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Research article

Solving Transshipment Problem in Glove Manufacturing Under the FSC Standard

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Abstract: This study proposes a mathematical transshipment model to optimize transportation in glove manufacturing by Forest Stewardship Council (FSC) standards. The objective is to minimize total transportation costs across a multi-tiered network comprising rubber farmers, small-scale intermediary traders, large-scale intermediary traders, a concentrated latex factory, and a rubber glove factory. Unlike conventional transshipment models, this approach explicitly distinguishes parallel product flows from FSC-certified and non-FSC-certified sources, reflecting segregation requirements mandated by FSC standards. This dual-flow structure introduces unique routing constraints and decision variables that are rarely addressed in the existing literature. The model incorporates real-world constraints related to supply availability, demand fulfillment, and transportation capacity, based on empirical data from a representative case study. The optimization problem was solved using LINGO software. The case study involved 250 farmers (125 non-FSC-certified and 125 FSC-certified), 125 small-scale intermediary traders, 6 large-scale intermediary traders, a concentrated latex factory, and a rubber glove factory producing approximately 50% FSC-certified and 50% non-FSC-certified gloves. This separation is critical for ensuring FSC compliance and achieving precise cost optimization. Before implementation, transportation costs totaled 82,228 baht per million gloves produced. Upon applying the model, costs decreased to 75,503.33 baht per million gloves, indicating a reduction of 6,724.67 baht or approximately 8.18%. These results affirm the effectiveness of mathematical modeling in reducing logistics costs within sustainable supply chains and offer a framework adaptable to other industries with similarly structured supply chains.

Keywords: Transshipment model; logistics cost reduction; transportation cost optimization; rubber glove manufacturing; mathematical model

1. Introduction

Thailand's rubber glove manufacturing industry is crucial in the global market, particularly during the COVID-19 pandemic, which significantly increased global demand for rubber gloves. As a result, Thailand became one of the leading producers and exporters of high-quality rubber gloves. However, despite Thailand's production capabilities, the process of transporting raw materials from production sources to factories is complex and faces several challenges, particularly high transportation costs. This is due to the multiple stages in the supply chain and the involvement of many stakeholders, ranging from farmers who grow rubber to small and large intermediaries, then to latex concentration factories, and finally to rubber glove manufacturing plants. These factors contribute to the high transportation costs, which affect the industry's competitiveness in the global market [1]. Additionally, the rubber glove manufacturing industry faces pressure to adhere to sustainable management standards, as requested by customers, such as the Forest Stewardship Council (FSC) standards.

The Forest Stewardship Council (FSC) standard represents an internationally recognized certification for sustainable forest management. Products bearing this certification must be produced in a manner that is environmentally, economically, and socially responsible. For example, rubber trees harvested during production must be replanted or allowed to regenerate naturally. Forest management under FSC guidelines requires careful consideration of environmental impacts, biodiversity, and the well-being of surrounding communities [2]. While compliance with FSC standards promotes sustainability, it also adds complexity to the supply chain due to the need for strict oversight and comprehensive control throughout both production and transportation processes. These requirements can lead to increased operational and logistics costs. Nevertheless, FSC-certified products often gain a competitive edge, with studies showing potential sales growth of over 4%. 66% of consumers express a willingness to support brands that demonstrate environmental commitment [3]. In 2020, the European Union (EU), Japan, and several other countries announced that they would cease importing wood, rubber, and derivative products unless sourced from FSC-certified plantations. This shift has elevated the importance of FSC compliance in industries such as rubber glove manufacturing. Although FSC-certified gloves are generally more expensive to produce than their conventional counterparts, global demand has surged to approximately 280 billion pieces annually. To remain competitive while adhering to FSC standards, manufacturers must adopt advanced technologies and decision-support tools to enhance the efficiency of their logistics operations. Among these tools, the LINGO optimization program has proven particularly effective for solving complex supply chain problems. Additionally, building a sustainable supply chain by FSC principles requires systematic planning and strategic optimization. Mathematical models play a crucial role in simulating complex supply chain networks and identifying cost-saving opportunities [4–7]. For instance, Mula et al. developed models for coordinating production and transportation across multi-stage supply chains, addressing both cost and capacity constraints [8]. In the agri-food sector, Ahumada and Villalobos demonstrated how mathematical programming can facilitate efficient resource allocation and strategic planning [9].

Lingo is a powerful software tool developed by LINDO Systems Inc. that is used to solve mathematical models that have already been developed. This program is designed to assist analysts and researchers in solving complex optimization problems, particularly those that require finding the best solution under specified constraints [10]. Several studies have confirmed Lingo's effectiveness in solving logistics network problems, especially in uncertain or complex environments, such as stochastic supply chain network planning [11], fresh food supply chain simulation [12], and milk run transportation optimization [13]. Lingo has been widely applied in both agricultural and industrial logistics research [16], providing precise and cost-efficient solutions for complex decision problems [10, 15, 18]. For example, the case study by F. M. Puspita et al. [14] focused on optimizing waste collection routes in the Kalidoni district of Palembang. The objective was to minimize both transportation distance and time by considering critical factors such as "time windows" and "deadlines." Waste was categorized into work zones, and the RC-OCVRPTWD model was solved using LINGO 13.0. Results showed that Work Area 1 had a distance of 28.6 km with a completion time of 2 hours and 51 minutes, Work Area 2 covered 23.6 km in 1 hour and 42 minutes, and Work Area 3 covered 38 km in 3 hours and 16 minutes. Dandi Nurdiansyah [15] also demonstrated Lingo's usefulness in optimizing egg delivery costs at AyamSehat.com in Cimahi. Initially, the North West Corner (NWC) method was used, resulting in a cost reduction from Rp. 278,000 to Rp. 255,000. Further optimization with LINGO reduced the cost to Rp. 240,000. This study highlights how combining heuristic methods, such as NWC, with mathematical tools, like LINGO, can significantly improve distribution efficiency. In a related study, E. Yuliza et al. [16] addressed the Capacitated Vehicle Routing Problem (CVRP) in the context of LPG gas distribution. They first applied the Clarke and Wright heuristic and then refined the solution using Lingo. The heuristic approach resulted in a total distance of 151.94 km, while Lingo yielded 161.59 km, suggesting that the heuristic method was more efficient for this particular case. This reinforces the value of hybrid approaches in routing optimization. Finally, D. Buakum and W. Wisittipanich [17] proposed a mixed-integer programming (MIP) model to solve internal task scheduling in a cross-docking terminal, inspired by operations at Thailand Post Distribution Co., Ltd. Their model, solved with LINGO 14.0, aimed to minimize makespan while managing limited resources such as working teams and transfer equipment. The results showed that while LINGO provided optimal solutions for small instances, larger problems posed computational challenges. The study's cost and sensitivity analysis confirmed the trade-off between resource usage and operational efficiency. Together, these studies confirm Lingo's reliability and flexibility in solving diverse logistics optimization problems from waste management and food distribution to cross-docking and industrial routing. These findings support the application of this approach in the current research to enhance cost efficiency within the FSC-certified rubber glove supply chain. While these studies collectively demonstrate the broad applicability and effectiveness of LINGO in solving various logistics optimization problems, they primarily address general transportation, routing, or scheduling challenges without explicitly incorporating sustainability certification requirements. Unlike prior models, the transshipment model proposed in this study directly integrates FSC Chain of Custody constraints by explicitly separating FSC-certified and non-certified latex flows through dedicated decision variables and independent supply-demand constraints. This structural distinction ensures compliance with rigorous FSC standards throughout all transportation stages, setting this work apart from conventional transshipment approaches that do not address certification-mandated segregation. As a result, the model contributes a novel framework for simultaneously optimizing logistics costs and sustainability compliance within certified supply chains.

In this study, the goal is to determine the most cost-effective transportation route from the rubber plantations to the rubber glove manufacturing factory, which involves multiple stakeholders, including 250 farmers, 125 small intermediaries, 6 large intermediaries, a latex production factory, and a rubber glove manufacturing plant. The supply chain includes both FSC-certified and non-FSC-certified raw materials, which adds complexity to the logistics process. Lingo software is used to solve the mathematical model that calculates transportation costs, addressing the Transshipment Problem, which involves intermediate distribution points in the supply chain. The objective is to reduce transportation costs under the FSC standard while optimizing the multi-stage supply chain. By applying the Lingo program, the study aims to identify the lowest-cost transportation methods while ensuring compliance with sustainability standards. Ultimately, this research seeks to enhance the competitiveness of Thailand's rubber glove manufacturing industry in the global market. Furthermore, to demonstrate the robustness and adaptability of the proposed model, this study also includes a sensitivity analysis on key parameters such as fuel prices and product demand levels. By simply modifying the input data used in the computations, the model can evaluate different economic scenarios and assess the impact of fluctuations in operational costs and market demand. This highlights the flexibility of the mathematical framework to accommodate diverse conditions, thereby reinforcing its practical value as a decision-support tool for sustainable and cost-efficient supply chain management under FSC standards.

2. Materials and Methods

To enhance the accuracy and effectiveness of transportation cost reduction in the rubber glove manufacturing industry, adhering to Forest Stewardship Council (FSC) standards, this study was designed using a mathematical modeling approach. The methodology involves collecting real-world supply chain data, constructing a transshipment model to simulate transportation flows, and applying the Lingo program to solve and optimize the model. The following sections describe the data collection process, model development, and solution approach.

2.1 Data Collection

This research aims to reduce transportation costs in the rubber glove manufacturing supply chain, adhering to Forest Stewardship Council (FSC) standards, by utilizing real-world data from a powder-free glove factory certified by FSC. The supply chain in this case study comprises 250 farmers, consisting of 125 non-FSC-certified farmers and 125 FSC-certified farmers, 125 small-scale intermediary traders, 6 large-scale intermediary traders, 1 concentrated latex factory, and 1 rubber glove factory. The key data used to develop the model includes

2.1.1 Transportation distances between supply chain points

2.1.2 Supply and demand quantities at each stage

2.1.3 Transportation capacity limits

2.1.4 Unit transportation costs

All data were collected through structured questionnaires and in-depth interviews with stakeholders across the supply chain, conducted between March and April 2023. An overview of the supply chain structure is illustrated in Figure 1.

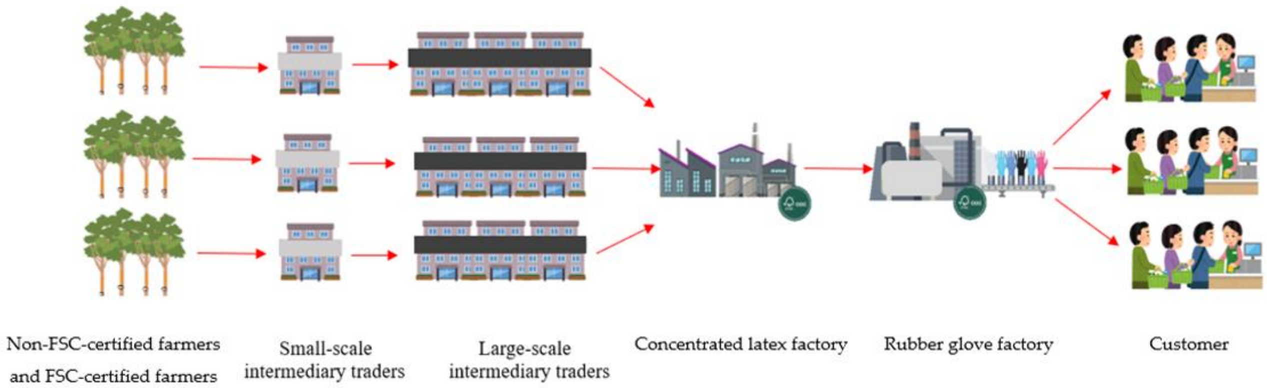

Figure 1. Rubber Glove Industry Supply Chain.

2.2 Transshipment Model Development

This research developed a transshipment model, a type of linear programming model, to identify the most cost-effective multi-stage transportation routes for latex in the supply chain. The model aims to minimize total transportation costs while adhering to the constraints of the FSC system, which includes environmental, social, and economic considerations.

2.2.1 Transportation Network Structure

The model is structured into five stages, reflecting the actual sequence of the supply chain

i : Non-FSC-certified farmers

i' : FSC-certified farmers

j : Small-scale intermediary traders

k : Large-scale intermediary traders

l : Concentrated latex factory

m : Rubber glove factory

2.2.2 Definition of constraints

The objective of the model is to minimize total transportation costs, subject to the following three key constraints

2.2.2.1 Supply constraints at the farmer level

2.2.2.2 Demand constraints at the rubber glove factory

2.2.2.3 Capacity constraints for each transportation route

To ensure compliance with FSC Chain of Custody (CoC) standards, the mathematical model explicitly separates the transportation flows of FSC-certified and non-FSC-certified latex. This segregation is enforced by using distinct decision variables and independent supply-demand constraints for each type of latex. As a result, the model prevents the mixing of FSC and non-FSC materials across all transportation and transshipment stages. This directly affects routing decisions by mandating dedicated transportation trips and transshipment handling for FSC latex, reflecting the operational requirements imposed by FSC certification.

Additionally, the model incorporates parameters such as the number of vehicles and their capacities, which are based on actual transportation data collected from the case study. Each vehicle type (n = 1, 2, 3, 4) corresponds to a specific transportation link in the supply chain, reflecting operational realities. For example, n=1 and n=2 represent trips from farmers to small-scale intermediary traders, n=3 covers transportation from small to large intermediaries, and n=4 handles movements from the latex factory to the glove factory. These parameters ensure that vehicle assignment and capacity constraints are realistically applied, directly influencing transportation planning and cost optimization within the FSC-certified supply chain.

Furthermore, by ensuring the strict segregation and traceability of FSC-certified latex throughout the supply chain, the model inherently upholds the social and environmental objectives of the FSC standard. This includes supporting fair practices for certified smallholder farmers and protecting ecosystems by maintaining the integrity of certified sourcing. The mathematical constraints thus do not merely enforce logistical separation but also safeguard the environmental stewardship and community welfare principles embedded in FSC certification.

2.2.3 Mathematical Model Formulation

The transshipment model was formulated using a linear programming approach.

Indices

i : Non-FSC-certified farmers
i' : FSC-certified farmers
j : Small-scale intermediary traders
k : Large-scale intermediary traders
l : Concentrated latex factory
m : Rubber glove factory

Parameters

c_{ij} : Transportation cost from non-FSC-certified farmers to small-scale intermediary traders (Baht per trip)
$c_{i'j}$: Transportation cost from FSC-certified farmer to small-scale intermediary traders (Baht per trip)
c_{jk} : Transportation cost from small-scale intermediary traders to large-scale intermediary traders (Baht per trip)
c_{kl} : Transportation cost from large-scale intermediary traders to concentrated latex factory (Baht per trip)
c_{lm} : Transportation cost from concentrated latex factory to rubber glove factory (Baht per trip)
s_i : Latex production capacity of non-FSC-certified farmer (kilograms per lot)
$s_{i'}$: Latex production capacity of FSC-certified farmer (kilograms per lot)
s_j : Latex receiving capacity of small-scale intermediary traders (kilograms per lot)
s_k : Latex receiving capacity of large-scale intermediary traders (kilograms per lot)
s_l : Latex receiving capacity of concentrated latex factory (kilograms per lot)
D_j : Latex demand of small-scale intermediary traders (kilograms per lot)
D_k : Latex demand of large-scale intermediary traders (kilograms per lot)
D_l : Latex demand of concentrated latex factory (kilograms per lot)
D_m : Latex demand of rubber glove factory (kilograms per lot)
$capa_{i'n}$: Transportation capacity of latex from FSC-certified farmer (kilograms per trip)
$capa_{in}$: Transportation capacity of latex from non-FSC-certified farmer (kilograms per trip)
$capa_{jn}$: Transportation capacity of latex from small-scale intermediary traders (kilograms per trip)
$capa_{kn}$: Transportation capacity of latex from large-scale intermediary traders (kilograms per trip)
$capa_{ln}$: Transportation capacity of latex from concentrated latex factory (kilograms per trip)
$dist_{i'j}$: Transportation distance from FSC-certified farmer to small-scale intermediary traders (kilometers)
$dist_{ij}$: Transportation distance from non-FSC-certified farmer to small-scale intermediary traders (kilometers)
$dist_{jk}$: Transportation distance from small-scale intermediary traders to large-scale intermediary traders (kilometers)
$dist_{kl}$: Transportation distance from large-scale intermediary traders to concentrated latex factory (kilometers)
$dist_{lm}$: Transportation distance from concentrated latex factor to rubber glove factory (kilometers)
$tran_n$: Transportation cost per kilometer for vehicle type n (Baht per kilometer)
n : Type of vehicle (n = 1,2,3,4)

Decision Variable

x_{ij} : Number of trips from non-FSC-certified farmers to small-scale intermediary traders (trips)
$x_{i'j}$: Number of trips from FSC-certified farmers to small-scale intermediary traders (trips)
x_{jk} : Number of trips from small-scale intermediary traders to large-scale intermediary traders (trips)
x_{kl} : Number of trips from large-scale intermediary traders to concentrated latex factory (trips)
x_{lm} : Number of trips from concentrated latex factory to rubber glove factory (trips)
$y_{i'j}$: Quantity of latex transported from FSC-certified farmers to small-scale intermediary traders (kilograms per lot)
y_{ij} : Quantity of latex transported from non-FSC-certified farmers to small-scale intermediary traders (kilograms per lot)
y_{jk} : Quantity of latex transported from small-scale intermediary traders to large-scale intermediary traders (kilograms per lot)
y_{kl} : Quantity of latex transported from large-scale intermediary traders to concentrated latex factory (kilograms per lot)
y_{lm} : Quantity of latex transported from concentrated latex factory to rubber glove factory (kilograms per lot)

The mathematical model formulated to solve this transportation optimization problem is as follows.

Objective function

$$\text{Min Cost} = \sum_i \sum_j c_{ij}\, x_{ij} + \sum_{i'} \sum_j c_{i'j}\, x_{i'j} + \sum_j \sum_k c_{jk} x_{jk} + \sum_k \sum_l c_{kl}\, x_{kl} + \sum_l \sum_m c_{lm}\, x_{lm} \quad (1)$$

Constraints

Supply Constraints: Ensure that the amount of latex transported does not exceed the supply capacity at each stage.

$\sum_j y_{i'j} \le s_{i'}$; $\forall_{i'}$ (1)
$\sum_j y_{ij} \le s_i$; $\forall_i$ (2)
$\sum_k y_{jk} \le s_j$; $\forall_j$ (3)
$\sum_l y_{kl} \le s_k$; $\forall_k$ (4)
$\sum_m y_{lm} \le s_l$; $\forall_l$ (5)

Demand Satisfaction: Ensure that the demand at each downstream node is met.

$\sum_{i'} y_{i'j} \ge D_j$; $\forall_j$ (6)
$\sum_i y_{ij} \ge D_j$; $\forall_j$ (7)
$\sum_j y_{jk} \ge D_k$; $\forall_k$ (8)
$\sum_k y_{kl} \ge D_l$; $\forall_l$ (9)
$\sum_l y_{lm} \ge D_m$; $\forall_m$ (10)

Capacity Constraints: Ensure that the transported amount is consistent with the transportation capacity.

$\sum_{i'} y_{i'j} \le capa_{i'n} x_{i'j}$; $\forall_j, n = 1,2$ (11)
$\sum_i y_{ij} \le capa_{in} x_{ij}$; $\forall_j, n = 1,2$ (12)
$\sum_j y_{jk} \le capa_{jn} x_{jk}$; $\forall_k, n = 3$ (13)
$\sum_k y_{kl} \le capa_{kn} x_{kl}$; $\forall_l, n = 4$ (14)
$\sum_l y_{lm} \le capa_{ln} x_{lm}$; $\forall_m, n = 4$ (15)

Cost Calculation: Used to determine transportation costs based on distance and vehicle type.

$c_{i'j} = dist_{i'j}\, tran_n$; $\forall_{i'j}$, $n = 1,2$ (16)
$c_{ij} = dist_{ij}\, tran_n$; $\forall_{ij}$, $n = 1,2$ (17)
$c_{jk} = dist_{jk}\, tran_n$; $\forall_{jk}$, $n = 3$ (18)
$c_{kl} = dist_{kl}\, tran_n$; $\forall_{kl}$, $n = 4$ (19)
$c_{lm} = dist_{lm}\, tran_n$; $\forall_{lm}$, $n = 4$ (20)

Balancing Constraints: Ensure flow continuity where no storage is allowed: inflow equals outflow at each intermediate node.

$\sum_i y_{ij} + \sum_{i'} y_{i'j} = \sum_k y_{jk} \quad ; \forall_j$ (21)

$\sum_j y_{jk} = \sum_l y_{kl} \quad ; \forall_k$ (22)

$\sum_k y_{kl} = \sum_m y_{lm} \quad ; \forall_l$ (23)

Negativity Constraints: Ensure that all decision variables are non-negative.

$x_{i'j}, x_{ij}, x_{jk}, x_{kl}, x_{lm} \geq 0 \quad ; \forall_{i'j,ij,jk,kl,lm}$ (24)

$c_{i'j}, c_{ij}, c_{jk}, c_{kl}, c_{lm} \geq 0 \quad ; \forall_{i'j,ij,jk,kl,lm}$ (25)

$s_{i'}, s_i, s_j, s_k, s_l \geq 0 \quad ; \forall_{i',i,j,k,l}$ (26)

$D_j, D_k, D_l, D_m \geq 0 \quad ; \forall_{j,k,l,m}$ (27)

$y_{i'j}, y_{ij}, y_{jk}, y_{kl}, y_{lm} \geq 0 \quad ; \forall_{i'j,ij,jk,kl,lm}$ (28)

$capa_{i'n}, capa_{in}, capa_{jn}, capa_{kn}{}' capa_{ln} \geq 0 \quad ; \forall_{i'n,in,jn,kn,ln}$ (29)

$dist_{i'n}, dist_{in}, dist_{jn}, dist_{kn}, dist_{ln} \geq 0 \quad ; \forall_{i'n,in,jn,kn,ln}$ (30)

$tran_n \geq 0 \quad ; \forall_n$ (31)

Assumption: All intermediary traders (both small-scale and large-scale), concentrated latex factories, and rubber glove factories are assumed to be able to accept latex from both non-FSC-certified and FSC-certified farmers.

2.3 Using the Lingo Program to Solve the Transshipment Model

After the transshipment model was developed, it was solved using the LINGO program, a mathematical optimization software suitable for solving linear and nonlinear programming problems. In this study, Lingo was applied to compute the most cost-effective transportation routes from farmers to the rubber glove factory by minimizing the total transportation cost. In this study, the model formulation was input into Lingo using a matrix representation of the transportation flow, with the variable denoting the quantity of latex transported from farmer Non FSC Standards i, through under FSC Standards i', small-scale intermediary traders j, large-scale intermediary traders k, concentrated latex factory l to the rubber glove factory m. The program computed the optimal routing that minimized transportation costs while satisfying all supply, demand, and capacity constraints. The optimization results obtained from Lingo were then compared to the actual transportation costs before model implementation. The comparison demonstrated the model's effectiveness in significantly reducing logistics costs while maintaining full FSC compliance across the entire supply chain. Finally, the assessment of Lingo's effectiveness in computing the most cost-efficient transportation routes highlighted its benefits in reducing logistics costs. Not only did it improve transportation efficiency, but it also supported sustainability goals within the FSC-certified rubber glove supply chain.

This study adapts the general multi-stage transshipment optimization frameworks previously applied in logistics and supply chain contexts, such as the cross-docking scheduling model formulated by Buakum and Wisittipanich [17]. While their work focused on optimizing internal task scheduling to minimize makespan under resource constraints, the current study extends such mathematical programming approaches by explicitly incorporating FSC Chain of Custody (CoC) requirements. The main contribution lies in enforcing the segregation of FSC-certified and non-certified latex flows through separate decision variables and constraints within the transshipment model, ensuring full compliance with sustainability certification standards—an aspect not addressed in the earlier models.

3. Results and Discussion

3.1 Supply Chain Characteristics from Collected Data

The supply chain for FSC-compliant rubber gloves consists of three main segments: upstream, midstream, and downstream. The upstream segment comprises smallholder latex farmers or farmer groups that grow rubber trees and tap latex by FSC principles. These farmers must be certified by an authorized organization and maintain traceability through an FSC license code. The midstream segment includes FSC-certified latex processing plants that purchase raw latex from upstream farmers. These facilities process raw latex into concentrated latex, strictly adhering to FSC Chain of Custody (CoC) standards. The entire process, from receiving and storage to transportation and processing, must meet the FSC criteria before the product is passed on to the downstream stage. In the downstream segment, FSC-certified rubber glove manufacturers receive the processed latex and produce gloves while maintaining full product traceability. These manufacturers are also required to obtain FSC CoC certification. The finished products are then packaged and labeled with the FSC logo to signify that they meet social and environmental responsibility standards. The gloves are subsequently distributed to customers worldwide, including hospitals, retailers, and wholesalers.

In this study, the actual supply chain data were collected from an FSC-certified powder-free rubber glove manufacturer in southern Thailand. The structure analyzed includes 250 farmers (a mix of FSC-certified and non-certified), 125 small-scale intermediary traders, 6 large-scale intermediary traders, 1 concentrated latex factory, and 1 rubber glove factory. These stakeholders encompass the entire spectrum of supply chain roles, ranging from raw material production to final product distribution.

Quantitative data were collected on transportation distances between nodes, the quantity of latex supplied and demanded at each node, vehicle capacity limitations, and unit transportation costs. These data inputs reflect the real operational constraints, enabling the formulation of a transshipment model that captures the actual complexity of logistics operations within the FSC-certified supply chain. Incorporating both certified and non-certified nodes reflects real-world practices, particularly in terms of supply integration and logistical efficiency. This multi-tier data collection approach ensures the mathematical model can simulate various cost-minimization scenarios under both economic and sustainability constraints.

3.2 Cost Optimization Results Using Lingo

In this study, a transshipment model was developed to minimize transportation costs across the FSC-certified glove manufacturing supply chain. The model comprises 250 rubber farmers, including 125 non-FSC-certified farmers and 125 FSC-certified farmers, 125 small-scale intermediary traders, 6 large-scale intermediary traders, one concentrated latex factory, and one rubber glove factory. It incorporates practical operational constraints, including supply-demand balancing, transportation capacity limits, and route distances. The model was solved using an exact optimization method via the LINGO Solver (version 21.0.37), which was executed on a system equipped with an Intel Core i7 processor. Figure 2 presents the optimized transportation flows of latex across the supply chain tiers, along with the associated transportation costs. Before optimization, the total cost of transporting latex to produce 1 million gloves was THB 82,228. After solving the model, the optimized cost was reduced to THB 75,503.33, achieving a total reduction of THB 6,724.67, or 8.18%. These results demonstrate the model's effectiveness in achieving cost efficiency while maintaining feasibility across a multi-tiered supply network.

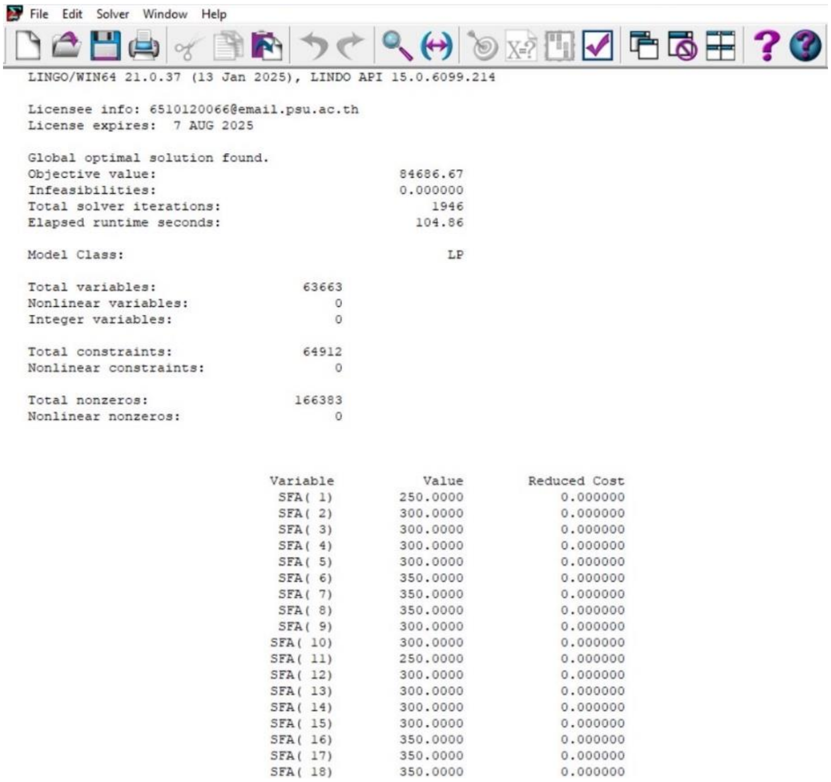

Figure 2. Transshipment Model Output via LINGO

To evaluate the accuracy and applicability of the model, the predicted transportation costs were compared with actual transportation costs from the case study, as shown in Table 1. The model's outputs closely aligned with real transportation expenditures, confirming the reliability of the proposed approach. Each dataset, structured according to the network size parameters (*i–i′–j–k–l–m*), successfully generated feasible solutions with accurate transportation quantities and minimized total costs.

Table 1. Preliminary Experimental Result by LINGO Optimization Solver.

No	Data set (*i–i′–j–k–l–m*)	Number of Transport Trips	Quantity of Transported Latex	Minimum Supply Chain Cost
1	2*2*2*2*1*1	✓	✓	✓
2	3*3*3*3*1*1	✓	✓	✓
3	4*4*4*4*1*1	✓	✓	✓
4	5*5*5*5*1*1	✓	✓	✓
5	6*6*6*6*1*1	✓	✓	✓
6	7*7*7*6*1*1	✓	✓	✓
7	8*8*8*6*1*1	✓	✓	✓
8	9*9*9*6*1*1	✓	✓	✓
9	10*10*10*6*1*1	✓	✓	✓
10	20*20*20*6*1*1	✓	✓	✓

Note: ✓ is correct solution by proposed model

Note: (*i–i′–j–k–l–m*)denotes the number of Non-FSC-certified farmers, FSC-certified farmers, Small-scale intermediary traders, Large-scale intermediary traders, Concentrated latex factory, and Rubber glove factory.

This table presents the results obtained from various network configurations, verifying the model's ability to handle different supply chain scales. As the complexity of the dataset increases, so too does the computational effort required to reach optimal solutions. Figure 3 illustrates the exponential growth in computation time as the number of supply chain nodes increases. While the model remains computationally feasible for small to medium-sized networks, the extended solution time for larger datasets may hinder its practical, real-time application in large-scale operations.

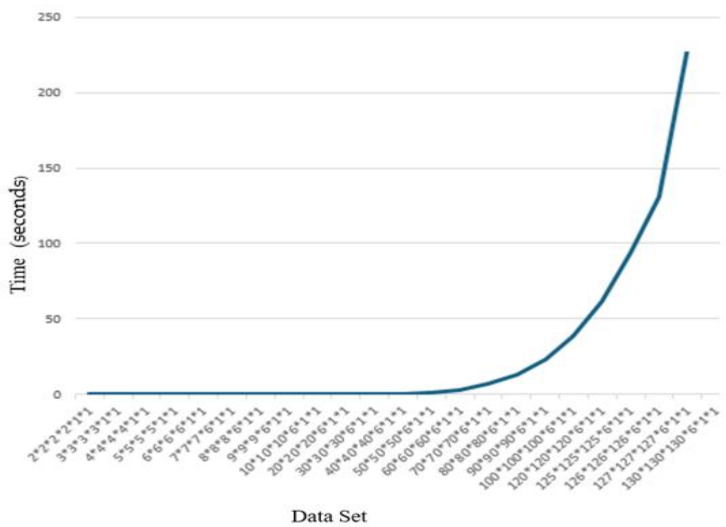

Figure 3. Relationship between dataset size and computation time

This performance trend highlights a fundamental trade-off between solution accuracy and computational efficiency. While exact methods, such as LINGO, are capable of delivering exact solutions, their scalability is inherently limited due to the exponential growth in processing time as the problem size increases.

3.3 Sensitivity Analysis on Fuel Prices and Demand Variations

A sensitivity analysis was conducted to assess the impact of changes in key economic parameters on total transportation costs. When fuel prices increased by 20%, the optimized transportation cost rose from THB 75,503.33 to THB 80,419. This represents a 6.5% increase, demonstrating that while costs are sensitive to fuel volatility, the model continues to provide cost-optimized routing compared to manual planning. Similarly, a 10% increase in demand (requiring additional latex volumes) resulted in a proportional rise in transportation cost to THB 83,053, reflecting the model's capacity to scale under varying operational scenarios. These findings reinforce the practical robustness of the model as a decision-support tool adaptable to different market and cost environments.

4. Conclusions

This study addressed the challenge of high transportation costs in the rubber glove manufacturing supply chain, adhering to Forest Stewardship Council (FSC) standards, by developing a mathematical transshipment model and solving it using the LINGO optimization program. The model was constructed based on real-world data from a certified powder-free glove factory, incorporating multiple stakeholders across five stages: from non-FSC and FSC-certified farmers to small-scale and large-scale intermediary traders, then to the concentrated latex factory, and finally to the rubber glove factory.

The model was solved using exact methods via the LINGO optimization software, which enabled the identification of the most cost-efficient transportation routes while satisfying various real-world constraints, including supply availability, factory demand, and vehicle capacity limits. LINGO's ability to process large-scale linear programming models with multiple variables and constraints proved essential to the successful resolution of the complex transshipment network. The results indicate a significant reduction in total transportation costs from THB 82,228 to THB 75,503.33 per one million gloves produced, representing an 8.18% improvement in logistics efficiency. Additionally, sensitivity analysis on key parameters such as fuel prices and demand levels demonstrated that while total logistics costs adjust under different scenarios, the model continues to deliver cost-optimized solutions, underscoring its robustness and practical applicability in real-world operations. This outcome demonstrates the effectiveness of the mathematical model and LINGO in identifying optimal transportation pathways in a constrained and sustainability-focused logistics environment. Beyond the numerical optimization, this study highlights the critical role of quantitative modeling in aligning supply chain efficiency with environmental certification standards. The inclusion of FSC-related parameters such as traceability, chain-of-custody compliance, and differentiated treatment of certified and non-certified farmers ensures that the model aligns not only with cost-saving goals but also with social and environmental imperatives. The proposed model thus reinforces the viability of integrating sustainability constraints within a formalized mathematical framework, making it especially relevant in today's global market, where eco-certification is both a regulatory requirement and a competitive differentiator. In practical terms, the findings provide a decision-support tool for logistics planners, supply chain analysts, and policymakers in the agro-industrial sector. The methodology developed in this research is replicable and can be adapted to other sectors that involve multi-stage production and distribution systems with sustainability requirements. For instance, agricultural cooperatives, bio-based chemical farmers, and eco-labeled consumer product manufacturers could all benefit from a similar optimization framework.

To address this limitation, future research should explore hybrid optimization strategies that integrate exact algorithms with heuristic or metaheuristic approaches. These methods offer a promising path forward, enabling improved scalability and faster response times without sacrificing the level of accuracy required in FSC-certified logistics systems where transparency, traceability, and cost control are critical. Moreover, the study's findings emphasize the strategic value of optimization-based tools in supporting sustainable logistics planning within certified supply chains. In the context of FSC-certified glove manufacturing, achieving transportation cost efficiency must be accompanied by adherence to environmental and ethical standards. The proposed transshipment model not only demonstrates substantial cost-saving potential but also respects the structural complexity and rigorous traceability requirements imposed by the FSC system. As supply chains become increasingly dynamic and multi-tiered, the integration of advanced decision support systems, such as the LINGO-based transshipment model, will be essential. With further enhancement, particularly through hybrid algorithmic techniques, this modeling framework holds promise as a scalable and adaptable solution for a wide range of industries seeking to balance sustainability, operational efficiency, and compliance.

Moreover, the study offers a platform for future research that could include dynamic or stochastic modeling approaches to address demand variability, seasonal fluctuations in latex production, and changes in fuel prices or transportation availability. Multi-objective optimization could also be introduced to balance cost reduction with carbon footprint minimization. Additionally, integrating geospatial data with the LINGO model could enable real-time route adjustments and enhance the practical implementation. In conclusion, this research not only validates the use of LINGO as a robust optimization tool but also contributes a novel transshipment modeling approach tailored for FSC-certified supply chains. It provides empirical evidence and practical guidelines for improving cost efficiency while adhering to international sustainability standards. As such, it stands as a valuable contribution to both academic literature and the operational management of sustainable supply chains. Looking forward, the adoption of such optimization-driven frameworks could be instrumental in shaping policy decisions around green logistics and sustainable certification systems. Governments and international organizations could leverage similar models to establish guidelines that encourage eco-compliance while promoting economic viability. In a global landscape increasingly shaped by climate targets and responsible sourcing, the integration of mathematically rigorous, sustainability-aware tools represents not only an operational necessity but also a strategic advantage. Therefore, the continued advancement and application of transshipment models such as the one presented in this study will play a crucial role in supporting resilient, transparent, and cost-effective supply chains of the future.

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