

Integrating Auditing and Inspection into Metaverse-Based Healthcare and Pharmaceutical Supply Chains

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Abstract—Metaverse-based healthcare and pharmaceutical supply chains aim to enhance operations by providing greater visibility, virtual representations of facilities and material flows, and innovative methods for coordination and training. However, these metaverse-based systems largely overlook critical regulatory functions, such as auditing and inspection. Audit planning, evidence review, and deviation assessment remain only loosely integrated with the live data streams and digital twin models available on these platforms. Consequently, risk oversight continues to be episodic and reactive, rather than continuous and proactive. To address this gap, we propose an architecture specifically designed to integrate auditing and inspection into metaverse-based healthcare and pharmaceutical supply chain environments. We integrate heterogeneous operational and sensor data with edge and cloud services, an analytics engine, and an immersive metaverse platform hosting interactive digital-twin models of facilities, logistics assets, and processes. We build on this infrastructure with a data lifecycle model supported by three algorithms for data collection, preprocessing, and analysis and risk assessment, enabling compliance-oriented monitoring and prioritization of anomalies and potential non-compliance events. We also consider constraints affecting metaverse-based audits, including technical limitations (i.e., connectivity, latency, device capabilities, and integration), regulatory requirements (i.e., data integrity, audit trails, and validation), and adoption and ethical considerations (i.e., training, human factors, privacy, and trust). Overall, we provide a structured blueprint for future implementations and empirical studies of immersive and data-driven audits in regulated metaverse-based healthcare and pharmaceutical supply chains.

Index Terms—Metaverse, Healthcare, Supply Chain, Audit, Inspection, Immersive Environment

I. INTRODUCTION

The global healthcare and pharmaceutical supply chain has become increasingly complex and geographically dispersed.

This growing complexity has created an interconnected network that delivers many of the medicines on which patients rely, yet a large share of pharmaceutical manufacturing, particularly the production of active pharmaceutical ingredients (APIs), occurs overseas, including in India and China [1]. In 2019, only 28% of U.S. API production facilities were located domestically [2]. Under these conditions, experts note that supply chains remain very complex, which makes oversight and quality assurance more difficult [1]. This complexity increases systemic risk. The World Health Organization (WHO) reports that approximately one in ten medicines in low and middle-income countries are substandard or falsified [3], leading to nearly US\$30.5 billion in global losses annually. The U.S. Food and Drug Administration (FDA) emphasizes that safeguarding this supply chain is challenging and requires a coordinated, global, multilayered approach [4]. Pharmaceutical supply chains operate under intensive regulatory scrutiny. Multiple agencies impose overlapping requirements on manufacturing, documentation, and traceability. For example, the U.S. Drug Supply Chain Security Act (DSCSA) mandates an interoperable electronic system to identify and trace prescription drugs at the package level throughout the supply chain [4]. Meeting such demands is burdensome, even routine audits require extensive data collection and on-site inspection, while compliance failures can incur multi-million-dollar fines. These challenges motivate the need for new tools that can streamline the auditing and inspection process.

Industries worldwide are undergoing rapid digital transformation. Forecasts predict approximately 21.1 billion connected IoT devices worldwide by 2025 [5]. In pharmaceutical supply chains, IoT sensors can monitor temperature, humidity, location, and other conditions in real time, vastly increasing visibility into each shipment and facility. At the same time,

digital twins, the live virtual replicas of physical processes, are being applied to supply chains. These digital models integrate streaming IoT data and analytics to mirror real operations. Recent work highlights that an IoT-enabled digital twin augmented with Augmented Reality (AR), Virtual Reality (VR) and Artificial Intelligence (AI) can provide real-time predictive analytics, simulation, and decision-making capabilities for supply chain management [6]. Extended reality (XR) technologies (augmented, virtual, and mixed reality) are also gaining momentum in healthcare operations. For instance, the healthcare AR market is projected to grow from USD 1.51 billion in 2025 to USD 4.99 billion by 2030 [7]. This reflects the rapid adoption of immersive tools. Major industry analysts note that digital twin integration with AR makes it possible for employees to collaborate regardless of location [8].

Existing solutions in healthcare and pharmaceutical supply chains integrate IoT devices, edge and cloud computing, digital-twin models, and immersive environments, including metaverse and VR applications, to support real-time data capture, timely analysis, robust storage, enhanced visibility, and coordinated decisions among stakeholders. Prior studies show that immersive interfaces and digital twins can represent production lines, warehouses, and logistics nodes, and support monitoring, staff training, and collaborative planning. These works, however, treat the metaverse as an operational and coordination layer. They do not define how regulatory authorities and quality units can audit and inspect supply chains that already operate within such metaverse environments. In current practice, quality and regulatory teams still conduct audits and inspections through separate processes and tools, even when rich operational data and virtual representations exist. Audit planning, evidence review, deviation assessment, and reporting often remain weakly linked to live supply chain data and to digital twin models in the metaverse. This study addresses how to audit and inspect metaverse-based healthcare and pharmaceutical supply chains. We focus on a compliance-oriented approach that incorporates audit and inspection workflows within the metaverse. Our aim is to provide regulators and quality teams with more continuous oversight of risk, rather than episodic and delayed insight based on conventional audit workflows.

In this paper, we propose an architecture for auditing and inspecting metaverse-based healthcare and pharmaceutical supply chains. The architecture integrates four key components: IoT devices and an edge computing network that collect live data from manufacturing and logistics processes, a cloud computing platform that stores this data and provides computing power for analysis, and a metaverse platform that visualizes the entire digital supply chain. Through this metaverse platform, users (e.g., managers, auditors, analysts) can explore supply chain processes. Together, these elements introduce interactive auditing and inspection in metaverse-based healthcare and pharmaceutical supply chains. Users can use VR headsets to walk through a virtual production facility while querying IoT sensor readings or reviewing records. The metaverse environment also supports annotation, simulation

of failure scenarios, and collaborative decision-making across geographic boundaries. The main contributions of this paper are as follows:

- 1) We propose an architecture for auditing and inspection in metaverse-based healthcare and pharmaceutical supply chains. The architecture integrates edge devices, cloud services, metaverse interfaces, and an analytics layer to support near real-time oversight.
- 2) We define a data lifecycle model with three concrete algorithms for data collection, data preprocessing, and analysis and risk assessment. The model is designed for compliance-focused auditing and inspection detection in regulated supply chains.
- 3) We present a multi-dimensional discussion of constraints associated with metaverse-based oversight. We examine technical limitations, regulatory and compliance requirements, and adoption and ethical issues in metaverse-based environments.

The rest of this paper is organized as follows: Section II reviews related work; Section III presents the proposed system architecture; Section IV discusses technical limitations, regulatory and compliance implications, and adoption and ethical considerations; and Section V concludes the paper.

II. RELATED WORK

The metaverse is widely conceptualized as a persistent and multi-user virtual environment that integrates multiple technologies, especially immersive technologies (VR, AR) and real-time data to mirror and extend physical processes [9]. Unlike standalone VR environments, a metaverse environment provides a shared, continuous virtual space that can enhance service-oriented sustainability and collaboration in supply chain contexts. In healthcare, early studies suggest that such environments can improve the transparency and monitoring of supply chain operations. For example, the authors of the study [10] demonstrate that a metaverse-based healthcare supply chain can enable real-time data monitoring and analysis. In their proposed healthcare supply chain use case, they show how emerging technologies (AI, Blockchain, IoT, extended reality, etc.) can construct a metaverse that oversees all stages of the healthcare supply chain. This approach promises significant improvements in efficiency and traceability for healthcare logistics. Digital twin simulations in the metaverse have been proposed to accelerate pharmaceutical development. Studies note that the use of digital twins with metaverse environments can be used for more precise diagnosis and for precision medicine by mirroring real-world patient conditions [11]. The metaverse also opens the door to remote medical activities. The study [12] highlights that the metaverse can be used to perform various medical activities, including remote surgery, medical therapy, and pain control. These developments indicate growing interest in metaverse-based systems in various medical domains, especially in supply chain oversight within healthcare and pharma. This shows the potential of metaverse solutions beyond traditional applications of AR in training or telemedicine. Parallel efforts are extending these concepts

TABLE I
COMPARISON OF SELECTED METAVERSE, XR, AND DIGITAL-TWIN-BASED STUDIES IN THE HEALTHCARE AND SUPPLY CHAIN DOMAIN.

Study	Domain	Technologies	Main objective	Audit / inspection support
[10]	Healthcare services	Metaverse concepts, immersive interfaces, IoT and cloud infrastructure	Survey metaverse applications in healthcare, including clinical workflows, telemedicine, and patient engagement.	No
[11]	Cross-domain (healthcare, industry, smart cities)	Digital twins, metaverse platforms, IoT, cloud computing	Provide a comprehensive survey of digital-twin and metaverse concepts, architectures, and use cases across multiple domains.	No
[13]	Agri-food supply chains	IoT, metaverse concepts, digital-twin and data-analytics platforms	Address agri-food supply chain visibility and quality management through digital technologies and virtual models of production and logistics stages.	No
[14]	Industrial/manufacturing systems	Industrial metaverse, digital twins, IoT, cyber-physical systems	Explore digital-twin inception in the industrial metaverse and its role in modeling and optimizing manufacturing systems.	No
[15]	Logistics and supply chain management	Metaverse environments, XR interfaces, IoT-enabled logistics platforms	Discuss metaverse opportunities and challenges for logistics and supply chain management with emphasis on coordination, transparency, and collaboration.	No

to food and broader logistics domains. The agri-food supply chain, for instance, is starting to incorporate the metaverse and related technologies for immersive traceability and stakeholder collaboration [13]. This study observes that retailers have begun using immersive virtual worlds to boost transparency and trust. Their work introduces a structured framework that covers various metaverse tools, from immersive 3D environments to real-time data integration. This work aims to improve communication, security, and resilience in agri-food networks. In the logistics sector, the concept of an industrial metaverse has emerged, wherein digital twins of industrial assets are integrated into an interactive virtual space. Such integrations provide a unified, live model of the supply network that stakeholders can observe and manipulate collaboratively [14], [16]. Digital twins, which are virtual replicas of physical entities synchronized via IoT sensors, play a pivotal role by feeding real-time operational data into the metaverse. For example, Charles and Emeka (2021) demonstrate that digital twin-driven visibility can be a new paradigm for future logistics. It enhances resilience, improves supply chain agility, mitigates risks, and ensures sustainable operations [6]. These studies suggest improvements in agility and crisis response, as well as more sustainable operations through precise monitoring. The potential benefits of metaverse adoption in supply chain operations, such as better coordination, data sharing, and resource management efficiency, have been mapped out in recent literature reviews [15]. Nonetheless, researchers emphasize that these technologies are still emerging in practice. There are significant challenges, such as high infrastructure costs, data security, lack of standards, and legal and ethical challenges, that still hinder widespread implementation. Importantly, regulatory frameworks have been identified as a constraint, indicating that governance and compliance mechanisms have yet to catch up with metaverse-driven supply chain innovation [17].

A. Research Gap

As shown in Table I, none of the existing works treat regulatory auditing and inspection of metaverse-based healthcare and pharmaceutical supply chains as a primary design goal. To the best of our knowledge, no existing system defines an architecture and data lifecycle that embeds audit and inspection workflows within the metaverse layer. Current metaverse-based supply chain applications focus on operational efficiency, visibility, and stakeholder collaboration rather than formal inspection protocols. The literature in this area is still in its infancy, primarily exploring conceptual frameworks without developing a dedicated, compliant, multi-user virtual inspection system for enforcing regulations in healthcare and pharmaceutical supply chains. This gap highlights the novelty of our proposed approach, which integrates metaverse environments, digital-twin models, IoT sensor networks, cloud services, and edge computing into a persistent virtual audit environment for regulated healthcare and pharmaceutical operations.

III. PROPOSED ARCHITECTURE FOR AUDITING AND INSPECTION IN METAVERSE-BASED HEALTHCARE AND PHARMACEUTICAL SUPPLY CHAINS

In this section, we present the proposed system architecture that supports auditing and inspection processes within metaverse-based healthcare and pharmaceutical supply chains. The section is divided into three subsections, providing a detailed overview of the system. The first subsection outlines the key system components and their interactions. The second subsection provides a step-by-step overview of the auditing process, from data collection to inspection and compliance reporting. Finally, the third subsection introduces the algorithms used to manage data throughout the process, including data collection, pre-processing, and analysis.

A. High-Level System Architecture

Figure 1 illustrates a high-level system architecture for the proposed use case, which integrates multiple components to facilitate efficient data processing, immersive visualization, and advanced analytics within the healthcare and pharmaceutical supply chain. The architecture begins with various data sources representing different stages of the supply chain, including manufacturing, storage, transportation, and distribution. These stages generate critical data related to production details, storage conditions, shipment routes, and delivery status. The goal is to capture comprehensive and real-time information about supply chain operations that can be used for auditing and inspection processes. The collected data is then routed to an edge computing layer for initial processing. At this stage, tasks such as data aggregation, standardization, and integration are carried out to ensure that the data meets consistency and quality standards. Preprocessing at the edge helps reduce the amount of raw data transmitted to the cloud, thereby decreasing latency and optimizing bandwidth usage. This approach ensures that the system remains efficient even when handling large volumes of data generated from diverse sources. Once preprocessed, the data is transferred to cloud storage, where it undergoes more extensive processing and transformation tasks. The cloud infrastructure not only stores the data but also serves as the primary environment for more complex processing operations, which may include further aggregation, filtering, or merging of datasets. These steps prepare the data for subsequent analysis and visualization. Central to the architecture is the metaverse platform, which hosts digital-twin representations of facilities, assets, and supply chain processes in an immersive virtual environment. This virtual representation supports real-time monitoring and visualization of assets and processes across the supply chain, from manufacturing to distribution, and provides a comprehensive view of its operational status. The platform supports immersive reporting and interactive data visualization, allowing stakeholders to obtain deeper, context-rich insights into supply chain operations. Moreover, it enhances auditing and inspection processes by allowing stakeholders to virtually explore supply chain activities, detect anomalies, and verify compliance.

The architecture also includes an analytics engine that processes the data received from the cloud. The engine performs real-time data analysis, processes data for visualizations, and outputs key reporting metrics that support decision-making. The insights derived from the analytics engine help optimize supply chain operations. Moreover, reveal trends, anticipate potential issues, and guide improvements. The analytics engine serves as a critical component for transforming raw data into actionable intelligence. Users such as supply chain managers, auditors, and analysts interact with the system primarily through the metaverse platform. The interactions include access to immersive reports, execution of virtual audits, and analysis of the supply chain's virtual representation. This level of engagement allows them to monitor the supply chain in real-time, ensure compliance, and perform thorough inspections.

B. System Workflow

The sequence diagram in Figure 2 illustrates a detailed and integrated process. It begins with the user interaction with the metaverse platform, which serves as the primary interface for engaging with the system. This platform handles users' requests for analysis, audit, and inspection and sets the stage for end-to-end monitoring of the supply chain. The metaverse platform requests data from cloud storage, which plays a central role in managing data. Meanwhile, the supply chain component collects data from various stages, including production information, storage conditions, shipment details, and delivery status. The collected data is sent to the edge computing unit for preprocessing, where it undergoes aggregation, standardization, and integration to ensure consistency and readiness for further analysis. After preprocessing, the data is stored in cloud storage along with metadata, and a backup process is conducted to maintain data integrity and ensure the availability of critical information. The next step involves requesting processed data from cloud storage and data analysis from the analytics engine, which performs real-time analysis to extract valuable insights. The processed data and analytics findings are then sent back to the metaverse platform. With this processed data, the platform generates a virtual replica of the supply chain that simulates real-world conditions. The system produces visualizations that illustrate the flow of the supply chain, inventory levels, and environmental conditions, providing a comprehensive view of the current state. When the user requests immersive reporting, the metaverse platform delivers interactive dashboards and 3D models of the supply chain, allowing the user to engage with the data in a visually rich environment. The user can conduct audits and inspections through the platform, which queries cloud storage to retrieve the latest updates and historical data on assets and processes. The metaverse platform then updates the visualizations and virtual replica based on that data. This approach provides an immersive, user-centric experience for the healthcare and pharmaceutical supply chain audit and inspection process. It integrates data collection, preprocessing, analysis, and visualization into a cohesive system that enhances decision-making and overall supply chain management.

C. Data Lifecycle Algorithms

We have designed three algorithms for the key processes of the system: data collection, data preprocessing, and data analysis and risk assessment. These algorithms work together to ensure that the data collected is accurate, standardized, and meaningful. The first algorithm focuses on real-time data collection from various sensors to ensure continuous monitoring of supply chain processes. The second algorithm handles data preprocessing, which involves cleaning, standardizing, and integrating the collected data to create a unified dataset suitable for further analysis. Finally, the third algorithm deals with data analysis, where statistical and risk assessments are conducted to detect trends, anomalies, and potential risks within the supply chain. All these algorithms are explained in detail in the rest of this section.

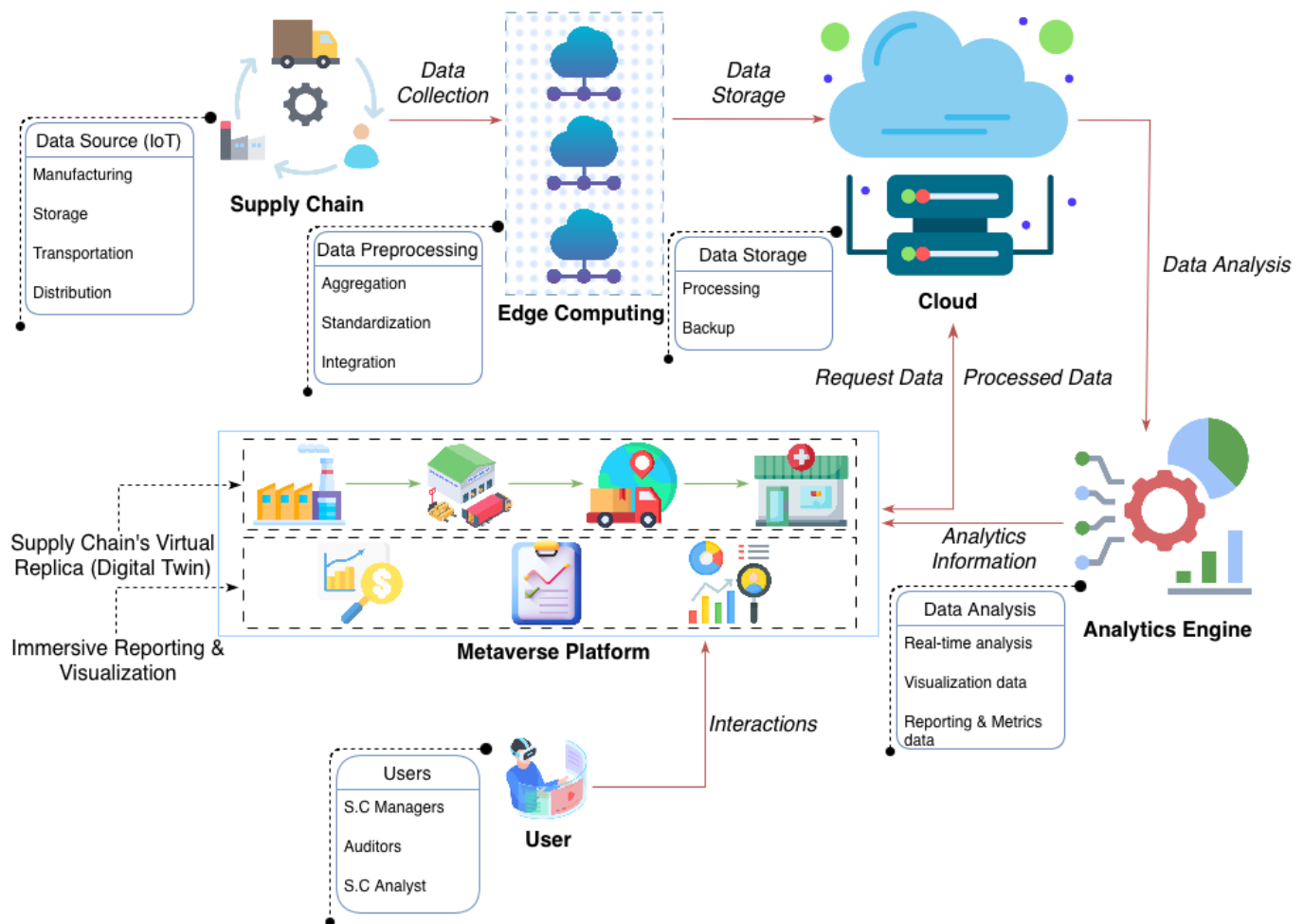


Fig. 1. System Architecture for Immersive Healthcare and Pharmaceutical Supply Chain Auditing and Inspection

Data Collection Algorithm: Algorithm 1 automates real-time sensor data capture and recording throughout the supply chain. The algorithm starts with sensor initialization, where each sensor is checked to ensure it is active and functioning. If any sensor is inactive, the malfunction details are captured. This step ensures the integrity of the data collection process by verifying that all sensors are operational. Once the sensors are verified, the algorithm moves into the data capture phase, where data from each sensor is continuously collected at specified intervals. This real-time monitoring captures critical parameters like temperature and humidity, which are essential for maintaining the quality of pharmaceutical products. After data collection, the algorithm logs the captured data and sensor malfunction details to the edge device for preprocessing.

Data Preprocessing Algorithm: Algorithm 2 helps maintain the quality and consistency of sensor data collected from various sources. The algorithm begins with data cleaning, where noise and outliers are filtered out based on predefined criteria that improve the reliability of the datasets. This step is essential because raw sensor data often contains inaccuracies that can skew analysis results. Following this, data

standardization is performed to convert the data into uniform formats, such as Celsius for temperature or relative percentage for humidity. Data standardization ensures that measurements from different sources become comparable and reduces variability introduced by diverse data formats. The algorithm then proceeds to data aggregation, where it integrates data points from various sensors along with associated metadata, creating a unified dataset that provides a comprehensive view of the monitored parameters. The final output is a processed dataset that is clean, standardized, and aggregated. This dataset is suitable for long-term storage, further analysis, and the creation of digital twins or virtual replicas.

Data Analysis and Risk Assessment Algorithm: Algorithm 3 aims to derive meaningful insights from the processed data. It begins with exploratory data analysis (EDA), where basic statistical measures such as the mean, median, and standard deviation are calculated for key data attributes to provide a quantitative overview. Visualizations, including histograms, scatter plots, and time-series graphs, help illustrate data distributions, highlight trends, and detect initial outliers. Following this, a trend analysis step identifies recurring patterns and

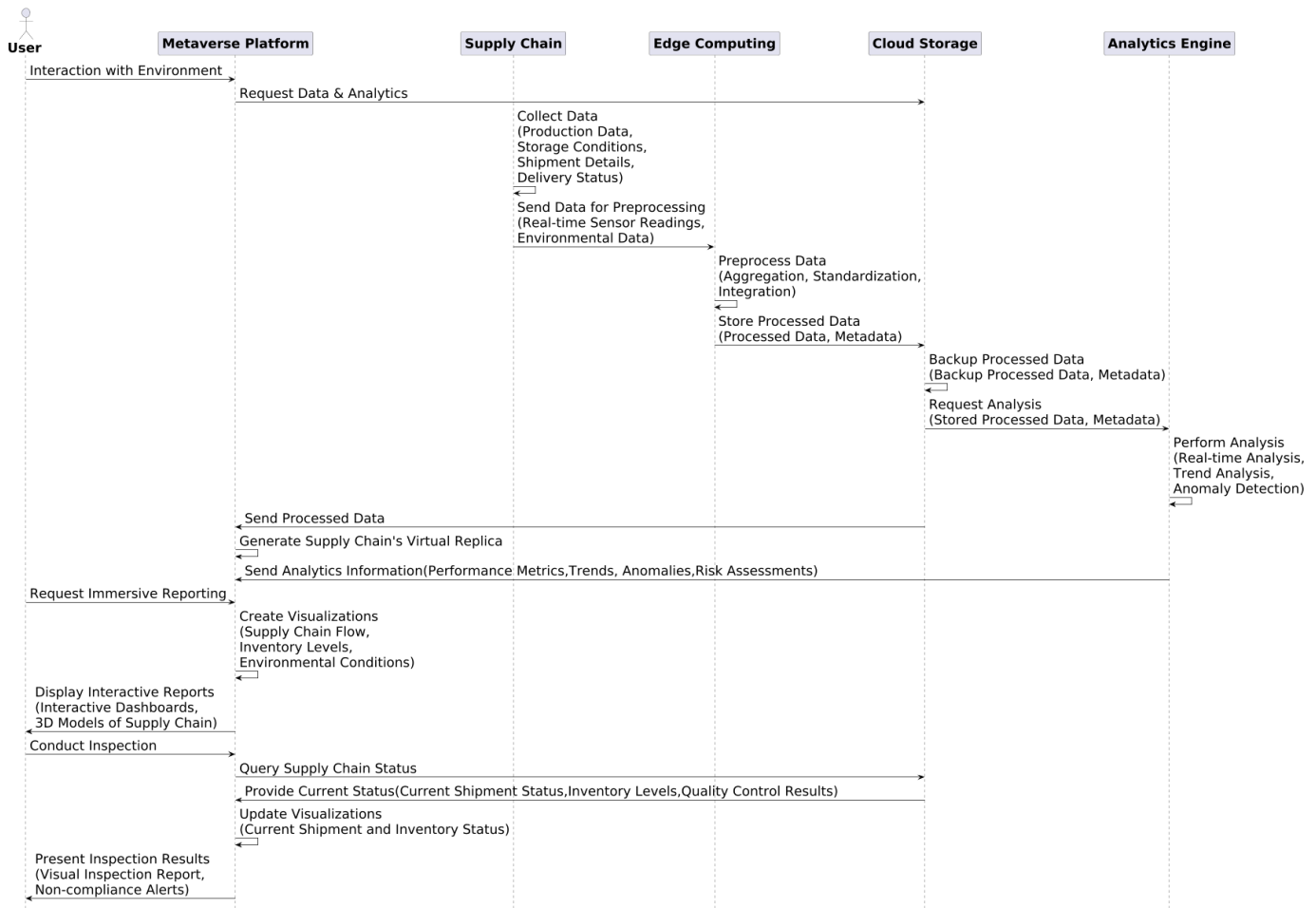


Fig. 2. Sequence diagram of proposed system

seasonal behaviors by applying smoothing techniques, such as moving averages, which reveal underlying trends within the data over time. The algorithm then performs anomaly detection to identify data points that deviate from expected ranges based on statistical thresholds, logging these anomalies for further evaluation. In the risk assessment phase, the algorithm evaluates the potential impact and likelihood of each anomaly, classifies each case as low, medium, or high risk, and appends the corresponding risk details to the results. Finally, all findings from EDA, trend analysis, anomaly detection, and risk assessment are compiled into a comprehensive report. This report summarizes the key insights, detected anomalies, and identified risks.

IV. DISCUSSION

This section presents the constraints associated with the metaverse-based solutions that affect their adoption in the proposed system.

A. Technical Limitations

The proposed metaverse-based system can face several technical limitations. The metaverse-based systems demand robust digital infrastructure, including reliable high-bandwidth

connectivity and low-latency networks to stream real-time augmented visuals without lag. In practice, inconsistent wireless coverage in manufacturing facilities can disrupt real-time data communication [18]. The need for edge computing at sites is evident to process IoT sensor data and digital twin updates locally, which minimize round-trip latency for XR interactions [19]. Additionally, device limitations pose challenges. The current head-mounted displays have limited battery life and field of view, which requires periodic downtime and potentially missed peripheral details [18]. Pilot studies of mixed-reality GMP inspections have highlighted such issues, inspectors noted ad hoc network drops and battery depletion as hindrances [18]. Furthermore, the system's sophistication introduces a steep learning curve. Auditors and personnel must be trained to operate XR interfaces and interpret digital twin analytics, which can slow initial adoption [20]. High implementation costs and the need for specialized technical expertise are non-trivial barriers for many organizations. These technical constraints highlight that, although the system is feasible, its success depends on stable infrastructure, including backup connectivity, on-premise edge servers, and comprehensive user training.

Algorithm 1 Data Collection Algorithm

```

1: Input: Sensors data (e.g., temperature, humidity), collec-
   tion interval  $t_{interval}$ , acceptable parameter ranges  $R$ 
2: Output: Real-time data log
3: Step 1: Sensor Initialization
4: for each sensor  $S_i$  in the supply chain do
5:   Connect to  $S_i$  and check status
6:   if sensor  $S_i$  is inactive then
7:     Capture malfunction details  $M_i$  for sensor  $S_i$ 
8:     Store  $M_i$  in the malfunction buffer
9:     Continue to the next sensor
10:  end if
11: end for
12: Step 2: Data Capture
13: while true do
14:   for each sensor  $S_i$  in the supply chain do
15:     Collect data  $D_i$  from sensor  $S_i$ 
16:     Store  $D_i$  in the data buffer
17:   end for
18:   Wait for  $t_{interval}$  before the next collection cycle
19: end while
20: Step 3: Data Logging
21: for each data point  $D_i$  in the data buffer do
22:   Log  $D_i$  to the edge device
23: end for
24: for each malfunction detail  $M_i$  in the malfunction buffer
   do
25:   Log  $M_i$  to the edge device
26: end for

```

B. Regulatory and Compliance Implications

The use of the latest technologies in healthcare and pharmaceutical supply chains requires careful alignment with existing compliance frameworks. Any digital audit system must uphold GxP guidelines in good manufacturing, distribution, and laboratory practices, and ensure that its records and processes meet regulatory requirements. Notably, regulators are beginning to accommodate such innovations. Accelerated by COVID-19, agencies like the EMA (European Medicines Agency), EDQM (European Directorate for the Quality of Medicines & Healthcare), and US FDA (US Food & Drug Administration) have explored remote inspection approaches, issuing guidance for remote GxP inspections and remote regulatory assessments [18]. These developments signal an openness to virtual or hybrid audits, provided that data integrity and patient safety are maintained. However, the regulatory environment still lacks specific standards for emerging tools like industrial metaverse platforms or digital twins in compliance auditing. For example, while the FDA and EMA emphasize data integrity and computerized system validation in pharma (e.g, 21 CFR Part 11 and GAMP guidelines), there are currently no dedicated guidelines for digital twin-driven audits [21]. This implies that implementers must interpret and apply existing principles, ensuring ALCOA (Attributable, Legible, Contemporaneous,

Algorithm 2 Data Preprocessing Algorithm

```

1: Input: Raw sensor data  $D_{raw}$  (temperature, humidity,
   GPS data, etc.), metadata  $M$  (time of collection, location)
2: Output: Clean, standardized, and aggregated dataset
    $D_{processed}$ 
3: Step 1: Data Cleansing
4: for each data point  $d_i$  in  $D_{raw}$  do
5:   if  $d_i$  is a noise or outlier based on predefined criteria
     then
6:     Remove  $d_i$  from  $D_{raw}$ 
7:   end if
8: end for
9: Step 2: Data Standardization
10: for each data point  $d_i$  in  $D_{raw}$  do
11:   if data type is temperature then
12:     Convert temperature to Celsius
13:   else if data type is humidity then
14:     Convert humidity to percentage
15:   else if data type is GPS data then
16:     Format GPS coordinates to a standardized format
       (e.g., decimal degrees)
17:   end if
18: end for
19: Step 3: Data Aggregation
20: Initialize an empty dataset  $D_{aggregated}$ 
21: for each sensor  $S_i$  do
22:   Combine data points from  $S_i$  with corresponding
     metadata  $M$ 
23:   Append the aggregated data to  $D_{aggregated}$ 
24: end for
25: Step 4: Final Output
26: Set  $D_{processed} = D_{aggregated}$ 
27: Return  $D_{processed}$ 

```

Original, Accurate) data logs, secure access controls, and audit trails to these new modalities. In our system, all sensor readings, virtual inspection logs, and auditor annotations are expected to be securely time-stamped and tamper-evident to ensure compliance. Prior studies show the importance of transparent audit trails. The real-time IoT data logging can create a comprehensive record of each production and distribution step, and blockchain-backed logs have been proposed to further guarantee immutability [20], [22], [23]. This is also crucial to ensure that the metaverse audit tools do not compromise confidentiality. Strong measures must be in place to protect sensitive facility data and to restrict virtual access to authorized inspectors only, in line with EMA/FDA data security expectations. Notably, a recent pilot of remote XR mock inspections demonstrated that such technologies can be executed under current GMP standards without regulatory deviation [18]. Still, companies adopting the latest systems should be prepared for rigorous validation and possibly closer scrutiny from regulators until more formalized guidelines emerge.

Algorithm 3 Data Analysis and Risk Assessment Algorithm

```

1: Input: Processed dataset  $D_{processed}$  (clean, standardized,
   and aggregated)
2: Output: Analytical results  $A_{results}$ , including statistical
   summaries, trends, detected anomalies, and risk assess-
   ment
3: Step 1: Exploratory Data Analysis (EDA)
4: Calculate basic statistics for each data type (mean, median,
   standard deviation)
5: Plot histograms, scatter plots, and time-series graphs to
   visualize data distributions and trends
6: Identify any initial patterns or outliers in the dataset
7: Step 2: Trend Analysis
8: for each data attribute  $A_i$  in  $D_{processed}$  do
9:   Apply a smoothing technique to highlight trends over
   time
10:   Detect seasonality or recurring patterns
11: end for
12: Step 3: Anomaly Detection
13: for each data attribute  $A_i$  in  $D_{processed}$  do
14:   if data value deviates from the expected range (based
   on statistical thresholds) then
15:     Mark the data point as a potential anomaly
16:     Store the anomaly details (timestamp, attribute,
   value) in a log
17:   end if
18: end for
19: Step 4: Risk Assessment
20: for each identified anomaly in the anomaly log do
21:   Assess the potential impact and likelihood of the
   anomaly
22:   Classify the risk level (e.g., low, medium, high) based
   on predefined criteria
23:   if the risk level is medium or high then
24:     Add risk details to  $A_{results}$ 
25:   end if
26: end for
27: Step 5: Result Compilation
28: Compile the results from EDA, trend analysis, anomaly
   detection, and risk assessment into  $A_{results}$ 
29: Generate a report summarizing the key findings, includ-
   ing visualizations, detected insights, and risk assessment
   outcomes
30: Step 8: Output the Analysis Results
31: Return  $A_{results}$ 

```

C. Adoption and Ethical Considerations

Beyond technical and regulatory aspects, the success of an immersive auditing system depends on human factors and ethical adoption. User experience and well-being are paramount. The metaverse sessions can induce XR fatigue or cybersickness. The users may experience visual strain, disorientation, or nausea if immersed for long periods. Reports indicate that significant fractions of VR users, upwards of 20-80%, can suffer side effects without proper mitigation [24]. To address this, auditing protocols need to enforce regular breaks and limit continuous immersion times, while ergonomic improvements to headsets need to reduce discomfort. Training and change management also play a role in user acceptance. Veteran inspectors might be wary of new interfaces. Hence, the demonstration of the system's reliability and clear training on its operation will help build trust. Advanced metaverse setups might favor larger, well-resourced manufacturers and regulators, potentially widening gaps with smaller firms or emerging economies. Infrastructure disparities mean some regions lack stable internet or technical staff to fully participate [25]. To ensure fair uptake, stakeholders need to invest in capacity-building (e.g, subsidizing equipment, sharing cloud infrastructure) so that all parties in the supply chain can benefit from the technology. Data trust and ethics are another pillar of adoption. Regulators and industry partners must trust the digital evidence presented through the metaverse platform. This necessitates strong data governance. All sensor data and virtual records must be secure from tampering and comply with privacy laws. The integration of blockchain or other verifiable ledgers has been suggested as a way to enhance transparency and trust in supply chain data by providing an immutable audit trail [20]. By proactively addressing these human-centered and ethical issues, organizations can enhance stakeholders' confidence in the system. This, in turn, will smooth the path for broad adoption of metaverse technology in the pharmaceutical supply chain, complementing its technical capabilities with a foundation of trust and social responsibility.

V. CONCLUSION AND FUTURE WORK

In this paper, we have proposed an architecture for auditing and inspection in metaverse-based healthcare and pharmaceutical supply chains. We integrated heterogeneous operational and sensor data with edge and cloud services, an analytics engine, and an immersive metaverse platform hosting interactive digital-twin models of facilities, logistics assets, and processes. We built on this infrastructure with a data lifecycle model, which is supported by algorithms for data collection, preprocessing, analysis, and risk assessment, to support compliance-oriented monitoring and the prioritization of anomalies and potential non-compliance events. We also addressed technical, regulatory, and adoption constraints, including connectivity, latency, device capabilities, data integrity, audit trails, validation, training, human factors, privacy, and trust. By providing a structured blueprint, our work extends oversight beyond manual audits and establishes a foundation for future implementations and empirical evaluation of immersive, data-

driven auditing in regulated metaverse-based healthcare and pharmaceutical supply chains. In future work, we aim to develop prototypes and conduct empirical evaluations, including performance assessments and user studies with regulators and quality professionals. We also aim to explore integration with blockchain audit trails and AI-driven risk models to advance metaverse-based oversight from a conceptual framework into a practical tool for healthcare and pharmaceutical supply chains.

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