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DIGITAL TWIN AND CYBER-PHYSICAL SYSTEM FOR SMART WAREHOUSE OPTIMIZATION USING REAL-TIME ANALYTICS AND INTELLIGENT DECISION SUPPORT An Integrated Web-Based Framework for Inventory, AGV, Predictive Maintenance, and Safety Monitoring

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ABSTRACT:

This paper presents a Digital Twin and Cyber-Physical System (CPS) framework for smart warehouse optimization using real-time operational monitoring, IoT sensor simulation, intelligent decision support, and interactive analytics. Conventional warehouse management systems often provide isolated inventory, order, and equipment monitoring, resulting in limited operational visibility and delayed decision-making. The proposed system addresses these limitations by developing a virtual representation of warehouse operations that continuously reflects simulated physical warehouse conditions. The framework integrates a React-based frontend, Node.js and Express.js backend, and MySQL database to manage inventory, orders, sensor readings, AGV tracking, equipment health, alerts, and warehouse analytics. The Digital Twin represents storage racks, conveyor belts, Automated Guided Vehicles (AGVs), forklifts, loading areas, and sensor checkpoints. Simulated IoT data are used to monitor temperature, humidity, vibration, energy consumption, occupancy, and equipment status. A route optimization mechanism is incorporated to reduce AGV travel distance and congestion, while rule-based predictive maintenance identifies potential equipment risks based on temperature, vibration, and runtime conditions. The system also provides automated safety alerts for events such as restricted-area entry, high temperature, fire, and gas leakage. An interactive dashboard presents warehouse Key Performance Indicators (KPIs), inventory trends, AGV movements, equipment health, energy consumption, and recent alerts. The proposed framework demonstrates how Digital Twin and CPS concepts can be integrated into a web-based smart warehouse environment to improve operational visibility, resource utilization, safety monitoring, and managerial decision support.

Index Terms—Digital Twin, Cyber-Physical System, Smart Warehouse, Internet of Things, AGV, Inventory Optimization, Route Optimization, Predictive Maintenance, Real-Time Analytics, Decision Support.

I. INTRODUCTION

The rapid development of Industry 4.0 has transformed conventional manufacturing and logistics environments into intelligent, connected, and data-driven systems. Warehouses are an important component of modern supply chains because they are responsible for receiving, storing, processing, picking, and dispatching products. Increasing product variety, shorter delivery requirements, and growing operational complexity have created a need for warehouse systems capable of monitoring physical operations and supporting rapid decision-making.

Traditional warehouse management approaches generally depend on manual monitoring, isolated software systems, and periodic data collection. Such approaches can result in inaccurate inventory information, inefficient material movement, delayed identification of equipment problems, and poor visibility of warehouse conditions. Automated Guided Vehicles (AGVs), conveyors, forklifts, RFID systems, barcode scanners, and IoT sensors can improve warehouse automation; however, simply collecting data from these devices does not provide a complete understanding of the warehouse as an integrated system.

A Digital Twin provides a virtual representation of a physical system and enables its operational state to be monitored through continuously updated data. When combined with a Cyber-Physical System (CPS), the physical and virtual environments can interact through sensing, communication, processing, and decision-making mechanisms. In a smart warehouse, a Digital Twin can represent storage racks, inventory, AGVs, conveyors, forklifts, loading areas, and environmental conditions while providing a centralized view of warehouse operations.

The proposed work develops a web-based Digital Twin and CPS framework for smart warehouse optimization. The system uses simulated IoT sensor data to represent warehouse conditions and synchronizes these data with a virtual warehouse environment. The backend is implemented using Node.js and Express.js, while MySQL is used for structured storage of operational data. A React-based frontend provides interactive visualization of warehouse conditions, inventory, AGV movement, equipment health, safety events, and analytics.

The proposed system integrates inventory management, order processing, AGV tracking, route optimization, predictive maintenance, safety monitoring,

energy monitoring, and decision-support functionality within a single platform. Instead of treating each warehouse activity independently, the system provides a unified operational model through the Digital Twin.

The major contributions of this work are as follows:

- A web-based Digital Twin model for representing warehouse infrastructure and operational entities.
- Integration of CPS concepts with simulated IoT sensor data for continuous warehouse monitoring.
- Real-time visualization of inventory, AGV positions, equipment status, environmental conditions, and alerts.
- A route optimization mechanism for AGV movement and congestion management.
- A rule-based predictive maintenance mechanism based on equipment temperature, vibration, and runtime.
- Automated safety monitoring and alert generation.

II. RELATED WORK

Digital Twin technology has emerged as an important concept in Industry 4.0 because it enables physical assets and processes to be represented in a corresponding virtual environment. A Digital Twin can receive operational data from the physical system and use those data for monitoring, simulation, prediction, and optimization.

Cyber-Physical Systems integrate computational components with physical processes through sensing, communication, and control. In warehouse environments, CPS technologies can connect AGVs, sensors, conveyors, RFID devices, and warehouse software systems to provide improved operational visibility.

IoT-based warehouse systems have also been investigated for inventory tracking, environmental monitoring, asset identification, and equipment management. RFID and barcode technologies can provide product-level identification, while temperature, humidity, vibration, and energy sensors can provide information about environmental and equipment conditions.

AGV-based warehouse automation has received considerable attention because AGVs can reduce manual material transportation. However, inefficient routing and congestion can reduce the effectiveness of AGV-based systems. Shortest-path algorithms and dynamic route planning can therefore be used to select suitable paths based on distance, congestion, and operational constraints.

Predictive maintenance is another important component of intelligent warehouse management. Instead of waiting for equipment failure, equipment parameters such as temperature, vibration, and runtime can be monitored to identify potential failure conditions.

Despite these developments, many systems focus on individual functions such as inventory monitoring, AGV management, or equipment monitoring. The proposed work addresses this gap by integrating Digital Twin visualization, CPS monitoring, inventory management, AGV tracking, route optimization, predictive maintenance, safety monitoring, and analytics into a unified smart warehouse platform.

Table 1. Comparison of conventional and proposed warehouse monitoring.

Feature	Conventional System	Proposed System
Inventory monitoring	Periodic/manual	Real-time dashboard
Warehouse visualization	Limited	Digital Twin
AGV monitoring	Separate system	Integrated
Route optimization	Static/manual	Dynamic
Equipment monitoring	Reactive	Rule-based predictive
Safety monitoring	Manual	Automated alerts
Sensor monitoring	Isolated	Integrated
Analytics	Limited	Interactive
Decision support	Limited	Integrated

III. RESEARCH METHODOLOGY

3.1 System Architecture

The overall architecture consists of five major layers: IoT and warehouse simulation, data acquisition and backend processing, database storage, Digital Twin and intelligence, and visualization and decision support.

The IoT and simulation layer generates warehouse operational data such as temperature, humidity, equipment status, inventory movement, AGV position, and energy consumption. The Node.js and Express.js backend receives and processes these data before storing them in the MySQL database.

The Digital Twin layer retrieves the latest warehouse state and updates the virtual warehouse representation. The intelligence layer performs route optimization, low-stock detection, equipment-risk identification, congestion detection, and safety analysis. Finally, the React frontend displays the processed information through dashboards, charts, KPI cards, alerts, and an animated warehouse layout.

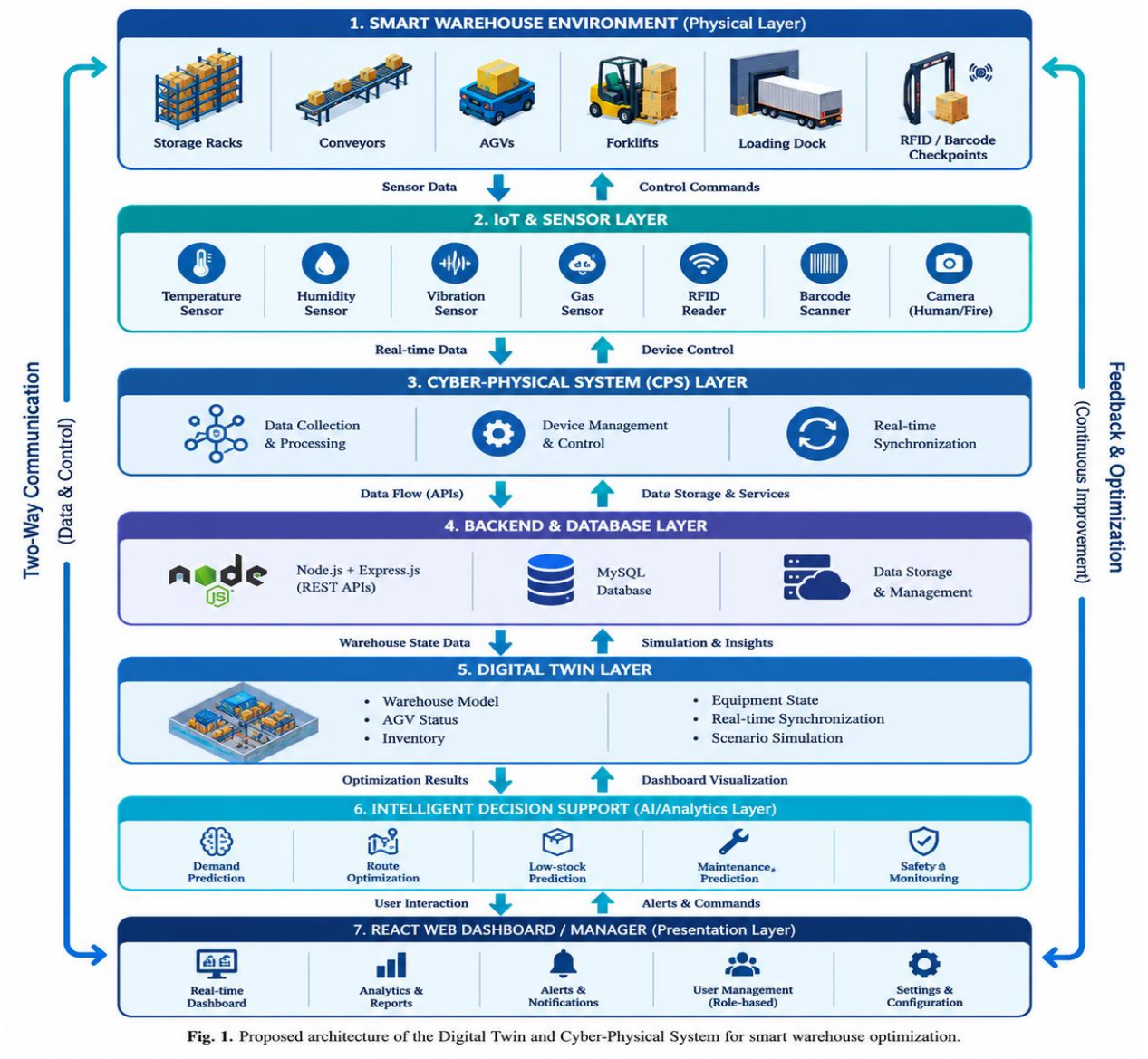


Fig. 1. Proposed architecture of the Digital Twin and Cyber-Physical System for smart warehouse optimization.

Figure 1. Proposed architecture of the Digital Twin and Cyber-Physical System.

3.2 Digital Twin Model

The Digital Twin represents the major physical and operational components of the warehouse. The model includes storage racks, inventory, conveyor belts, AGVs, forklifts, loading docks, RFID checkpoints, barcode checkpoints, sensors, and restricted areas.

Each digital object is associated with attributes such as identification, position, status, operational condition, and timestamp. For example, an AGV object contains its identifier, current coordinates, speed, battery level, destination, route, and operational status. Whenever new simulated tracking information is received, the corresponding virtual AGV is updated.

3.3 Cyber-Physical System Model

Physical Layer. This layer represents AGVs, forklifts, conveyor systems, storage racks, RFID devices, barcode scanners, and sensors.

Communication Layer. The communication layer transfers operational information between the simulated physical environment and backend services through REST APIs.

Processing Layer. The Node.js and Express.js backend validates and processes incoming data.

Digital Layer. The Digital Twin maintains a virtual representation of the warehouse.

Intelligence Layer. This layer performs route optimization, low-stock detection, maintenance-risk analysis, congestion detection, and safety-event processing.

User Layer. Managers, operators, and administrators interact with the system through the React web interface.

3.4 Data Sources and Sensor Simulation

Since the prototype does not use physical industrial sensors, software-based sensor simulation is used to generate representative warehouse data. The simulated parameters include temperature, humidity, vibration, energy, occupancy, equipment status, inventory, orders, AGV activity, and warehouse efficiency.

Table 2. Sample simulated warehouse operating data.

Parameter	Sample Value
Temperature	28 °C
Humidity	60 %
Inventory	5200 items
Orders	320
Active AGVs	6
Forklifts	4
Rack Occupancy	82 %
Energy Usage	65 %
Warehouse Efficiency	95 %

These values represent simulated operational conditions and are not claimed as measurements from a physical warehouse. Sensor values are periodically generated and transmitted to the backend. The backend stores the readings and updates the corresponding Digital Twin objects.

3.5 Database Design

MySQL is used as the primary relational database. The database consists of the major entities Users, Inventory, Orders, Sensor Logs, AGV Tracking, Maintenance, Alerts, Warehouse Layout, and Analytics. The relational database provides structured storage and supports relationships between products, orders, equipment, sensor records, and warehouse locations.

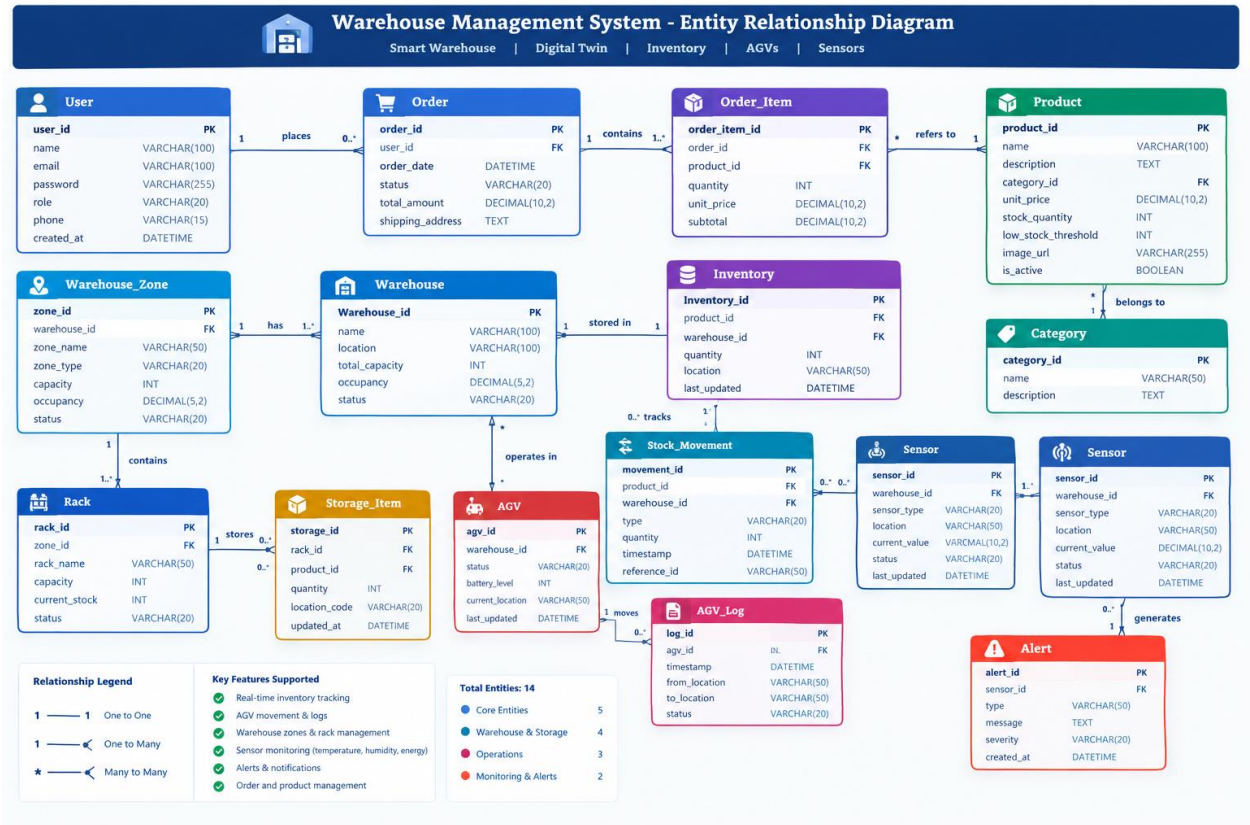


Figure 2. Entity relationship diagram of the proposed warehouse database.

3.6 Inventory Management

The inventory module provides product creation, modification, deletion, search, barcode identification, RFID tracking, stock monitoring, minimum stock configuration, and low-stock alerts.

The low-stock detection mechanism is represented by:

$S_i < S_{min}$

(1)

where S_i represents the current stock of product i and S_{min} represents its minimum acceptable stock level. When this condition is satisfied, the system generates a low-stock alert.

3.7 Order Management

Orders are categorized into four states: Pending, Processing, Completed, and Cancelled. The order workflow consists of Order Creation → Inventory Verification → Picking Location → AGV Assignment → Route Optimization → Picking → Packing → Dispatch. The Digital Twin reflects the operational status of the order throughout this process.

3.8 AGV Tracking and Route Optimization

AGVs are monitored using position, speed, battery, destination, route, and status. The proposed route optimization mechanism considers travel distance and warehouse congestion.

A simplified route-cost function is defined as:

$C(R) = D(R) + \lambda C^{g}(R) + \mu C^{b}(R)$

(2)

where C(R) is total route cost, D(R) is travel distance, $C^{g}(R)$ is congestion penalty, $C^{b}(R)$ is battery-related penalty, and λ and μ are weighting factors. The route having the minimum calculated cost is selected. A shortest-path algorithm such as Dijkstra's algorithm or A* can be used for path computation.

3.9 Congestion Detection

AGV positions are continuously monitored within the Digital Twin. When multiple AGVs enter the same predefined warehouse region, the system identifies a possible congestion condition. The system then generates a congestion alert, identifies alternative paths, calculates route costs, selects an alternative route, and updates the Digital Twin.

3.10 Predictive Maintenance

The maintenance module monitors temperature, vibration, runtime hours, and equipment status. A rule-based approach is used in the prototype.

Risk = High, if $T > T_{max}$ and $V > V_{max}$

(3)

The system classifies equipment as Normal, Warning, or Critical. This approach provides an initial intelligent decision-support mechanism and should not be interpreted as a trained machine-learning failure prediction model.

3.11 Safety Monitoring

The safety module detects simulated events including restricted-area entry, fire, high temperature, gas leakage, and human detection. When a safety threshold is exceeded, an alert is generated with alert type, severity, location, timestamp, and status.

$T > T_{safety}$ → High Temperature Alert

(4)

IV. SYSTEM IMPLEMENTATION

4.1 Frontend Implementation

The frontend is developed using React.js. React components are used to create reusable interface elements including KPI cards, charts, tables, alerts, navigation panels, and Digital Twin objects. The main pages include Login, Dashboard, Digital Twin, Inventory Management, Order Management, AGV Tracking, Predictive Maintenance, Safety Monitoring, Analytics, and Settings. The interface uses a dark industrial theme with blue and cyan highlights.

4.2 Backend Implementation

The backend is implemented using Node.js and Express.js. The REST API provides endpoints for authentication, inventory, orders, sensors, AGV tracking, analytics, prediction, and alerts. Authentication is implemented using JWT-based authorization and password hashing.

Table 3. REST API specification.

Module	Method	Endpoint
Authentication	POST	/api/auth/login
Authentication	POST	/api/auth/register
Inventory	GET	/api/inventory
Inventory	POST	/api/inventory

Inventory	PUT	/api/inventory/:id
Inventory	DELETE	/api/inventory/:id
Orders	GET	/api/orders
Orders	POST	/api/orders
Sensors	GET	/api/sensors
AGV	GET	/api/agv
Analytics	GET	/api/analytics
Prediction	GET	/api/prediction
Alerts	GET	/api/alerts

4.3 Dashboard Implementation

The dashboard provides an overview of warehouse performance. The major KPIs include total inventory, orders today, active AGVs, forklifts, temperature, energy consumption, rack occupancy, and alerts. Additional components include a live inventory chart, warehouse heatmap, AGV movement map, recent activities, sensor status, equipment health, energy meter, recent alerts, and performance score.

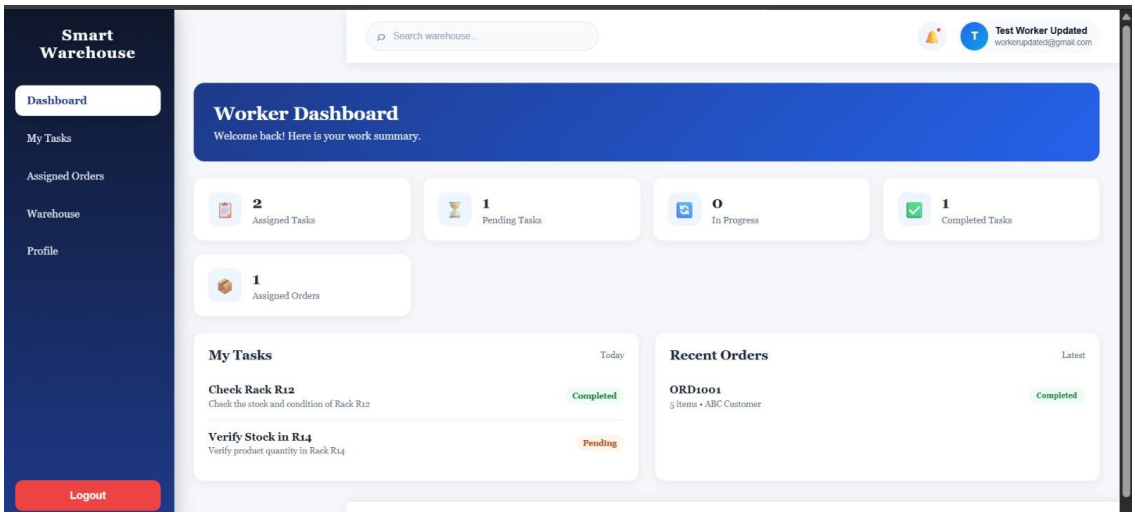


Figure 3. Smart warehouse real-time monitoring dashboard.

4.4 Digital Twin Visualization

The Digital Twin interface uses SVG/Canvas-based visualization to represent warehouse objects. The virtual layout contains racks, AGVs, forklifts, conveyors, loading docks, and checkpoints. AGV positions are updated based on backend tracking information.

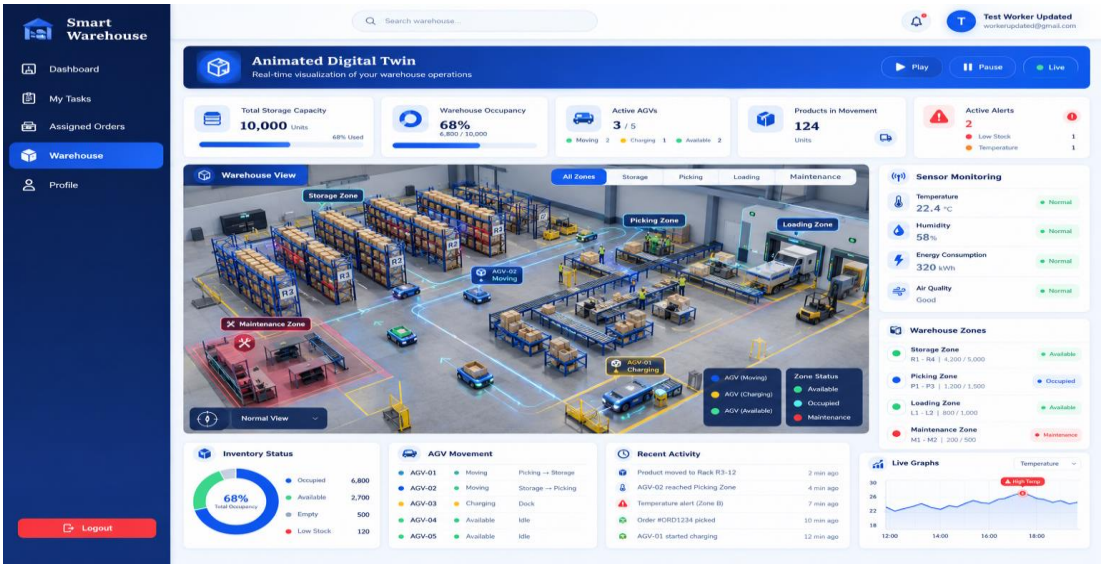


Figure 4. Animated Digital Twin representation of the warehouse.

V. RESULTS AND DISCUSSION

The proposed system was evaluated using simulated warehouse operating scenarios. The evaluation focuses on functional behavior, state synchronization, alert generation, route processing, and dashboard visualization.

Under normal operating conditions, the system displays simulated values such as 28 °C temperature, 82% rack occupancy, six active AGVs, and four operating forklifts. The dashboard provides centralized visibility of these parameters.

When inventory falls below the configured minimum threshold, the system identifies the product and generates a low-stock alert. This demonstrates the ability of the system to automatically identify inventory risks without requiring continuous manual inspection.

When multiple AGVs are assigned to overlapping routes, the system identifies congestion and evaluates alternate routes. The Digital Twin visually represents the changing AGV positions and routes.

When simulated equipment temperature and vibration exceed warning thresholds, the maintenance module changes the equipment health status from normal to warning or critical. This allows operators to identify potentially abnormal equipment conditions before a simulated failure occurs.

When a simulated restricted-area entry, high-temperature event, fire condition, or gas leakage is detected, the system generates an alert containing the event type, location, severity, and timestamp.

Table 4. Functional test scenarios.

Scenario	Input Condition	Expected Output
Normal operation	Normal sensor values	Normal status
Low inventory	Stock below threshold	Low-stock alert
AGV congestion	Multiple AGVs in same region	Congestion alert
High temperature	Temperature above threshold	Safety alert
High vibration	Vibration above threshold	Maintenance warning
Restricted entry	Unauthorized entry detected	Safety alert
Normal equipment	Normal temperature/vibration	Healthy status

VI. PERFORMANCE EVALUATION

The system can be evaluated using API response time, alert detection time, route computation time, inventory search time, dashboard update interval, order completion rate, warehouse utilization, and AGV utilization. Actual numerical performance results should be calculated from measurements obtained during system testing rather than fabricated values.

Order Completion Rate:

$$OCR = (\text{Completed Orders} / \text{Total Orders}) \times 100 \quad (5)$$

Warehouse Utilization:

$$WU = (\text{Occupied Storage Space} / \text{Total Storage Space}) \times 100 \quad (6)$$

AGV Utilization:

$$AU = (\text{AGV Operating Time} / \text{Available AGV Time}) \times 100 \quad (7)$$

VII. ADVANTAGES

- Centralized warehouse monitoring.
- Virtual representation of warehouse operations.
- Improved inventory visibility.
- AGV movement visualization.
- Route optimization support.
- Early identification of equipment-risk conditions.
- Automated safety alerts.
- Interactive analytics.
- Role-based access.
- Extensible architecture for future IoT hardware integration.

VIII. LIMITATIONS

The current prototype has several limitations. First, the sensor readings are simulated rather than collected from physical industrial sensors. Second, the AGV movement is simulated within the Digital Twin instead of being controlled through physical AGV hardware. Third, predictive maintenance is implemented using predefined rules rather than a machine-learning model trained on historical failure data. Similarly, advanced demand forecasting requires a larger historical dataset for reliable model training. These limitations provide opportunities for extending the prototype toward a real industrial

deployment.

IX. FUTURE WORK

Future development can integrate physical IoT sensors using protocols such as MQTT. Real AGVs, RFID readers, barcode scanners, and PLC-controlled conveyors can be connected to the Digital Twin. Machine-learning models can be trained using historical equipment data for predictive maintenance and demand forecasting. Reinforcement learning can also be investigated for dynamic AGV route optimization.

The Digital Twin can further be extended into a three-dimensional environment using WebGL or similar technologies. Edge computing and cloud deployment can be incorporated to support large-scale warehouses. Computer vision can also be integrated for human detection, safety monitoring, and automated inventory verification.

X. CONCLUSION

This paper presented a Digital Twin and Cyber-Physical System framework for smart warehouse optimization. The proposed system integrates IoT sensor simulation, inventory management, order processing, AGV tracking, route optimization, predictive maintenance, safety monitoring, and real-time analytics into a unified web-based platform.

The architecture combines React.js for interactive visualization, Node.js and Express.js for backend processing, and MySQL for structured data management. The Digital Twin provides a virtual representation of warehouse assets and operational conditions, while the CPS architecture enables the interaction between simulated physical processes and the virtual environment.

The proposed framework demonstrates the potential of Digital Twin technology for improving warehouse visibility and intelligent decision support. Although the current implementation relies on simulated sensor data and rule-based prediction, its modular architecture provides a foundation for future integration with physical IoT devices, machine-learning models, real AGVs, and industrial automation systems.

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REFERENCES

[1] M. Grieves and J. Vickers, “Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems,” in Transdisciplinary Perspectives on Complex Systems, Springer, 2017.

[2] A. Fuller, Z. Fan, C. Day, and C. Barlow, “Digital Twin: Enabling Technologies, Challenges and Open Research,” IEEE Access, vol. 8, pp. 108952–108971, 2020.

[3] M. Qi and X. Tao, “Digital Twin and Cyber-Physical Systems for Smart Manufacturing and Logistics,” relevant peer-reviewed literature should be verified before submission.

[4] F. Tao, H. Zhang, A. Liu, and A. Y. C. Nee, “Digital Twin in Industry: State-of-the-Art,” IEEE Transactions on Industrial Informatics, relevant bibliographic details should be verified before submission.

[5] Additional verified papers on smart warehouses, IoT, AGV routing, predictive maintenance, CPS, and warehouse Digital Twins should be added from IEEE Xplore, ScienceDirect, Springer, ACM Digital Library, or other scholarly databases.