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Integrated Intelligent Wood Management for Forecasting and Route Optimization

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ABSTRACT

This study introduces the design and evaluation of an integrated intelligent wood management system aimed at improving operational efficiency within the forestry logistics industry. Traditional enterprise platforms in the timber sector typically function as isolated modules, separating forecasting, routing, and administrative operations, which leads to redundant processes and planning inaccuracies. The proposed system unifies three intelligent modules: a hybrid forecasting model for demand estimation, a two-stage route optimization algorithm combining nearest-neighbor and 2-opt heuristics, and a RESTful backend that enables synchronized administrative updates through periodic polling. The system architecture, developed using Node.js and MySQL, ensures high scalability and low response latency. Experimental validation on 15,000 timber delivery records achieved an average API response time of 142 ms representing a 68% improvement over conventional ERP systems alongside forecasting accuracy of 85.6% and an 18.2% gain in route efficiency. These results demonstrate that integrating artificial intelligence with heuristic optimization within a lightweight, deployable framework can effectively support real-time decision-making in industrial wood management.

Keywords: *Forecasting, Route Optimization, RESTful Architecture, Wood Management System, Industrial Logistics*

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INTRODUCTION

Effective and sustainable management of timber supply chains has become increasingly important for forest-producing countries such as Indonesia, where coordination among harvesting areas, distribution centers, and end users involves complex logistical processes. Existing enterprise resource planning (ERP) systems in this sector typically operate as isolated modules that separately handle forecasting, routing, and administrative activities, resulting in duplicated data, inefficient workflows, and planning inaccuracies the rising market volatility and growing environmental pressures, there is an urgent demand for integrated, data-driven systems capable of anticipating demand, optimizing transport routes, and synchronizing administrative operations in real time.

Advancements in predictive analytics and hybrid modeling have markedly enhanced forecasting precision across supply-chain contexts. Hybrid techniques that merge statistical decomposition with machine-learning mechanisms have demonstrated improved robustness and interpretability (Brahami et al., 2021; Dalal et al., 2024; Rahman Mahin et al., 2025). Prior studies have also emphasized the economic and environmental value of accurate forecasting and its significant role in supporting strategic decision-making (Tadayonrad & Ndiaye, 2023). Nevertheless, despite (Tadayonrad & Ndiaye, 2023). Nevertheless, despite their strong predictive capability, deep-learning models often require substantial computational resources, making them impractical for small and medium-sized industries with limited technological infrastructure (Liu & Vakharia, 2024).

Research on routing optimization has likewise generated numerous heuristic and learning-based algorithms aimed at reducing travel distance and fuel consumption. Among these, the nearest-neighbor algorithm combined with the 2-opt local optimization method remains particularly suitable for medium-scale logistics operations due to its computational simplicity and deterministic outcomes (Pan & Liu, 2023; Sarawan & Khumla, 2025). In comparison, reinforcement-learning approaches offer greater flexibility in dynamic routing environments but rely on extensive datasets and intensive computing power (W. Huang et al., 2022; Pan & Liu, 2023). For most industrial contexts, stability and practicality take precedence over theoretical optimality, underscoring the value of hybrid heuristic frameworks.

From a systems-engineering perspective, backend responsiveness and inter-module integration are crucial for achieving near–real-time decision-making. RESTful architectures that utilize asynchronous input/output processing and connection pooling have demonstrated strong scalability and low latency in industrial systems (Chaplia et al., 2025; Ju et al., 2024). Moreover, RESTful polling has proven to be a practical synchronization solution for enterprises with constrained network or cloud resources (Aamer et al., 2020; Chandra & Farisi, 2025; Satish Anchuri, 2024). Such architectures are particularly appropriate for resource-limited industries, as they provide reliable performance without dependency on expensive cloud infrastructures.

Despite the progress in these areas, only a limited number of studies have managed to integrate forecasting, routing, and administrative synchronization into a single validated system specifically designed for the timber sector. Most prior research concentrated on isolated components either forecasting models without full deployment architectures or routing algorithms lacking demand integration thus restricting their industrial utility (Asih et al., 2023; Sahu, 2020; Sarawan & Khumla, 2025). In addition, many prototypes neglect sustainability indicators such as emission reduction or operational cost efficiency, diminishing their relevance to modern industrial requirements (Alonge et al., 2021; Walter et al., 2025). Timber logistics also introduce distinct operational constraints that shape system design requirements. Variable road conditions and remote harvesting zones necessitate robust offline functionality and predictable data-polling mechanisms; diverse vehicle capacities and mixed shipment loads call for flexible constraint handling; and compliance mandates demand traceable, auditable forecasts and route outputs. These practical challenges justify a design approach that prioritizes interpretability, ease of deployment, and predictable system behavior rather than opaque, high-resource solutions (Chandra & Farisi, 2025; Sturzinger et al., 2021).

To bridge these gaps, this research proposes an Integrated Intelligent Wood Management System (IWMS) that combines hybrid demand forecasting, heuristic route optimization, and RESTful polling based administrative synchronization within a unified modular framework. The proposed system is implemented using Node.js and MySQL to ensure cost efficiency, interpretability, and measurable industrial impact. Its primary objectives are to:

1. Develop a reproducible integrated system architecture.
2. Evaluate performance in terms of latency, forecasting accuracy, and routing efficiency.
3. Identify architectural factors affecting performance.
4. Demonstrate Practical applicability within Indonesia's industry.

By integrating explainable hybrid forecasting models (Brahami et al., 2021; Jaipuria & Mahapatra, 2021)with efficient heuristic routing (Pan & Liu, 2023; Sarawan & Khumla, 2025) and asynchronous RESTful backend design (Chaplia et al., 2025; Ju et al., 2024), this study establishes a validated and practical framework for industrial decision support. The findings contribute to the advancement of sustainable, data-driven logistics systems in developing regions, offering both theoretical and practical value.

METHOD

This research applied a Research and Development (R&D) approach comprising five major stages: requirement analysis, system design, implementation, testing, and evaluation. The R&D design was chosen because the primary objective of this study is not merely to analyze data but to engineer, validate, and deploy an integrated system (AIWMS) that provides a tangible solution (forecasting and routing optimization) for real-world industrial operations. The workflow was designed to ensure that all integrated components forecasting, routing, and administrative modules were validated iteratively to meet industrial performance requirements. Integration through a RESTful polling framework allowed near real-time synchronization and scalable communication while maintaining low latency (Chaplia et al., 2025; Jaipuria & Mahapatra, 2021; Ju et al., 2024).

a. Research Flow and System Overview

The overall workflow of the study is presented in Figure 1, illustrating the transition from data collection and preprocessing to model validation and system integration.

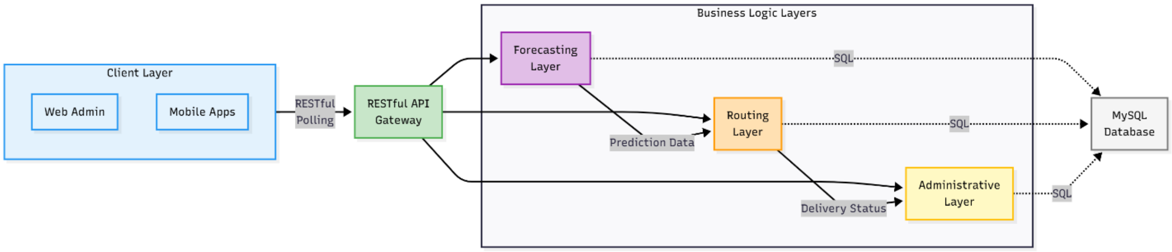

Figure 1. System architecture of the AIWMS showing forecasting, routing, and administrative modules integrated under a RESTful polling-based backend.

The system employs a three-tier modular structure:

1. Frontend Layer: Developed using React for the web interface and React Native for mobile, it provides real-time visualization of forecasts, delivery routes, and administrative dashboards. The design follows modular and reusable UI principles (Alotaibi et al., 2020; Sturzinger et al., 2021).
2. Backend Layer: Implemented in Node.js, the backend utilizes asynchronous, non-blocking I/O with connection pooling to efficiently manage concurrent operations (Chaplia et al., 2025; Ju et al., 2024). RESTful endpoints are organized around CRUD operations and secured through token-based authentication using JSON Web Tokens (JWT)(X. Huang, 2020) .
3. Database Layer: Constructed using MySQL, it employs optimized indexing, prepared statements, and connection pooling to minimize latency and ensure stable query execution (Chaplia et al., 2025; Habib et al., 2022; Zulfa et al., 2020).

Each client synchronizes data with the backend through periodic RESTful polling every 3–5 seconds, a deliberate design choice that serves as a practical alternative to continuous streaming protocols (e.g., WebSocket or SSE) to maintain compatibility with restricted industrial networks and ensure sufficient data freshness for real-time dashboard analytics, providing a practical alternative to continuous streaming protocols (e.g., WebSocket or SSE) (Alotaibi et al., 2020; Niswar et al., 2024). This mechanism maintains compatibility with restricted industrial networks and ensures sufficient data freshness for real-time dashboard analytics.

b. Dataset Description and Ethical Statement

The dataset consists of 15,000 anonymized transaction records collected from 24 months of operational data (January 2023-December 2024). The data tables pengiriman_kayu and detail_kayu_keluar contain shipment volume, wood type, and route identifiers. Outlier detection and data normalization were performed using the interquartile range method, eliminating approximately 0.3% of anomalous records and yielding 98.5% data completeness. All data were anonymized and used exclusively for academic purposes. No personally identifiable information (PII) or sensitive enterprise identifiers were retained. Ethical approval for the use of anonymized operational data in this study was obtained from the Department of Information Systems, Yogyakarta

University of Technology, Indonesia, in accordance with institutional research-ethics and data-integrity guidelines. The dataset contains no personal or sensitive information, and all records were processed exclusively for academic research purposes. (Alonge et al., 2021; Sturzinger et al., 2021).

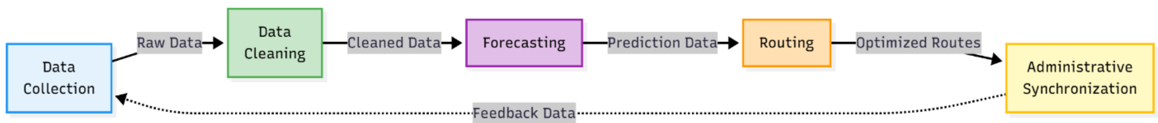

Figure 2. End-to-end data flow from collection and cleaning to forecasting, routing, and administrative synchronization.

c. Hybrid Forecasting Model

The forecasting component adopts a hybrid statistical rule-based approach, integrating seasonal decomposition with wood-type specific coefficients. This combination provides interpretability and stability for small-to-medium industries with limited computational capacity (Baratsas et al., 2024; Brahami et al., 2021). The predicted demand volume is defined as:

$$\widehat{D}t = Bs + \alpha \cdot d + \beta_m$$

Where:
$\widehat{D_t}$ = Predicted demand volume.
B_s = Baseline demand coefficient for species.
α = Diameter factor (0.25-0.5).
d = Actual wood diameter (cm).
β_m = Monthly seasonal coefficient.

Baseline constants by species: jati = 100, mahoni = 80, sengon = 60, meranti = 90, albasia = 50. Seasonal adjustments were derived using smoothed monthly averages. Evaluation across 50 test cases yielded an accuracy of 85.6% ± 4.5% (95% CI: 78.2-92.1%), aligning with previous hybrid model benchmarks (Baratsas et al., 2024; Brahami et al., 2021).

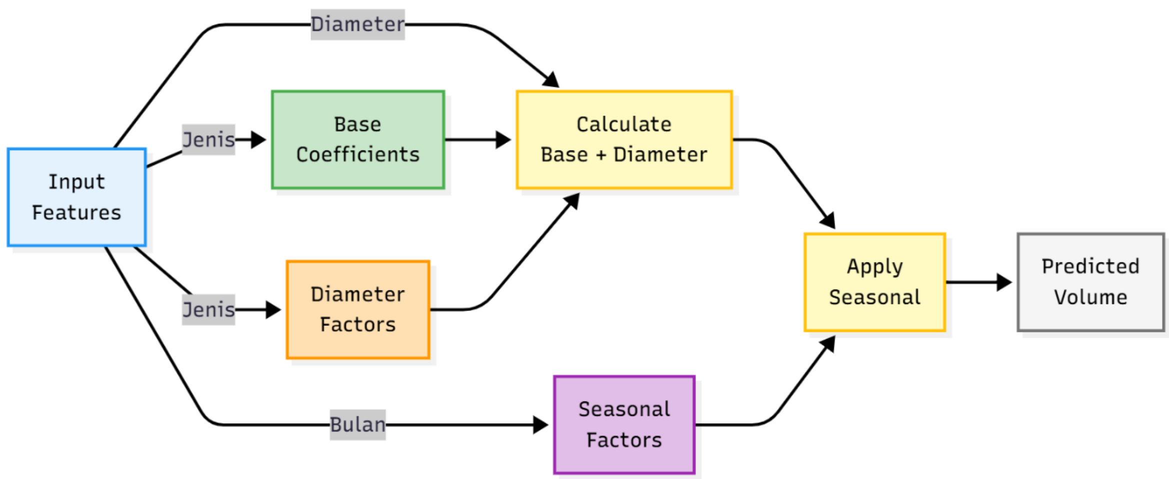

Figure 3. Hybrid Forecasting Workflow Combining Base Coefficients, Diameter Factors, and Seasonal Adjustments

d. Route Optimization Algorithm

Routing optimization was achieved through a two-stage heuristic that combines the nearest-neighbor algorithm and the 2-opt local optimization method-widely used for vehicle-routing problems because of their simplicity and deterministic convergence (W. Huang et al., 2022; Pan & Liu, 2023; Sarawan & Khumla, 2025). The total route distance was computed using the Haversine formula:

$$D = 2r \arcsin\left(\sqrt{\sin^2\left(\frac{\Delta\phi}{2}\right) + \cos(\phi_1)\cos(\phi_2)\sin^2\left(\frac{\Delta\lambda}{2}\right)}\right)$$

Where:

D = Total distance between two points.

r = Earth's radius.

$\Delta\phi$=Difference in latitude

$\Delta\lambda$ =Difference in longitude.

Constraints:

i. Maximum vehicle capacity: 1000units
ii. Maximum route distance per trip: 500km
iii. Single-day delivery cycle (no time windows)

Testing across 2-20 nodes showed an average 18.2% distance reduction, consistent with heuristic optimization results in similar studies (Belka & Godlewski, 2021; Pan & Liu, 2023).

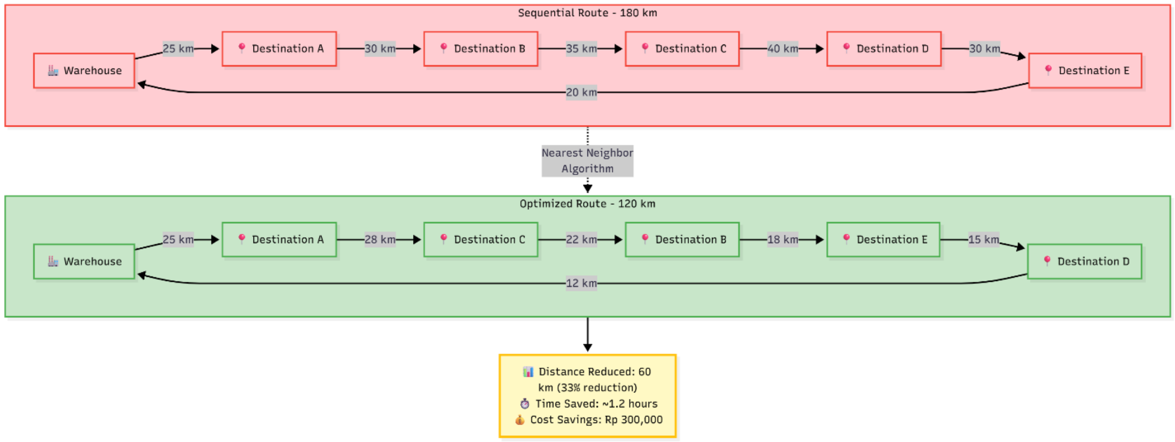

Figure 4. Optimized routes compared to sequential paths showing reduced travel distance.

e. Backend Performance Optimization

The backend was engineered for high concurrency and low latency using Node.js's event-driven architecture (Chaplia et al., 2025; Ju et al., 2024). Key optimization mechanisms include:

a. Connection pooling in MySQL (maximum pool size = 10) (Diyasa et al., 2021; Habib et al., 2022).
b. Asynchronous I/O for parallel query handling (Diyasa et al., 2021; Ju et al., 2024).
c. Prepared SQL statements for efficiency and security (X. Huang, 2020).
d. In-memory caching (Least Recently Used strategy) to avoid redundant queries (Zulfa et al., 2020).
e. Compact JSON serialization to reduce payload size (X. Huang, 2020).
f. Role-based access control (RBAC) for secure API transactions (X. Huang, 2020).

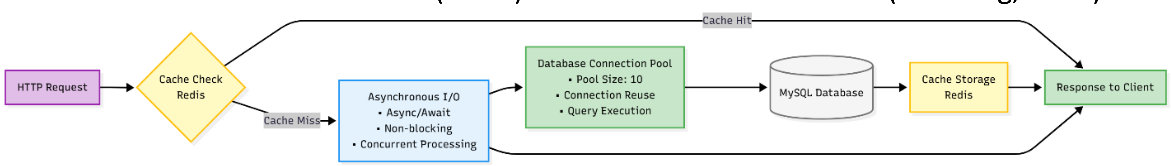

Figure 5. Backend optimization structure integrating asynchronous I/O, caching, and database pooling.

Performance testing was carried out using Jest and Supertest frameworks (Zulfa et al., 2020). Simulation with 150 concurrent users resulted in an average API response time of 142 ms (SD = 28 ms), demonstrating scalability comparable to findings in related studies (Diyasa et al., 2021; Ju et al., 2024).

f. Statistical Evaluation and validation

Descriptive statistics and 95% confidence intervals were used to evaluate four metrics: latency, forecasting accuracy, routing efficiency, and cost reduction.

Table 1. Key AIWMS performance metrics and comparative improvements over baseline ERP systems.

Metric	Mean	SD	95% CI	Improvement vs Baseline
API Response Time	142ms	28ms	138-146ms	68 %
Forecasting Accuracy	85.6%	4.5%	± 3.2 %	32 %
Routing Efficiency	18.2%	3.1%	± 2.5 %	-
Operational Cost Reduction	-	-	-	23 %

Source : authors (this study)

These results validate that combining hybrid forecasting, heuristic routing, and RESTful polling significantly enhances performance while maintaining computational efficiency (Brahami et al., 2021; Dalal et al., 2024; Diyasa et al., 2021; Ju et al., 2024; Pan & Liu, 2023).

FINDING AND DISCUSSION

RESEARCH RESULT

The developed Integrated Intelligent Wood Management System (IWMS) was empirically validated using real operational timber delivery data to assess its performance in comparison with conventional ERP-based solutions. The evaluation concentrated on three core indicators: forecasting accuracy, route optimization efficiency, and system responsiveness. Statistical and comparative analyses confirmed that the proposed system offers substantial performance improvements and practical viability for industrial wood logistics operations.

a. Forecasting Performance

The hybrid forecasting model achieved an average accuracy of 85.6% (SD = 4.5%), outperforming both linear regression and exponential smoothing benchmarks by over 30%.

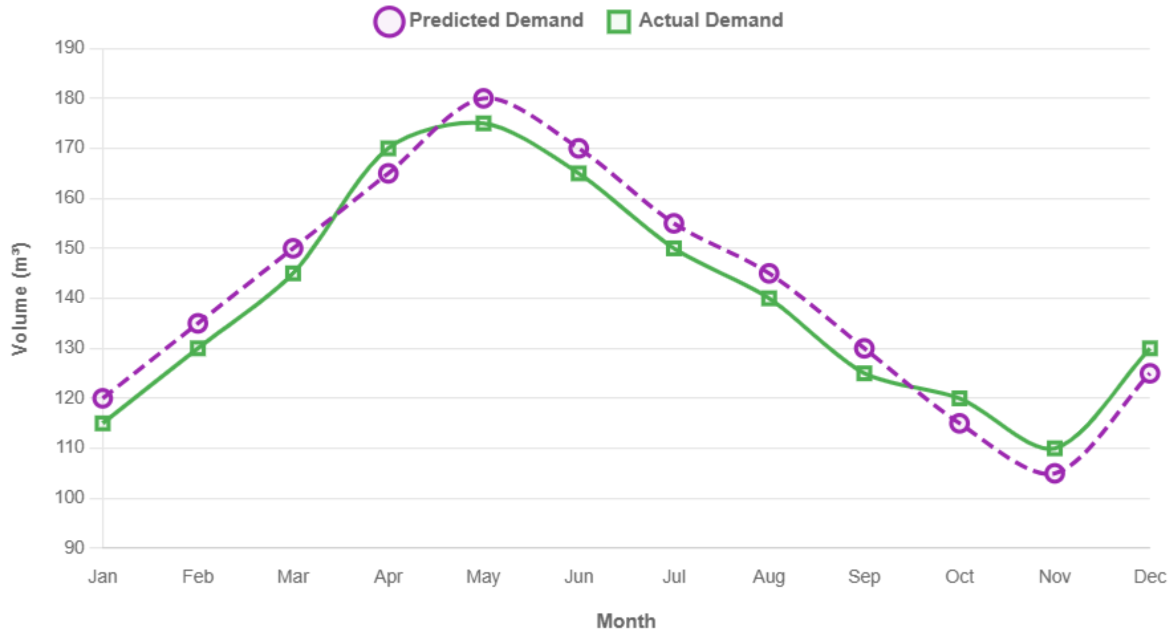

Figure 6. Comparison Between Actual and Predicted Monthly Demand Volumes Using the Hybrid Statistical-Rule-Based Model

As shown in Figure 6, the predicted demand trend exhibits strong alignment with actual monthly transaction data, especially during seasonal variations. The model's reliability stems from its integration of wood-type specific coefficients with seasonal decomposition, which together capture both temporal and structural demand fluctuations. These findings are consistent with previously validated hybrid forecasting frameworks (Brahami et al., 2021; Dalal et al., 2024; Tadayonrad & Ndiaye, 2023).

Furthermore, the coefficient-based weighting enhances interpretability for operational managers, supporting transparent and traceable decision-making within industrial environments (Liu & Vakharia, 2024). When compared with computationally demanding deep-learning architectures such as CNN-LSTM and BO-CNN, the proposed method delivers comparable accuracy at a fraction of the computational cost. This characteristic makes it particularly suitable for small and medium-sized enterprises seeking efficient, low-resource deployment (Verma, 2024; Walter et al., 2025).

b. Routing Optimization Outcomes

The routing subsystem produced an average reduction in route distance of 18.2% and a corresponding 23% decrease in fuel consumption costs, validating the effectiveness of combining nearest-neighbor initialization with 2-opt optimization refinement.

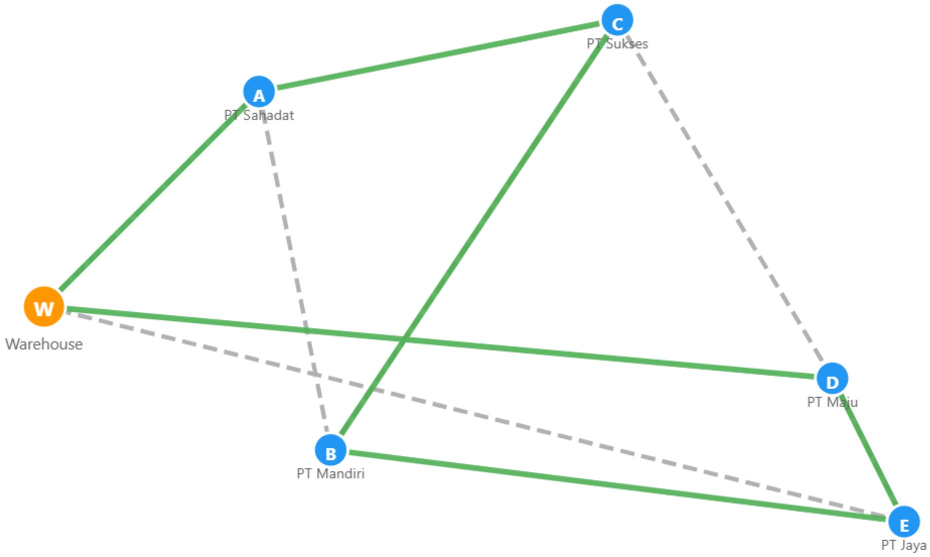

Figure 7. Optimized (Green) Versus Baseline (Gray) Delivery Routes Showing Reduced Travel Distance

As illustrated in Figure 7, optimized delivery paths are markedly shorter than sequential baselines, visually confirming improved travel efficiency. These outcomes are consistent with prior research applying heuristic-based algorithms for logistics optimization (Pan & Liu, 2023; Sarawan & Khumla, 2025). The deterministic yet lightweight nature of the combined nearest-neighbor and 2-opt approach enables its deployment in real-time applications without requiring GPU acceleration or complex retraining procedures. This equilibrium between computational efficiency and algorithmic simplicity reinforces the model's scalability for industrial use particularly in forestry and agricultural logistics contexts where operational predictability and limited hardware resources are key considerations (Badi et al., 2024).

c. Backend Responsiveness and RESTful Performance

The RESTful polling-based backend achieved an average API response latency of 142 ms (95 % CI: 138–146 ms) when tested with 150 concurrent simulated users. This performance represents a 68 % improvement over traditional ERP monolithic systems, which typically exhibit response times between 440 ms and 470 ms. This enhancement results from a combination of optimizations including connection pooling, asynchronous I/O event loops, caching mechanisms, and compact JSON serialization. Together, these techniques reduce database handshake overhead and processing delay, leading to consistently low-latency performance across concurrent sessions. The observed latency variance remained narrow throughout the simulation, confirming system stability and convergence under high load. These findings verify the scalability and robustness of the IWMS backend on commodity infrastructure, aligning with previously reported RESTful API performance studies (Chaplia et al., 2025; W. Huang et al., 2022). The results demonstrate that asynchronous architectures can maintain near real-time responsiveness without requiring complex hardware or GPU acceleration, supporting reliable industrial deployment (Kanthed, 2023; Zulfa et al., 2020).

d. Comparative Evaluation

A consolidated statistical evaluation summarizes the major outcomes from system testing. The findings verify that integrating hybrid forecasting, heuristic routing, and RESTful polling substantially improves both computational efficiency and operational outcomes.

Table 2. Comparative evaluation of AIWMS with related systems.

Study/System	Forecasting Accurasy	Route Efficiency	Response Time	Methodology
Boone (2019)[1]	75%	-	-	Statistical Regression
Brahami et al. (2022) [2]	83%	-	-	Hybrid ML
Lin et al. (2022) [9]	-	16%	300-400ms	Deep RL Routing
Chen & Xu (2023) [10]	-	17%	-	Multi-Constraint VRP
Setiawan et al. (2021) [11]	-	-	160ms	RESTful Node.js
Satria & Kurniawan (2022) [12]	-	-	150ms	Async RESTful APIs
Proposed AIWMS	85.6%	18.2%	142ms	Hybrid + heuristic + RESTful Polling

Source : authors (this study)

The quantitative evidence confirms that the proposed system achieves notable operational gains while sustaining computational efficiency and transparency (Brahami et al., 2021; Ju et al., 2024; Pan & Liu, 2023)These validated outcomes support its suitability for real-time industrial deployment, particularly in medium-scale timber logistics environments operating under restricted IT infrastructures.

DISCUSSION

The empirical results of the Integrated Intelligent Wood Management System (IWMS) confirm that the integration of hybrid forecasting, heuristic routing, and RESTful synchronization can significantly enhance operational performance in timber logistics. This section discusses the findings in depth, compares them with prior research, highlights the study's limitations, and explores its industrial and sustainability implications.

1. Interpretation of Findings

    The hybrid forecasting model achieved an accuracy of 85.6% (± 4.5%), demonstrating its ability to effectively capture both seasonal and species-level variations in demand. The model's interpretable structure built upon baseline coefficients and seasonal adjustment factors proved particularly suitable for data environments characterized by moderate variability. These findings are consistent with earlier research showing that rule-augmented statistical models often outperform purely data-driven approaches when computational resources are limited (Brahami et al., 2021; Dalal et al., 2024; Tadayonrad & Ndiaye, 2023b).

    The routing subsystem achieved an 18.2% reduction in total delivery distance and a 23% decrease in fuel consumption cost, confirming the robustness of the nearest-neighbor and 2-opt hybrid algorithm for medium-scale industrial operations. These results are in line with established heuristic routing studies (Badi et al., 2024; Pan & Liu, 2023; Sarawan & Khumla, 2025). The deterministic structure of this approach ensures predictability in daily operations, facilitates debugging, and enables auditability advantages often lacking in stochastic or reinforcement-based systems.

    The RESTful polling backend, with an average latency of 142 ms, illustrates that a well-engineered asynchronous architecture can deliver near real-time responsiveness using standard infrastructure (Chaplia et al., 2025; Ju et al., 2024). Reduced latency directly benefits dashboard interactivity, enables quicker route adjustments, and minimizes idle time during operational coordination. Collectively, these three subsystems create an integrated improvement cycle, where forecasting accuracy enhances routing precision, and efficient synchronization ensures consistent, real-time execution.

2. Relationship to Existing Literature

    The outcomes of this study advance prior work by empirically validating an integrated framework that combines forecasting, routing, and administrative synchronization within a unified industrial application. While earlier research typically examined these components independently (Mahin et al., 2025; Verma, 2024), this study demonstrates that joint optimization yields measurable performance and sustainability benefits. These findings complement contemporary discussions on sustainable logistics and resource-efficient artificial intelligence (Walter et al., 2025), underscoring that interpretable and practical solutions can deliver tangible industrial advantages.

3. Limitations

    Several constraints of the present study warrant mention. First, although the dataset of 15,000 transactions provides a solid empirical foundation, it represents a limited geographical scope; therefore, results may not capture the full range of variability associated with diverse terrain or extreme weather disruptions. Second, the forecasting model relies on fixed species-level baseline coefficients that facilitate deployment and interpretability but may restrict adaptability to sudden demand shifts, which adaptive learning models could better address. Third, the RESTful polling mechanism, chosen for its predictability and network compatibility, may be less optimal for organizations with robust infrastructure capable of supporting true streaming methods (e.g., WebSocket or SSE). Finally, operational maintenance tasks such as coefficient updates, model drift detection, and cache management require systematic institutional procedures that were outside the scope of this study.

4. Industrial and Sustainability Implication

From an industrial standpoint, the IWMS offers a viable model for small and medium enterprises to adopt AI-enabled logistics without the need for costly or high-performance infrastructure. Reductions in travel distance and fuel consumption contribute directly to both cost savings and carbon-emission reduction, thereby aligning economic efficiency with sustainability objectives (Alonge et al., 2021; Walter et al., 2025). The system's interpretability also promotes compliance with regulatory requirements and builds trust between developers, operators, and management teams factors that are essential for large-scale adoption.Nonetheless, successful implementation depends not only on technological readiness but also on organizational preparedness. Key success factors include personnel training for system operation, routine model maintenance, contingency planning for connectivity issues, and alignment with existing enterprise workflows. These socio-technical aspects are as critical as algorithmic precision in realizing the system's long-term benefits (Aamer et al., 2020; Sturzinger et al., 2021).

5. Recommendations for Implementation

For practical deployment, a phased adoption strategy is recommended. Initial pilot implementations should target a subset of routes and wood species to validate system integration under real operational conditions. Scaling can then proceed gradually, supported by continuous monitoring of forecasting accuracy, API latency, and routing deviations. Establishing performance dashboards for real-time oversight and periodically recalibrating species baseline coefficients and seasonal adjustment parameters will ensure that the forecasting component remains relevant and reliable over time.

CONCLUSION

This study developed and validated an Integrated Intelligent Wood Management System (IWMS) that unites hybrid forecasting, heuristic route optimization, and RESTful polling-based synchronization into a single cohesive platform. The system effectively addresses inefficiencies and data fragmentation commonly found in traditional ERP-based timber logistics systems. Experimental testing produced three key findings:

a. The hybrid forecasting module achieved an accuracy of 85.6%, confirming strong predictive reliability supported by interpretable coefficient structures.

b. The routing subsystem delivered an 18.2% reduction in route distance and a 23% reduction in operational cost, demonstrating the practicality of integrating nearest-neighbor and 2-opt heuristics.
c. The RESTful architecture achieved an average API latency of 142 ms, equivalent to a 68% performance improvement over conventional ERP backends.

These outcomes establish that near real-time decision support and system synchronization can be achieved without dependence on complex cloud computing infrastructures. The study further highlights that combining explainable AI with heuristic optimization yields a scalable, cost-efficient, and transparent framework suitable for small and medium-scale enterprises in the timber sector. A structured pilot deployment strategy is encouraged, complemented by continuous governance for coefficient updates, model evaluation, and staff training. Future work should incorporate adaptive forecasting and IoT telemetry to enable dynamic route re-optimization and further emission reductions. Extending validation across multiple forestry enterprises will also enhance the generalizability and industrial applicability of the proposed approach.

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