

A Multi-Period MILP Model for Multi-Origin, Multi-Echelon CPO Distribution: A Case Study of PTPN IV–PT INL

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Abstract

Efficient crude palm oil (CPO) distribution is essential for maintaining the competitiveness of vertically integrated palm oil industries. This study addresses a multi-origin, multi-echelon CPO distribution problem involving 37 internal palm oil mills, external suppliers, dual operational hubs, and refinery capacity constraints at PT Industri Nabati Lestari (INL). A multi-period Mixed Integer Linear Programming (MILP) model is developed within a Minimum Cost Flow (MCF) framework to optimize CPO allocation to INL and Belawan Port. The model incorporates daily production data over a one-year horizon, refinery throughput limits, inventory carry-over, binary operational decisions, and transportation costs. The model was solved using the HiGHS solver with a Branch-and-Cut algorithm across nine refinery-throughput scenarios ranging from 1,800 to 4,500 tons/day (40%–100% utilization), comprising 108 monthly sub-problems. All sub-problems reached true optimality with a final MIP gap of 0.00%, with an average runtime of approximately one minute per sub-problem. Under the representative $Q = 1,800$ tons/day scenario, which most closely reflects the company's 2025 operating conditions, the optimized annual logistics cost was Rp335.46 billion, with a unit transportation cost of Rp129.78/kg, compared with the historical cost of Rp162.58/kg, representing a reduction of Rp32.80/kg or 20.2%. At $Q = 4,500$ tons/day, the annual transportation cost decreased to Rp308.49 billion. The results demonstrate that prioritizing low-cost internal suppliers while using external suppliers to compensate for seasonal shortages can reduce transportation costs. The proposed framework provides decision support for supply allocation, inventory planning, transportation management, and refinery capacity utilization in large-scale palm oil supply chains.

KEYWORDS

crude palm oil; mixed integer linear programming; multi-origin distribution; multi-echelon network; minimum cost flow; supply chain optimization.

Introduction

Crude Palm Oil (CPO) is one of the world's most important agricultural commodities and serves as the primary raw material for numerous downstream products, including cooking oil, oleochemicals, cosmetics, pharmaceuticals, and biofuels. As the world's largest producer and exporter of palm oil, Indonesia plays a strategic role in the global vegetable oil market. The competitiveness of Indonesia's palm oil industry depends not only on plantation productivity but also on the efficiency of logistics and distribution systems that connect upstream production facilities with downstream processing industries. Inefficient transportation planning, unbalanced allocation of raw materials, and suboptimal utilization of processing facilities may significantly increase logistics costs and reduce the competitiveness of vertically integrated palm oil companies (Taha, 2017). Beyond direct cost implications, inefficient

logistics planning also undermines broader sustainable supply chain management objectives that increasingly shape agro-industrial competitiveness (Ahi & Searcy, 2013).

In vertically integrated palm oil industries, CPO distribution is considerably more complex than conventional transportation problems because multiple production facilities simultaneously supply several downstream destinations with different operational functions. In practice, distribution decisions must simultaneously consider production capacity at each palm oil mill, refinery throughput limitations, transportation costs, inventory availability, and fluctuating daily production volumes. Consequently, determining the optimal allocation of CPO shipments becomes a large-scale network optimization problem involving multiple origins, multiple destinations, and operational constraints that vary over time (Sitek & Stefański, 2017).

PT Perkebunan Nusantara IV (PTPN IV), one of Indonesia's largest state-owned palm oil companies, operates dozens of internal palm oil mills (PKS) distributed across North Sumatra. These mills continuously produce CPO, which is transported either to PT Industri Nabati Lestari (PT INL) for further refining or directly to Belawan Port for export and external distribution. Besides internal production, PT INL may procure additional CPO from external suppliers whenever internal production cannot satisfy refinery demand. Consequently, managers must determine daily distribution decisions that minimize transportation costs while satisfying refinery processing capacity, maintaining sufficient inventory, and ensuring continuous production. Because production volumes fluctuate throughout the year due to seasonal harvesting patterns, distribution planning based on average monthly production often fails to represent actual operational conditions. This challenge is consistent with broader findings on Indonesian palm oil logistics, which show that geographically dispersed mills, variable feedstock availability, and infrastructure constraints substantially affect the efficiency of CPO supply chains (Harahap et al., 2019; Widayat et al., 2024; Widodo et al., 2010).

Optimization techniques based on Linear Programming (LP) and Mixed Integer Linear Programming (MILP) have been widely applied to logistics and supply chain management because of their ability to generate globally optimal solutions under complex operational constraints. This body of work can be grouped into three methodological threads, each of which addresses a different aspect of the distribution problem while leaving a specific gap relevant to vertically integrated palm oil logistics. The first thread applies MILP primarily to strategic-level decisions, such as facility location, processing capacity, and transportation mode selection within palm oil supply chains (Andrianto et al., 2025; Lilis et al., 2023; Peña González et al., 2021) however, these formulations generally treat the distribution network as a static, single-period structure rather than as a recurring operational allocation problem. The second thread, comprising multi-echelon distribution models, shows that coordinating material flows across multiple facilities can meaningfully improve logistics efficiency (Hadi et al., 2025; Pramestari & Djatna, 2024; Rafiei et al., 2018), but is formulated around conventional serial supply chains-suppliers, warehouses, and retailers-that do not reflect the dual-hub, vertically integrated structure examined in this study. The third thread applies Minimum Cost Flow (MCF) formulations to minimize logistics costs subject to supply-demand balance constraints (Ahuja et al., 1993; Setiadi, 2025; Sitek & Stefański, 2017), but typically does so under simplified, single-origin network topologies rather than the multi-origin, multi-echelon configuration of an integrated palm oil producer.

Taken together, this literature provides valuable methodological foundations but leaves several limitations

unresolved. Most previous studies primarily investigate upstream supply chains involving Fresh Fruit Bunches (FFB) and crude palm oil production, or focus on strategic network design and supplier selection rather than operational distribution planning. Existing transportation models generally assume single-period planning with constant supply conditions and rarely incorporate dynamic production variability over time. Furthermore, previous studies typically model conventional serial multi-echelon supply chains consisting of suppliers, warehouses, and retailers, whereas vertically integrated palm oil industries operate more complex distribution structures involving multiple production origins, refinery processing facilities, and export hubs with distinct operational roles. Consequently, the integration of multi-origin supply, dual operational hubs, refinery processing constraints, and inventory continuity within a unified optimization framework has received limited attention in the existing literature (Lucia Diawati, 2025; Saputri et al., 2019). Related studies on Indonesian CPO logistics have similarly concentrated on single-route transportation optimization or downstream emissions accounting rather than integrated multi-origin, multi-echelon planning (El Hathat et al., 2023; Pramestari & Djatna, 2024). More recently, stochastic and multi-objective formulations have been proposed to address demand and parameter uncertainty in palm oil and related agro-industrial supply chains (Kohansal et al., 2023; Peter John & Mishra, 2026), as well as to balance multiple competing objectives in large-scale distribution network design under uncertainty (Bhowmik & Parvez, 2024; Liu et al., 2020). However, these studies do not jointly address the specific combination of multi-origin supply, dual-hub distribution, and refinery capacity constraints under real daily operational data investigated in this study, indicating that a deterministic, single-objective formulation remains an appropriate and tractable starting point for this operational context.

Another important limitation concerns the temporal dimension of distribution planning. Daily CPO production in palm oil mills varies considerably throughout the year due to harvesting seasons, weather conditions, and operational interruptions. Single-period optimization models using average production values cannot adequately capture these temporal dynamics, potentially resulting in suboptimal allocation decisions. Multi-period optimization models, on the other hand, enable inventory carry-over, dynamic capacity utilization, and more realistic operational planning by explicitly considering inter-period relationships (Sitek & Stefański, 2017).

To address these research gaps, this study proposes a multi-period Mixed Integer Linear Programming (MILP) model formulated within a Minimum Cost Flow (MCF) framework for optimizing CPO distribution in a vertically integrated palm oil supply chain. The proposed model simultaneously determines the optimal allocation of CPO from 37 internal palm oil mills and external suppliers to PT Industri Nabati Lestari (PT INL) and Belawan Port while minimizing total transportation costs under refinery throughput limitations, inventory balance, and operational constraints. Unlike previous studies, this research utilizes daily operational data covering one year of production activities, allowing the model to capture seasonal production variability and dynamic inventory behavior. The previous studies such as Application of the Mixed-Integer Linear Programming (MILP) Method to Minimize Distribution Costs of NPK Fertilizer (Wicaksono et al., 2024), A Mixed-Integer Linear Programming Model for the Rice Supply Chain in Karawang Regency to Minimize Costs (Mansur et al., 2025), Optimization of Power Plant Operational Planning Based on Mixed-Integer Linear Programming (MILP) in Selayar's Isolated System (Ardiansyah & Wati, 2026) which can be seen in Table 1.

Relative to these benchmark studies, the specific elements of the proposed formulation that are genuinely new are: (i) the

Table 1. Comparison of Manuscript's Novelty

Reference	Novelty Points
(Wicaksono et al., 2024)	Applies MILP-based CVRPTW specifically to address customer service time window constraints in fertilizer manufacturing delivery.
(Mansur et al., 2025)	Combines a multi-echelon MILP supply chain model with the HIRA / RPN risk assessment framework for agricultural commodities.
(Ardiansyah & Wati, 2026)	Optimizes unit commitment scheduling for isolated hybrid microgrids (Diesel-PV) under a 15% spinning reserve constraint.
(Peña González et al., 2021)	Formulates a strategic-level MILP for oil palm supply chain network design, incorporating facility location, processing capacity, and transportation mode decisions; however, the model is single-period and does not represent daily operational allocation, dual-hub routing, or inventory carry-over.
(Sidki et al., 2026)	Develops a real-world, multi-period MILP model integrating production scheduling, pipeline distribution, and multiproduct inventory management in a mining supply chain; however, the network considers a single production-to-terminal structure rather than multi-origin sourcing, dual export hubs, or external procurement integration.
Author's Research	Simultaneously models CPO flows from 37 internal mills and external procurement options toward two primary operational hubs (Refinery and Export Port). Overcomes the limitations of static single-period models by leveraging 1-year actual daily production data to capture seasonal harvest variability and inter-period inventory accumulation. Directly links transportation routing decisions with refinery throughput analysis to identify system bottlenecks and establish adaptive internal supply prioritization.

joint multi-origin-to-dual-hub routing structure, in which each internal mill is assigned to a fixed port destination while simultaneously retaining an independent routing option to the refinery (Equations 4-7); (ii) the daily adaptive refinery demand target, which sets refinery intake equal to the minimum of a fixed capacity and the total available system-wide supply on each day rather than a rigid fixed demand (Equation 9); (iii) the port-level inventory carry-over mechanism linking each day's ending inventory to the next day's opening inventory across a full annual horizon (Equation 10); and (iv) the adaptive minimum-batch vessel shipment constraint, which ties the minimum shipment volume to the lesser of a fixed batch size and the estimated realized inflow (Equation 12). None of the benchmark studies in Table 1 combine these four elements within a single multi-period, multi-origin, dual-hub formulation solved against a full year of real daily operational data

The primary contribution of this research is threefold. First, it develops a multi-origin, multi-echelon, dual-hub optimization model that more accurately represents real operational conditions in the palm oil industry. Second, it integrates refinery processing capacity, inventory continuity, and external procurement decisions into a unified multi-period optimization framework. Third, the proposed model provides a practical decision-support tool that can assist logistics managers in improving transportation planning, refinery utilization, and strategic supply allocation while minimizing overall logistics costs. Beyond its practical application, this study also extends the literature on network flow optimization by demonstrating how Minimum Cost Flow concepts can be expanded into a space-time network using Mixed Integer Linear Programming for large-scale industrial logistics systems.

Methods

Research Design

This study employed a quantitative optimization approach using Mixed Integer Linear Programming (MILP) to determine the optimal allocation of crude palm oil (CPO) distribution within a vertically integrated palm oil supply chain. The optimization model was formulated as a multi-period Minimum Cost Flow (MCF) network that simultaneously considers multiple production origins, dual operational hubs, refinery processing capacity, inventory continuity, and external procurement decisions. The objective is to minimize

the total logistics cost while satisfying all operational constraints.

The mathematical model was developed based on the actual operational network of PT Perkebunan Nusantara IV (PTPN IV), which consists of 37 internal palm oil mills, external CPO suppliers, PT Industri Nabati Lestari (PT INL) refinery, and Belawan Port. Historical daily production and transportation data covering one operational year were used as model input. The optimization problem was solved using the HiGHS solver (version 1.8.1) through the Pyomo modelling framework (version 6.8.3, the latest stable release available at the time of model development), accessed via the appsi_highs persistent solver interface (highspy backend), applying a Branch-and-Cut algorithm for Mixed Integer Linear Programming problems(Hall, 2020; Huangfu & Hall, 2018; Taha, 2017). All solver options were left at their HiGHS default values: automatic (enabled) presolve, no explicit time limit imposed (solver default: unbounded), and the default relative MIP-gap tolerance (mip_rel_gap = 0.0001, i.e., 0.01%). For the representative scenario reported in this study (Q = 1,800 tons/day), all 12 monthly sub-problems terminated with solver status "optimal," meaning the final incumbent objective value was equal to the best proven lower bound in every sub-problem, yielding a final optimality gap of 0.00% (well within the 0.01% default tolerance); the annual total across the 12 sub-problems for this scenario was Rp335,460,695,244. The model was implemented in Python (developed in Visual Studio Code 1.126), together with the pandas, numpy, matplotlib, folium, openpyxl, calendar, and dataclasses libraries for data processing, computation, and visualization. Each monthly sub-problem contained approximately 48,240 decision variables and 11 groups of constraints, and was solved sequentially across 9 throughput scenarios and 12 months (108 sub-problems in total), all of which reached optimal status under the same default settings and gap tolerance described above. All computations were performed on a Lenovo ThinkBook 14s Yoga laptop with 16 GB of RAM, with an average running time of approximately 1 minute per sub-problem.

Daily input data were processed as follows. A complete calendar covering 1 January to 31 December 2025 was first generated; dates that did not appear at all in the production records were categorized as national holidays, on which all flows in the network - including shipments to PT INL - were set to zero. For dates present in the calendar but not reported by a given mill, that mill's production was treated as zero for that day. This procedure identified 359 operating days and 6

PTPN IV CPO Distribution Network

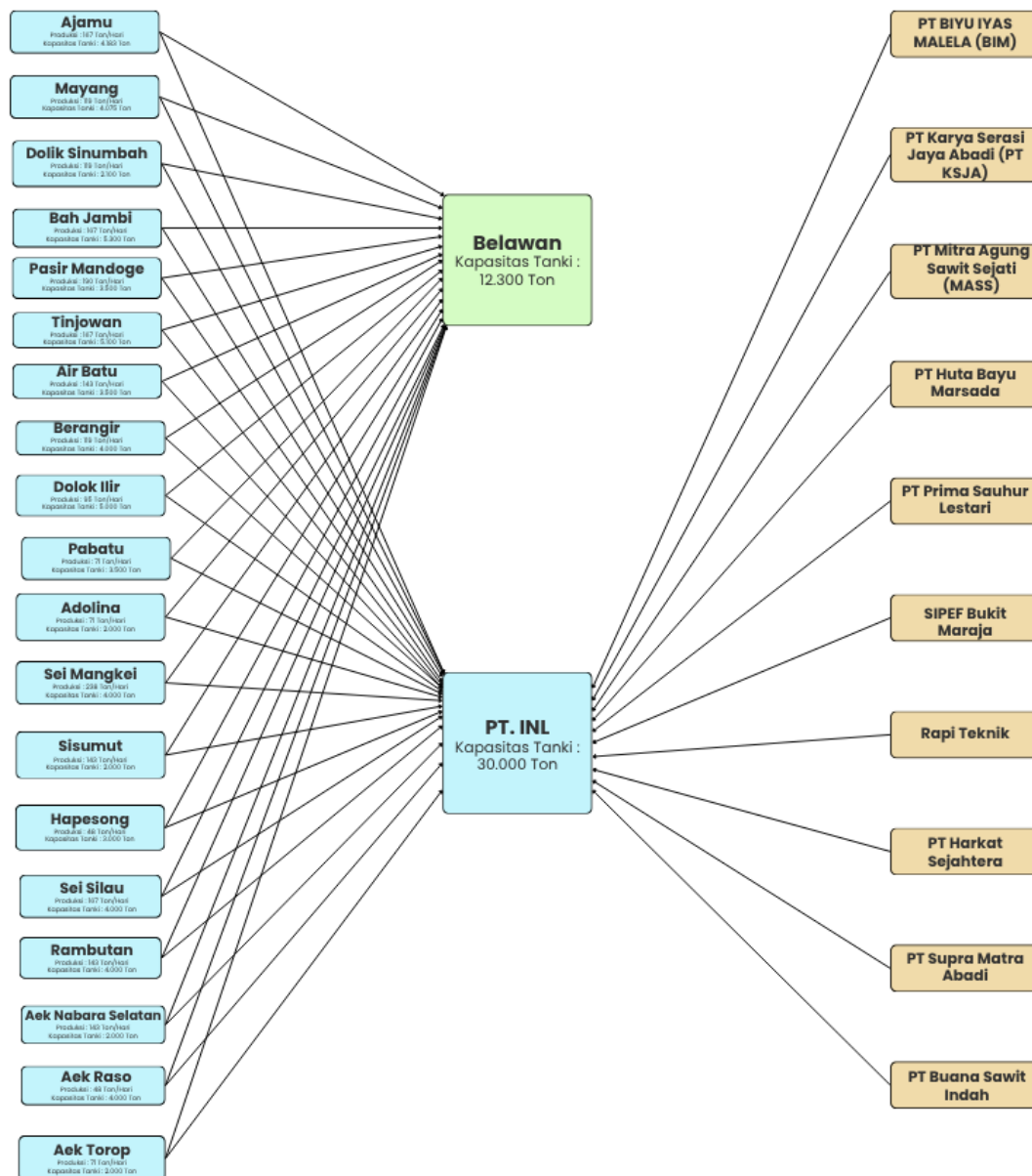


Figure 1. Multi-Origin Multi-Echelon Dual-Hub Distribution Network

holidays within the one-year planning horizon. Initial inventory at PT INL was set to zero for January, reflecting the conservative assumption that no CPO stock was carried over from the previous year; for all subsequent months, the initial inventory was set equal to the ending inventory of the preceding month through an inventory carry-over mechanism.

Problem Description

The distribution network investigated in this study consists of three major components: supply nodes, intermediate processing facilities, and final distribution hubs. Internal palm oil mills continuously produce CPO with varying production capacities throughout the year. Additional CPO may also be procured from external suppliers whenever refinery demand exceeds internal production.

All available CPO must be optimally allocated either to PT Industri Nabati Lestari (PT INL) for further refining or directly to Belawan Port for shipment. PT INL possesses limited daily

processing capacity, whereas Belawan Port mainly functions as a logistics hub for export and downstream distribution. Consequently, allocation decisions must simultaneously satisfy refinery capacity limitations, inventory balance, transportation cost differences, and production variability over multiple planning periods.

Unlike conventional transportation problems that assume constant supply and demand, this study explicitly incorporates temporal dynamics through a multi-period optimization framework (Figure 1). Inventory remaining from one period is carried over to the subsequent period, enabling the model to capture realistic operational conditions.

Model Assumptions

The proposed optimization model was developed under the following assumptions:

1. The transportation cost for each origin–destination route remains constant throughout the planning horizon.

- Daily production at each palm oil mill follows historical operational records.
- Refinery throughput capacity is predetermined for each planning period.
- Transportation lead time is negligible within one planning period.
- Product quality remains unchanged during transportation and storage.
- Inventory is allowed only at PT INL.
- External suppliers possess sufficient production capacity whenever procurement is required.
- Shortage and backorder are not permitted.
- Decision variables are non-negative, while operational activation variables are binary.

These assumptions are supported by both field observations and standard practice in deterministic MILP-based supply chain planning. The constant-tariff assumption reflects that transportation tariffs in the study network are set through periodic (e.g., quarterly) contracts rather than daily spot pricing, consistent with common practice in deterministic transportation planning models (Taha, 2017). The negligible lead-time assumption is reasonable given that the origin-destination distances in the PTPN IV network are covered within a single operational day, so that shipments dispatched on day t are consistently received within the same planning period. The assumption of unconstrained external supplier capacity reflects that, in practice, external suppliers are only activated as marginal sources once lower-cost internal capacity is exhausted, so their practical capacity ceiling is rarely binding within the observed operational range. Finally, restricting inventory accumulation to PT INL reflects the actual physical layout of the network, in which port facilities function as shipment-consolidation buffers rather than long-term storage points.

Mathematical Formulation

The sets, the parameter, and the decision variables are determined as follows.

Indices

i	Set of palm oil mills $i \in I$
p	Set of destinations $p \in P$
j	Set of external suppliers $j \in J$
t	Set of planning periods $t \in T$
NO_{INL_ROUTE}	Set of palm oil mills with no transportation route to INL

Parameter

c_{iN}	Cost of CPO transported from POM i to INL
c_{ip}	Cost of CPO transported from POM i to Port p
c_j	Cost of CPO transported from external supplier j
s_{ti}	Maximum CPO supply available at POM i on day t
$port_i$	The designated port destination for POM i
T_j	Maximum capacity of external supplier j
Q	Daily fixed demand target of INL
s_{maxt}	Maximum total adaptive supply available from all sources on day t
$inflow_{tp}$	Total CPO entering port p on day t
inv_{MAXp}	Maximum CPO inventory capacity at port p
$B_{min,p}$	Minimum CPO shipment batch required for a vessel at port p

$E(inflow_p)$ Estimated total CPO inflow entering port p over the planning period

Decision Variable

x_{tiN}	Amount of CPO from POM i to INL on day t
x_{tip}	Amount of CPO from POM i to Port p on day t
y_{tj}	Amount of CPO from external supplier j to INL on day t
z_{it}	1 if POM i operates on day t ; 0 otherwise
inv_{tp}	CPO inventory at port p at the end of day t
$ship_{tp}$	Volume of CPO shipped from port p on day t

Objective Function

$$\begin{aligned} \text{Min } Z = & \sum_{t \in T} \sum_{i \in I} c_{iN} \times x_{tiN} \times 1000 \\ & + \sum_{t \in T} \sum_{i \in I} \sum_{p \in P} c_{ip} \times x_{tip} \\ & \times 1000 \\ & + \sum_{t \in T} \sum_{j \in J} c_j \times y_{tj} \times 1000 \end{aligned} \quad (1)$$

A conversion factor of 1,000 is used in the objective function because the variables are measured in tons, whereas the cost is expressed in Rp/kg

Subject to

Supply flow upper bound and flow lower bound (linearization of z)

$$x_{tiN} + \sum_{p \in P} x_{tip} \leq s_{ti}, \quad \forall i, t \quad (2)$$

POM binary status

$$z_{it} = 0 \text{ if } s_{ti} = 0, \quad \forall i, t \quad (3)$$

Port routing per POM

$$x_{tip} = 0 \text{ if } port(i) \neq p \quad (4)$$

POMs without routes to INL

$$x_{tiN} = 0, \quad \forall i \in NO_{INL_ROUTE} \quad (5)$$

Sei Mangkei mandatory to INL (port restriction)

$$x_{tip} = 0, \quad \forall p, t \text{ if } i = \text{Sei Mangkei} \quad (6)$$

Sei Mangkei mandatory to INL (total production)

$$x_{tiN} = s_{ti}, \quad \forall t \text{ if } i = \text{Sei Mangkei} \quad (7)$$

External supplier capacity

$$y_{tj} \leq T_j, \quad \forall j, t \quad (8)$$

INL demand (equality, daily adaptive)

The model represents a Daily Adaptive Demand Target, not a strict or rigid demand constraint

$$\sum_i x_{tiN} + \sum_j y_{jt} = \min(Q, s_{maxt}) \quad \forall t \quad (9)$$

Port inventory balance

$$inv_{tp} = inv_{t-1p} + inflow_{tp} - ship_{tp} \quad (10)$$

Port inventory capacity bound

$$inv_{pt} \leq inc_{MAXp}, \quad \forall p, t \quad (11)$$

Minimum vessel batch per month (adaptive)

$$\left(\sum_{t \in T} ship_{tp} \right) \geq \min(B_{min,p}, E(inflow_p)) \quad (12)$$

Vessel shipment feasibility

$$ship_{tp} \leq inv_{t-1p} + inflow_{tp}, \quad \forall p, t \quad (13)$$

The min operator does not cause non-linearity because its parameters are calculated prior to optimization (pre-computed constants).

Solution Procedure

The proposed MILP model was implemented in Python and solved using the HiGHS optimization solver through the Branch-and-Cut algorithm, an exact solution approach that combines cutting-plane generation with branch-and-bound search to

Table 2. Production Data Summary year

POM	QTY Production / Year
Adolina	37.619.216
Aek Nabara Selatan	60.798.034
Aek Raso	41.763.441
Aek Torop	47.823.557
Air Batu	36.176.951
Ajamu	39.337.882
Bah Jambi	78.363.365
Berangir	32.007.065
Cot Girek	42.723.924
Dolok Ilir	55.342.436
Dolok Sinumbah	37.365.117
Gunung Bayu	36.444.922
Hapesong	27.707.550
Kwala Sawit	37.240.350
Mayang	35.784.216
Pabatu	28.302.941
Pagar Merbau	38.610.896
Pasir Mandoge	56.093.707
Pulau Tiga	30.548.826
Pulu Raja	35.666.291
Rambutan	56.876.885
Sawit Hulu	30.015.782
Sawit Langkat	32.863.425
Sawit Seberang	35.292.452
Sei Baruhur	45.957.204
Sei Daun	63.397.279
Sei Mangkei	57.338.843
Sei Silau	66.476.551
Sisumut	46.128.614
Sosa	54.092.506
Tanah Putih	36.272.323
Tanjung Medan	41.442.753
Tanjung Seumantoh	40.872.309
Timur	38.393.483
Tinjowan	40.590.144
Torgamba	53.002.830
Grand Total	1.574.734.070

guarantee optimality in large-scale integer programs (Bixby, 2002; Padberg & Rinaldi, 1991). Daily production data, transportation costs, refinery throughput, and inventory levels were used as model inputs. The optimization process generated the optimal CPO allocation for each planning period while satisfying all operational constraints, with the historical dataset summarized in Table 2.

To evaluate the robustness of the proposed model, several refinery throughput scenarios were analyzed. The resulting solutions were further examined using sensitivity analysis, marginal analysis, and break-even analysis to identify critical parameters influencing the optimal distribution policy.

Result and Discussion

This section presents the optimization results obtained from the proposed multi-period Mixed Integer Linear Programming (MILP) model. The analysis focuses on the optimal allocation of crude palm oil (CPO) from internal palm oil mills and external suppliers to PT Industri Nabati Lestari (PT INL) and Belawan Port while satisfying refinery throughput constraints and minimizing total logistics costs. The optimization was performed using actual operational data covering one year of production activities.

Distribution Network Characteristics

The distribution network consists of 37 internal palm oil mills (PKS), several external suppliers, PT Industri Nabati Lestari (PT INL) as the refinery, and Belawan Port as the export hub, as illustrated in Figure 2. Each production facility possesses different production capacities, transportation costs, and geographical distances to the destination facilities. Consequently, the optimization model must determine the most economical allocation pattern while satisfying refinery demand and operational constraints.

The transportation network exhibits a typical multi-origin multi-echelon structure in which each production facility can distribute CPO through multiple alternative routes. Internal mills generally provide lower transportation costs than external suppliers; however, seasonal production fluctuations occasionally require additional procurement from external suppliers.

Optimization Results

The proposed MILP model successfully generated an optimal distribution plan for every planning period while satisfying all operational constraints, with the detailed optimization results summarized in Table 3. The optimization process allocated CPO shipments according to transportation cost efficiency, refinery processing capacity, available production, and inventory balance.

Overall, the model consistently prioritized internal palm oil mills with lower transportation costs before allocating supplies from more expensive production facilities. External suppliers were utilized only when internal production could not satisfy refinery demand due to seasonal production shortages or refinery throughput requirements.

The optimization also demonstrated that inventory played an important role in balancing production variability across planning periods. During periods of high production, excess CPO was stored at PT INL and subsequently utilized during low-production periods, thereby reducing dependence on external procurement.

Transportation Cost Analysis

One of the primary objectives of this study was minimizing the total transportation cost of CPO distribution.

The optimization results indicate that transportation cost is strongly influenced by route selection, as demonstrated by the comparison presented in Table 4. Routes connecting nearby internal mills to PT INL were consistently selected because they offered significantly lower transportation costs than alternative routes. Conversely, shipments from geographically distant mills or external suppliers were activated only when necessary to satisfy refinery throughput constraints.

The model therefore produced a transportation pattern that minimizes unnecessary long-distance shipments while maintaining sufficient refinery input throughout the planning horizon. To assess the real-world benefit of the proposed model, the optimized results were compared against the company's actual 2025 operational baseline. Based on historical records, the actual total CPO volume delivered to PT INL in 2025 was 300,597,967 kg, incurring a total logistics cost of Rp48,873,217,230, equivalent to an actual unit cost of Rp162.58/kg. Under the closest comparable scenario ($Q = 1,800$ tons/day), the optimization model produced a unit logistics cost of Rp129.78/kg, representing a cost reduction of approximately 20.2% relative to actual historical practice. This comparison provides direct empirical evidence that the proposed optimization framework can generate measurable logistics cost savings beyond current company practice, rather than being a purely theoretical improvement.

Table 3 also reveals an important trade-off as refinery throughput (Q) increases: the transport cost per kg rises steadily from Rp129.78/kg at $Q = 1,800$ tons/day to

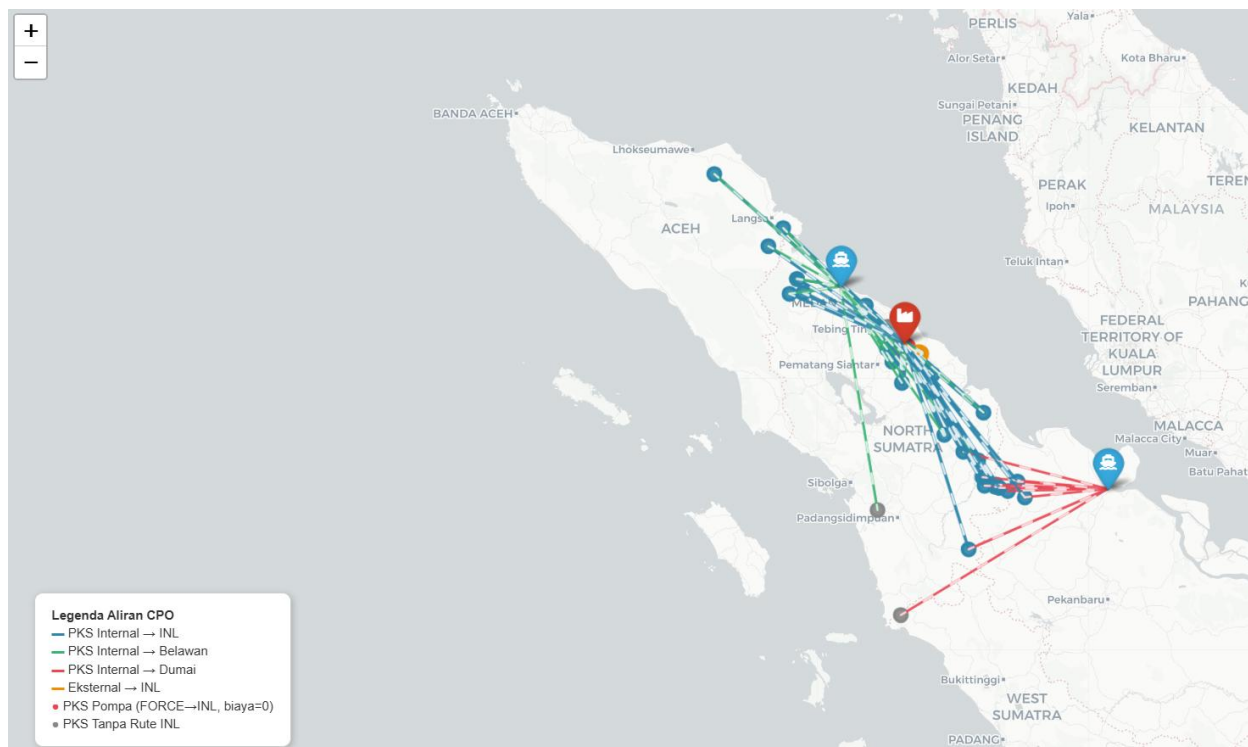


Figure 2. Distribution Network of PTPN IV

Table 3. Optimal Distribution Allocation Internal to INL

POM	Volume (Ton)	Cost (Rp)	Average Vol/day	Average Cost (Rp/Kg)
Bah Jambi	78.363	7.087.966.364	273,04	90,45
Sei Silau	66.477	4.985.741.325	193,81	75,00
Sei Mangkei	57.339	-	183,78	0,00
Pasir Mandoge	56.094	8.369.181.094	233,72	149,20
Dolok Ilir	55.342	8.038.488.839	175,13	145,25
Aek Nabara Selatan	51.155	13.282.849.653	167,17	259,66
Sisumut	46.129	9.460.056.160	147,85	205,08
Tinjowan	40.590	4.306.614.275	212,51	106,10
Dolok Sinumbah	37.365	2.911.489.909	127,96	77,92
Gunung Bayu	36.445	5.671.558.757	132,53	155,62
Air Batu	36.177	5.028.596.189	123,05	139,00
Mayang	35.784	2.880.629.393	129,18	80,50
Pulu Raja	35.666	7.302.316.423	151,13	204,74
Pagar Merbau	34.476	7.126.465.753	122,25	206,71
Berangir	32.007	6.177.363.545	117,67	193,00
Pabatu	28.303	3.486.922.328	142,23	123,20
Adolina	27.917	4.759.807.223	114,41	170,50
Ajamu	20.167	5.552.011.438	113,30	275,30
Aek Torop	18.200	5.368.922.722	168,52	294,99
Torgamba	16.218	4.878.118.012	148,79	300,78
Aek Raso	13.697	4.088.114.933	130,45	298,47
Sawit Langkat	11.096	2.881.153.604	105,68	259,66
Sei Daun	10.988	3.438.616.359	171,68	312,95
Sei Baruhur	10.099	3.101.915.770	138,34	307,16
Kwala Sawit	7.374	1.948.965.376	105,35	264,29
Sawit Hulu	7.212	1.931.173.036	92,46	267,77
Sawit Seberang	7.161	1.842.872.218	111,89	257,34
Tanjung Seumantoh	5.500	1.657.511.947	141,03	301,36
Sosa	4.920	1.770.499.942	144,70	359,87
Tanah Putih	4.498	1.451.885.643	102,22	322,80
Pulau Tiga	4.062	1.207.582.837	92,31	297,31
Tanjung Medan	3.103	1.059.241.878	107,01	341,33
Cot Girek	3.048	1.215.116.041	138,54	398,68

Rp171.01/kg at $Q = 4,500$ tons/day, while the total system cost per kg falls from Rp379/kg to Rp293/kg over the same range. This pattern occurs because, at higher throughput

levels, the refinery must draw additional CPO from more distant internal mills and external suppliers whose marginal transportation cost is higher than that of nearby sources,

Table 4. Throughput Scenario Comparison

Q (t/hr)	INL Vol. (tons/yr)	Transport Cost (Rp/kg)	Fixed Cost (Rp/kg)	Total System (Rp/kg)	Implication
1,800	646,200	129.78	249.00	378.78	40% Utilization, highest cost/kg
2,000	718,000	132.66	230.00	362.66	44% Utilization
2,300	825,012	136.93	207.00	343.93	51% Utilization
4,000	1,403,347	161.55	134.00	295.55	89% Utilization, efficient
4,100	1,435,844	163.30	132.00	295.30	91% Utilization
4,200	1,468,122	165.12	129.00	294.12	93% Utilization
4,300	1,500,275	167.02	127.00	294.02	96% Utilization
4,400	1,532,301	169.00	124.00	293.00	98% Utilization
4,500	1,563,949	171.01	122.00	293.01	100% Utilization, lowest total/kg

Table 5. Internal and External Supply Allocation by Period

Month	Int. INL Vol. (tons)	Ext. INL Vol. (tons)	Total INL Vol. (tons)	Belawan Vol. (tons)	Dumai Vol. (tons)	Int. INL Cost (Rp)	Int. Port Cost (Rp)	Ext. INL Cost (Rp)	Transport Cost (Rp)
January	65,833	53,453	119,286	15,000	5,000	11,767,843,940	3,902,560,312	9,617,320,576	25,287,724,828
February	66,729	51,610	118,339	15,000	5,000	13,252,431,121	3,999,740,467	9,285,688,832	26,537,860,420
March	70,616	55,296	125,912	15,000	5,000	12,635,209,622	3,931,344,168	9,948,952,320	26,515,506,110
April	68,323	49,766	118,089	15,000	5,000	11,009,408,393	3,860,845,066	8,954,057,088	23,824,310,547
May	78,447	57,139	135,586	15,000	5,000	12,414,438,255	3,727,338,215	10,280,584,064	26,422,360,534
June	77,271	55,265	132,536	15,000	5,000	11,563,859,871	3,735,693,436	9,941,910,276	25,241,463,583
July	82,503	56,971	139,474	15,000	5,000	11,888,937,524	3,666,403,438	10,242,021,100	25,797,362,062
August	79,891	56,794	136,685	15,000	5,000	11,036,419,591	3,646,265,852	10,201,718,771	24,884,404,214
September	78,036	55,111	133,147	15,000	5,000	11,349,166,774	3,716,306,217	9,907,687,710	24,973,160,701
October	80,158	57,139	137,297	15,000	5,000	12,253,759,437	3,719,195,385	10,280,584,064	26,253,538,886
November	77,375	55,294	132,669	15,000	5,000	12,560,958,094	3,723,391,564	9,948,405,816	26,232,755,474
December	77,790	57,139	134,929	15,000	5,000	12,537,316,744	3,703,456,923	10,280,584,064	26,521,357,731
Total in Year	902,972	660,977	1,563,949	180,000	60,000	144,269,749,366	45,332,541,043	118,889,514,681	308,491,805,090

causing the transport cost component per kg to increase. At the same time, the fixed cost component per kg-which includes port handling, administrative, and other volume-independent costs-declines sharply because it is spread across a substantially larger total volume. Since the fixed-cost component dominates this trade-off, its reduction outweighs the rising marginal transport cost, so the total system cost per kg continues to decrease even as the transport cost per kg increases. This finding indicates that maximizing refinery utilization remains cost-effective at the system level despite the higher unit transportation cost it entails.

Internal and External Supply Allocation

The proposed optimization model simultaneously evaluates internal production and external procurement alternatives. Internal mills remained the dominant supply source because of their relatively low transportation costs and direct integration within the PTPN IV production system. Nevertheless, external suppliers contributed significantly during periods when internal production was insufficient to satisfy refinery throughput requirements, with the comparative breakdown across periods detailed in Table 5. This adaptive allocation mechanism ensures uninterrupted refinery operations while maintaining minimum logistics costs.

Sensitivity Analysis

Sensitivity analysis was conducted to evaluate the robustness of the proposed optimization model under different refinery throughput capacities, with the comparative metrics summarized in Table 6. The analysis indicates that increasing refinery throughput allows greater utilization of lower-cost internal production, thereby reducing dependence on external suppliers. Conversely, lower refinery capacities increase inventory accumulation and may require additional transportation adjustments to satisfy demand. Overall, the optimization model demonstrates stable performance across various operational scenarios, indicating its suitability as a decision-support tool for long-term logistics planning.

Mass-Balance and Feasibility Audit

To verify the physical consistency of the proposed Mixed-Integer Linear Programming (MILP) model and ensure that no material is lost or artificially created within the network, a strict annual mass-balance audit was conducted. Table 6 reports the reconciled annual flow totals for the representative scenario (tons/day) and the maximum throughput scenario (ons/day) in consistent units of Metric Tons (MT). A notable observation in the optimization results is that the monthly shipment volumes at Belawan Port and Dumai Port remain exactly at 15,000 MT and 5,000 MT, respectively, across all periods. These fixed monthly volumes are model-generated outcomes rather than imposed input constraints.

The model includes an adaptive minimum vessel shipment constraint which dictates that the monthly shipping volume must meet a minimum threshold ($B_{min, Belawan} = 15,000$ MT and $B_{min, Dumai} = 5,000$ MT) to ensure vessel feasibility. Because transporting CPO to the export ports incurs additional logistics costs compared to the highly cost-efficient refinery route (such as Sei Mangkei's pipeline with Rp0/kg tariff), the cost-minimizing objective function naturally allocates the absolute minimum volume required to satisfy the lower bound of the minimum shipment constraint. Consequently, the solver pushes the port shipment volumes down to exactly 15,000 MT and 5,000 MT to prevent unnecessary transportation expenditures. This makes the minimum-batch vessel constraint strictly binding (100% active) across the entire planning horizon (Table 7).

The optimization results demonstrate that integrating multi-origin supply allocation, refinery capacity constraints, and inventory continuity into a unified multi-period MILP framework is able to improve distribution planning compared with conventional transportation models. The proposed model consistently prioritizes internal palm oil mills with lower transportation costs while dynamically utilizing external suppliers only when internal production is insufficient. This allocation strategy reflects the

Table 6. Sensitivity Analysis Results

Q (Ton/day)	Vol. INL (Ton/year)	Transportation Cost (Rp/kg)	Fixed Cost (Rp/kg)	Total Cost (Rp/kg)
1,800	646,200	129.78	249.00	379.00
2,000	718,000	132.66	230.00	363.00
2,300	825,012	136.93	207.00	344.00
4,000	1,403,347	161.55	134.00	296.00
4,100	1,435,844	163.30	132.00	295.00
4,200	1,468,122	165.12	129.00	294.00
4,300	1,500,275	167.02	127.00	294.00
4,400	1,532,301	169.00	124.00	293.00
4,500	1,563,949	171.01	122.00	293.00

Table 7. Annual Mass-Balance and Feasibility Audit (in Metric Tons, MT)

Flow Component	Q = 1,800 MT/day	Q = 4,500 MT/day	Mass-Balance Verification Equation
Initial Port Inventory (inv _{0,p})	0	0	Boundary condition at t = 0
Total Internal Production	1,574,734	1,574,734	Sum of all 37 internal mills
- Allocated to Refinery (INL)	646,200	902,972	Internal CPO routed to INL
- Allocated to Ports (Bel/Dum)	240,000	240,000	Internal CPO routed to ports
Unused Internal Production	688,534	431,762	Leftover at mills (not shipped)
External Procurement	0	660,977	Purchased from external suppliers
Total Refinery Inflow (INL)	646,200	1,563,949	Internal to INL + External Procurement
Total Port Inflow	240,000	240,000	Sum of internal CPO to ports
- Belawan Port Inflow	180,000	180,000	Shipped from designated internal mills
- Dumai Port Inflow	60,000	60,000	Shipped from designated internal mills
Total Vessel Shipments	240,000	240,000	Sum of CPO shipped out by vessels
- Belawan Shipments	180,000	180,000	Outflow from Belawan Port
- Dumai Shipments	60,000	60,000	Outflow from Dumai Port

fundamental principle of minimum-cost network flow, in which commodities are routed through the least-cost feasible paths while satisfying all operational constraints (Taha, 2017).

The findings further indicate that refinery throughput capacity constitutes the primary operational bottleneck affecting the overall distribution network. Although sufficient CPO supply may be available from internal production facilities, limited refinery capacity restricts the amount of CPO that can be processed during each planning period. Consequently, inventory accumulation and shipment allocation become highly dependent on refinery throughput rather than solely on transportation costs. This bottleneck effect is further supported by quantitative evidence from the minimum-batch shipment constraint at both ports: across all 108 month-scenario combinations (9 throughput scenarios x 12 months), the optimal monthly shipment volume was found to sit exactly at the minimum-batch threshold (15,000 tons at Belawan Port and 5,000 tons at Dumai Port) in every instance, indicating that this constraint is binding 100% of the time and consistently shapes the optimal allocation decision. This observation highlights the importance of simultaneously optimizing logistics and production capacities rather than treating them as independent planning problems.

While this study does not programmatically solve a daily single-period optimization model on the same operational dataset as a controlled mathematical benchmark, the proposed multi-period formulation structurally illustrates how temporal interactions among production, transportation, processing, and inventory can be captured. The model indicates that inventory accumulated at the refinery during peak crop seasons can theoretically provide operational flexibility during periods of reduced CPO availability, thereby suggesting a potential mathematical pathway to minimize reliance on expensive external procurement.

However, this finding must be interpreted with caution as a case-specific representation of the PTPN IV–PT INL network, rather than a generalized proof of improved decision quality under all operational settings. The optimization operates under several deterministic assumptions, which abstract from real-world stochasticity. In actual industrial applications,

factors such as fluctuating spot-market tariffs, road conditions, transport availability, and production uncertainty may limit the direct transferability of these model-generated recommendations. Consequently, the practical implementation of these theoretical inventory-balancing pathways remains dependent on the logistics managers' capability to adapt these deterministic insights to highly volatile and stochastic operating environments.

Lilis et al. (2023) successfully employed Mixed Integer Linear Programming to optimize supplier selection and upstream CPO supply chain activities. However, their model primarily focused on supplier allocation and did not explicitly represent intermediate refinery operations, multi-origin distribution, or temporal inventory dynamics. The present study broadens the optimization scope by simultaneously integrating internal production facilities, external suppliers, refinery throughput limitations, dual operational hubs, and inventory carry-over within a single mathematical model.

Similarly, multi-echelon optimization improves logistics efficiency through coordinated material flows across several distribution stages, a finding corroborated by peer-reviewed work on multi-center distribution networks that jointly optimize cost and environmental performance (Ren et al., 2022). Nevertheless, their research considered conventional hierarchical supply chains involving suppliers, warehouses, and retailers. In contrast, the distribution structure investigated in this study represents a vertically integrated palm oil industry where intermediate processing facilities perform dual operational functions as both inventory storage and refinery processing centers. Consequently, the proposed model better reflects the operational complexity encountered in large-scale agro-industrial supply chains.

The concept of Minimum Cost Flow applied in this study is also consistent with the space-time network formulation proposed by (Sitek & Stefański, 2017). However, unlike previous research that primarily addressed transportation networks, this study incorporates binary operational decisions, refinery capacity constraints, external procurement alternatives, and multi-period inventory balance into the network flow formulation. These additional decision layers

significantly enhance the applicability of the model for real industrial logistics systems.

Furthermore, classical hub-location and network-flow optimization studies such as (Saputri et al., 2019), which formulated a capacitated multiple-allocation hub-location model for logistics transportation, generally assume predetermined supply quantities and static transportation conditions. The present study advances this perspective by integrating fluctuating daily production data and seasonal supply variability, allowing the optimization process to produce operational decisions that are considerably closer to actual industrial practice.

More broadly, the multi-period MILP formulation adopted in this study is consistent with well-established theoretical foundations of linear and integer optimization (Dantzig, 1963; Wolsey, 1998) and with network flow theory underlying the space-time representation of the distribution problem (Bertsekas, 1998; Bertsimas & Tsitsiklis, 1997; Ford & Fulkerson, 1962). Similar mixed-integer and multi-echelon optimization approaches have also proven effective across a wide range of industrial and logistics contexts, including sugar-bioethanol supply chains (Lima et al., 2023), two-echelon delivery networks (Liu et al., 2020), and hospital inventory management (Abu Zwaïda et al., 2021), reinforcing the generalizability of the proposed modelling framework beyond the palm oil sector. In parallel, the growing body of research on sustainable and resilient supply chain design (Becerra et al., 2021; Jayarathna et al., 2021) and on supply chain disruption management during large-scale shocks such as the COVID-19 pandemic (Chowdhury et al., 2021) underscores the importance of embedding operational optimization models, such as the one proposed here, within a broader sustainability and resilience agenda for agro-industrial logistics.

Scientific Contribution

First, the proposed model introduces a comprehensive multi-origin multi-echelon dual-hub distribution framework specifically designed for vertically integrated palm oil industries. Previous optimization studies have generally examined supplier selection, transportation planning, or network design independently, whereas this research integrates these operational decisions into a unified optimization framework.

Second, this study extends the classical Minimum Cost Flow formulation into a multi-period space-time network capable of representing temporal production fluctuations, inventory continuity, and refinery processing constraints. The inclusion of inter-period inventory balance enables the optimization model to capture dynamic operational conditions that cannot be represented by conventional single-period transportation models.

Third, the utilization of actual daily operational data covering one year substantially enhances the practical relevance of the proposed model. Rather than relying on average production values, the optimization process explicitly considers seasonal production variability, resulting in more realistic and implementable distribution plans.

Managerial Implications

Increasing refinery processing capacity may generate greater logistics savings than reducing transportation costs alone because higher throughput enables larger utilization of low-cost internal production.

The model also supports strategic supplier management by identifying periods in which external procurement becomes economically justified. Consequently, companies can negotiate procurement contracts more effectively while minimizing unnecessary dependence on external suppliers.

In addition, the proposed model can be integrated into

digital logistics planning systems to support daily operational decision-making. By continuously updating production data and transportation costs, the optimization framework can generate adaptive distribution plans that respond to changing operational conditions in real time.

Limitations and Future Research

First, transportation costs were assumed to remain constant throughout the planning horizon. In practice, fuel prices, road conditions, and transportation availability may fluctuate over time. Incorporating stochastic or dynamic transportation costs would improve model realism.

Second, this study considers only refinery throughput constraints without explicitly modelling loading, unloading, and vehicle scheduling activities. Integrating vehicle routing or fleet scheduling decisions into the optimization framework would provide a more comprehensive logistics planning model.

Third, uncertainty associated with CPO production, market demand, and transportation disruptions was not explicitly incorporated into the mathematical formulation. Future studies may extend the proposed model using stochastic programming, robust optimization, or simulation-based optimization to improve decision robustness under uncertain operating environments.

Finally, although the proposed framework was developed using operational data from PTPN IV, the modelling approach can be adapted to other vertically integrated agro-industrial supply chains with similar network characteristics, thereby expanding its applicability across different industrial sectors.

Conclusion

This study proposed a multi-period Mixed Integer Linear Programming (MILP) model formulated within a Minimum Cost Flow (MCF) framework to optimize crude palm oil (CPO) distribution in a vertically integrated palm oil supply chain. The proposed model simultaneously considers multiple internal production facilities, external suppliers, dual operational hubs, refinery throughput limitations, transportation costs, and inventory continuity over multiple planning periods. By integrating these operational components into a unified optimization framework, the model provides a more comprehensive representation of real-world CPO distribution systems than conventional transportation models.

The optimization results demonstrate that the proposed model is able to identify the optimal allocation of CPO shipments while satisfying all operational constraints and minimizing total logistics costs. The multi-period formulation effectively captures seasonal production variability and enables inventory balancing between consecutive planning periods, thereby reducing unnecessary external procurement and improving refinery utilization. The findings also indicate that refinery throughput capacity represents one of the most influential operational constraints affecting overall distribution efficiency, emphasizing the importance of coordinated planning between logistics and production operations (Jakfar, 2024).

From a scientific perspective, this research contributes to the logistics and supply chain optimization literature in three important aspects. First, it develops a mathematically consistent, multi-origin, multi-echelon, dual-hub distribution model specifically designed for vertically integrated palm oil industries. The network formulation strictly guarantees physical mass-balance and consistency across 37 internal mills, external suppliers, and dual destinations through port-level inventory carry-over equations and daily adaptive demand allocations (Equation 9), ensuring zero material loss across the distribution system.

Second, it extends the classical Minimum Cost Flow formulation by incorporating multi-period inventory dynamics,

refinery processing constraints, and external procurement decisions into a single Mixed-Integer Linear Programming (MILP) framework. This model was solved using the exact HiGHS solver with a relative MIP-gap tolerance of 0.01%. The solver successfully achieved absolute optimality with a final gap of 0.00% across all 108 monthly sub-problems, requiring an average computational runtime of approximately 1 minute per sub-problem.

Third, the validation and benchmarking of the proposed optimization model using 359 operating days of actual daily operational data demonstrates its robust capability to support complex industrial logistics planning under realistic operating conditions. For the selected representative scenario of $Q = 1,800$ tons/day, which corresponds most closely to the company's actual 2025 operating conditions, the model generates an optimal unit transportation cost recommendation of Rp129.78/kg and a total annual logistics cost of Rp335.46 billion. When benchmarked against the historically implemented baseline actually executed by the company in 2025—which incurred a unit logistics cost of Rp162.58/kg over a total volume of 300,597,967 kg (totaling Rp48.87 billion)—the model's optimized routing plan yields a validated potential unit transportation cost reduction of Rp32.80/kg, representing an absolute 20.2% cost saving. This comparative benchmarking clearly distinguishes the

model's optimized, mathematically proven recommendations from the empirical decision-making patterns historically implemented by the company. From a managerial perspective, the proposed optimization framework can serve as a decision-support tool for determining daily CPO allocation, improving refinery capacity utilization, reducing transportation costs, and supporting strategic procurement decisions. The model enables logistics managers to evaluate alternative distribution scenarios systematically and allocate available resources more efficiently while maintaining operational continuity throughout the supply chain.

Although the proposed model provides significant practical and theoretical contributions, several limitations remain. The optimization assumes deterministic transportation costs, production quantities, and refinery capacities throughout the planning horizon. Future research may incorporate stochastic production uncertainty, dynamic transportation costs, vehicle routing decisions, carbon emission considerations, and multi-objective optimization approaches to develop a more comprehensive and sustainable logistics planning framework. In addition, the proposed methodology can be extended to other agro-industrial supply chains that exhibit similar multi-origin and multi-echelon network characteristics.

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