and reliability of emergency supply chains [3]. Blockchain's secure and decentralised architecture enables transparent tracking of transactions [4]. The recent literature suggests that the adoption of blockchain can significantly mitigate inefficiencies and fraud in supply chains during crises [5]. This study aims to introduce a novel approach to managing emergency supply chains by integrating blockchain technology with simulation models.

This method is specifically designed to address the unique challenges posed by high-risk environments, where rapid and effective distribution is paramount [6].

A significant advancement in emergency supply chain management arose from the distribution and supply issues encountered during recent pandemics, particularly concerning vaccine supply chains (VSCs). According to Liu and Lou, vaccine shortages can result from various constraints, including production and supply disruptions, unexpectedly high demand, and insufficient resources, such as insufficient healthcare infrastructure for vaccine administration [7]. Production-related challenges, such as uncertainty in manufacturing yields, can substantially impact the overall supply chain. Angelus and Özer in 2022 highlight that low and unpredictable production yields have long posed a major challenge for large-scale vaccine manufacturers [8]. A pertinent example is AstraZeneca, which faced difficulties in meeting the European Union's demand for COVID-19 vaccines due to yield uncertainties. In developing countries, yield variability often leads to shortages of critical vaccines, such as those for hepatitis [9,10].

Conversely, a sudden surge in vaccination demand can also cause temporary supply chain disruptions. A notable instance of this occurred during the initial rollout of the COVID-19 vaccine, when a sharp increase in demand led to short-term shortages within the VSC. Despite these disruptions, vaccination rates may eventually decline over time. However, a well-structured supply chain with appropriate strategies in place can mitigate the impact of shortages on vaccination efforts. For example, decision-makers can implement measures such as maintaining buffer stock to address demand surges or redistributing inventory between healthcare facilities in different regions to reduce risks and enhance service quality. Filia et al. (2022) observe that only a limited number of European countries have expert committees or established processes to address stock-outs and shortages [11]. Similarly, Lydon et al. (2017) report that, in 96% of cases where shortages occur, district-level stock-outs disrupt immunisation services [12].

The objective of this paper is to present an optimised approach for adjusting VSC stock and delivery policies compared to those applied during the COVID-19 emergency. This approach leverages emerging technologies such as the Internet of Things (IoT), blockchain, and digital modelling. The study will demonstrate how different stock management policies can yield varying outcomes within the VSC, ultimately contributing to more resilient and efficient emergency supply chains.

Building on the invaluable lessons learned from the COVID-19 emergency supply chains, it is possible to extend the primary limitations observed during that crisis to other types of supply chains. Unlike traditional logistics networks, which operate under relatively stable conditions, emergency supply chains must rapidly adapt to unpredictable events, fluctuating demand, and resource constraints. Existing emergency logistics frameworks frequently fail due to a lack of visibility, inefficient coordination, slow response times, and imbalances between supply and demand, resulting in shortages, wastage, and delays in the delivery of critical supplies.

Some primary reasons for the failure of traditional emergency supply chain management are the fragmented flow of information and the absence of real-time visibility. The distribution of critical supplies, such as vaccines and medical aid, necessitates up-to-the-minute data on stock levels, transportation conditions, and environmental factors, such as temperature for cold chain logistics. However, current supply chains often rely on manual reporting, outdated IT systems, and siloed databases, leading to delays and discrepancies in decision-making. Blockchain technology addresses this issue by providing a decentralised, tamper-proof ledger where all transactions and inventory movements are transparently recorded. This ensures that all stakeholders, including governments, NGOs, suppliers, and

logistics providers, access the same real-time data, reducing misinformation and enabling faster, more coordinated responses.

Other major weaknesses of existing emergency supply chains are inefficient resource allocation and stock management. Supply shortages and overstocking frequently occur simultaneously in different regions, creating bottlenecks and wastage. Traditional inventory models struggle to accommodate sudden demand surges or supply chain disruptions. The introduction of IoT sensor networks enhances this by enabling real-time tracking of inventory conditions, transportation status, and environmental variables such as humidity and temperature. By integrating IoT data into a blockchain-secured system, supply chains can automate stock monitoring and dynamically adjust distribution based on real-time needs. This capability is particularly critical for perishable goods, such as vaccines and medical supplies, where improper storage or transportation can lead to irreversible losses.

Another challenge in emergency logistics is the rigidity of traditional supply chain planning models, which do not allow for rapid adjustments in response to unfolding crises. Decision-makers often rely on static contingency plans, which are insufficient when faced with real-time disruptions, infrastructure failures, or unexpected shifts in demand. Digital twin technology addresses this limitation by creating a real-time virtual replica of the supply chain, integrating live data from IoT sensors and blockchain records. This technology enables logistics managers to simulate different disruption scenarios, test alternative delivery routes, and dynamically optimise resource allocation. Such predictive capabilities are essential for responding effectively to supply chain shocks, allowing organisations to anticipate bottlenecks before they occur and reallocate resources accordingly.

Another critical failure in traditional emergency logistics is the delay in procurement and distribution caused by bureaucratic inefficiencies and reliance on manual processes. Emergency supply chains frequently suffer from slow approval mechanisms, a lack of automation, and prolonged procurement cycles, all of which hinder timely response efforts. Blockchain-based smart contracts automate these processes by executing predefined actions when specific conditions are met. For example, if stock levels drop below a specified threshold, a smart contract can automatically trigger a purchase order, notify suppliers, and coordinate transportation, thereby eliminating administrative delays. This automation enhances efficiency, reduces human error, and accelerates response times, which is particularly vital in crisis situations where every minute counts.

Finally, poor coordination among multiple stakeholders remains a significant obstacle in emergency logistics. Governments, humanitarian organisations, private companies, and local authorities often operate within independent and disconnected systems, leading to redundancy, inefficiencies, and miscommunications. A blockchain-integrated supply chain establishes a single source of truth, ensuring that all entities involved in emergency response have access to the same data. This enhanced transparency and trust facilitate smoother collaboration, prevent duplication of efforts, and ensure that critical supplies reach the appropriate locations at the right time.

In summary, traditional emergency supply chains fail due to fragmented data, inefficient resource allocation, static planning models, slow procurement, and a lack of coordination. All these aspects reduce the resilience of the supply chains. This study highlights how an integrated approach involving blockchain, digital twin technology, and sensor networks can address these limitations and significantly enhance the resilience of emergency supply chains.

2. State of the Art

Emergency supply chain management has become an increasingly critical field, particularly in light of global disruptions such as the COVID-19 pandemic. Current advancements

in this domain can be categorised into two main areas: the design and management of emergency logistics chains and the utilisation of enabling technologies from the Fourth Industrial Revolution to enhance these processes.

Traditional supply chain frameworks, while effective under normal circumstances, often struggle to respond to the unpredictability and urgency of crises. Recent events have revealed significant vulnerabilities within supply chains, including delays in information flow, poor coordination among stakeholders, and inefficiencies in stock allocation. The complexity of managing logistics during emergencies necessitates adaptive strategies and resilient supply chain designs capable of rapid response and real-time adjustments to changing conditions [13]. Approaches such as pre-positioning critical supplies, real-time information sharing, and fostering collaboration among stakeholders are essential to facilitating rapid responses [4,14]. However, challenges persist due to the absence of robust frameworks that ensure supply continuity during crises, highlighting substantial opportunities for improving planning, execution, and overall supply chain performance [1,15].

To gain a deeper understanding of the previously discussed aspects, the vaccine supply chain (VSC) serves as an exemplary case study. Vaccine shortages present a significant threat to public health, as they can lead to reduced immunisation rates, an increased spread of preventable diseases, and heightened costs within the VSC. In low- and middle-income countries, where access to vaccines is already constrained, such shortages further exacerbate existing healthcare disparities and widen gaps in health outcomes. Addressing the root causes of vaccine shortages is crucial for strengthening healthcare systems and ensuring equitable access to life-saving vaccines across all communities [7,16,17].

Stock-outs in supply chains can arise from various factors, including supply chain disruptions, distribution challenges, and inaccurate demand forecasting [18,19]. In lower-income nations, stock-outs are often attributed to inadequate infrastructure and logistical barriers [20,21]. These challenges are further exacerbated by weak healthcare systems, inefficient transportation networks, and limited storage capacity [12]. Additional issues, such as production delays, quality control failures, and cold chain breakdowns, can further contribute to supply shortages [22,23]. In the context of the vaccine supply chain (VSC), these shortages have a profound impact on public health, increasing the strain on healthcare systems and exacerbating existing health disparities [24,25].

So, all these issues seem to be addressed through the enhancement of resilience in the specific supply chain (SC). Given the significance of the resilience concept in this research, we now introduce it in a more specific manner, as it is intended for the purposes of this study. It is worth noting that numerous sources define resilience in the context of supply chains. However, these references generally describe supply chain network resilience as a combination of flexibility, responsiveness, adaptability, and other related factors [26]. According to Jüttner and Maklan (2011), and later confirmed by Chopra and Sodhi (2014), supply chain resilience is the ability of an enterprise to return to normal operations under the influence of various risk factors. Their research identified flexibility, speed, visibility, and collaboration as the key determinants of resilience [27,28]. Thus, resilience emerges as a concept that depends on several practical aspects, such as flexibility and responsiveness, which can be measured in different ways depending on the specific case under analysis.

Advancements in technology provide promising tools for enhancing emergency supply chain management [29]. Technologies associated with the Fourth Industrial Revolution—such as blockchain, the Internet of Things (IoT), artificial intelligence (AI), and big data analytics—are being leveraged to address various supply chain challenges [30,31]. Blockchain technology, characterised by its transparent, secure, and immutable ledger of transactions, enhances traceability and trust among stakeholders. By utilising smart contracts and distributed ledger capabilities, blockchain enables participants to access

verifiable, tamper-proof records of each transaction and supply chain activity, ensuring compliance with predefined protocols. This not only reduces the need for intermediaries but also minimises the risks of fraud and human error [5]. In industries such as healthcare and pharmaceuticals, blockchain has demonstrated significant potential in improving visibility and accountability [4]. Another notable application is the use of IoT devices to enhance the monitoring and tracking of shipments, particularly in cold chain logistics, where conditions such as temperature and humidity are critical [32]. Sensors collect real-time data, and, when integrated with blockchain technology, this information is instantly recorded and validated, providing an immutable trail that stakeholders can trust [33]. AI and machine learning techniques are also being employed to optimise routing, predict disruptions, and automate decision-making processes in emergency scenarios [1]. These technologies enhance responsiveness and efficiency in supply chain operations, facilitating adaptive and data-driven decision-making during crises.

Simulation methods, particularly agent-based and discrete-event models, are employed to analyse the behaviour of complex supply chain systems under various scenarios [34]. By simulating disruptions and evaluating different interventions, stakeholders can enhance their preparedness for real-world contingencies [35]. However, the application of simulation to blockchain-enhanced supply chains remains an emerging field, presenting substantial potential for enhancing the robustness and adaptability of emergency logistics [6].

Alkhoori et al. introduced a blockchain-based system incorporating smart containers capable of monitoring shipment conditions and detecting violations that could compromise the integrity of the contents [36]. Singh et al. proposed a blockchain architecture integrating IoT sensors and QR codes to store comprehensive information related to production and distribution processes. During transportation, IoT sensors continuously monitor conditions and record data on the blockchain, with smart contracts automatically verifying compliance with predefined conditions before accepting product delivery [37].

Chauhan et al. proposed the utilisation of smart contracts to control and automate vaccine distribution processes, ensuring a secure and tamper-proof environment. To enhance patient safety, vaccine batches are tracked to enable the tracing of vial lots in the event of adverse side effects [38]. Kamenivskyy et al. described a blockchain structure integrated into the existing COVID-19 vaccine supply chain, detailing how blockchain interacts differently with physical components and users at each level [5].

The potential for generating purchase orders via smart contracts was assessed by Omar et al., who connected all supply chain stakeholders—manufacturers, distributors, wholesalers, and healthcare providers—through a blockchain network. Their approach enabled hospitals to automatically purchase vaccines from distributors using smart contracts [39]. Sun et al. conducted a simulation-based analysis to improve vaccine distribution performance by testing various scenarios to optimise transport routes and vehicle allocation. However, despite offering a ready-made solution for optimisation—simulation analysis, their study lacked flexibility [40].

Liu et al. developed a vaccine supply chain model and analysed its coordination based on blockchain technology, comparing fixed-fee and proportional-fee scenarios. Additionally, they examined the impact of blockchain implementation on the vaccine supply chain [7].

An analysis of the current literature has identified critical challenges in managing emergency supply chains where blockchain technology could serve as a viable solution [41]. These challenges include issues related to vaccine supply chains (VSCs), such as vaccine counterfeiting and expiration, vial security, distribution inefficiencies, patient registration problems, and data processing security concerns. Despite these considerations, relatively few studies have focused on developing decision-making models based on

blockchain technology for the allocation and distribution of vaccines, as observed during the COVID-19 pandemic.

After introducing the state of the art regarding blockchain, IoT, and digital models, attention must be directed towards the challenges of managing emergency supply chains, particularly in vaccine distribution, as documented in the literature and summarised in Table 1. This focus is crucial, given the significant impact of the COVID-19 VSC. The objectives of the VSC align closely with those of the food supply chain, where reducing total inventory costs and minimising supply unavailability are critical considerations. Several researchers have proposed blockchain-based solutions to address challenges in the distribution of perishable goods.

For instance, Hasan et al. proposed a blockchain-based solution incorporating smart containers equipped with IoT sensors for the real-time monitoring of shipment conditions [42]. Their study implemented smart contracts to manage shipments, automate payments, identify recipients, and provide refunds in the event of violations. Kamenivskyy et al. utilised data flow diagrams to illustrate a system aimed at reducing counterfeit vaccines and records, enhancing communication between stakeholders, improving security, and streamlining inventory and handling processes [5].

Musamih et al. highlighted that existing platforms for COVID-19 vaccine distribution lack transparency, traceability, immutability, and reliability. They proposed implementing blockchain technology and smart contracts to generate notifications for stakeholders throughout the distribution process, reporting any violations encountered during shipment [7]. Similarly, Yong et al. developed a system integrating blockchain and smart contracts to address vaccine expiration and data integrity issues. Their approach employed machine learning to process stored information and provide recommendations to stakeholders [43].

Shah et al. proposed an architecture based on Hyperledger Fabric blockchain technology for the healthcare sector, ensuring secure storage, management, and transfer of sensitive patient information while preserving data privacy for healthcare participants. Their model incorporates proxy re-encryption mechanisms and leverages IPFS with Arweave to enhance data privacy, ensure immutability, and guarantee long-term data permanence [44].

Omar et al. integrated all key participants in the supply chain—including manufacturers, distributors, wholesalers, and healthcare providers—into a blockchain network. Within this framework, stakeholders interact using smart contracts, which facilitate automated processes. Specifically, smart contracts enable hospitals to place automatic vaccine orders with distributors, streamlining the purchasing process [39].

Table 1. Critical points in the management of the COVID-19 vaccine supply chain by the international scientific literature.

Author	Year	Criticality	Description
Hasan et al. [42]	2019	Monitoring the temperature of vaccines	Blockchain technology offers the possibility of automating the monitoring and control of transport conditions by combining smart contracts and IoT sensors.
Kamenivskyy et al. [5]	2022	Updating and checking the expiry date	Smart contracts can check the expiry date of the vaccines and automatically update them by scanning their QR code.
Musamih et al. [7]	2021	Preventing the distribution of counterfeit vaccines	The use of blockchain technology facilitates the traceability processes and allows the players of the supply chain to guarantee the origin and authenticity of vaccines.
Shah et al. [44]	2023	Lack of communication among supply chain players	Blockchain networks offer transparency and improve communication along the supply chain as the information is shared and visible, and, to achieve this, an architectural solution is proposed.
Omar et al. [39]	2021	Delays in deliveries because of inaccurate demand forecasting	Using smart contracts, it is possible to automatically place vaccine orders, reducing the procurement lead time.

In addition to the previously introduced literature, a brief overview of inventory management theories applicable to emergency supply chains is provided for the reader's convenience. Although these theories are not the primary focus of this research, they will be utilised to create different scenarios for analysis and testing in the methodology section. The following is a concise presentation of several inventory management policies applicable to the case analysed.

One common approach is the fixed-period policy [45], in which inventory levels are reviewed at predetermined intervals, and orders are placed based on current stock levels and demand forecasts. This method is particularly useful for organisations that prefer a structured restocking schedule. Another widely used model is the Economic Order Quantity (EOQ) [46], which determines the optimal order size to minimise total costs. EOQ seeks to balance frequent ordering, which increases administrative costs, and excessive stockholding, which elevates storage costs. A variation of EOQ is the Economic Production Quantity (EPQ) [46], applicable to businesses that manufacture their own products rather than purchasing them in bulk. Unlike EOQ, EPQ allows inventory to be replenished gradually as production continues instead of receiving stock all at once. For more dynamic inventory management, businesses can employ the Wagner–Whitin Algorithm, which calculates the most cost-effective ordering schedule over a given period. This method is particularly advantageous when demand fluctuates and ordering costs vary. Alternatively, the lot-for-lot (L4L) [46] approach adopts a straightforward method by ordering exactly the required quantity for each period, avoiding excess stock. This strategy is especially beneficial for Just-in-Time (JIT) systems [47], where minimising storage costs is a priority. Other policies aim to optimise cost efficiency in different ways. The Silver–Meal policy [48], for example, evaluates inventory costs over a short-term horizon, identifying the optimal balance between ordering and holding costs within that timeframe. Similarly, the Least Unit Cost (LUC) method [49] determines the order quantity that minimises the cost per unit while ensuring demand is met. A slightly different approach, Part-Period Balancing (PPB) [50], extends order periods until the cost of holding stock equals ordering costs, thereby creating a more flexible and adaptive inventory strategy. Each of these approaches serves distinct purposes, and the optimal choice depends on factors such as demand patterns, production processes, and cost structures. While some organisations benefit from fixed, predictable ordering schedules, others may find dynamic, cost-sensitive models more advantageous. Selecting the appropriate inventory strategy can significantly reduce costs and enhance operational efficiency.

To summarise, emergency supply chains operate under extreme conditions, requiring rapid adaptability, real-time decision-making, and resilience against disruptions. However, traditional emergency logistics models face significant challenges, including a lack of visibility across the supply chain, delays in data transmission, inefficient inventory allocation, and the risk of fraud or mismanagement. The integration of blockchain technology, sensor networks, and digital twins, as proposed in this article, presents a viable solution for overcoming these limitations and enhancing the effectiveness of emergency supply chain management.

One of the most critical issues in emergency logistics is the lack of real-time visibility and traceability. Traditional supply chains often rely on fragmented information systems, resulting in delays in shipment tracking, inaccurate stock levels, and poor coordination among stakeholders. By integrating blockchain technology, all transactions and movements within the supply chain are recorded in a secure, immutable, and transparent ledger. This ensures that every stakeholder, from suppliers to frontline responders, has immediate access to verified data, reducing decision-making delays and improving accountability. Moreover, blockchain's decentralised nature minimises the risks associated with centralised

control, making it more resistant to cyberattacks and data manipulation—major concerns in crisis situations. Other significant challenges are inefficient resource allocation and inventory management. Emergency supply chains frequently experience overstocking in some areas while facing shortages in others, often due to inaccurate demand forecasting and rigid distribution models. Integrating sensor networks into supply chain operations enables continuous monitoring of stock levels, transportation conditions, and environmental variables such as temperature and humidity. This is particularly crucial for perishable goods, including food and medical supplies, where real-time monitoring helps prevent spoilage and ensures product integrity. The use of IoT sensors facilitates automatic data collection, which, when linked to blockchain, ensures that this information remains tamper-proof and immediately accessible. A fundamental limitation of current emergency logistics is the inability to test different supply chain scenarios and dynamically optimise responses. Decision-makers often rely on static models that do not adapt well to rapidly changing conditions. The incorporation of digital twins—virtual replicas of physical supply chains—enables organisations to simulate various disruption scenarios, predict potential bottlenecks, and evaluate the outcomes of different inventory and distribution strategies. By leveraging real-time data from sensors and blockchain records, digital twins provide an adaptive and continuously updated model that can optimise logistics operations even as conditions evolve. This capability is particularly beneficial in large-scale crises, where logistics networks must be adjusted dynamically based on fluctuating needs and unforeseen constraints. Additionally, delays in procurement and order processing often hinder emergency response efforts. Bureaucratic inefficiencies, manual processing, and lack of automation slow the movement of critical supplies. Blockchain-based smart contracts can automate procurement, inventory replenishment, and distribution processes by triggering predefined actions when specific conditions are met. For instance, when stock levels at a distribution centre fall below a critical threshold, a smart contract can automatically initiate an order with a supplier, reducing reliance on human intervention and accelerating response times. Finally, the lack of coordination among multiple stakeholders remains a major barrier to efficient emergency supply chain management. Governments, NGOs, private companies, and local authorities often operate with siloed information systems, leading to inefficiencies and miscommunication. A blockchain-integrated system provides a single source of truth, ensuring that all entities involved in emergency logistics operate with the same real-time data. This fosters better collaboration, improves decision-making, and prevents redundant or conflicting actions.

The integration of blockchain technology, sensor networks, and digital twins, as proposed in this article, offers a comprehensive solution to the core limitations of current emergency supply chain management. By ensuring real-time visibility, dynamic adaptability, automation, and secure data sharing, this approach enhances the resilience and responsiveness of emergency logistics networks. Implementing such a system would significantly improve efficiency, reduce waste, and enable better preparedness for future crises.

3. Methodology

To address the challenges faced by emergency supply chains, we propose an advanced methodology integrating blockchain technology and digital twin models for the design and management of logistics operations. The proposed action framework aims to achieve higher levels of visibility, real-time decision-making, and enhanced coordination, to improve the variables that enhance the resilience of a supply chain (SC). It is worth noting that this procedure, by itself, cannot improve the resilience of the system as a whole. However, through its potential enhancements in key aspects such as visibility and real-time decision-making, it can assist decision-makers in strengthening the system's

resilience. The methodology, illustrated in Figure 1, comprises the following components: (i) Blockchain Architecture; (ii) Digital Model for Logistics; (iii) IoT-Enabled Real-Time Monitoring; (iv) Scenario-Based Decision-Making with Digital Models; and (v) Integration of Smart Contracts for Automation.

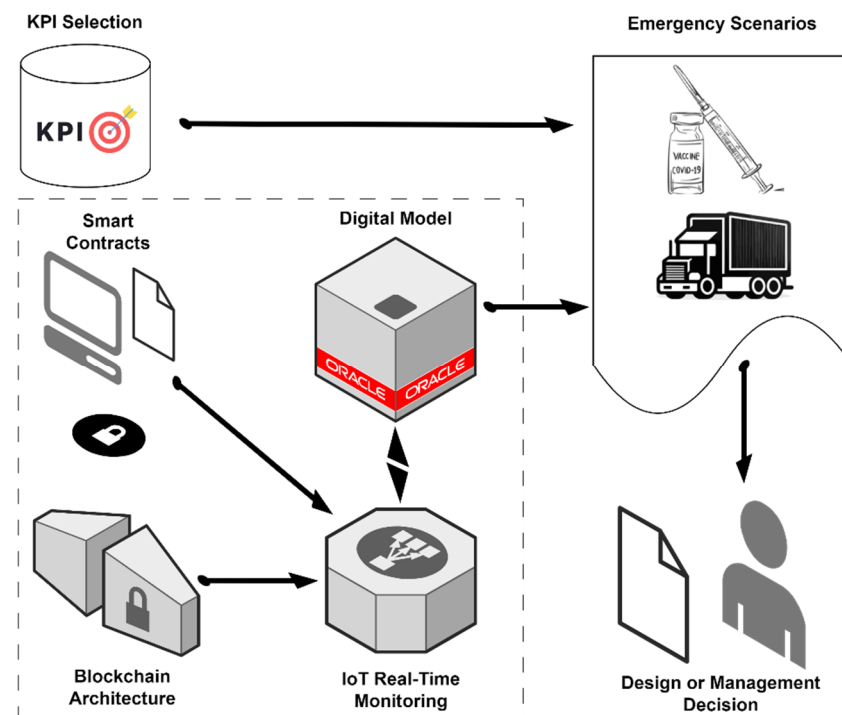


Figure 1. Proposed design and management decision support framework.

The blockchain platform is utilised to establish an immutable ledger of all transactions within the supply chain. Each stage, from manufacturing to delivery at the final distribution site, is recorded on the blockchain. Smart contracts are deployed to automate processes such as inventory management, order placement, and compliance verification. Blockchain technology ensures trust, transparency, and traceability, mitigating issues such as fraud, temperature control failures, and inefficiencies, as highlighted by Hasan et al. in 2019 [42].

A digital twin serves as a real-time virtual replica of the supply chain, capturing the dynamics of the physical logistics system. By integrating real-time data from IoT sensors and blockchain, the digital twin enables stakeholders to monitor and predict the performance of the supply chain. This integration facilitates the identification of potential bottlenecks and supports proactive decision-making. For instance, containers equipped with IoT sensors monitor environmental parameters (e.g., temperature, humidity) and synchronise these data with the blockchain to maintain a reliable record of conditions during transit [37].

IoT devices are deployed throughout the supply chain to collect critical environmental and performance data. The collected parameters will be incorporated into KPI calculations during scenario simulations. These data are automatically logged onto the blockchain, ensuring both transparency and traceability. The combination of IoT and blockchain allows real-time monitoring of temperature, location, and the integrity of critical supplies. Using this mechanism, smart contracts can trigger automated alerts and actions, such as rerouting shipments or initiating replacement orders if specific conditions are violated [6,7].

The digital model is also employed to simulate different emergency scenarios and assess the resilience of the supply chain under varying conditions. By combining blockchain's historical data with the digital twin's simulation capabilities, stakeholders can predict the outcomes of specific disruptions and develop suitable mitigation strategies. The com-

parison between different scenarios will be conducted using selected KPIs. For example, by simulating potential supply interruptions, decision-makers can effectively reallocate resources or pre-position critical supplies in high-risk areas [43]. It is important to note that the first scenario selected should represent the current state (as-is) if the analysed supply chain already exists. For the purposes of this paper, to demonstrate the effectiveness of the proposed framework in an emergency supply chain such as the VSC, it is intuitive to focus on key aspects related to stock availability where needed, thereby avoiding stock-outs. Therefore, in this study, the scenarios compared to achieve a higher level of resilience are represented by different stock policies. However, it is important to note that, in other specific cases, different scenarios may be proposed to assist decision-makers in selecting the best alternative to enhance the resilience of the analysed supply chain, as previously defined. For instance, factors such as the number of supply chain levels, the service level along the value or distribution chain, and other relevant aspects could serve as valid alternatives in scenario selection when comparing different supply chain configurations. This characteristic makes the proposed methodology widely applicable to various types of emergency supply chains and, more broadly, to supply chains in general.

Clarified this aspect, subsequent scenarios should be chosen from among applicable stock policies specific to the case under analysis. For instance, it would be impractical to select an Economic Order Quantity (EOQ) or Economic Production Quantity (EPQ) model for a supply chain that does not follow a replenishment inventory scheme. Similarly, Just-in-Time (JIT) stock policies would not be suitable for a system that does not operate as a demand-driven inventory system.

Smart contracts are utilised to enforce pre-agreed terms and automate logistics processes. For instance, they can automatically validate shipments, release payments, and execute inventory management tasks without requiring intermediaries. This automation enhances efficiency and reduces human error, ultimately leading to faster and more reliable supply chain operations [38].

The implementation of the proposed framework involves multiple phases, including the design of the digital twin and blockchain network, KPI selection, sensor integration, and the establishment of communication protocols. The process begins with capturing data from IoT devices and logging them into the blockchain ledger. Subsequently, historical data are used to calibrate the digital twin, simulate different scenarios, and adjust the system as needed. Finally, supply chain operations are continuously monitored using the integrated digital twin, while blockchain ensures a trusted and transparent record of all transactions.

This methodology aims to enhance the resilience and responsiveness of emergency supply chains by ensuring transparency, trust, real-time visibility, and efficient decision-making. Blockchain guarantees data integrity, while the digital twin facilitates predictive analysis and optimised responses to various emergency scenarios. The proposed framework is designed to be proactive in supply chain design, serving as an innovative tool that integrates multiple previously introduced aspects to support decision-makers. Its objective is to minimise undesired effects caused by a lack of coordination (such as the bullwhip effect) while maximising key supply chain performance indicators, including total order cost efficiency and the percentage of successful deliveries.

The proposed methodology integrates blockchain technology with supply chain simulation to enhance the responsiveness and reliability of emergency distribution for critical supplies, ultimately improving the resilience of the system. The model consists of two key components:

1. **Blockchain Architecture:** The blockchain platform is utilised to establish an immutable ledger of all transactions within the supply chain. Each step, from manufacturing to delivery at the final distribution site, is recorded on the blockchain. Smart contracts

are deployed to automate processes such as inventory management, order placement, and compliance verification.

2. Digital Model: A simulation model is developed to replicate the real-world distribution network of critical supplies. This model incorporates real-world data, including the number of units distributed, regional demand, and available infrastructure. The simulation is used to analyse different scenarios, such as supply chain disruptions and variations in demand, based on the selected KPIs specifically designed for this purpose. The objective is to identify optimal logistics strategies under different emergency conditions.

The integration of blockchain technology ensures greater trust in the supply chain, particularly by reducing errors in data collection and acquisition from the field. This is further enhanced by integrating blockchain with monitoring technologies such as sensors. These improvements provide decision-makers with a higher level of confidence in the management process, ultimately mitigating the bullwhip effect that may impact the analysed supply chain.

The use of a digital twin enables the analysis of various action scenarios, facilitating the assessment of the impact of different management strategies on the specific supply chain under study. This approach enhances decision-making by allowing stakeholders to compare alternative solutions quantitatively.

Both blockchain and digital twin technologies significantly impact supply chain resilience and responsiveness while also contributing to the reduction of the bullwhip effect, as defined by Chen et al. in 2000 [51]. Blockchain's ability to enhance the trustworthiness of data transmitted from field operations to higher supply chain levels—reinforced by digital technologies—helps to reduce distortions in information sharing across the supply chain. This directly addresses one of the primary causes of the bullwhip effect: poor coordination between supply chain levels. Additionally, the capability to test different management approaches using digital twins enables the selection of solutions that maximise resilience and responsiveness while minimising the bullwhip effect.

The integration of these components enables real-time tracking and verification of supplies, thereby minimising the risk of errors, fraud, and inefficiencies. The use of smart contracts further automates key processes, reducing the need for manual interventions and enabling faster response times.

The reduction of risks, achieved through the integration of a real-time monitoring system with a blockchain-based data acquisition approach and a simulation-based methodology, provides decision-makers with a higher level of resilience. Resilience, as defined in the technical literature, refers to “the adaptive capability of a supply chain to prepare for and/or respond to disruptions, to make a timely and cost-effective recovery, and therefore progress to a post-disruption state of operations—ideally, a better state than prior to the disruption” [52].

The application of the proposed methodology enhances adaptability and responsiveness to disruptions, which can be demonstrated through various performance measures depending on the specific context. For instance, in automotive supply chains, resilience improvements can be quantified using a combination of indicators such as total order cost, number of deliveries relative to demand, service level, and the variation coefficient, among others. In the subsequent sections of this paper, a selection of relevant indices will be proposed for the specific case study analysed, reflecting the need to demonstrate performance improvements within a given supply chain.

4. The Impact of the Proposed Framework on the COVID-19 Vaccine Supply Chain

The proposed model has been applied in this paper to the case of the COVID-19 vaccine supply chain, which faced unique challenges due to its reliance on an extensive cold chain system to preserve vaccine integrity and efficacy. Governments procured vaccines directly from manufacturers, bypassing traditional wholesalers, necessitating the rapid establishment of new distribution channels. The logistics involved managing vast quantities of doses that required swift delivery under strict storage conditions, such as ultra-low temperatures (-90°C to -60°C) for vaccines like Pfizer–BioNTech’s Comirnaty. This cold chain was maintained using refrigerated trucks, ultracold freezers at distribution hubs, and specialised logistics infrastructure.

The distribution network comprised multiple stages and stakeholders, including pharmaceutical manufacturers, logistics providers, governmental agencies, and healthcare institutions. Robust coordination and precise timing were essential to prevent temperature excursions that could compromise vaccine efficacy. Challenges at the manufacturing stage included limited availability of ultracold storage units, particularly in low-income regions. Transportation relied on refrigerated vehicles and dry-ice-filled containers, requiring a continuous supply of dry ice and skilled personnel to handle delicate processes. Regional hubs required adequate storage capacity and real-time monitoring systems, with shortages leading to deployment delays. The final delivery to local vaccination centres was complicated by poor infrastructure, unpredictable weather, and inadequate local storage facilities, where any temperature deviation could render doses unusable.

This paper examines the Italian case of vaccine distribution, incorporating its numerical characteristics. The study was conducted in four main phases. Initially, data from the Italian vaccination campaign were analysed to understand the criteria and logic underlying the actual distribution strategy. Next, a discrete-event simulation model was developed using Microsoft Excel to replicate the existing vaccine supply chain (VSC). The model was subsequently validated by comparing its results with real-world data. Finally, a future scenario was modelled in which a blockchain (BC) mechanism was introduced to assess its impact on the system’s behaviour. A three-level supply network was considered to simulate the allocation and distribution of vaccine doses from the National Hub (NH) to the 20 Regional Hubs (RH), testing the impact of different inventory management policies on the efficiency of the COVID-19 vaccine distribution system. The material flow of this supply chain is depicted in Figure 2 (specific to Pfizer’s vaccine). It is important to note that the stock policy management model is primarily based on the demographic analysis of the 20 Italian regions, with no adjustments made based on the actual usage of vaccines. This approach by the Italian government is understandable, as blockchain, IoT, and digital model technologies were not sufficiently developed when the pandemic emerged. In contrast, this paper proposes an alternative approach, wherein stock policy management policies integrate these advanced technologies in accordance with the framework presented in Figure 1 and the material flow decision-making model illustrated in Figure 2. In this proposed approach, usage data are reported to a central management entity to calculate effective distribution quantities. The material and information flow was designed based on a framework developed by Rinaldi et al. in 2023, represented in Figure 2 [53].

In the AS-IS model, the National Hub (NH) distributes vaccine doses to Regional Hubs (RHs) based on both dose availability and population characteristics, such as the number of healthcare personnel and elderly individuals [54–58]. This initial allocation enters the blockchain (BC) module (represented as the TO-BE section in Figure 3), where it is adjusted according to the daily stock levels at each RH and the selected inventory policy. The information flow is updated using BC technology and smart contracts, enabling

real-time stock monitoring at RHs and determining lot sizes based on citizen requests (final demand).

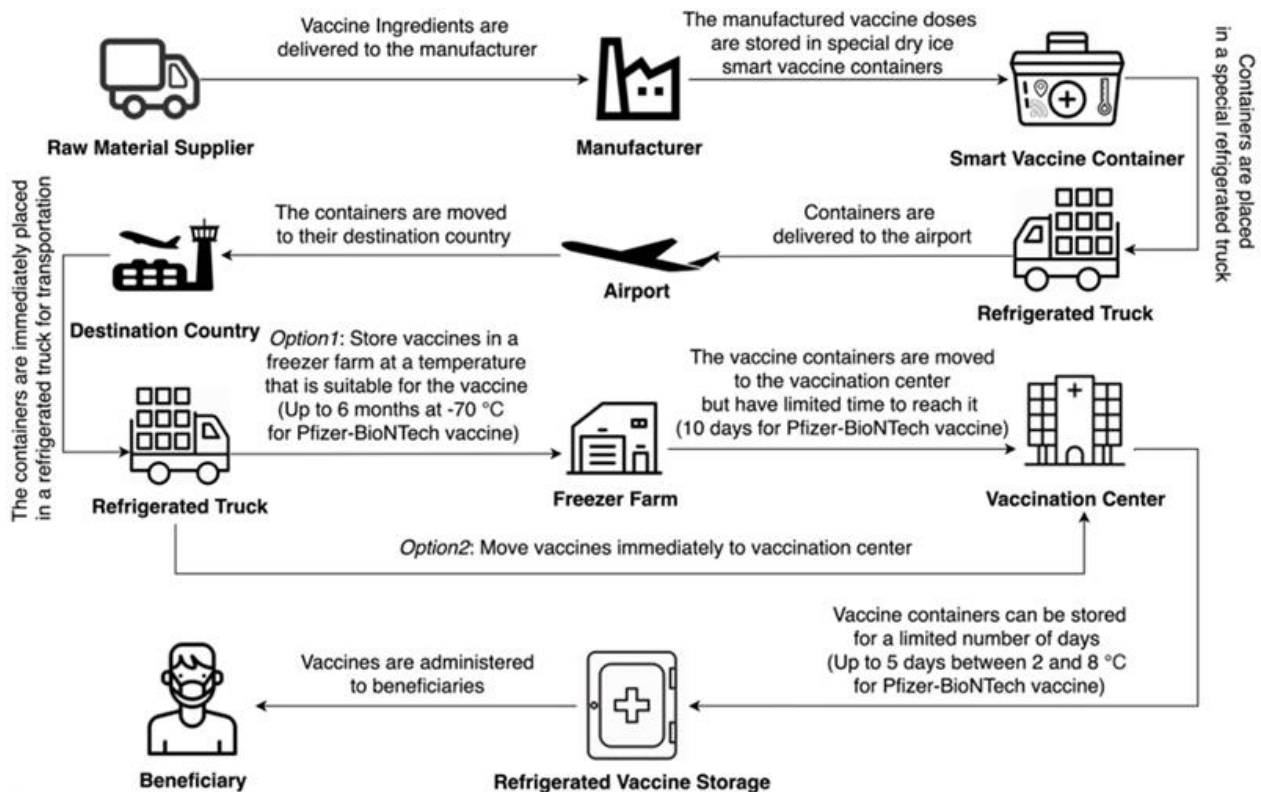


Figure 2. Pfizer vaccine cold chain.

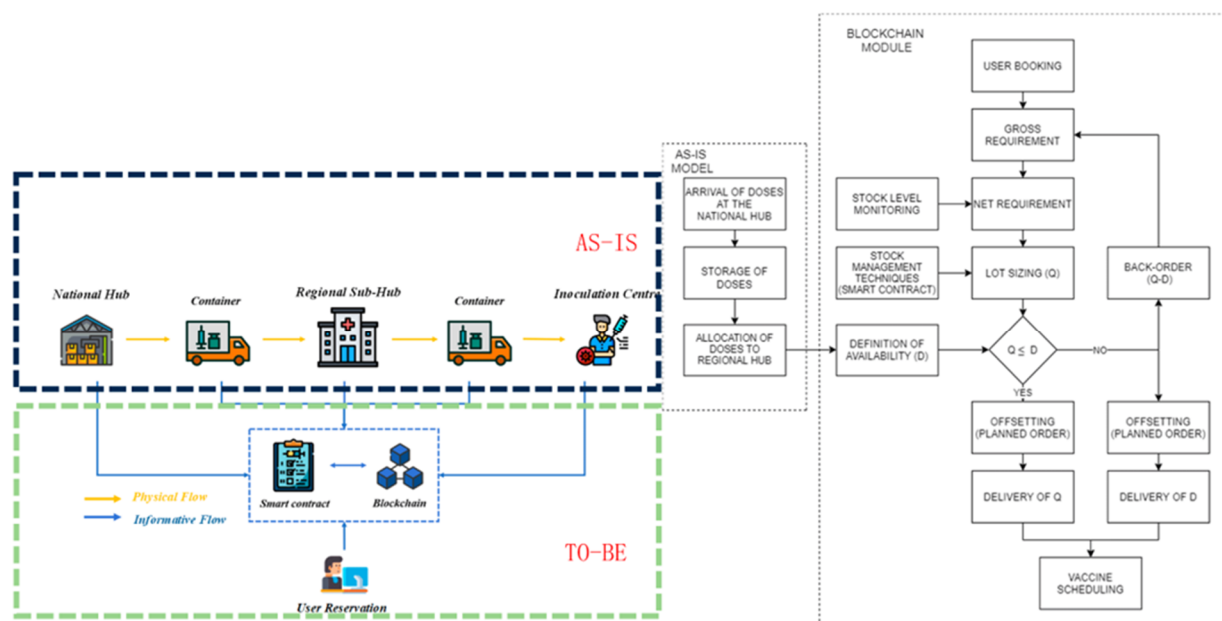


Figure 3. The logical framework and the simulation model flowchart.

The simulation model schedules deliveries from the NH to the RHs and evaluates the impact of different inventory management policies on distribution system efficiency. Unlike the real-world system, the proposed model does not immediately deliver allocated doses; instead, it defines the availability (D) for each RH. Citizen bookings and any backorders

determine the gross requirement of each RH, while real-time stock monitoring allows for the calculation of net requirements.

Lot size (Q) is determined through the simulation of smart contracts, which replicate the logic of a predefined inventory management policy. A dedicated module simulates the function of smart contracts, automatically activating when the system needs to decide on the quantity to allocate and deliver to an RH. If Q is less than or equal to the availability (D) at the NH for a specific RH, the order is fulfilled in full. Otherwise, only the available quantity (D) is delivered, with any unmet demand becoming a backorder to be fulfilled once stock becomes available. Vaccination scheduling is based on the delivered quantities.

The availability (D) at the NH for each RH is cumulative. The simulation model enhances delivery planning efficiency by aligning distributions with actual demand while ensuring that the allocation criteria established by authorities remain intact.

As outlined in the framework presented in Figure 1, a set of key performance indicators (KPIs) was established to assess the effectiveness of various inventory policies and to compare them against the existing distribution system. Specifically, the KPIs measure key factors related to lot sizes and different ordering intervals, along with their impact on vaccine supply chain (VSC) costs. A brief description of the KPIs is provided below, each referring to the entire simulated period:

- N_{SO} : Number of times in which the demand is greater than the number of doses available.
- $SO_{MAX} S_{MAX}$ [units]: Maximum stock-out value.
- Q_{MAX} [units]: Maximum number of doses delivered per single order. This KPI helps evaluate the fleet size, determining the number and capacity of vehicles required to ensure deliveries, which affects both transportation and overall costs.
- Q_{MED} [units]: Average number of doses delivered per single order. This KPI enables the evaluation of the procurement process efficiency, influencing both transportation and overall costs.
- N_D : Number of deliveries.
- A_{AVG} [%]: The percentage of vaccine administration over the entire period (average value) is calculated by comparing the number of doses administered to the number of doses delivered.
- OC [€]: The cost incurred for each order placed is determined by multiplying the unit cost per order (C_o [€/unit]) by the total number of orders placed (N_o):

$$OC = C_o \times N_o$$

- HC [€]: It is calculated by taking into account the average stock (S_{AVG} [units]) and the unit holding cost (C_{HS}), which is derived from the purchase cost:

$$HC = S_{AVG} \times C_{HS}$$

- TC [€]: It is calculated as the total of the daily transportation costs ($C_{t,i}$ [€/day]) incurred throughout the simulated period. These costs are made up of two components: a fixed part ($C_{t,i}^{FIX}$) and a variable part ($C_{t,i}^{VAR}$). The variable part depends on the distance traveled by the vehicle and fuel consumption, and is then multiplied by the number of vehicles needed to complete the order (N_V):

$$TC = \sum_{i=1}^N C_{t,i} = \sum_{i=1}^N (C_{t,i}^{FIX} + C_{t,i}^{VAR}) \times N_V$$

- C_{tot} [€]: The total cost is calculated as the sum of three components: the holding cost (HC), the order cost (OC), and the transportation cost (TC):

$$C_{tot} = HC + OC + TC$$

A vaccine supply chain (VSC) consisting of one National Hub (NH) and 21 Regional Hubs (RHs) [54–58] was modelled, with the described logic applied at each level. The simulation period corresponds to the most critical phase of the vaccine procurement process, spanning 30 weeks from late December 2020 to the end of July 2021. Real-world data were used to simulate NH availability and citizen demand across different regions.

The primary objective of this study is to evaluate how the performance of the VSC changes when blockchain (BC) is implemented alongside various inventory management policies, with a particular focus on cost reduction and distribution system efficiency. To achieve this, six scenarios were analysed, each differing in the stock management policy applied, such as lot sizes and order intervals. The scenarios were selected based on their applicability to the specific case under analysis. While other potential scenarios exist, this selection does not affect the general applicability of the proposed methodology.

The six scenarios are described below:

Scenario 1 (S1): The actual vaccine distribution system in Italy is replicated. Each Regional Hub (RH) operates its own vaccination booking system, with allocation and distribution plans based solely on the current AS-IS model, as illustrated in Figure 3.

The remaining scenarios are made possible by leveraging the framework presented in Figure 1, which enables the implementation of alternative stock management policies. These policies take into account the knowledge and usage data of vaccines administered at each local distribution centre.

Scenario 2 (S2): A fixed-period policy is applied, where orders are placed at regular intervals (every three days). The order quantity corresponds exactly to the amount required to meet demand for the subsequent three days.

Scenario 3 (S3): The lot-for-lot technique is employed, with orders placed daily. The quantity ordered precisely matches the demand for that day. This approach aims to minimise stock holding costs and reduce the risk of obsolescence by ensuring only the necessary amount is procured each day.

Scenario 4 (S4): The Silver–Meal policy is simulated. This method calculates the total cost per period based on the number of periods the current order covers, stopping when this cost begins to increase. This approach allows for dynamic adjustments to both lot size and order interval, which remain flexible throughout the process.

Scenario 5 (S5): The Least Unit Cost method is applied. As a variation of the Silver–Meal policy, it also seeks to minimise total costs. However, rather than stopping when the total cost per period increases, the decision is made by minimising the total cost per unit.

Scenario 6 (S6): The Part-Period Balancing method is implemented. Similar to the Silver–Meal policy, this method determines lot size and order interval by balancing ordering and holding costs. The decision criterion is based on the point at which the difference between these costs reaches an optimal balance.

5. Results and Discussion

As previously stated, this paper highlights the differences in management and effectiveness of the vaccine supply chain (VSC) if real-time usage data were available through an architecture such as the one presented in Figure 1. The assumption is that scenarios 2 to 6 are feasible only if such a solution is implemented. Without it, the policies outlined in these scenarios would be too risky for public health during the emergency. Therefore, the objective of this section is to present and discuss the potential results of alternative stock management policies compared to the approach adopted by the Italian government during the pandemic. It is hoped that this study will encourage the development of such an architecture to enhance supply chain management in future emergencies.

The results provide a comparative analysis of the six tested scenarios. All KPIs are aggregated for all 21 RHs over a 30-week observation period, as previously mentioned. Beginning with the analysis of stock-outs (Figure 4a), it is evident that the fixed-period (S2) and lot-for-lot (S3) approaches yield similar results to the AS-IS model (S1). However, the other policies—Silver-Meal (S4), Least Unit Cost (S5), and Part-Period Balancing (S6)—exhibit a higher number of stock-outs. Despite this, given the 30-week simulation period and the KPI being defined as the total number of stock-outs across all 21 RHs, this outcome remains acceptable when considering the benefits these techniques provide, as further discussed.

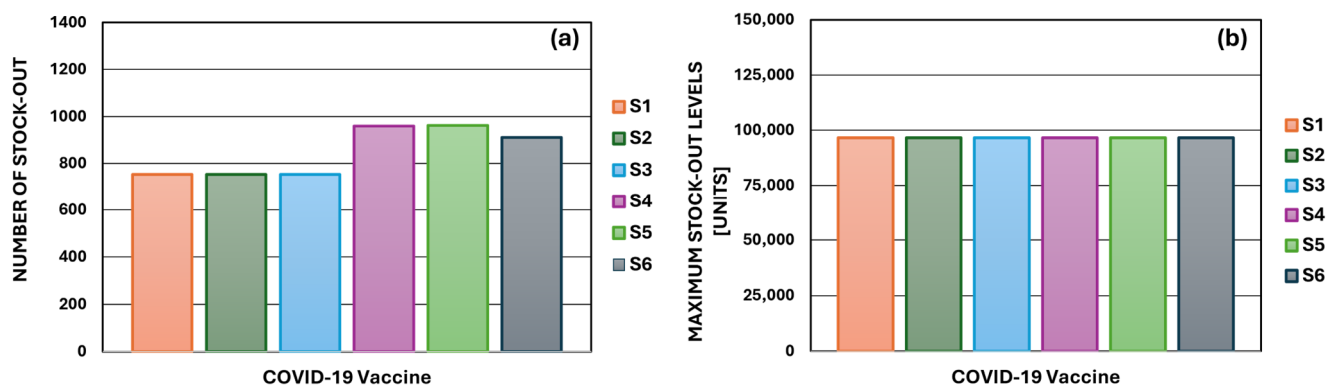


Figure 4. (a) Number of stock-outs. (b) Maximum stock-out levels.

Additionally, while some policies result in a higher number of stock-outs compared to the AS-IS model, this does not significantly impact the S_{OMAX} KPI (as shown in Figure 4b), which is primarily influenced by NH availability. It is important to note that the Silver-Meal (S4) and Least Unit Cost (S5) policies, along with the Part-Period Balancing (S6) policy to a lesser extent, underperform in this KPI compared to the other scenarios. This is likely due to their slower response to demand variations. However, it is also important to emphasise that the impact of this performance limitation is mitigated by supply chain deliveries on the following day. Consequently, stock-out levels remain stable even when these stock policies are applied.

Thus, while these policies may appear to reduce supply chain resilience, and thus responsiveness when evaluating the number of stock-outs, their effect does not significantly influence the stock-out levels KPI. This observation suggests that, for the case study analysed, these KPIs are not critical factors in determining which stock policy would best enhance the resilience of the supply chain.

Figure 5a illustrates Q_{MAX} , representing the maximum number of units shipped to the RHs in a single day. This information is particularly valuable for determining the required vehicle fleet size and the necessary number and capacity of transport units to ensure timely deliveries. Regarding this KPI, it is noteworthy that all inventory management policies demonstrate an improvement compared to S1, resulting in a lower maximum number of units shipped per day than the AS-IS model (S1).

The reduction in delivered quantities enables the system to operate with fewer cargo runs, leading to a more manageable logistics operation and reducing the number of unused doses. It is important to emphasise that, in scenarios 2 to 6, delivery lots are based on real usage data obtained from local distribution centres, facilitated by sensors and blockchain (BC) technology. This trend is further confirmed in Figure 5b, which presents the mean quantities delivered.

BC technology enhances inventory management efficiency by providing real-time insights into both final demand and existing stock levels. This allows for a more precise adjustment of stock quantities to actual requirements, thereby minimising excess inven-

tory risk. The best performance in terms of these KPIs is observed in scenario 3, which implements the lot-for-lot policy. This outcome is likely due to the nature of the policy itself, which functions as a continuous response to demand fluctuations, operating as a pure pull system.

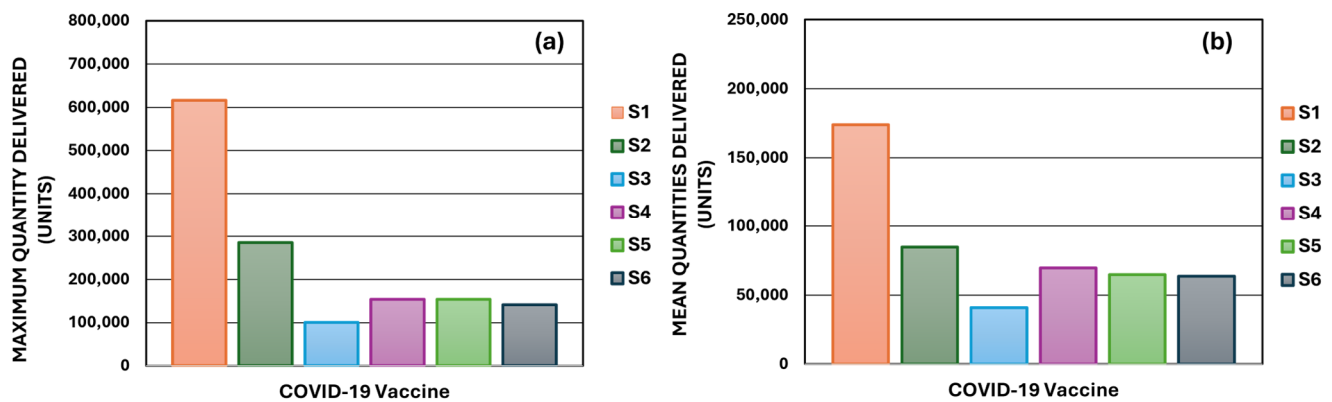


Figure 5. (a) Maximum quantities delivered. (b) Mean quantities delivered.

Such a policy effectively manages planning system variability within the supply chain by breaking down demand into smaller, more frequent orders, thereby reducing the impact of demand fluctuations over the planning period. Given the high variability of emergency supply chains, the lot-for-lot policy appears to positively influence responsiveness and precision, thereby enhancing overall resilience.

Figure 6a,b present the N_D KPI for each RH and the OC, which is directly proportional to N_D . It is evident that, except for the lot-for-lot method (S3), which exhibits the highest rate due to its daily ordering of the exact quantities required, the other policies demonstrate similar performance levels. Both the AS-IS model (S1) and the fixed-period policy (S2) maintain a consistent 3-day ordering interval, while the remaining techniques (S4–S6) adopt a variable interval that is adjusted incrementally. The comparable performance across these methods suggests that the fixed 3-day ordering interval policy is optimal for balancing and minimising costs effectively. It is important to highlight that this result is strongly influenced by the specific conditions of the VSC in Italy during the COVID-19 pandemic. Furthermore, although the lot-for-lot scenario (S3) exhibits the poorest performance in terms of deliveries and associated costs, it is crucial to recognise that this parameter is less relevant when evaluating emergency supply chains. In such supply chains, deliveries must be completed regardless of cost constraints, as operational efficiency is secondary to ensuring the availability of critical supplies. For instance, in Italy, logistics and transportation were managed by the military to ensure rapid and reliable distribution. Therefore, these KPIs may not be the most relevant indicators for identifying the most resilient stock policy within the context of an emergency supply chain. The unique operational constraints and priorities of emergency logistics require an alternative approach to assessing supply chain resilience and effectiveness.

Examining the average administration rates (AAVG), the results presented in Figure 7 highlight the potential improvements that blockchain (BC) technology can introduce to the distribution system. The BC module consistently achieves higher average administration rates across all inventory management policies compared to the AS-IS scenario. Notably, the lot-for-lot method (S3) attains the highest average, despite its higher associated costs. It is also noteworthy that all stock policies, except the AS-IS model, demonstrate superior performance in terms of the number of vaccines effectively administered relative to the doses delivered. The best performance is observed in the lot-for-lot policy, which, as previously mentioned, excels in responding to demand fluctuations. By effectively mitigating demand

variance in deliveries, this approach enhances the efficiency of vaccine administration. Once again, the most resilient policy—particularly in terms of maximising the number of doses effectively administered—is the lot-for-lot method, as it ensures the most effective response to demand variability.

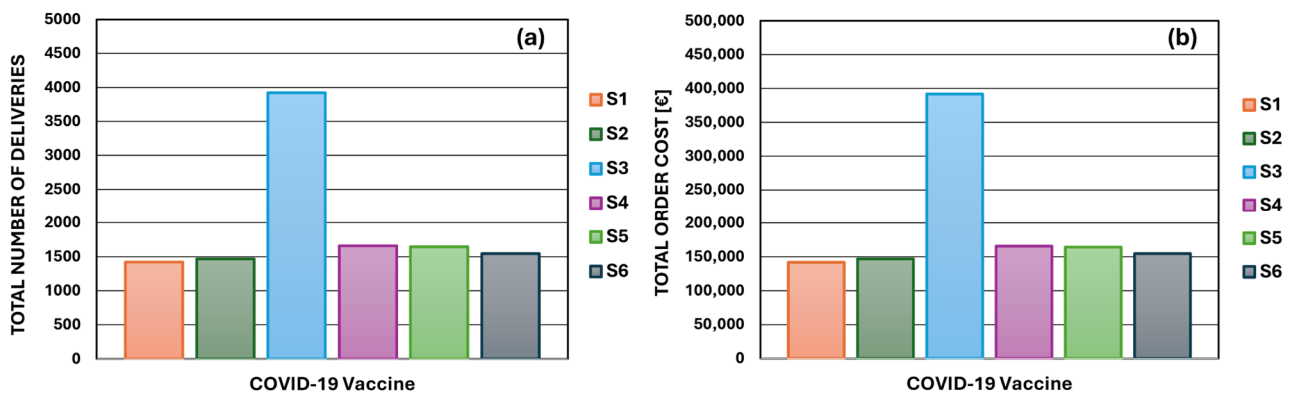


Figure 6. (a) Total number of deliveries. (b) Total order cost.

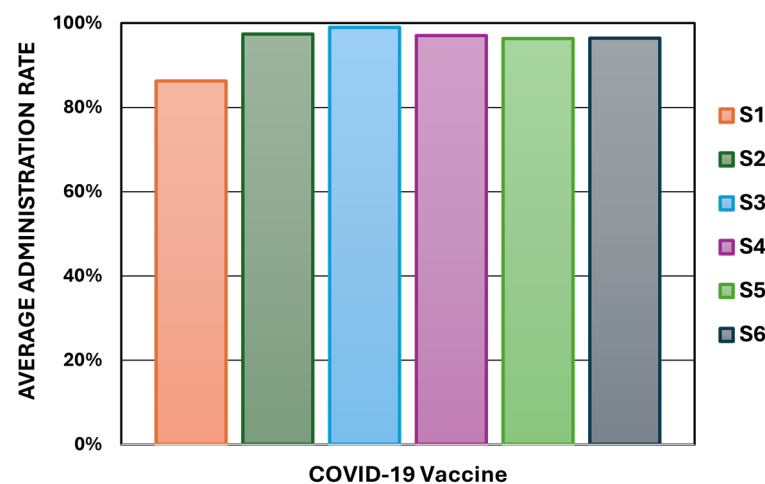


Figure 7. Average administration rate.

Figure 8 presents the total holding cost (HC , Figure 8a) and the total transportation cost (TC , Figure 8b). In terms of total holding cost, blockchain (BC) technology provides significant advantages by enabling inventory management that closely aligns with real demand and current stock levels. This approach facilitates stock minimisation, thereby reducing holding costs. This is particularly crucial for COVID-19 vaccines, which are highly sensitive to temperature and require specialised storage conditions, including ultra-low-temperature freezers, which are costly. Maintaining the minimum necessary stock significantly reduces supply chain risks. Notably, the lot-for-lot method (S3) incurs no holding costs, as it supplies the exact quantity required each day. As expected, cost optimisation techniques such as the Silver–Meal (S4) and Least Unit Cost (S5) approaches result in lower holding costs compared to the AS-IS model (S1) and the fixed-period method (S2). However, it is important to emphasise that these techniques focus on cost minimisation over specific periods rather than the entire simulation period, meaning their long-term performance is not always guaranteed. The Part-Period Balancing method (S6), designed to balance ordering and holding costs, proves to be the most effective policy when focusing specifically on minimising holding costs. Regarding transportation costs, the lot-for-lot method (S3) incurs the highest expenses, as it necessitates daily deliveries based solely on immediate demand, without optimising for cost efficiency. In contrast, the other

techniques reduce transportation costs by decreasing delivery frequency, consolidating orders, and optimising shipments to ensure full-load deliveries.

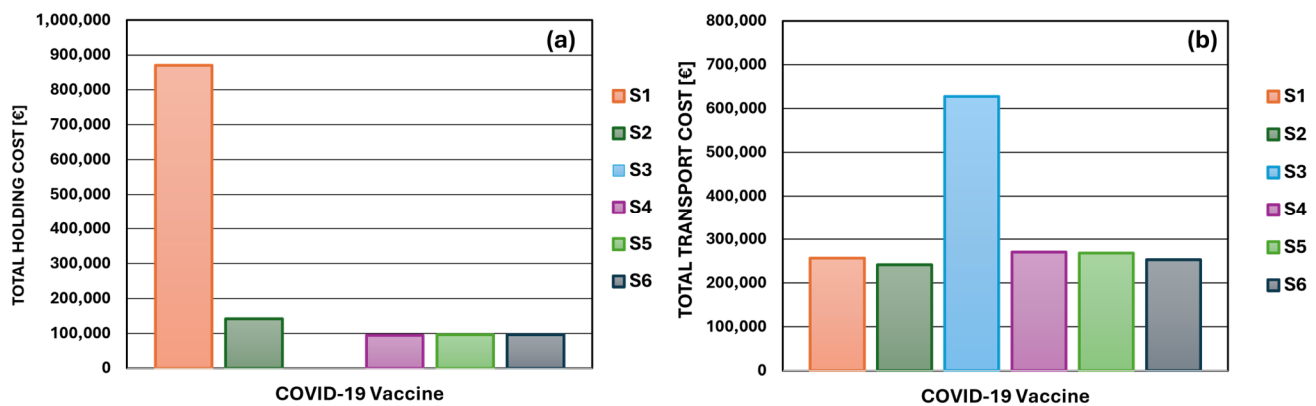


Figure 8. (a) Total holding cost. (b) Total transport cost.

Once again, in terms of holding costs, the most resilient stock policy appears to be the lot-for-lot approach, which maintains a very low stock level, thereby minimising holding costs and mitigating risks associated with cold chain constraints. This conclusion remains valid despite the higher transportation costs associated with the lot-for-lot method, given the fundamental characteristic of emergency supply chains—deliveries must be completed regardless of cost constraints. Therefore, considering both holding and transportation costs, the most resilient stock policy appears to be the lot-for-lot method, as implemented in S3.

In conclusion, based on the total cost (C_{tot}) shown in Figure 9, it can be inferred that, while adopting daily deliveries slightly improves the administration rate, it also results in significantly higher costs. Conversely, a strategy focused on cost minimisation or balancing provides a more efficient solution, achieving better performance in both administration rates and cost control compared to the AS-IS scenario. It is evident that scenarios based on economic optimisation (S4–S6) outperform both the fixed-order period strategy and the lot-for-lot approach. Among these, the lot-for-lot method (S3) exhibits the weakest performance compared to all stock policies, except for the AS-IS scenario (S1). However, it still demonstrates an improvement in performance relative to S1. It is important to note that this KPI is highly dependent on other cost parameters and serves primarily as a summary metric from an economic perspective, providing an overarching view of cost efficiency within the analysed supply chain.

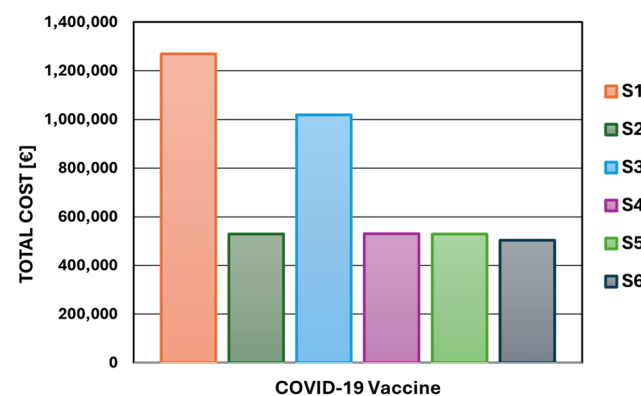


Figure 9. Total cost.

Based on the analysis conducted, it can be concluded that, if the decision-maker primarily considers technical KPIs without focusing on economic factors, the most resilient

stock policy, as revealed by the scenario-based assessment, is the lot-for-lot stock policy. However, if economic parameters are also taken into account, the decision becomes more complex and necessitates the development of a unified, non-dimensional index incorporating weighted economic and technical parameters. Furthermore, it is important to emphasise that scenario 3 (S3) is the most resilient under the assumption that the supply chain integrates the aforementioned sensor and blockchain (BC) technologies. In the absence of these technologies, the risk associated with breaking down demand on a day-by-day basis becomes excessively high for an emergency supply chain. Given that the primary objective of such a supply chain is to minimise the impact of disruptions on people and critical resources, the feasibility of implementing S3 without these technologies would be considerably reduced.

The case study results demonstrate that integrating blockchain and digital twins into vaccine supply chains (VSC) offers significant opportunities for improvement. Beyond VSC, the proposed resilience framework can enhance various emergency supply chains, including disaster relief, food security, and critical infrastructure logistics. Blockchain ensures transparency and traceability, while digital twins enable real-time monitoring and scenario analysis, providing crucial decision-making tools in crisis situations.

In disaster response, rapid and efficient delivery of essential supplies is critical. Blockchain enhances coordination among governments, NGOs, and private suppliers by ensuring transparent resource allocation. Digital twins simulate disaster impact scenarios, optimising logistics routes and reducing inefficiencies. A similar approach benefits food supply chains, where blockchain improves traceability and mitigates fraud, while digital twins help supply chain managers model risks and adjust stock management strategies accordingly. A key challenge in emergency supply chains is systemic vulnerability. Global disruptions have exposed the fragility of Just-in-Time systems and reliance on a limited number of suppliers. While improved inventory policies help, ensuring supply chain resilience requires redundancy and diversification. Pre-positioning critical supplies minimises transportation disruptions, while blockchain enables real-time stock verification, reducing the risks of hoarding and misallocation. Additionally, integrating multi-sourcing strategies into digital twins allows decision-makers to simulate supplier failures and adjust procurement plans dynamically. Decentralising decision-making further strengthens emergency supply chains. Centralised logistics networks can lead to delays in information flow and slow response times. Blockchain enables verified stakeholders to access real-time supply chain data, improving response speed. In disaster logistics, blockchain-based smart contracts could autonomously reorder supplies based on stock levels, reducing reliance on centralised approvals. A similar approach benefits energy supply chains, where decentralised networks could allocate fuel and electricity based on immediate needs. Despite its advantages, implementing blockchain and digital twins in emergency supply chains presents challenges. Many regions, particularly in low-income areas, lack the necessary digital infrastructure for real-time IoT monitoring and blockchain networks. Integration is complex due to multiple stakeholders using different data formats and legacy systems. Additionally, blockchain's high cost and scalability concerns, especially for proof-of-work systems, pose adoption barriers. A hybrid approach, combining blockchain with cloud-based systems, could provide partial decentralisation while managing computational costs. Standardising digital twin interoperability will also be essential for broader adoption.

Looking ahead, AI-driven predictive analytics could further enhance emergency supply chain resilience by identifying risks before they escalate. AI models can analyse historical crisis data, anticipate disruptions, and enable proactive resource allocation. These models optimise logistics dynamically based on evolving crisis conditions, reducing delays caused by manual decision-making. For instance, AI-powered simulations integrated with

digital twins could help predict supply chain bottlenecks due to geopolitical disruptions, while climate-related forecasts could inform stockpiling strategies for essential goods. By integrating blockchain, digital twins, and AI-driven analytics, emergency supply chains can transition from reactive crisis management to a more proactive and resilient approach. Strengthening these networks with digital tools will enhance preparedness for future disruptions, enabling a more effective response to global challenges.

6. Conclusions

This paper addresses the challenges faced by emergency supply chains, with a particular focus on the distribution of critical supplies such as vaccines during crises. The case study analysed in this paper is highly relevant due to the global scale of the COVID-19 emergency, which disrupted traditional logistics channels worldwide. This case study provides insights that can be applied to various other contexts, even those with less severe challenges.

The study investigates the integration of blockchain (BC) technology and digital twins to enhance transparency, traceability, and operational efficiency in emergency logistics. It contributes to the literature by providing a detailed analysis of the COVID-19 vaccine supply chain, a critical and timely issue given the global pandemic. The state-of-the-art review highlights recent advancements in emergency supply chain management, emphasising the role of Fourth Industrial Revolution technologies such as blockchain, IoT, and AI. While the existing literature acknowledges the potential of blockchain in enhancing transparency and minimising fraud, this study identifies a gap in the integration of BC and digital models for dynamic management in emergency contexts. By bridging this gap, the research provides a more robust and adaptive solution.

The application of the proposed methodology demonstrates that integrating BC technology with digital models significantly improves traditional supply chain management. The findings indicate that real-time data sharing enhances administration rates, reduces stock-outs, and lowers costs related to stock management and transportation. Notably, smart contracts automate inventory control, minimising human error and expediting response times. This study stands out by simulating the real-world impact of these technologies, enabling stock management policies that would otherwise be unfeasible without their application. Unlike previous studies, which were largely conceptual or limited in scope, this research offers practical insights based on comprehensive simulation. However, the study also acknowledges certain limitations. While blockchain and digital twins enhance supply chain resilience, they cannot entirely mitigate challenges such as delayed vaccine deliveries or inadequate infrastructure. Furthermore, the high energy consumption and investment required for blockchain implementation pose economic and environmental concerns that warrant further investigation.

The integration of blockchain and digital twins in emergency supply chains, as demonstrated in the case of COVID-19 vaccine distribution, establishes a strong foundation for improving transparency, resilience, and efficiency in crisis logistics. However, expanding this approach beyond the healthcare sector requires addressing infrastructure gaps, interoperability challenges, and the need for decentralised decision-making. Future emergency supply chains can transition from reactive crisis management to proactive resilience planning by incorporating multi-sourcing strategies, predictive AI models, and decentralised response mechanisms. This shift will enable better preparedness for future global disruptions.

In summary, this study provides a valuable contribution to the literature by demonstrating how the combination of blockchain and digital twin technology enables new stock management policies in emergency supply chains, particularly for vaccine distribution. Its

innovative approach lays the groundwork for further exploration into resilient and adaptive logistics systems for future crises. Nevertheless, even though the general applicability of the model has been demonstrated, a limitation of this research is the limited number of stock policies considered. In future works, additional stock policies could be explored and applied.

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