INTEGRATING DIGITAL TWIN AND BARCODE TECHNOLOGIES FOR PREDICTIVE AND COMPARE INVENTORY OPTIMIZATION IN PUBLIC UTILITY WAREHOUSES

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Abstract

Purpose: This study aims to address the operational limitations of centralized Enterprise Resource Planning (ERP) systems in public utility warehouses by examining the effectiveness of a localized Warehouse Management System (WMS) integrated with Digital Twin (DT), QR Code tracking, and Machine Learning (ML) forecasting.

Design/Methodology/Approach: A quasi-experimental pretest–posttest design was employed across eight regional warehouses operated by Thailand's Provincial Electricity Authority (PEA). Six months of historical SAP ERP data were compared with two months of post-implementation WMS data. The prototype system integrated QR-based asset tracking, DT simulation for operational optimization, and ML models (Random Forest and LSTM) for workload forecasting. Statistical analysis included t-tests, effect size measurement, and evaluation of predictive models against baseline forecasting methods.

Findings: The localized WMS demonstrated significant improvements, with an average processing time decrease of 28.9%, an increase in inventory accuracy from 96.5% to 98.8%, and a 47.3% reduction in error rates. Inventory turnover improved by 15.6%. In predictive analytics, ML models outperformed baseline moving averages, with the LSTM achieving a 20.8% reduction in MAE and a 17.8% reduction in RMSE, enhancing resource allocation and demand planning.

Originality / Value: This study provides one of the first empirical evaluations of integrating DT, QR, and ML technologies in a full-scale ERP-to-WMS migration within a public utility context. It extends the literature on supply chain decoupling by demonstrating how localized digital solutions can deliver superior agility and accuracy compared to centralized systems, offering a replicable framework for digital transformation in asset-intensive sectors.

Keywords: Digital Twin, Warehouse Management System, QR Code, Machine Learning, Supply Chain Decoupling, Public Utility Logistics

Introduction

The rapid digitalization of supply chains has revealed the structural limitations of centralized Enterprise Resource Planning (ERP) systems. While platforms such as SAP provide effective corporate integration and data governance, they often lack the necessary agility for managing geographically dispersed warehouses. For the Provincial Electricity Authority (PEA) of Thailand, reliance on SAP has resulted in delayed inventory updates, manual data entry, and limited integration with modern technologies—factors that increase costs and reduce responsiveness.

The concept of Supply Chain Decoupling offers a pathway to address these challenges by shifting from globalized ERP systems toward localized Warehouse Management Systems (WMS) that provide real-time visibility, flexible workflows, and integration with advanced technologies. Prior studies have highlighted the value of Digital Twin (DT) for simulation, QR Code tracking for traceability, and Machine Learning (ML) for predictive forecasting. However, research has largely treated these technologies separately, and evidence of their combined application within the public utility sector remains limited.

This study addresses that gap by investigating the migration from SAP ERP to a localized WMS prototype enhanced with DT, QR, and ML across eight regional warehouses of PEA. The objectives are: (1) to compare operational performance between SAP and WMS; (2) to design and evaluate the WMS prototype; and (3) to develop and validate ML models for workload forecasting. By situating the study within the supply chain decoupling framework, the research contributes empirical evidence on how localized digital solutions can deliver efficiency and agility in public utility logistics.

Literature Review

Limitations of Centralized ERP in Warehouse Operations

Enterprise Resource Planning (ERP) systems such as SAP have been central to integrating financial, procurement, and organizational processes across enterprises. Despite their strengths in central data governance, ERP platforms are not designed for real-time operational control (Zhou et al., 2021). In warehouse contexts, this limitation often results in delayed inventory updates, reliance on manual data entry, and restricted compatibility with emerging technologies such as IoT sensors, barcode systems, and QR-based tracking (Utami et al., 2020). These shortcomings elevate error rates and reduce responsiveness, particularly in geographically dispersed operations.

Warehouse Management Systems in the Digital Era

Warehouse Management Systems (WMS) are designed to manage warehouse-floor activities, including receiving, putaway, picking, and dispatch. Unlike ERP systems, WMS platforms emphasize real-time control and optimization of operational processes (Istiqomah et al., 2020; Hamdy et al., 2020). Evidence suggests that WMS adoption improves order accuracy, reduces cycle times, and enhances traceability compared to ERP-only solutions (López-Torres et al., 2022; Yasin et al., 2024). Furthermore, WMS can integrate seamlessly with technologies such as QR scanners and IoT devices, thereby enabling decentralized decision-making while still feeding performance data into central systems. This balance aligns with the supply chain decoupling paradigm, which emphasizes local adaptability supported by overarching strategic oversight.

Enabling Technologies for Next-Generation WMS

Three technologies have become particularly significant for enhancing WMS capabilities. Digital Twin (DT) provides a virtual model of warehouse operations, enabling managers to test scenarios, identify bottlenecks, and optimize processes before execution (Aziz et al., 2023; Cesur et al., 2024**).** QR Code tracking supports rapid and low-cost item-level visibility, reducing manual errors and enhancing inventory accuracy. Meanwhile, Machine Learning (ML) techniques, such as Random Forest and Long Short-Term Memory (LSTM) models, enable more accurate demand forecasting and workload prediction (Jumahat et al., 2023). These predictive capabilities improve labor planning, resource allocation, and stock utilization, making WMS more proactive and resilient.

WMS in the Public Utility Context

While the private sector has widely adopted WMS and related technologies, empirical applications in public utilities remain limited. Public utilities often face distinct challenges, including budgetary restrictions, compliance obligations, and the critical requirement of service reliability. These conditions underscore the potential of localized WMS in enhancing efficiency and resilience. Tikwayo and Mathaba (2023) argue that integrating WMS with IoT and real-time analytics can substantially reduce errors and strengthen operational transparency in public-sector logistics.

Research Gap

Although existing literature has confirmed the individual benefits of DT, QR, and ML in improving warehouse performance, few empirical studies have examined their combined implementation within a migration from ERP to WMS in public utilities. This study directly addresses that gap by evaluating the operational and predictive outcomes of integrating these technologies into a localized WMS framework under the supply chain decoupling paradigm.

Research Methodology

Research Design

This study adopts a quasi-experimental pretest–posttest design to evaluate the operational and predictive impacts of transitioning from a centralized ERP (SAP) environment to a localized WMS prototype. This approach allows for empirical comparison between historical performance data and post-implementation results while maintaining ecological validity within live operational contexts (Creswell, 2014). By applying the concept of supply chain decoupling, the design enables assessment of how localized systems integrated with DT, QR, and ML improve warehouse performance compared with globalized ERP structures.

Research Scope and Setting

The research was conducted across eight regional warehouses of the Provincial Electricity Authority (PEA) in Thailand. These facilities differ in demand intensity, storage capacity, and operational complexity, providing a robust basis for evaluating system performance under varying conditions. The study consists of two phases:

1.Pretest (SAP ERP): Six months of transaction data extracted from the centralized SAP system.

2.Posttest (WMS Prototype): Two months of operational data generated following the deployment of the localized WMS.

This dual-phase approach ensures both historical benchmarking and empirical validation of the prototype.

System Development and Integration

The localized WMS prototype was designed to address limitations of SAP ERP and to incorporate advanced technologies:

1.WMS Core: Real-time stock visibility and QR-based inbound, putaway, picking, and dispatch functions.

2.Digital Twin Module: A virtual model of warehouse layout and workflows, enabling real-time bottleneck detection and scenario simulation (Aziz et al., 2023).

3.Machine Learning Module: Predictive models using Random Forest for categorical decision-making and Long Short-Term Memory (LSTM) networks for time-series demand forecasting (Jumahat et al., 2023).

Data Collection

Data were collected from multiple sources to ensure reliability and triangulation:

1.SAP ERP logs: Six months of historical records validated against audit reports.

2.WMS logs: Automated capture of real-time operational transactions.

3.QR scan records**:** Timestamped data for inbound and outbound movements.

4.DT simulation logs: Throughput and bottleneck metrics generated during live operations.

Performance Metrics

Two groups of metrics were applied:

1.Operational KPIs: Processing time, inventory accuracy, error rate, and inventory turnover (López-Torres et al., 2022).

2.Predictive KPIs: Mean Absolute Error (MAE), Root Mean Squared Error (RMSE), and forecast bias, enabling evaluation of ML model accuracy compared with baseline moving average forecasts.

Data Analysis

Data analysis comprised three stages:

Descriptive Statistics: Mean and standard deviation to summarize central tendencies and variability.

Inferential Statistics: Independent samples *t*-tests to compare SAP (pretest) and WMS (posttest) performance, with significance set at $p < 0.05$. Effect sizes were reported using Cohen's *d* to determine the magnitude of observed differences (Cohen, 1988).

Predictive Model Evaluation: ML models were trained on historical workload data using an 80/20 split and five-fold cross-validation. Results were benchmarked against baseline moving averages to assess relative forecasting improvements (Jumahat et al., 2023).

Success Criteria and Limitations

The migration was considered successful if cycle times and error rates decreased significantly, inventory accuracy exceeded 98%, and ML models outperformed baseline forecasts in both accuracy and stability. Limitations include the short posttest duration (two months), potential learning-curve effects among operators, and variability across warehouses with different demand profiles.

<u>Result and Discussion</u>

Quantitative Performance

The transition from SAP ERP to the localized WMS yielded significant improvements in operational efficiency across all measured KPIs. Table 1 summarizes the comparative analysis, while Figure 1 illustrates the reduction in average processing time.

KPI	SAP ERP (Mean ±SD)	WMS (MEAN±SD)	% Improvement	P-value	Effrct Size (Cohen's d)
Processing Time (min/order)	15.2 ± 3.1	10.8 ± 2.5	-28.9%	0.001	0.72 (medium)
Inventory Accuracy (%)	96.5 ± 1.2	98.8 ± 0.8	+2.3%	0.004	0.65 (medium)
Error Rate (/1,000 txns)	22.4 ± 5.3	11.8 ± 3.9	-47.3%	0.000	0.81 (large)
Inventory Turnover Ratio	3.2 ± 0.6	3.7 ± 0.7	+15.6%	0.012	0.55 (medium)

Table 1 : Comparative performance between SAP ERP and localized WMS

The WMS reduced processing time by nearly one-third and halved the error rate, demonstrating the effectiveness of QR-enabled verification and DT-based workflow optimization. Inventory accuracy improved beyond 98%, surpassing the audit threshold typically required in utility logistics.

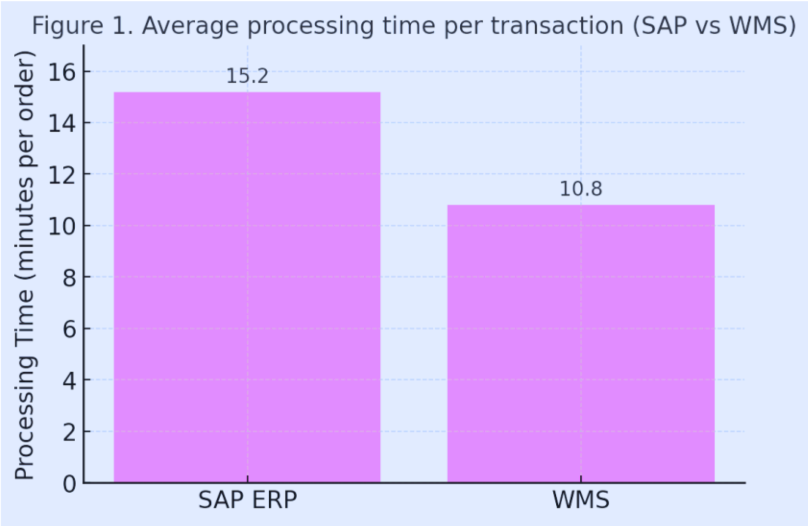

Figure 1 : Average processing time per transaction (SAP vs WMS). The results show that the WMS reduced the average processing time from 15.2 minutes to 10.8 minutes per order, representing a 28.9% improvement compared with the SAP ERP baseline.

Predictive Model Performance

Model	MAE	RMSE	Forecast Bias	R^2	Improvement vs Baseline
Moving Average	12.5	15.2	-4.2%	0.42	
Random Forest	10.3	13.1	+1.5%	0.63	MAE ↓17.6%, RMSE ↓13.8%
LSTM	9.9	12.5	+2.1%	0.71	MAE ↓20.8%, RMSE ↓17.8%

Table 2 : Forecasting performance comparison

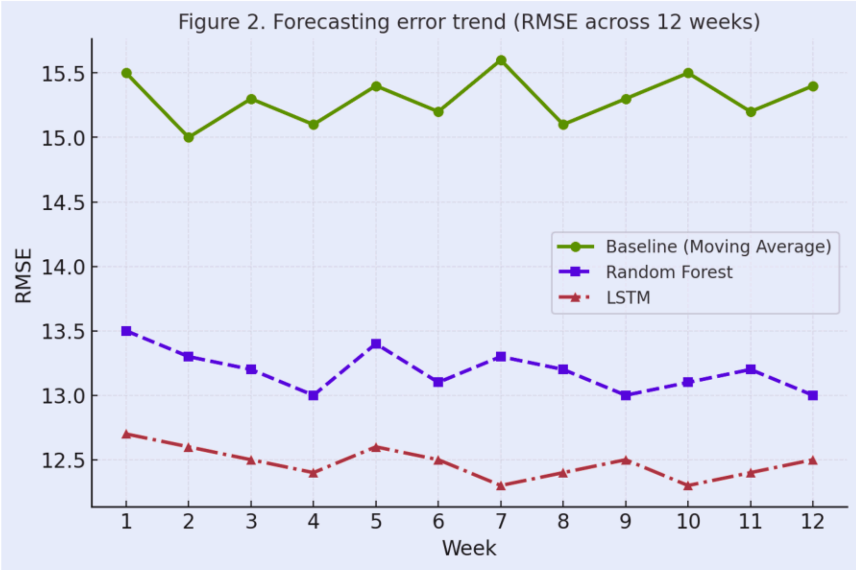

Figure 2 **:** Forecasting error trend (RMSE across 12 weeks). The results indicate that the LSTM model consistently achieved the lowest and most stable error, followed by Random Forest, while the baseline moving average exhibited the highest volatility and forecasting error.

The results provide empirical support for the strategic value of Supply Chain Decoupling. By migrating from SAP ERP to a localized WMS integrated with DT, QR, and ML, the PEA achieved measurable improvements in speed, accuracy, and predictive capability.

- Operational Agility: The reduction in processing time and error rates reflects the advantage of real-time visibility and automated verification processes.

- Role of Digital Twin: DT facilitated workflow simulations that informed layout and process optimization, aligning with studies emphasizing its diagnostic and prescriptive value in logistics (Aziz et al., 2023).

- QR Code Tracking: By embedding QR verification at multiple checkpoints, transaction integrity improved significantly, supporting findings by Enyejo et al. (2024) on traceability enhancement.

- Machine Learning Forecasting: ML models reduced forecasting errors by up to 20%, providing more balanced labor allocation and inventory planning, consistent with Espinosa-Jaramillo et al. (2024).

Collectively, these outcomes demonstrate that localized WMS platforms, when supported by advanced digital technologies, can surpass the operational performance of centralized ERP systems in public utility contexts.

Conclusion and Recommendations

This study evaluated the migration from SAP ERP to a localized WMS integrated with Digital Twin, QR Code tracking, and Machine Learning within eight warehouses of Thailand’s PEA. The results confirmed clear performance gains: processing time was reduced by nearly 29%, inventory accuracy improved to 98.8%, error rates declined by almost half, and turnover increased by 15.6%. ML models, particularly LSTM, outperformed baseline forecasts, demonstrating enhanced predictive capability.

The study contributes to supply chain decoupling literature by showing how localized, technology-enabled WMS platforms can outperform centralized ERP in public utility contexts. Practically, the findings offer a replicable framework for utilities and policymakers seeking digital transformation.

Recommendations

Based on the study findings, several recommendations are proposed for practice and policy. In the short term, utilities should implement a phased rollout of the localized WMS, beginning with warehouses handling the highest transaction volumes to maximize early impact. Adequate training programs for warehouse staff are essential to minimize operational disruptions and overcome the learning curve associated with system adoption. Integration with existing infrastructure should also be prioritized to reduce implementation costs and ensure continuity of service.

In the longer term, system capabilities should be expanded by incorporating external data sources, such as weather patterns or infrastructure development schedules, into ML forecasting models to improve predictive accuracy. The deployment of IoT sensors is recommended to enhance real-time asset monitoring and further support the Digital Twin framework. Finally, emerging technologies such as augmented reality for order picking and blockchain for transaction transparency should be explored to strengthen efficiency and trust across the supply chain.

Limitations and Future Research

The study's scope was limited to an **eight-month observation period** (six months SAP pretest, two months WMS posttest). This timeframe may not fully capture seasonal fluctuations or long-term system adaptation.

Future research should extend post-implementation observation over longer cycles, investigate scalability across other sectors, and incorporate external variables (e.g., weather, infrastructure projects) to strengthen predictive accuracy and generalizability.

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