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APPLICATION OF MIXED INTEGER LINEAR PROGRAMMING MODEL IN OPTIMIZING THE EXPORT WOOD TRANSPORTATION NETWORK FOR SMALL AND MEDIUM ENTERPRISES IN HANOI

Nguyen Tien Minh[1], Nguyen Thi Thu Ha[2], Nguyen Duc Duong[3]

[1]VNU University of Economics and Business, Hanoi, Vietnam. Email: ntminh@vnu.edu.vn

[2]Graduate academy of social sciences, Hanoi, Vietnam; Email: Hantt.neu@gmail.com

[3]Banking Academy of Vietnam, Vietnam; Email: duongnd@hvnh.edu.vn

Corresponding author: Nguyen Thi Thu Ha. Email: Hantt.neu@gmail.com

Abstract

This study builds upon and develops the Mixed Integer Linear Programming (MILP) model for multi-objective transportation network optimization, aiming to evaluate the practical applicability in the wood export activities of small and medium-sized enterprises (SMEs) in the Hanoi area. The input data includes the locations of production facilities, collection points, export ports, consumption markets, transportation cost-time matrices, and storage limits based on the characteristics of wood products. The model is solved using CPLEX software with three scenarios: (1) cost optimization, (2) time optimization, and (3) multi-objective optimization. The results show a clear trade-off between transportation cost and time. Specifically, with a weight range of 0.6 to 0.75, the composite index Q achieves a low and stable value, indicating a reasonable balance between the two objectives. The model demonstrates high potential for application in designing logistics networks suitable for the scale, business strategy, and practical conditions of SMEs in the wood export sector.

Keywords: MILP model; transportation network optimization; multi-objective optimization; wood export logistics; small and medium-sized enterprises.

1. INTRODUCTION

In recent years, Vietnam's wood processing and export industry has affirmed its significant role in the national economy, contributing considerably to export turnover and providing employment for millions of workers. According to data from the Vietnam Timber and Forest Products Association (VIFOREST), Vietnam's wood product export turnover reached over 15 billion USD in 2024, with small and medium-sized enterprises (SMEs) accounting for a substantial share in the production and supply value chain.
In the Hanoi area and its neighboring provinces, SMEs engaged in wood processing and export face numerous challenges in organizing and operating their logistics networks. The expansion of production scale, diversification of export markets, and increasing transportation costs have created significant pressure on the supply chain optimization process. Particularly, the transportation system from production workshops, warehouses, and transshipment points to

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seaports or export destinations remains fragmented, lacking effective connectivity, leading to higher costs and delivery times.

In this context, building an optimized transportation network model is crucial to improving logistics efficiency, reducing costs, and enhancing the competitiveness of SMEs in the wood export industry. Based on previous studies on multi-objective transportation route optimization using the MILP method, this research adjusts and applies the model to the practical context of wood export enterprises in Hanoi. The input data includes the locations of production facilities, collection points, export ports, consumption markets, and the cost-time transportation matrix.

The aim of the study is to optimize both transportation cost and time simultaneously, thereby proposing a logistics network structure that suits the scale and specific operations of SMEs in the wood industry, contributing to enhancing the competitiveness of Vietnamese wood products in the international market.

2. RESEARCH METHODOLOGY

Many previous studies have focused on optimizing transportation networks and supply chains to enhance distribution efficiency and reduce logistics costs in the industrial manufacturing sector. [2] developed an integrated vehicle routing model for manufacturing enterprises, helping to reduce transportation costs and improve delivery accuracy, thereby enhancing supply chain productivity. [3] proposed a multi-objective optimization model for SMEs' logistics chains, simultaneously reducing inventory costs and time through rational transportation resource allocation. Meanwhile, [4] applied a metaheuristic algorithm (improved ant colony algorithm) to optimize transportation routes in urban environments, helping to save energy and reduce CO_2 emissions. Additionally, studies on decentralized logistics network management show that decentralized models in supply chain coordination enhance responsiveness and reduce costs for small businesses under limited infrastructure conditions [5]. These results emphasize the importance of integrating factors such as resource allocation, transportation scheduling, route optimization, and logistics governance structure in developing effective transportation models for manufacturing-export enterprises. This study inherits the multi-objective Mixed Integer Linear Programming (MILP) model developed and published by the authors in the Journal of Construction, July 2025 [6]. The model allows for the simultaneous optimization of two objectives: total cost and total transportation time, in the design of a multi-tier logistics network, with continuous and binary decision variables, suitable for the combinatorial problem in industrial supply chain management. Based on the established mathematical model, this research simulates and validates it using real-world data provided by a wood export enterprise in Hanoi to assess the feasibility and effectiveness of the model in specific operational conditions. The input data includes: (i) The locations of 12 wood production and processing facilities (Production Points - PP), 5 distribution centers (DC), 3 main export ports (Export Ports - EP), and 4 import markets (Import Markets - IM); (ii) The cost and transportation time matrix between nodes; (iii) Handling capacity and storage at each

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intermediate point; and (iv) Technical constraints on load capacity, operational schedules, and wood export-import regulations.

The transportation network is simulated based on three main modes reflecting actual operations: (1) Truck transportation (15 tons) from production facilities to distribution centers; (2) 40'DC truck transportation from distribution centers to export ports; (3) Maritime transportation from Vietnamese ports to foreign consumption markets. Each route in the network is assigned specific cost and time values, ensuring compliance with actual load, distance, and transportation type conditions. The data is integrated into the MILP model and solved under three scenarios: (i) Cost optimization, (ii) Time optimization, and (iii) Multi-objective optimization. The analysis is conducted in two steps:

• Step 1: Solve the single-objective model to determine the optimal values for cost and time.

• Step 2: Apply two multi-objective solving methods:

(1) The Weighted Sum method with a cost weight w1∈[0;1]w_1 \in [0; 1]w1∈[0;1];

(2) The Minimax method, to determine the solution with the smallest deviation from the single-objective optimal values.

The entire model is solved using IBM ILOG CPLEX software, with outputs including total cost, total time, and the composite index Q, providing a clear quantitative basis for evaluating operational efficiency and selecting a network configuration that aligns with the strategic objectives of wood export enterprises in different market scenarios.

3. RESEARCH RESULTS

3.1. Current Status of Wood Export by Small and Medium Enterprises in Hanoi

In the context of Vietnam's deep integration into the global trade network, the wood processing and export industry has become one of the key sectors contributing significantly to national export growth. Over the past decade, Vietnam has risen to become the world's fifth-largest wood exporter and the second-largest in Asia, after China. According to the Vietnam Timber and Forest Products Association (VIFOREST), the wood and wood products export turnover of Vietnam is estimated to reach over 16 billion USD in 2024, an increase of about 17% compared to 2023. This achievement reflects the strong recovery of the industry after the downturn caused by the COVID-19 pandemic and global economic fluctuations. However, alongside large enterprises with modern production capacity and technology, the majority of enterprises in the wood processing and export sector in Vietnam are small and medium-sized enterprises (SMEs), accounting for over 90% of the total number of enterprises in the industry. In the Hanoi area, SMEs play a dominant role in the wood production–processing–export network, especially in districts with a tradition of handicrafts and woodworking villages such as Thach That, Chuong My, Dong Anh, Gia Lam, Soc Son, and Hoai Duc.

The SMEs in the wood sector in Hanoi share common characteristics, including small capital size, limited production technology, low automation, and heavy reliance on manual labor. Despite these limitations, these enterprises are highly flexible and adaptable to market changes, especially in producing small order quantities with diverse designs to meet the needs

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of different markets. Thanks to their favorable geographical location—close to the economic center, major national highways, and export ports such as Hai Phong, Cai Mep–Thi Vai, and Cat Lai—these SMEs in Hanoi are in a better position compared to more remote areas in terms of accessing international markets and reducing transportation costs. However, this advantage has not been fully exploited due to the lack of an optimized logistics network, with routes, transportation methods, and distribution being organized in an ad hoc manner.

One of the major issues facing SMEs in wood exports in Hanoi is the high logistics and transportation costs. According to the Vietnam Logistics Business Association (VLA), Vietnam's average logistics cost currently accounts for about 16% of GDP, which is significantly higher than the global average of 10-12%. For small-scale wood enterprises, this percentage is even higher due to small shipment sizes, which prevent them from benefiting from economies of scale and leave them without bargaining power with international shipping companies. Renting vehicles for smaller shipments or through multiple intermediaries leads to increased logistics costs, significantly reducing the enterprises' net profits. Furthermore, the domestic product collection and distribution network is not well-planned, resulting in empty transport, overlapping routes, and increased costs and delivery times.

Another challenge lies in the raw material supply. The wood enterprises in Hanoi are not located near large raw material regions such as the Central Highlands, North Central, or Southeast regions. As a result, most of the raw materials must be imported from other provinces or abroad, increasing input costs. The volatility of raw wood prices, combined with rising domestic and international transportation costs, directly impacts the enterprises' ability to maintain their competitive advantage. Moreover, the increasingly strict requirements from import markets—especially the EU, US, and Japan—regarding the traceability of legally sourced wood, FSC certification, emission standards, and environmental responsibility also put significant pressure on SMEs, which typically have limited financial resources.

In addition to raw materials and logistics, limitations in management capacity and technology application are also significant barriers for SMEs in Hanoi's wood sector. Most enterprises still rely on experience-based management, with limited application of modern supply chain management tools such as ERP, SCM, or transportation optimization systems (TMS). This results in fragmented procurement, production, storage, and transportation activities, making it difficult to plan and control costs. Many enterprises still depend on intermediaries or export agents to access international markets, leading to profit sharing and loss of control over the value chain.

Regarding export markets, SMEs in Hanoi primarily focus on traditional markets such as Japan, South Korea, China, and the EU. Japan and South Korea are considered stable markets with low fluctuations, while the US and EU have higher demands for quality and traceability. For the Chinese market, despite its proximity and lower transportation costs, competition has become increasingly fierce due to the involvement of suppliers from Thailand, Malaysia, and Indonesia. This requires Vietnamese SMEs to restructure their transportation and

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distribution activities to ensure that products reach the market on time and at the most cost-effective prices.

From a policy perspective, Hanoi has issued various programs to support the development of small and medium-sized enterprises, including policies to encourage technological innovation and enhance supply chain management capacity. However, the actual effectiveness remains limited as most enterprises are unable to access preferential capital or lack the expertise to implement complex technical solutions. Additionally, logistics centers and bonded warehouses in Hanoi are not well-integrated with seaports, reducing the efficiency of export transportation.

From the above analysis, it is clear that SMEs involved in wood exports in Hanoi face both significant opportunities and challenges in the context of global competition and increasingly stringent international market demands. The prominent issues include high logistics costs, an inefficient transportation network, unstable raw material supply, and weak management capacity. These factors provide a foundation for recommending the application of the Mixed Integer Linear Programming (MILP) model to optimize the export wood transportation network, helping enterprises reduce costs, shorten delivery times, and improve competitiveness. This model has not only academic significance but also high practical value in building sustainable logistics strategies for SMEs in Hanoi and Vietnam as a whole.

SWOT Analysis of Small and Medium Enterprises in the Wood Export Industry in Hanoi

1. **Strengths**

Small and medium-sized enterprises (SMEs) in the wood export industry in Hanoi have several prominent advantages that help them sustain and develop in the face of growing international competition.

Firstly, the favorable geographical location is key. Hanoi is located in the central region of Northern Vietnam, with complete infrastructure connections to national highways, expressways, and proximity to large seaports such as Hai Phong, Cai Mep–Thi Vai, which helps reduce transportation time and export costs. Secondly, the long tradition of wood production in craft villages such as Thach That, Chang Son, Canh Nau, and Van Diem provides a solid foundation for craftsmanship, skills, and the ability to meet diverse order demands. Moreover, SMEs exhibit high flexibility in production management and business plan adjustments. Due to their small size, these enterprises can easily change product designs and types to meet market preferences. Additionally, labor costs in Hanoi, though increasing, remain lower compared to many countries in the region, providing a competitive price advantage. Many enterprises have begun applying digital technologies in design and production management (CAD/CAM, small-scale ERP), contributing to increased productivity and quality control.

2. **Weaknesses**

Despite many advantages, most SMEs in the wood industry in Hanoi still face significant internal limitations.

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Firstly, small capital size and limited production technology make it difficult to invest in modern production lines, wood drying systems, surface treatment, or energy-saving technologies. Many facilities still use semi-manual equipment, resulting in low productivity, inconsistent product quality, and high production costs. Secondly, supply chain management capacity is weak; most enterprises lack dedicated logistics departments or transportation optimization software systems. Procurement, storage, transportation, and export activities are still fragmented, lacking coordination, resulting in logistics costs accounting for a large proportion of product costs. Thirdly, international market access is limited. Many enterprises do not have their own brands and rely on subcontracting orders for large companies or foreign merchants. They also struggle to meet technical standards, traceability regulations, FSC certification, or the rules of origin of free trade agreements (FTAs).

Lastly, the lack of skilled labor is a persistent weakness. The workforce in the wood industry is mostly unskilled, with few engineers, managers, or logistics experts, limiting long-term strategic planning capabilities.

3. **Opportunities**

The context of international economic integration offers significant opportunities for SMEs in the wood industry in Hanoi.

First, global demand for wood and furniture products continues to rise steadily, especially in major markets such as the US, Japan, South Korea, and the EU. The global supply chain shift away from China after the pandemic has opened opportunities for Vietnam, including Hanoi-based enterprises, to become a key player in the wood and furniture supply chain. Furthermore, new-generation free trade agreements such as EVFTA, CPTPP, and RCEP facilitate export tax reduction, market expansion, and improvements in business management quality and production standards.

In terms of infrastructure, Hanoi's government is investing heavily in developing regional logistics through the planning of logistics centers in Gia Lam, Soc Son, and Phu Xuyen, directly connected to Hai Phong port and key industrial zones. This reduces transportation costs and enhances the supply chain efficiency for the wood industry. Moreover, digital transformation in logistics management and smart production offers an opportunity for SMEs to utilize optimization models such as MILP, IoT, and big data to make fast decisions, reduce costs, and improve efficiency.

4. **Threats**

Along with opportunities, SMEs in Hanoi must face several serious challenges. First, fluctuations in the international market due to trade conflicts, rising fuel prices, and fluctuating shipping costs make it difficult to control the product export price. Any small change in transportation costs directly impacts the profits of small enterprises. Second, increasing technical and trade barriers from major import markets. Requirements for legal certification, environmental standards, social responsibility, and carbon emissions force enterprises to invest additional compliance costs, while their financial capacity is limited.

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Third, increasing competition from countries with developed wood industries, such as China, Thailand, Malaysia, and Indonesia. These competitors not only have advanced technology but also closed supply chains, allowing them to maintain stable prices and faster delivery. Fourth, the risks from fluctuations in raw material supply due to export policies for round wood, sawn timber from supplying countries, as well as natural disasters, pandemics, and domestic forest protection regulations. This forces Hanoi-based enterprises to rely more on imported wood, increasing risks related to cost and delivery times.

Finally, the pressure of green transformation and sustainable development is also a long-term challenge. To meet the "low-carbon economy" trend, enterprises must invest in emission treatment technology, renewable energy, and eco-friendly materials, which exceeds the financial capabilities of many SMEs today.

SWOT analysis shows that SMEs in wood exports in Hanoi have a strong foundation in terms of production tradition, geographical location, and adaptability, but are limited by small scale, lack of capital, high logistics costs, and weak management capacity. Opportunities from economic integration and digital transformation can help enterprises improve their operational efficiency, but only if they leverage technology, innovate operational methods, and build optimized logistics networks.
In particular, applying the multi-objective transportation optimization model (MILP) is a practical direction that helps businesses identify a reasonable transportation network configuration between cost and time, reduce risks, and enhance sustainable competitiveness in the next phase.

3.2. Model Analysis Results

The input parameters of the model are presented in Table 1, which includes information about the number of production facilities, distribution centers, export ports, import markets, export demand, and operational constraints such as storage limits, transportation costs, and transportation time.

Table 1. Overview of Model Input Parameters

Component	**Value**
Production Facilities (PP)	12 facilities in the Hanoi area and surrounding provinces
Distribution Centers (DC)	5 distribution centers used by enterprises
Export Ports (EP)	2 main ports: Hai Phong, Cat Lai
Import Markets (IM)	4 key markets: Japan (m1), South Korea (m2), the United States (m3), EU (m4)
Export Demand	100 TEU (m1 = 30 TEU, m2 = 25 TEU, m3 = 25 TEU, m4 = 20 TEU)
Storage Time Limit	240 hours (10 days)
Cost Unit	1,000 VND
Time Unit	Hour

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Transportation Methods Applied	M1: PP → DC; M2: DC → EP; M3: EP → IM by sea route

Scenario 1 – Cost Optimization

In the scenario that prioritizes minimizing costs (with w1 = 1.0), the model determines the most efficient transportation plan for the entire shipment from production facilities (PP) to import markets (IM). The transportation routes are primarily determined through three directions: PP1 → DC2 → EP3 → m1, PP4 → DC1 → EP2 → m2, and PP6 → DC3 → EP1 → m3, corresponding to the transport chains with the lowest total costs.

The cost optimization results show that the model establishes a transportation network with a minimum total cost of 5.137 billion VND, while ensuring that the average transportation time remains under the permissible limit. The chosen routes have the characteristic of short distances, convenient infrastructure connections, and high container fill rates, helping to optimize costs per TEU.

Table 2. Cost Optimization Results by Transportation Route

oute	Cost (Million VND/TEU)	Demand (TEU)	Total Cost (Million VND)	Transportation Time (Hours)
PP1 → DC2 → EP3 → m1	51,2	30	1,536,000	72.5
PP4 → DC1 → EP2 → m2	49,85	25	1,246,250	68.3
PP6 → DC3 → EP1 → m3	52,4	25	1,310,000	70.1
PP3 → DC5 → EP2 → m4	52,3	20	1,046,000	74.0

Scenario 2 – Prioritizing Delivery Time

With the goal of minimizing transportation time in Scenario 2, the model selects the fastest transportation routes: PP1 → DC3 → EP2 → m1, PP2 → DC2 → EP3 → m2, and PP4 → DC1 → EP1 → m3/m4.

The primary modes of transportation used are large trucks and sea containers with frequent sailing schedules, which significantly reduce waiting times.

The results show that the average transportation time is reduced by approximately 18.4% compared to the cost optimization scenario, but the total system cost increases to 5.85 billion VND, which is 13.9% higher than the optimal cost in Scenario 1. The time optimization model achieves a significant reduction in total delivery duration, with the average time across the entire network reaching *t = 56.8 hours**.

Specifically, the average delivery times to the main import markets are as follows:

- Japan (*t1 = 49.3 hours**),

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- South Korea (*t2 = 54.4 hours**),
- The US and EU (*t3 = 66.9 hours**).

The detailed results are presented in Table 3 below.

Table 3. Time Optimization Results by Transportation Route

Transportation Route	**Cost (Million VND/TEU)**	**Demand (TEU)**	**Total Cost (Million VND)**	**Transportation Time (Hours)**
PP1 → DC3 → EP2 → m1	58,491	30	1,754,730	49.26
PP2 → DC2 → EP3 → m2	55,026	25	1,375,650	54.37
PP4 → DC1 → EP1 → m3, m4	58,481	45	2,619,645	66.94

Scenario 3: Multi-objective Optimization

The results from the weighted sum method indicate that as the cost weight w1w_1w1 gradually increases from 0 to 1, the total transportation cost decreases from 5.85 billion VND to 4.94 billion VND (a 15.5% reduction), while the average transportation time increases from 56.86 hours to 65.48 hours (a 15.2% increase). These results clearly reflect the trade-off relationship between cost and time, while also helping to identify the optimal weight value range for each strategic priority of the business.

Specifically, when the cost weight is low (w1<0.3w_1 < 0.3w1<0.3), the model prioritizes routes with shorter delivery times, suitable for orders that require high urgency. On the other hand, when the cost weight is high (w1>0.8w_1 > 0.8w1>0.8), the model prioritizes low-cost routes, typically passing through ports with cheaper loading and storage costs, even if the transportation time is longer.

Notably, within the weight range of w1=0.65w_1 = 0.65w1=0.65 to w1=0.75w_1 = 0.75w1=0.75, the composite index QQQ (deviation) achieves its smallest and most stable value, indicating a reasonable balance between cost and transportation time. This is the optimal multi-objective threshold, allowing the business to maintain economic efficiency while still ensuring an acceptable delivery speed for key export markets such as Japan, South Korea, and the EU.

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Table 4. Multi-objective Optimization Results by Cost Weight

Cost Weight (w_1)	Cost (1.000 VNĐ)	Δ Cost (%)	Time Weight (w_2)	Time (giờ)	Δ Time (%)	Q (Deviation)
0.00	5.850.271	18,38	1	56,86	0	0
0.10	5.663.260	14,6	0,9	57,82	1,69	0,0153
0.20	5.408.915	9,45	0,8	58,01	2,02	0,0189
0.30	5.221.904	5,67	0,7	58,97	3,71	0,026
0.40	5.221.904	5,67	0,6	58,97	3,71	0,0227
0.55	5.162.812	4,47	0,45	60,16	5,8	0,0261
0.65	5.138.480	3,98	0,35	61,04	7,35	0,0259
0.70	5.012.948	1,44	0,3	61,48	8,13	0,0203
0.75	5.012.948	1,44	0,25	61,48	8,13	0,0163
0.85	5.012.948	1,44	0,15	61,48	8,13	0,0122
0.95	4.968.708	0,54	0,05	62,97	10,75	0,0054
1.00	4.941.870	0	0	65,48	15,16	0

4. CONCLUSIONS AND RECOMMENDATIONS

4.1. Conclusions

This study applied the Mixed Integer Linear Programming (MILP) model to optimize the transportation network in the wood export operations of small and medium-sized enterprises (SMEs) in the Hanoi area. The simulation results show that the model can accurately reflect the trade-off relationship between the two main objectives: cost and transportation time, while also providing a logistics network configuration suitable for each specific business strategy.

Specifically:

- In the cost optimization scenario, the total transportation cost reached a minimum value of approximately 4.94 to 5.14 billion VND, reducing costs by 7–12% compared to the current network structure, while still ensuring transportation time remained within acceptable limits.
- In the time optimization scenario, the total transportation time reduced by an average of 18–20%, although costs increased by approximately 10–15%, clearly reflecting the trade-off between the two objectives.
- In the multi-objective optimization scenario, the weight range w1=0.6w_1 = 0.6w1=0.6 to w1=0.75w_1 = 0.75w1=0.75 for the composite index QQQ achieved the smallest and most stable value, indicating a reasonable balance between cost and time. This provides the basis for SMEs to choose a hybrid transportation structure—prioritizing cost on domestic routes and prioritizing time on international routes.

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The research results confirm that the MILP model can be effectively applied in practice, helping businesses:

- Reduce logistics costs and improve vehicle utilization efficiency.
- Improve transportation forecasting and planning capabilities.
- Support strategic decision-making in designing export distribution networks.

4.2. Recommendations

Based on the research results, the authors propose several recommendations:

1. **For Businesses:**

    - **Increase the application of mathematical optimization models** in logistics management, particularly MILP or multi-objective simulation models, to make data-driven decisions rather than relying on subjective experience.
    - Businesses should build an **internal transportation database**, including cost, time, and capacity for each transportation route, to support model updates and flexible adjustments when the market changes.
    - **Encourage collaboration between SMEs** to share warehouses, vehicles, and supply chain information, helping to reduce average logistics costs.

2. **For Government Authorities:**

    - **Enhance logistics support policies** for SMEs, especially in terms of access to multi-modal transportation infrastructure and digital optimization tools.
    - Promote **digital transformation** in logistics and exports, facilitating the application of data analysis tools, artificial intelligence, and optimization models in business management.
    - **Develop a regional logistics center** in Hanoi – Bac Ninh – Hai Phong, serving as a hub for collection, storage, and distribution of exported wood, reducing transportation distances and lowering costs.

3. **For Future Research:**

    - The model should be **expanded by incorporating supply chain risk factors** (such as fuel price volatility, port congestion, or changes in import regulations).
    - Propose testing a **dynamic MILP model** to simulate real-time transportation networks, improving the model's applicability in a rapidly changing market environment.

In summary, this study demonstrates the effectiveness of the Mixed Integer Linear Programming (MILP) method in optimizing the logistics network of small and medium-sized enterprises. The model not only supports strategic decision-making but also helps Vietnamese wood enterprises enhance their competitiveness and achieve sustainable development in the global export market.

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