IJMRSETM

e-ISSN: 2395 - 7639

INTERNATIONAL JOURNAL OF MULTIDISCIPLINARY RESEARCH

IN SCIENCE, ENGINEERING, TECHNOLOGY AND MANAGEMENT

Volume 12, Issue 5, May 2025

INTERNATIONAL STANDARD SERIAL NUMBER INDIA

Impact Factor: 8.214

International Journal of Multidisciplinary Research in Science, Engineering, Technology & Management (IJMRSETM)

| ISSN: 2395-7639 | www.ijmrsetm.com | Impact Factor: 8.214 | A Monthly Double-Blind Peer Reviewed Journal |

| Volume 12, Issue 5, May 2025 |

Ensuring Transparency and Security in Vaccine Supply Chains: A Blockchain-Enabled Framework

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ABSTRACT: Counterfeit and mismanaged pharmaceuticals pose serious risks to public health, especially in vaccine distribution where cold-chain integrity and provenance are critical. We propose a blockchain-driven framework that enhances transparency, immutability, and trust across the vaccine supply chain. Our design employs distributed ledgers and smart contracts to record each transaction — from manufacturing through delivery — in an unchangeable audit trail. Large or sensitive documents (e.g., temperature logs, certificates) are stored off-chain (e.g. via IPFS) with their cryptographic hashes on-chain, minimizing data overhead while preserving verifiability. A prototype implementation (e.g. on an Ethereum testnet) demonstrates low transaction costs and robust security. By eliminating single points of failure and automating verification (such as batch authentication and expiry checks), the system deters counterfeit vaccines and empowers stakeholders with real-time traceability. Preliminary evaluation indicates that the framework can substantially improve efficiency and trust in vaccine logistics without sacrificing scalability or performance.

KEYWORDS: Blockchain, Pharmaceutical Supply Chain, Smart, Drug Traceability, Data Provenance, distributed ledgers, Counterfeit Prevention, Supply Chain Transparency, Immutability, traceability.

I. INTRODUCTION

The pharmaceutical sector faces significant challenges, including fragmented distribution networks and the growing issue of counterfeit drugs. This problem is particularly severe in vaccine distribution, where it is estimated that up to 30% of medicines in developing regions are counterfeit. Counterfeit or mishandled vaccines can lead to ineffective treatments and pose serious risks to public health. Traditionally, regulatory bodies and intermediaries have attempted to ensure vaccine authenticity and proper handling. However, centralized databases used for this purpose are vulnerable to tampering, latency issues, and a lack of shared visibility. To address these limitations, the Drug Supply Chain Security Act (DSCSA) in the United States has introduced stringent traceability requirements, underscoring the urgent need for a more reliable tracking solution. Blockchain technology offers a promising alternative due to its immutable ledger and decentralized consensus mechanisms. In a blockchain-based system, every transaction—such as the transfer of a vaccine batch or a change in storage condition—is cryptographically sealed and replicated across all nodes in the network. This architecture ensures that any attempt to alter a record is easily detectable, thereby enhancing the integrity of the supply chain. Smart contracts, which are self-executing programs deployed on the blockchain, can automate and enforce critical supply chain rules. For example, they can verify batch authenticity, monitor expiration dates, and trigger alerts in response to deviations in transport conditions. Since all stakeholders—manufacturers, distributors, healthcare providers, and regulators—interact with the same ledger, the system promotes transparency, fosters trust, and improves accountability across the entire network. Recent pilot implementations have demonstrated the practical potential of blockchain in pharmaceutical supply chains. One FDA-supported project utilized a Hyperledger Fabric-based system developed in collaboration with major industry players and successfully met rigorous traceability standards, enabling recall notifications within seconds. Other research efforts have introduced blockchain solutions specifically for vaccine distribution. For instance, permissioned blockchain framework, uses smart contracts to manage vaccine import compliance and stock tracking. Another initiative leveraged Ethereum to build a vaccine distribution platform that incorporates off-chain storage for handling large datasets while maintaining low operational costs and high data security.

II. RELATED WORK

Blockchain technology has been extensively explored for applications in pharmaceutical traceability and vaccine logistics. Research in this domain consistently emphasizes three foundational attributes of blockchain systems: decentralization, immutability, and transparency. These characteristics make blockchain particularly suitable for managing complex supply chains that require high levels of trust and verification.

Earlier work, such as that by Akunyili (2007), underscored the dangers of counterfeit drugs in unregulated markets, highlighting the urgent need for secure and traceable supply chains. This aligns with global health organization reports that point to the prevalence of counterfeit medications, particularly in developing nations.

Among the various blockchain-based prototypes, Vacledger (Munasinghe et al., 2023) has gained attention as a permissioned blockchain solution designed specifically for vaccine traceability. It implements four distinct smart contracts to manage regulatory compliance, vaccine registration, stock tracking, and location updates across national borders. The evaluation of Vacledger demonstrated its capability to maintain immutable event logs and to compute gas usage efficiently, showcasing its potential for practical deployment in real-world scenarios.

In the public blockchain space, Jayaraman et al. (2021) introduced an Ethereum-based system for managing COVID-19 vaccine distribution. This solution incorporates off-chain storage mechanisms—such as the InterPlanetary File System (IPFS)—to handle large and sensitive data. The smart contracts in their system automated the tracking of vaccine batches and facilitated open auditing. Their performance assessments indicated the platform was both cost-effective and secure, reinforcing the value of Ethereum's flexibility and its suitability for decentralized pharmaceutical networks.

Industry-led initiatives have also demonstrated the practicality of blockchain in this sector. A notable example is the collaboration between IBM, Merck, Walmart, and KPMG, which resulted in the development of a Hyperledger Fabric prototype tailored to meet the U.S. Food and Drug Administration's (FDA) Drug Supply Chain Security Act (DSCSA) requirements. This system not only addressed core track-and-trace functionality but also enabled real-time product recall alerts—achieving notification times as short as 10 seconds compared to the traditional delay of several days. These results underscore the scalability and reliability of permissioned blockchain solutions for fragmented and multi-stakeholder supply chains. Collectively, the body of existing research confirms that blockchain technology can effectively unify disparate actors within the pharmaceutical supply chain, all without reliance on a central authority. However, there remains a gap in the literature with regard to blockchain frameworks specifically tailored to the distinct needs of vaccine distribution—such as cold-chain compliance, real-time monitoring, and batch-level validation. The framework presented in this paper addresses this gap by focusing on these unique requirements while leveraging established blockchain design elements, including smart contracts, off-chain storage, and cryptographic hashing.

III. METHODOLOGY

The development of a blockchain-based framework for vaccine supply chain management involves several structured steps to ensure transparency, immutability, and security. Initially, a comprehensive requirement analysis is conducted to identify the key stakeholders such as manufacturers, distributors, hospitals, and regulatory bodies. This step also defines the essential system requirements, including real-time tracking, secure data sharing, and tamper-proof record maintenance. Based on these needs, a suitable blockchain platform like Ethereum or Hyperledger is selected. Following this, the system architecture is designed using a modular approach. A permissioned blockchain network is preferred to restrict access to authorized entities only. Smart contracts are implemented to automate transactions across the supply chain, and large data such as compliance documents or reports can be stored securely using IPFS or cloud storage. The main functional modules of the system include user registration with role-based access, vaccine lot creation and tracking, integration with temperature and condition monitoring systems, and the maintenance of an immutable transaction log for auditing purposes. Smart contract development is a critical phase where decentralized logic is coded to manage tasks such as registering participants, recording transactions, validating authenticity, and detecting tampering. These smart contracts ensure the automation of key processes and maintain the integrity of supply chain events.The frontend of the system is developed using Angular to provide an interactive interface for various stakeholders, while the backend is built using technologies like Node.js or Flask to manage API calls and blockchain interactions. Additionally, Firebase may be utilized to enhance real-time data access, notifications, and secure user authentication, offering a hybrid storage solution where necessary. The next step is blockchain integration, where smart contracts are deployed on a test network such as Ropsten or Goerli using tools like Remix IDE or Truffle. Interactions between the application and the blockchain are managed through libraries like Web3.js or ethers.js. Rigorous testing and validation are carried out by simulating real-world vaccine distribution scenarios to ensure that the system maintains data integrity, provides accurate updates, and enforces access control effectively.Finally, the system is deployed on a reliable cloud platform, such as Firebase or AWS, followed by regular maintenance and security audits of the smart contracts. Feedback is collected from pilot users to continuously improve the usability, trustworthiness, and performance of the platform.

IV. PROPOSED FRAMEWORK

System Architecture and Workflow

The proposed system is a decentralized platform for tracking vaccines across their entire lifecycle. It consists of three main components: a blockchain network, off-chain storage mechanisms, and client applications tailored to various stakeholders. These stakeholders include vaccine manufacturers, distributors, healthcare providers (such as hospitals and clinics), regulatory agencies, and end-users or patients. Each stakeholder operates a node or client interface that interacts with the blockchain to perform specific functions relevant to their role.

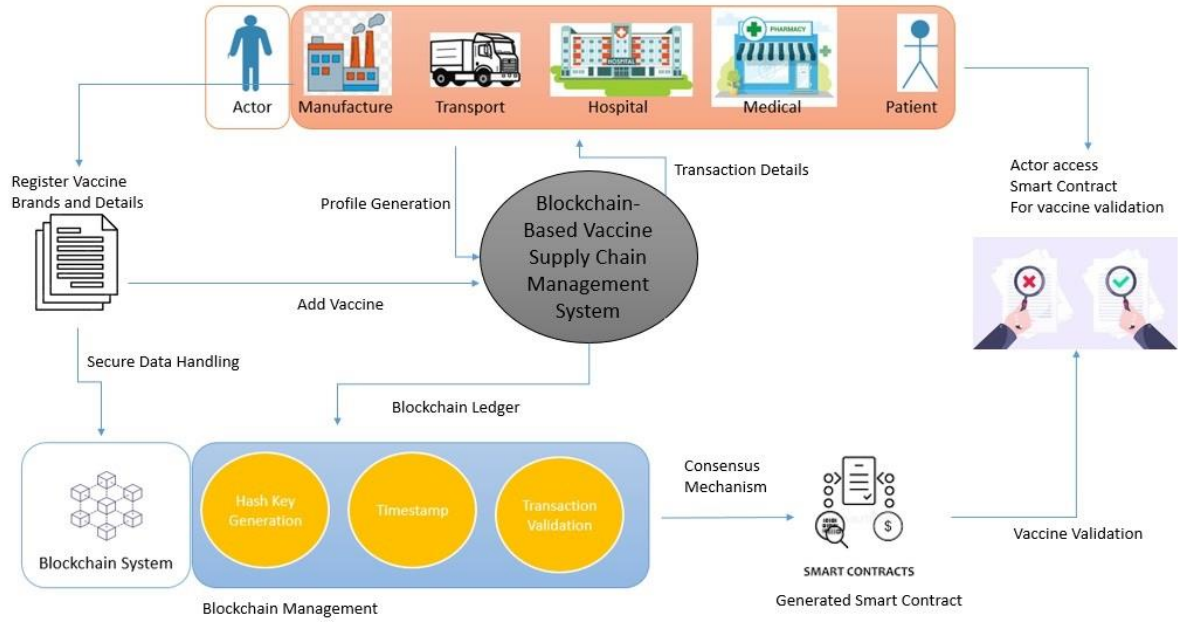

Fig. System Architecture

1. **Batch Registration**
   When a vaccine manufacturer produces a new batch, it registers the batch details—including the batch ID, production date, and content specifications—via a smart contract. This data is hashed using the SHA-256 cryptographic algorithm, and the resulting hash is stored on the blockchain. This process ensures that an immutable record of the vaccine batch is created, containing essential attributes such as expiration date and the manufacturer's digital signature**.**
2. **Transit Events**
   As the vaccine batch moves through various stages of the supply chain—from the manufacturer to regional warehouses and eventually to healthcare providers—each handoff is logged using another smart contract. Each transaction records the involved parties, timestamps, and transfer conditions. To maintain transparency and traceability, these events are time-stamped and immutably stored on the blockchain. If applicable, Internet of Things (IoT) sensors can capture environmental data, such as temperature or humidity, and send this information to the system. While large sensor data logs are stored off-chain using decentralized storage platforms like the InterPlanetary File System (IPFS), their cryptographic hashes are stored on-chain for verification purposes.
3. **Verification at Delivery**
   Upon reaching a clinic or pharmacy, the receiving party—whether it be a healthcare provider or even a patient—can query the blockchain through a user-friendly interface. The system validates the authenticity of the vaccine batch by comparing the recorded hash and signature history against known valid values. Any discrepancy caused by data tampering or substitution will result in a mismatch, signaling potential fraud.

This architecture ensures complete traceability from production to administration. Each vaccine dose is linked to a blockchain-anchored record, enabling stakeholders to audit the vaccine's journey in real-time. By eliminating centralized control, the system mitigates risks of manipulation and promotes trust and transparency throughout the supply chain**.**

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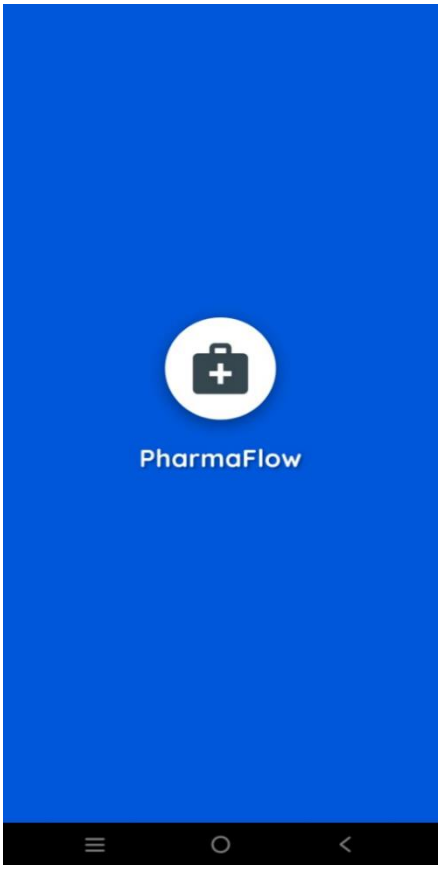
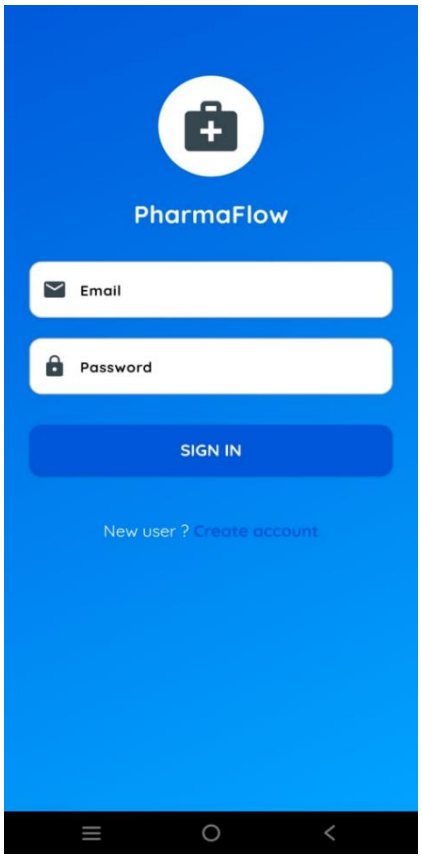
V. SYSTEM OVERVIEW

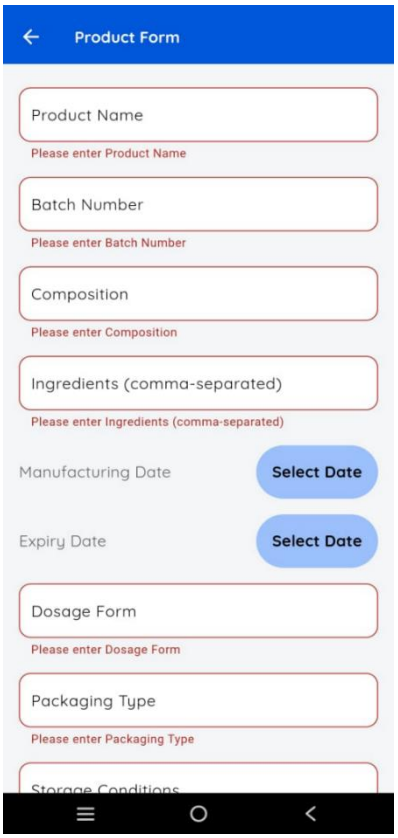
The proposed blockchain-based framework is designed to enhance the efficiency, transparency, and security of vaccine supply chains by leveraging decentralized technologies. The system comprises multiple interconnected modules that collectively ensure the safe and reliable distribution of vaccines from manufacturers to end-users. At the core of the system is a permissioned blockchain network that records every transaction related to the vaccine supply chain, such as production, packaging, shipping, storage, and administration. Each stakeholder, including manufacturers, transporters, warehouses, healthcare facilities, and government authorities, is given role-based access to interact with the system through a secure and user-friendly interface. Smart contracts play a key role in automating critical operations and enforcing rules, such as verifying the authenticity of vaccine batches, triggering alerts during temperature deviations, and ensuring proper handover at each checkpoint. The system is integrated with IoT devices that monitor and log environmental conditions like temperature and humidity in real-time, which are crucial for maintaining vaccine efficacy. All data, once entered into the blockchain, becomes immutable, thereby preventing tampering or unauthorized changes. Furthermore, the system provides dashboards and tracking tools to help stakeholders monitor the real-time status of vaccine shipments, view historical records, and generate reports for audits or regulatory compliance. This blockchain-based solution eliminates the need for a central authority, reduces the chances of fraud, and enhances public trust in the vaccination process. Overall, the system is a comprehensive digital infrastructure aimed at securing and modernizing the vaccine supply chain. The overall goal of this cutting-edge technology is to enable people to improve their interviewing skills in an easy-to-use and interactive way, boosting their self-assurance and success in actual interviews..

VI. RESULTS

The Blockchain-Based Vaccine Supply Chain Android App enhances the efficiency and transparency of vaccine distribution by automating critical processes such as vaccine tracking, inventory updates, and stakeholder communication. By leveraging blockchain technology, the system ensures secure, tamper-proof records, reduces delays in supply chain operations, and enables real-time monitoring of vaccine movement from manufacturers to end-users. This results in a more reliable, transparent, and accountable vaccine supply chain experience, accessible through a user-friendly mobile interface.







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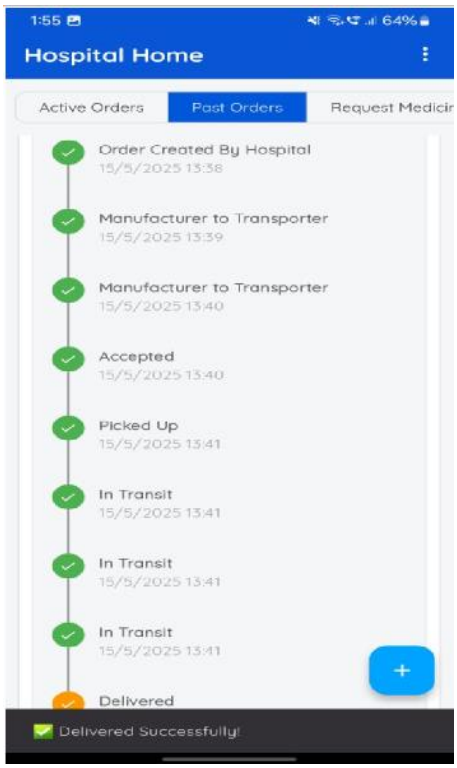

VII. CONCLUSION

Blockchain-based framework designed to enhance the security and transparency of vaccine supply chains. By integrating immutable ledgers, smart contracts, and decentralized storage solutions, the system ensures that each vaccine dose is traceable and verifiable throughout its journey—from the point of manufacture to administration. The framework's core contributions include a clearly defined stakeholder model encompassing manufacturers, distributors, healthcare providers, regulatory bodies, and patients, each with role-based access control. It also features smart contract algorithms that automate essential processes such as vaccine batch registration, transfer logging, and authenticity verification. Additionally, the use of a hybrid data storage approach—combining on-chain record-keeping with off-chain storage for large or sensitive files—strikes an effective balance between security, scalability, and performance. This architecture is inherently resistant to counterfeiting. Any attempt to introduce unauthorized products or manipulate the transaction history is immediately detectable through cryptographic hash mismatches or signature validation failures. Overall, the proposed system establishes a trustworthy, tamper-proof infrastructure that enhances efficiency, builds confidence among stakeholders, and supports the global effort to maintain the integrity of vaccine distribution.

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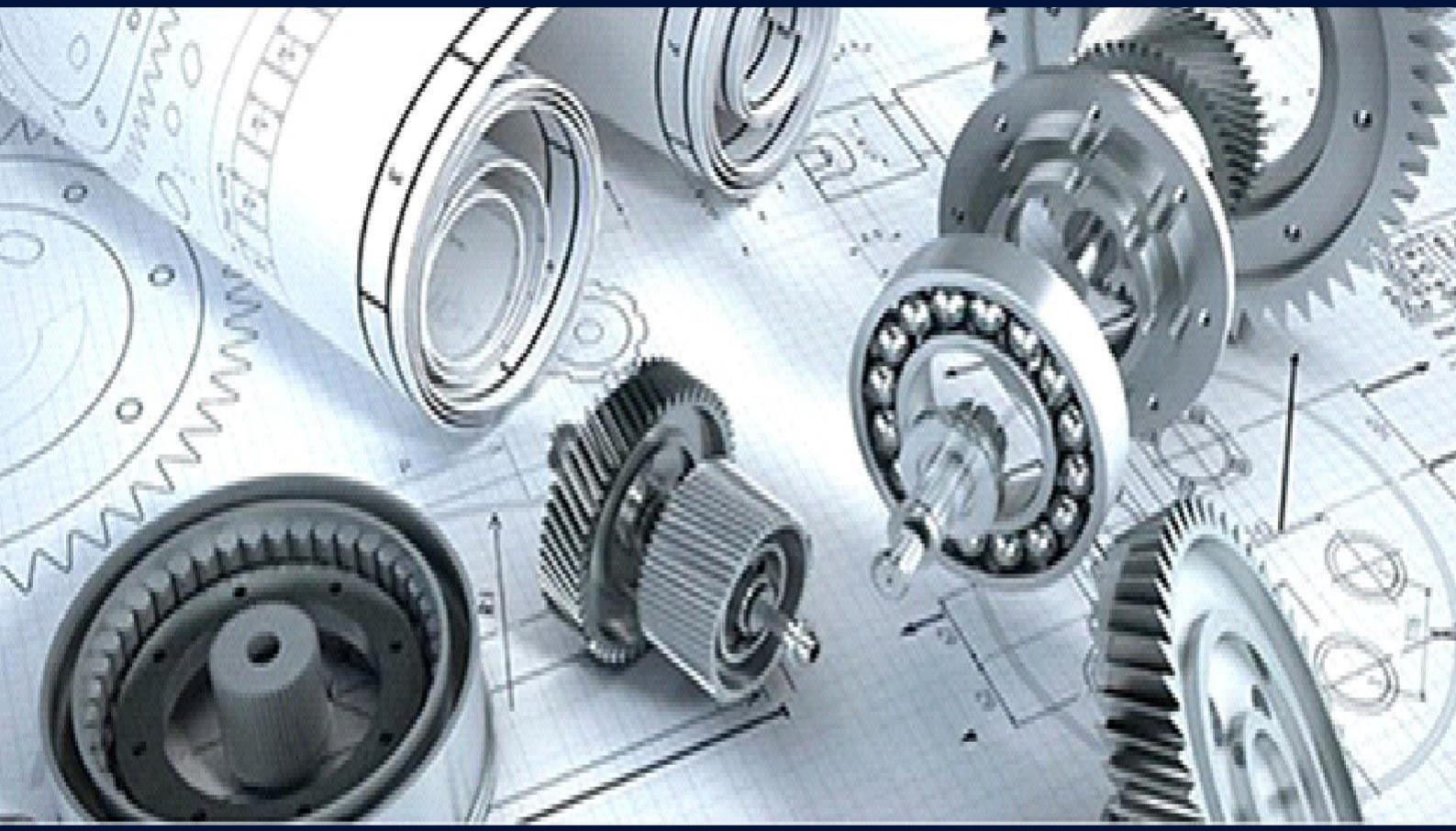

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