

Maritime Logistics Optimization for Bio-based Diesel Fuel Commodities in Indonesia: Costs and Vessel Suitability Analysis

Artya Lathifah

Department of Industrial Engineering, Universitas Indonesia, Indonesia
Email: artya.lathifah@ui.ac.id (*Corresponding Author*)

Komarudin

Department of Industrial Engineering, Universitas Indonesia, Indonesia
Email: komarudin74@ui.ac.id

Danang Sismartono

Department of Industrial Engineering, Universitas Indonesia, Indonesia
LEMIGAS Oil and Gas Testing Center, Ministry of Energy and Mineral Resources, Indonesia
Email: danang.sismartono@esdm.go.id

Muhammad Dliya'ul Haq

Department of Information Management, National Sun Yat-sen University, Taiwan R.O.C
Email: haq@g-mail.nsysu.edu.tw

Nurul Lathifah

Department of Industrial Engineering, Universitas Indonesia, Indonesia
Email: nurul.lathifah02@ui.ac.id

Herbert Wibert Victor Hasudungan

Department of Industrial Engineering, Universitas Islam Internasional Indonesia, Indonesia
Directorate General of New Renewable Energy and Energy Conservation, Ministry of Energy and Mineral Resources, Indonesia
Email: herbert.hasudungan@uiii.ac.id

ABSTRACT

The distribution of bio-based diesel fuel commodities in Indonesia faces efficiency challenges due to fluctuating demand, geographically dispersed delivery points, and mismatches between shipment volumes and vessel capacities. Since maritime transport is a dominant mode in the national distribution network, optimizing sea-based logistics is crucial to reducing costs and ensuring reliable energy supply chains. This study addresses these challenges by focusing on maritime transportation and utilizing real-world allocation data from 2024 in Indonesia, consisting of 22 origin points and 51 destination points, with a total shipment volume of 9 million kiloliters. A monthly planning model based on recurring demand patterns is developed to design routes and number of deliveries, leveraging empirical data and addressing a real-world national logistics issue. A trip-based cost optimization model tailored to maritime logistics is employed to evaluate the effects of vessel suitability, consolidation strategies, and demand variability on delivery efficiency. This study shows that aligning vessel capacities with shipment volumes significantly reduces transportation costs, and implementing split deliveries when full consolidation is insufficient to meet monthly demand further enhances flexibility. Moreover,

optimizing multi-destination routing combined with dynamic vessel selection and split delivery yields notable efficiency gains, achieving an overall cost reduction of more than 18% compared to the traditional point-to-point model. These findings highlight that consolidation, optimal vessel assignment and flexible split delivery can significantly enhance transportation efficiency. Finally, this study offers insights to improve the cost-efficiency of Indonesia's bio-based diesel fuel that contributes to the reliability of its energy delivery systems.

Keywords: *bio-based fuel, consolidation, maritime, shipping cost, trip-based*

1. INTRODUCTION

The expansion of bio-based diesel forms a key part of Indonesia's national strategic initiative to promote energy diversification and reduce dependence on fossil fuels (IEA, 2022; IESR, 2023; Kementerian ESDM, 2024). As part of its broader renewable energy agenda, the government has actively accelerated the adoption of biodiesel blending, positioning bio-based diesel as a major component in the national energy mix. Distributed palm oil-based (bio-based)

from production facilities to fuel mixing terminals, the mixed fuel which is produced by blending fossil diesel with palm oil-based biodiesel faces persistent efficiency challenges due to fluctuating demand, dispersed delivery locations, and mismatched shipment volumes. These logistical complexities are further exacerbated by Indonesia's vast archipelagic geography, resulting in higher transportation costs and operational inefficiencies.

Given Indonesia's vast archipelagic geography, maritime transport plays a central role in the distribution of bio-based diesel. However, the current logistics system predominantly relies on a point-to-point model under a Cost and Freight (CFR) scheme, where shipments are arranged directly from producers to delivery points, and transportation costs are calculated per liter. Many routes lack official cost references, creating challenges for accurate planning and costing. To address this issue, a specialized cost formula has been introduced to estimate trip-based transportation costs using vessel type, real navigational distance, and parcel size, while also incorporating buffer time to account for operational contingencies. Unlike the traditional shipping cost per liter method, which considers only the quantity shipped without factoring in vessel capacity utilization, the trip-based formula provides a more realistic and consistent cost assessment by aligning transportation expenses with actual vessel loading and voyage conditions.

Despite the central role of maritime transport, Indonesia's bio-based diesel distribution has historically relied on a strict point-to-point model, pairing each biodiesel production facility with a single fuel mixing terminal. This fragmented structure has limited shipment consolidation, resulting in routing inefficiencies, underutilized vessel capacities, and rising logistics costs. Studies have shown that adopting point-to-many distribution strategies, supported by vessel optimization and split delivery mechanisms, can enhance scale efficiency, reduce transportation costs, and improve operational flexibility in archipelagic contexts (Fazi *et al.*, 2020). To address these challenges, the problem can be approached using a capacitated routing problem framework, like Ransikarbum *et al.* (2024), but extended by incorporating a trip-based cost formula, shipment consolidation, and split delivery mechanisms. The introduction of a trip-based cost formula, which accounts for real navigational distances, vessel capacities, and buffer times, further makes point-to-many routing a feasible and practical alternative to the traditional model. This transition aligns with the Heterogeneous Vehicle Routing Problem with Split Delivery (HVRP-SD) framework, which addresses capacity variations and enables more flexible multi-route delivery planning. Applying this integrated approach to maritime logistics facilitates improved vessel assignment, greater route efficiency, and better cost control under real-world operational conditions (Avci & Topaloglu, 2016; Fazi *et al.*, 2020; Hennig *et al.*, 2015; Rajaei *et al.*, 2022; Yoshizaki, 2009).

To systematically address these operational inefficiencies, this study evaluates four progressive scenarios, from the existing point-to-point model to a point-to-many strategies with split deliveries. The overarching research question is: Can adopting a point-to-many distributions model with split delivery improve cost efficiency in Indonesia's national strategic liquid commodity

maritime logistics system? To answer this, the following research questions are proposed:

RQ1: How can shipment allocation optimization under the point-to-point model, using available shipping cost per liter data, reduce annual transportation costs?

RQ2: How can trip-based cost formula perform compared with the cost per liter data?

RQ3: When applying a trip-based cost formula, what are the optimal vessel types and monthly delivery frequencies to minimize transportation costs under the point-to-point model?

RQ4: How does a point-to-many strategies with split deliveries, considering vessel capacity constraints and dynamic vessel selection, affect annual transportation costs compared to the optimized point-to-point model?

Considering that the problem involved 22 suppliers and 51 delivery points, the distribution network size remained manageable for Linear Programming using Simplex optimization. To reflect practical conditions in biodiesel distribution across Indonesia's vast geography, consolidation prioritized geographically proximate delivery points, and mathematical solvers were applied to derive optimal or near-optimal routing solutions (Archetti *et al.*, 2014; Archetti & Speranza, 2008; Lysgaard *et al.*, 2004; Mor & Speranza, 2022; Zhang & Yao, 2025). The results of the optimization confirm that adopting a point-to-many maritime distributions model with split deliveries substantially improves cost efficiency. Compared to the conventional point-to-point system, the point-to-many approach reduces total annual transportation costs by optimizing vessel utilization, minimizing the number of trips, and enhancing overall operational planning. These findings highlight the practical and strategic value of integrating consolidated routing strategies into Indonesia's national strategic liquid commodity maritime logistics system.

2. LITERATURE REVIEW

Our study is connected to the cost formula under investigation, which forms the foundation for proposing the development of new routes that were previously unavailable. Additionally, it is aligned with the transportation problem and heterogeneous vehicle routing problem incorporating split delivery.

2.1 Freight Costs Formula (Trip-Based)

Government regulations concerning biodiesel allocation in Indonesia have undergone several revisions. The most recent, stipulated in the Ministerial Decree of Energy and Mineral Resources No. 158.K/EK.05/DJE.S/2024 (issued on September 13, 2024), amended the previous decree No. 149.K/EK.05/DJE.S/2023, outlining the allocation of biodiesel blending volumes for the January–December 2024 period. The total allocated FAME volume reached 13.4 million kiloliters (KL), representing 74.6% of the national installed production capacity. This allocation is regionally distributed as follows: Sumatra (42%), Java (24%), Kalimantan (31%), and Sulawesi (3%). Distribution is carried out via three transportation modes: pipeline (4.4%), truck (21.2%), and ship (74.4%). Maritime transport, which dominates the distribution network, involves 22 supply points or Badan Usaha Bahan Bakar Nabati (BUBBN) and 51 delivery points or the Badan Usaha Bahan Bakar Minyak (BUBBM).

Indonesia's biodiesel distribution network is highly complex due to the geographical mismatch between production centers, mainly in Sumatra and Java, and widespread national demand. Managing this distribution efficiently is critical, as transportation costs affected by distance, mode, and regional factors account for a major share of supply chain expenses. In maritime transport, shipping costs are shaped not only by distance but also by vessel characteristics, weather, port infrastructure, and waterway conditions, requiring careful consideration of sailing, loading, and unloading activities. Recognizing that

costs depend on shipment volume, vessel type, and operational dynamics, a trip-based costing formula was jointly developed by the LEMIGAS Oil and Gas Testing Center, Ministry of Energy and Mineral Resources, together with academic and regulatory stakeholders in 2024. Designed to better capture real-world operational conditions, this formula also facilitates the identification of new shipping routes previously unaccounted for in cost estimates, thereby supporting a more flexible and efficient biodiesel distribution system.

Table 1 Shipping distribution activity and its fuel consumption.

Shipping Activity Status	Number of Days (NoD)	Fuel Consumption (FC) (KL/day)	Description
Voyage with parcel	Distance/(vessel's speed*24)	6.5	Sailing days from supply point to blending terminal (distance /speed).
Loading	1	1.5	Total days to transfer biodiesel from storage tank to vessel (at supply port).
Discharge	1	2.0	Total days to unload biodiesel from vessel to storage tank (at terminal port).
Waiting-Discharge Port	4	1.2	Total days for queuing at both supply and terminal ports
Voyage without parcel	Distance/(vessel's speed*24)	6.5	Total sailing days of returning in empty vessel condition
Buffer	1	6.5	Total days required for anticipating all risks during the travel

Referring to Table 1, a trip-based calculation accounting for vessel charter fees, bunker (fuel) costs, and port charges, provides a more realistic and operationally grounded evaluation of maritime distribution expenses, enabling more accurate planning and optimization of Indonesia's biodiesel logistics system.

- Vessel charter fees

$$F = \text{Total No D} \times \text{RateDay(USD)} \times \text{Con. Currency} \quad (1)$$

- Bunker Costs

$$C = \sum \text{NoD} \times \text{FC} \times 1000 \times \text{Fuel Costs Liter (IDR)} \quad (2)$$

- Port Charges (PC) in Billion IDR

$$PC = 0,1687 \times \text{BUBBM visited} \quad (3)$$

- Trip-based calculation (TC) from BUBBN to BUBBM with a vessel type selected

$$TC = (VF + BC + PC) \quad (4)$$

Therefore, the monthly cost is

$$TC = (VF + BC + PC) \times MT, \text{ where } MT = \left\lceil \frac{A_m}{P_s} \right\rceil \quad (5)$$

where MT is the roundup of total trip in a month based on A_m (Monthly allocation in KL) and P_s is the parcel size of each BUBBM

- Total yearly transportation cost calculation

$$YC = 12 \times MTC \quad (6)$$

This cost calculation formula is utilized to identify potential new pairings between BUBBN (biodiesel production facilities) and BUBBM (fuel blending terminals) that are not covered by existing shipping cost figures in the Ministerial Decree. By applying the trip-based cost estimation approach, the study aims to discover new maritime routes that can potentially reduce the overall transportation cost of delivering bio-based diesel fuel from BUBBN to BUBBM, thereby supporting a more efficient and cost-effective distribution network.

2.2 Transportation Problem

In Scenario 2, we adopt the classical balanced transportation problem framework (Amaliah *et al.*, 2022; Christiansen *et al.*, 2023; Harrath & Kaabi, 2018; Sabbagh *et al.*, 2015; Singh & Gupta, 2014), utilizing shipping cost data as regulated in the official Ministry Decree. This approach is suitable when transport costs are explicitly predefined and centralized, as is the case in Indonesia's biodiesel distribution. A balanced transportation model is employed because the total supply and demand across BUBBN and BUBBM nodes are intentionally equal (see Equations 8 and 9), ensuring that national production targets are fully absorbed by regional demand commitments.

$$\text{Min } Z = \sum_{i \in I} \sum_{j \in J} c_{ij} \cdot x_{ij} \quad (7)$$

Subject to

$$\sum_{j \in J} x_{ij} = S_i \quad \forall i \in I \quad (8)$$

$$\sum_{i \in I} x_{ij} = D_j \quad \forall j \in J \quad (9)$$

$$x_{ij} \geq 0 \quad \forall i \in I, \quad \forall j \in J \quad (10)$$

Where,

I Set of Supply points

J Set of Delivery points

S Supply capacity

D Demand requirement

c_{ij} Shipping cost per unit from i to j

x_{ij} Decisions number of unit shipped from source i to destination j

2.3 Heterogenous Vehicle Routing Problem

Recent studies, such as Rajaei *et al.* (2022) and Kabadurmus and Erdogan (2023), highlight that integrating heterogeneous fleets with split deliveries significantly enhances vehicle routing flexibility and cost efficiency. These insights are particularly relevant for maritime logistics in Indonesia, where conventional point-to-point biodiesel distribution has led to routing inefficiencies. Additionally, research by Ozfirat and Ozkarahan (2010), Fazi *et al.* (2020), Avci and Topaloglu (2016), and Hennig *et al.* (2015) supports the effectiveness of point-to-many strategies and vessel optimization under the Heterogeneous Vehicle Routing Problem with Split Delivery (HVRP-SD) framework in improving vessel utilization, reducing transportation costs, and enhancing operational flexibility, especially in archipelagic contexts.

The mathematical model used in this study is slightly modified to suit the maritime biodiesel distribution problem in Indonesia and is presented in Section 4. Scenario 4 incorporates all four critical elements: heterogeneous fleet, multi-point routing, split delivery, and a maritime context, a

combination that is rarely addressed together in the existing literature.

While Ransikarbum *et al.* (2024) integrated clustering with heterogeneous fleet routing for healthcare logistics, their model did not incorporate split deliveries or address maritime-specific complexities. Arevalo-Ascanio *et al.* (2024) also reviewed location-routing models and pointed out the lack of attention to heterogeneous fleets and sector-specific adaptations. However, their work remained largely theoretical, and land based.

In contrast, this paper advances the literature by developing a heterogeneous vessel routing model with split delivery planning and trip-based cost optimization, explicitly tailored to the operational realities of biodiesel distribution in an archipelagic environment. Scenario 4 demonstrates how the integration of these components enables dynamic shipment consolidation and partial fulfillment across multiple destinations. These advancements offer a significant contribution by combining cost-efficient routing with practical constraints in maritime logistics. Table 2 summarizes this study's positioning relative to prior works.

Table 2 Position of this study.

Paper	Transportation problem	Heterogeneous fleet	Multi-point	Split Delivery	Maritime logistics
Amaliah <i>et al.</i> (2022)	✓				
Christiansen <i>et al.</i> (2023)	✓				
Harrath and Kaabi (2018)	✓				
Sabbagh <i>et al.</i> (2015)	✓				
Singh and Gupta (2014)	✓				
Rajaei <i>et al.</i> (2022)	✓	✓	✓	✓	
Kabadurmus and Erdogan (2023)	✓	✓	✓	✓	
Ozfirat and Ozkarahan (2010)	✓	✓	✓	✓	
Fazi <i>et al.</i> (2020)	✓	✓	✓	✓	
Avci and Topaloglu (2016)	✓	✓	✓		
Hennig <i>et al.</i> (2015)	✓	✓	✓	✓	✓
Ransikarbum <i>et al.</i> (2024)	✓	✓	✓		
This paper	✓	✓	✓	✓	✓

3. DATA DESCRIPTION

3.1 BUBBN and BUBBM Supply and Demand

The following Table 3 and Table 4 present the real-world data gathered from a strategic shipping company responsible for oil and gas distribution in Indonesia. The shipping volume and order size reflect the median values of shipping and receiving capacities based on the observed data patterns from January to September 2024 with the total 9.037.567 KL. These data will serve as the basis for selecting the appropriate vessel types to ensure optimal matching between shipment volumes and vessel capacities, thereby avoiding underutilization or overcapacity. The parcel size, derived from historical weekly demand data, will be utilized to determine the vessel type for each trip, as it represents the expected demand volume per shipment cycle. The shipping cost per liter based on the Ministry Decree is provided in Appendix 1.

In the dataset for January to September 2024, BUBBN 10 and BUBBN 12 were excluded in the optimization process due to the absence of shipping activities, and their corresponding Shipping Cost columns were removed. Similarly, BUBBM 1, BUBBM 3, BUBBM 8, BUBBM 18,

BUBBM 23, BUBBM 26, BUBBM 27, BUBBM 28, BUBBM 30, BUBBM 33, BUBBM 34, BUBBM 38, BUBBM 40, BUBBM 43, and BUBBM 50 were removed at the row level due to no receiving activities. Nonetheless, the proposed optimization model remains flexible and can incorporate these nodes should future shipping or demand activities arise.

3.2 Types and Configuration of Vessels

Selecting the appropriate vessel is crucial, as each type offers different capacities, speeds, and costs. There are five types of vessels available: BL, SI, SII, GP, and MR as presented in Table 5. Smaller vessels, such as BL and SI, are suited for lower-volume shipments, while larger vessels, such as GP and MR, although requiring higher volumes to be cost-effective, can support multi-point delivery operations to maximize utilization and reduce costs. Matching vessel size with shipment demand is essential to ensure shipping efficiency. We assumed across all vessels types the number of available vessels is unlimited.

3.3 The Cluster of BUBBN

The clustering was conducted to support a more efficient determination of the vessel types and quantities

required for each region. This cluster data is given from the discussion jointly developed by the LEMIGAS Oil and Gas Testing Center, Ministry of Energy and Mineral Resources, together with academia. Specifically, as presented in Table 6 the clusters segment Indonesia into five distinct geographical areas based on logistical distribution considerations: Northern Sumatra and Western Kalimantan, Eastern

Kalimantan and Southern Kalimantan, Padang, Lampung, and the Western Region of Java, Northern Sulawesi, and Central Kalimantan and Eastern Java. This regional division enables a more targeted and effective planning of shipping operations aligned with the distribution characteristics of each area.

Table 3 BUBBN supply and shipping volume.

No	BUBBN	Supply (in KL)	Shipping Volume (in KL)	No	BUBBN	Supply (in KL)	Shipping Volume (in KL)
1	BUBBN 1	256,256	5,281.31	12	BUBBN 12	-	3,898.96
2	BUBBN 2	1,131,693	4,790.57	13	BUBBN 13	380,776	7,396.18
3	BUBBN 3	251,885	11,895.58	14	BUBBN 14	457,983	3,988.43
4	BUBBN 4	275,677	4,993.42	15	BUBBN 15	719,988	4,006.91
5	BUBBN 5	453,979	3,990.69	16	BUBBN 16	305,322	3,941.01
6	BUBBN 6	353,278	3,957.66	17	BUBBN 17	164,511	3,981.46
7	BUBBN 7	100,444	3,398.75	18	BUBBN 18	1,008,330	3,971.01
8	BUBBN 8	364,291	1,990.89	19	BUBBN 19	184,893	1,999.35
9	BUBBN 9	932,042	6,926.79	20	BUBBN 20	526,130	8,947.32
10	BUBBN 10	-	6,926.79	21	BUBBN 21	734,070	4,790.57
11	BUBBN 11	82,725	3,898.96	22	BUBBN 22	353,294	7,501.62
		Total				9,037,567	

Table 4. BUBBM demand.

No	BUBBM	Demand/ year (in KL)	Parcel Size (in KL)	No	BUBBM	Demand/ year (in KL)	Parcel Size (in KL)
1	BUBBM 1	-	1,994.0	27	BUBBM 27	-	1,986.7
2	BUBBM 2	105,532	1,986.8	28	BUBBM 28	-	3,989.1
3	BUBBM 3	-	2,995.5	29	BUBBM 29	225,483	3,943.3
4	BUBBM 4	113,256	2,497.7	30	BUBBM 30	-	6,418.6
5	BUBBM 5	312,921	3,994.0	31	BUBBM 31	255,992	3,971.7
6	BUBBM 6	199,597	2,996.2	32	BUBBM 32	552,395	4,997.4
7	BUBBM 7	101,380	1,058.6	33	BUBBM 33	-	12,134.3
8	BUBBM 8	-	346.7	34	BUBBM 34	-	2,500.0
9	BUBBM 9	5,770	2,020.0	35	BUBBM 35	251,885	9,997.4
10	BUBBM 10	48,372	2,037.4	36	BUBBM 36	526,130	8,946.2
11	BUBBM 11	530,024	4,772.8	37	BUBBM 37	424,519	3,990.7
12	BUBBM 12	100,444	3,493.1	38	BUBBM 38	-	3,971.4
13	BUBBM 13	97,286	2,491.9	39	BUBBM 39	734,070	7,501.8
14	BUBBM 14	2,419	300.0	40	BUBBM 40	-	300.0
15	BUBBM 15	51,744	2,185.2	41	BUBBM 41	932,042	6,915.9
16	BUBBM 16	520,835	3,974.3	42	BUBBM 42	155,919	4,995.0
17	BUBBM 17	4,616	300.0	43	BUBBM 43	-	3,990.9
18	BUBBM 18	-	3,989.8	44	BUBBM 44	63,517	1,999.3
19	BUBBM 19	27,709	2,541.7	45	BUBBM 45	24,939	1,994.4
20	BUBBM 20	796,115	11,988.3	46	BUBBM 46	269,232	3,991.4
21	BUBBM 21	855,526	9,278.9	47	BUBBM 47	33,464	1,196.3
22	BUBBM 22	207,015	1,988.4	48	BUBBM 48	5,385	1,600.8
23	BUBBM 23	-	5,448.9	49	BUBBM 49	19,996	2,279.9
24	BUBBM 24	256,256	5,448.9	50	BUBBM 50	-	4,500.0
25	BUBBM 25	75,782	4,994.5	51	BUBBM 51	150,000	4,805.9
26	BUBBM 26	-	9,972.0	Total		9,037,567	

4. MODEL DEVELOPMENT

To evaluate the effectiveness of the trip-based cost formula, four scenarios were developed. Scenarios 1 (Business-as-Usual) and 2 (Optimization of Business-as-Usual) use the per-liter shipping cost specified in the Ministerial Decree, while Scenarios 3 and 4 apply the trip-based cost formula.

Scenario 1 (Business-as-Usual) serves as the baseline, calculating total shipping costs without optimization. Scenario 2 (Optimization of Business-as-Usual) improves

upon this by selecting vessel types based on shipment volume and solving a balanced transportation problem using data from Tables 3 and 4 for more efficient resource allocation. Scenario 3 (Point-to-Point with Trip-Based Cost) simulates a classical transportation problem adapted for maritime logistics by incorporating vessel selection and shipment allocation using the trip-based cost formula. Like Scenarios 1 and 2, it assumes a point-to-point approach, where each BUBBN supplies one BUBBM. Scenario 4 (Multi-Point with Trip-Based Cost) extends this by

introducing shipment consolidation and split deliveries under the Heterogeneous Vehicle Routing Problem with Split Delivery (HVRP-SD) framework, enabling multi-route planning with heterogeneous fleet capacities. These four scenarios enable a structured comparison between traditional cost estimation using Ministerial Decree shipping cost/litre

(Scenarios 1 and 2) and the trip-based cost approach (Scenarios 3 and 4), across both single-destination and multi-destination strategies. Subsections 4.1 and 4.2 present the model development for Scenarios 3 and 4, respectively.

Table 5 Vessel configuration.

Vessel Type	BL	SI	SII	GP	MR
Vessel Index	1	2	3	4	5
Capacity	2,500	4,500	9,000	25,000	60,000
Speed	9.00	10.00	10.00	11.00	12.00
Rate/day (USD)	2,500	4,250	8,000	13,500	15,000
Fuel Cost / Liter (IDR)			14,000		

Table 6 BUBBN clusters.

No	Region	BUBBN
1	North Part of Sumatera and West Kalimantan	BUBBN 1, BUBBN 3, BUBBN 9, BUBBN 10, BUBBN 11, BUBBN 12, BUBBN 13, BUBBN 14, BUBBN 18, BUBBN 21
2	East Kalimantan dan South Kalimantan	BUBBN 2, BUBBN 4, BUBBN 5, BUBBN 15
3	Padang, Lampung dan West Part of Java	BUBBN 6, BUBBN 7, BUBBN 17, BUBBN 22
4	North Sulawesi	BUBBN 8
5	Central Kalimantan dan East Java	BUBBN 16, BUBBN 19, BUBBN 20

4.1 Transportation Problem with Vessel Selection

In Scenario 3, we adopt an approach like the transportation problem, but with the addition of selecting appropriate vessels in the context of maritime logistics. The mathematical model, slightly modified, incorporates a trip-based formula as shown in equations (1) - (6). This case closely resembles the approach used in Vehicle Routing Problems for both vessels and other vehicles, as demonstrated by Panda *et al.* (2014), Šedivý *et al.* (2022), Tian *et al.* (2023), and Zolfani *et al.* (2022). The minimize cost of a monthly trip-based formula is calculated by optimizing the following mathematical model

$$\text{Min } Z = \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} MT_{ij}^k \cdot x_{ij}^k \cdot MT_j \quad (11)$$

Subject to

$$\sum_{i \in I} \sum_{k \in K} Q_k x_{ij}^k \geq D_j \quad \forall j \in J \quad (13)$$

$$\sum_{k \in K} x_{ij}^k \leq 1 \quad \forall i \in I, \forall j \in J \quad (14)$$

$$x_{ij}^k \in \{0,1\} \quad \forall i \in I, \forall j \in J, \forall k \in K \quad (15)$$

Suppose $I = \{1, 2, 3, \dots, 22\}$ and $J = \{1, 2, 3, \dots, 51\}$ is the set of BUBBN and BUBBM, respectively and K is the set of vessel type that can be selected, Q_k is the capacity of vessel type k (in KL). The decision variable x_{ij}^k is defined as binary, taking the value 1 if vessel type k is assigned from BUBBN_{*i*} to BUBBM_{*j*}, otherwise 0. The supply and demands constraints are presented in Eq. (12) and Eq. (13), respectively. Each demand j of BUBBM_{*j*} must be fully

satisfied, potentially from multiple BUBBN but for each supplier-demand pair (i, j) only one vessel type k can be selected, as specified in Eq. (14) and non-negativity in Eq. (15).

In this model, the monthly number of trips for each BUBBM j , corresponding to the number of vessels (of the same type) needed, is calculated using MT as defined in Eq. (5) for each j . Since MT_j depends solely on the monthly allocation and parcel size of BUBBM j and does not vary with the BUBBN i or vessel type k , it is treated as a constant parameter during the optimization process. Thus, incorporating MT_j into the objective function (Eq. 11) enables the model to evaluate shipping costs monthly without altering the underlying optimization structure or decision logic.

4.2 Heterogeneous Vehicle Routing Problem with Split Delivery

To enhance the efficiency of bio-based diesel distribution, Scenario 4 is proposed. This scenario adopts the Heterogeneous Vehicle Routing Problem with Split Delivery (HVRP-SD) framework, introducing a multi-point delivery approach as a practical and implementable strategy tailored to Indonesia's strategic distribution context. Scenario 4 extends the modified transportation problem introduced in Scenario 3 by incorporating both split delivery and multi-point routing. By integrating vessel type selection and trip-based cost calculation, Scenario 4 aligns with the Heterogeneous Vehicle Routing Problem with Split Delivery (HVRP-SD), adapted specifically to the context of maritime logistics.

The flowchart in Figure 1 outlines the process of optimizing bio-based diesel distribution through consolidation and split delivery. Following the initial assignment of supplier-demand-vessel pairings in Scenario 3, the model identifies demand points eligible for

consolidation based on having the same supplier and parcel sizes that are relatively close in volume indicate that the shipment quantities are comparable, which may facilitate route consolidation or vessel assignment. When consolidation is feasible, meaning that multi-point distribution is achievable from the same BUBBN, either a new vessel or the same vessel assigned in Scenario 3 is

selected to minimize shipping costs, with the number of monthly trips recalculated accordingly. Any remaining demand that cannot be accommodated through consolidation is fulfilled using the original vessel assignments, with adjusted trip counts. The final objective is to minimize the total monthly shipping cost across all routes.

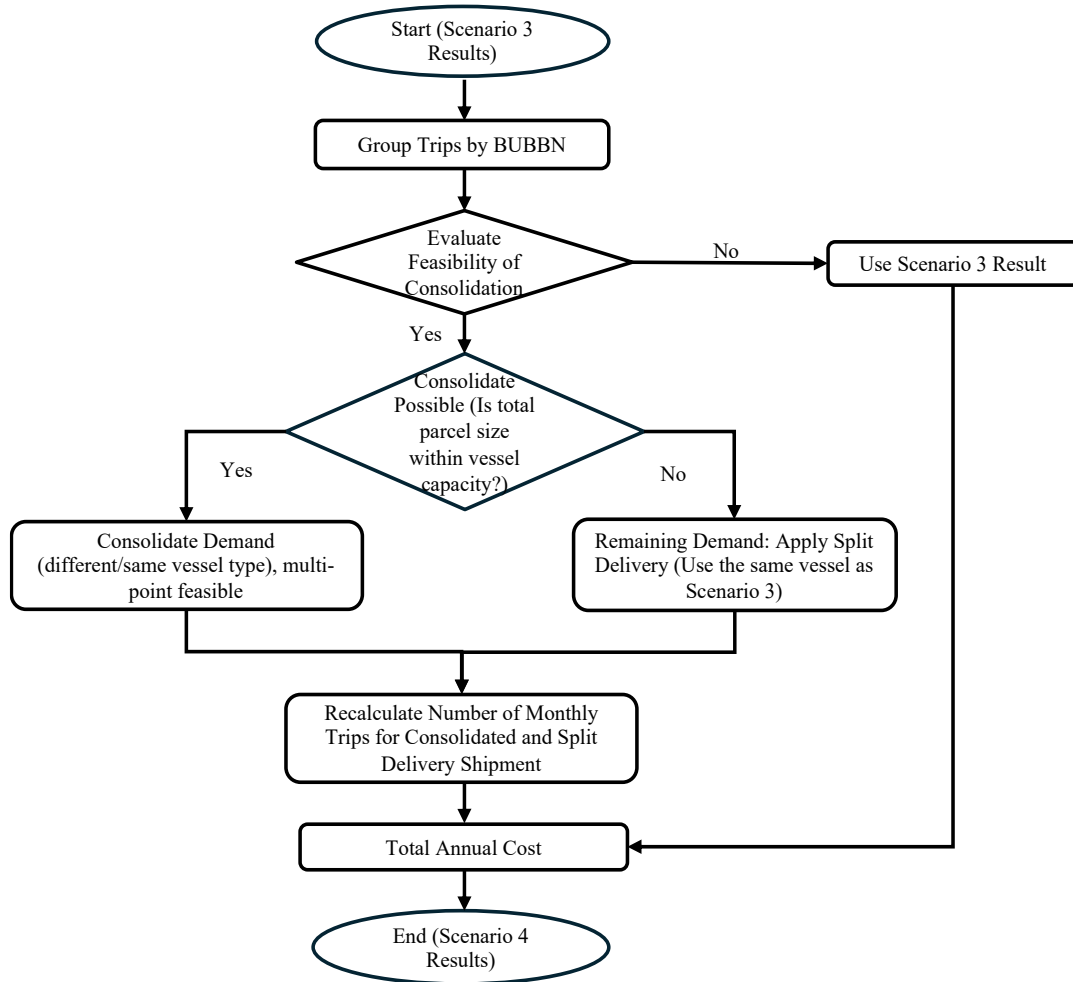


Figure 1 Flowchart of the consolidation and split delivery process for multi-point bio-based diesel distribution optimization.

Now we define p in P as a group of demand points $\{j1, j2, j3 \dots\}$ such that all demand points in p are supplied by the same supplier i and all demand points in p from the same BUBBN, that is $MT_{j1} = MT_{j2} = \dots$. The decision variable y_{ip}^k is defined as binary (Eq. 21), taking the value 1 if BUBBN i consolidates group p using vessel k and 0 if otherwise. Suppose α_{jp} is the proportion of consolidated shipment allocated to demand point j within group p (satisfying $\sum_{j \in P} \alpha_{jp} = 1$). In this multi-point scenario, the minimize cost of a monthly trip-based formula is calculated by optimizing the following mathematical model.

$$\text{Min } Z = \sum_{i \in I} \sum_{j \in J} \sum_{k \in K} \text{MTC}_{ij}^k x_{ij}^k MT_j + \sum_{i \in I} \sum_{p \in P} \sum_{k \in K} \text{MTC}_{ip}^{k'} y_{ip}^k MT_p' \quad (16)$$

$$\sum_{j \in J} \sum_{k \in K} Q_k x_{ij}^k + \sum_{p \in P} \sum_{k \in K} Q_k' y_{ip}^k \leq S_i \quad \forall i \in I \quad (17)$$

$$\sum_{i \in I} \sum_{k \in K} Q_k x_{ij}^k + \sum_{p \in P; j \in P} \sum_{k \in K} \alpha_{jp} Q_k' y_{ip}^k \geq D_j \quad \forall j \in J \quad (18)$$

$$\sum_{k \in K} x_{ij}^k \leq 1 \quad \forall i \in I, \forall j \in J \quad (19)$$

$$\sum_{k \in K} y_{ip}^k \leq 1 \quad \forall i \in I, \forall p \in P \quad (20)$$

$$x_{ij}^k \in \{0,1\} \quad \forall i \in I, \forall j \in J, \forall k \in K \quad (21)$$

$$y_{ip}^k \in \{0,1\} \quad \forall i \in I, \forall p \in P, \forall k \in K \quad (22)$$

where MT_p' is the recalculated number of trips for consolidated group p , determined by

$$MT_p' = \frac{\sum_{j \in P} D_j}{Q_k'} \quad (23)$$

The decision variables include individual shipment assignments x_{ij}^k (Eq. 21), and consolidated shipment assignments y_{ip}^k (Eq. 22). The objective function captures the total shipping cost resulting from both types of deliveries (Eq. 16). Constraints are incorporated to ensure that the total supply capacity of each supplier is respected (Eq. 17), that all demand points are fully satisfied either through direct shipment, consolidation, or a combination of both (Eq. 18), and that only one vessel type is assigned per shipment, whether individual or consolidated, as presented in Eq (19) and Eq. (20), respectively.

This flexible and practical modeling structure reflects real-world maritime logistics practices in Indonesia, where shipment consolidation typically occurs from the same supplier (BUBBN) to ensure operational simplicity and cost

control. It supports the national initiative to improve the cost efficiency and operational reliability of bio-based diesel fuel distribution across the country's archipelagic regions.

4.3 Illustrative Example

This subsection illustrates how the model works to find the optimal solution in Scenarios 2, 3, and 4.

4.3.1 Scenario 2

To confirm that the optimization in Scenario 2 aligns with the classical transportation problem, we validated it using a real-world case that fits the mathematical structure outlined in Equations (7) – (10), as shown in Tables 7 and 8. This case features multiple supply points (BUBBN) and delivery points (BUBBM), each with defined capacities and unit shipping costs.

Table 7 BUBBN to BUBBM partly supplied by BUBBM 9.

Supplier (BUBBN)	Allocation (KL)	Destination (BUBBM)	Cost/liter (IDR)	Total Yearly Cost (IDR)
BUBBN 7	19,731	BUBBM 24	152	2,999.112
BUBBN 18	733,643	BUBBM 41	260	190,747.180
BUBBN 21	482,185	BUBBM 32	240	115,724.400

Table 8 Demand from BUBBN 9 supplies to multiple BUBBM in scenario 2.

Destination (BUBBM)	Allocation (KL)	Cost/liter (IDR)	Total Yearly Demand (KL)	Total Yearly Cost (IDR)
BUBBM 14	2,419	281	2,419	679,739
BUBBM 24	236,525	225	256,256	57,657,600
BUBBM 32	70,210	407	552,395	224,824,765
BUBBM 37	424,519	210	424,519	89,148,990
BUBBM 41	198,369	203	932,042	189,204,526

Table 9. BUBBN 9 supplies to multiple BUBBM in scenario 3.

Destination (BUBBM)	Monthly Allocation (KL)	Vessel Type	Parcel Size	Monthly Trip (MT)	MTC/Month
BUBBM 14	300	BL	300	1	638,436,500
BUBBM 16	19,871	SI	3,974	5	5,710,015,833
BUBBM 17	300	BL	600	1	638,436,500
BUBBM 24	21,796	SII	5,449	4	8,106,112,667
BUBBM 32	4,997	SII	4,998	1	1,796,186,500
BUBBM 39	37,509	SII	7,502	5	11,327,379,334

Demand from BUBBN 9 which has total allocation of 932,042 KL supplies to Multiple BUBBM. The total cost of this case is IDR 870,986,312. BUBBN 9 thus acts as the primary supplier, allocating to multiple destinations, while other suppliers (BUBBN 7, 18, 21) fulfill only a single delivery point each (Eq. 8). The total outgoing shipment from BUBBN 9 is:

Each demand point also receives the exact required volume from one or more suppliers (Eq. 9):

- BUBBM 24: 236,525 (from BUBBN 9) + 19,731 (from BUBBN 7) = 256,256
- BUBBM 32: 70,210 (from BUBBN 9) + 482,185 (from BUBBN 21) = 552,395
- BUBBM 41: 198,369 (from BUBBN 9) + 733,673 (from BUBBN 18) = 932,042

Furthermore, all shipping quantities $x_{ij} \geq 0$ are greater than or equal to zero, satisfying the non-negativity constraint (Eq. 10).

4.3.2. Scenario 3

To validate that the trip-based optimization model in Scenario 3 operates as intended under its mathematical formulation (Equations 11–15), we analyzed a real case where BUBBN 9 supplies multiple BUBBM nodes with different demand levels and vessel types. As detailed in Table 9, BUBBN 9, with a monthly capacity of 85,074 KL, distributes shipments across several destinations. This instance confirms that the objective function accurately captures the number of monthly trips (MT) and the trip-based cost (MTC) for each BUBBN–BUBBM pair.

Table 10 BUBBN 9 supplies in scenario 4.

Route		Vessel Type	Parcel Size Consolidated	Monthly Trip	MTC/Month
BUBBN 9 - BUBBM 14 - BU BBM 17 - BUBBN 9	Multi-point, consolidated	BL	900	1	1,109,773,000
BUBBN 9 - BUBBM 16 - BUBBN 9	Split Delivery	SI	3,974	4	4,568,012,667
BUBBN 9 - BUBBM 24 - BUBBM 39 - BUBBN 9	Multi-point, consolidated	GP	12,951	4	20,277,296,545
BUBBN 9 - BU BBM 16 - BUBBM 32 - BUBBN 9	Multi-point	SII	8,972	1	2,780,389,667
BUBBN 9 - BUBBM 39 - BUBBN 9	Scenario 3	SII	7,502	1	2,831,844,833

We verify that this instance satisfies all three main constraints.

- Total supply capacity of BUBBN 9: 85,074 KL/month $\leq$ Total allocation from BUBBN 9 across all routes: 85,074 KL/month (Eq. 12)

Each BUBBM either receives its total demand from BUBBN 9 (BUBBM 14, BUBBM 17 and BUBBM 24), or is partially satisfied (BUBBM 16, BUBBM 32 and BUBBM 39) with the remaining fulfilled by other BUBBNs and it is allowed by the model (Eq. 13).

- No route uses multiple vessels; each supplier–demand pair employs exactly one vessel type (Eq. 14).

Decision variables respect binary logic and non-negativity (Eq. 15).

4.3.3. Scenario 4

To ensure that the optimization model in Scenario 4 operates in accordance with its mathematical formulation (Equations 16–22), we examine the routing and allocation results from BUBBN 9 and verify that all constraints: supply, demand, vessel assignment, and variable feasibility are fully satisfied. Using the same case of BUBBN 9 supplies to the BUBBMs as shown in subsection 4.3.2 of Scenario 2, now the route is changed to the following Table 10.

We verify that this instance satisfies all three main constraints.

- Total supply: $900 + 15,896 + 51,804 + 8,972 + 7,502 = 85,074$ KL/ per month $\leq 85,074$ KL/month (Eq. 17)
- All BUBBM demands are fully served via combination of consolidated or direct trips (like Scenario 3), maintaining proportionality with $\sum_{j \in P} \alpha_{jp} = 1$. For example, total Parcel size of BUBBM 14 and BUBBM 17 is 900 KL, therefore: $\alpha_{BUBBM14p1} = \frac{300}{900} = 0.333$ and $\alpha_{BUBBM17p1} = \frac{600}{900} = 0.667$. Total parcel size of BUBBM 24 and BUBBM 39 = 12,951, therefore $\alpha_{BUBBM24p1} = \frac{5,449}{12,951} = 0.421$, $\alpha_{BUBBM39p1} = \frac{7,502}{12,951} = 0.579$. Total parcel size of BUBBM 16 and BUBBM 32 = 8,972, therefore $\alpha_{BUBBM16p1} = \frac{3,974}{8,972} = 0.443$, $\alpha_{BUBBM32p1} = \frac{4,998}{8,974} = 0.557$. This reflects the percentage share of BUBBM's demand in the total consolidated demand, and it is used to proportionally assign the vessel capacity (i.e., parcel size per trip) to each delivery point within the group (Eq. 18). Total demand: $900 + 11,922 + 51,804 + 8,972 + 7,502 = 81,100$ KL/ per month.
- All routes in Scenario 4 use exactly one vessel type (Eq. 19 and Eq. 20).
- All decisions are made with binary values: route selected or not (Eq. 21 and Eq. 22).

5. RESULTS AND DISCUSSION

In this Section we present the four scenarios result. The scenarios are Scenario 1 (Business as Usual), Scenario 2 (Optimization of Business as Usual), employ shipping cost per liter data as stipulated by the Ministry Decree. The latter two scenarios are Scenario 3 (Point-to-Point with Trip-Based Cost) and Scenario 4 (Multi-Point with Trip-Based Cost). Scenario 2 and Scenario 3 were implemented and solved using Microsoft Excel (Mac version) with OpenSolver with the CBC solver and the Simplex LP method. All computations were conducted on a MacBook Air (13-inch, 2019) equipped with a 1.6 GHz Dual-Core Intel Core i5 processor, 8 GB 2133 MHz LPDDR3 RAM, and running macOS Sonoma 14.6.1.

5.1 Scenario 1: Business-as-Usual

The total yearly cost under the Business as Usual (BAU) scenario amounts to IDR 3,284,041,858,320 (IDR 3284 billion), corresponding to the shipment of approximately 9,037,567 kiloliters (KL) of bio-based diesel fuel. This cost baseline reflects the operational expenses under the current distribution model without optimization interventions.

5.2 Scenario 2: Optimization of Business-as-Usual

We optimized the shipping operations by employing the shipping cost per liter data as stipulated in the Ministry Decree, aiming to demonstrate that the Business-as-Usual (BAU) distribution model could, in fact, be significantly improved. The problem was formulated as a balanced transportation problem and solved using Microsoft Excel (Mac version) with OpenSolver with the CBC solver. The computation time per instance was approximately 0,1 seconds. The resulting yearly shipment allocation from BUBBN to BUBBM is presented in Table 11.

Table 11 presents the optimized distribution plan consisting of 54 routes point-to-point between BUBBN (supplier points) and BUBBM (demand points). The yearly cost for each route was calculated by multiplying the yearly shipment volume of each route by the shipping cost per liter, as stipulated in the Ministry Decree (see Appendix 1). For instance, the yearly shipment volume for Route 1 (BUBBN 1 – BUBBM 21 – BUBBN 1) is 256,256 liters, and with a shipping cost of IDR 500 per liter, the resulting yearly cost is IDR 128,128,000,000. This calculation was systematically applied across all routes, and the individual route costs were then summed to derive the total yearly cost. Therefore, an exact optimized total yearly cost of IDR 3,028,395,448,000.000 (IDR 3028 billion). It is important to note that in this scenario, vessel selection is not performed; the optimization focuses solely on minimizing shipping costs

based on either official cost references or trip-based cost estimations.

5.3 Scenario 3: Point-to-Point with Trip-Based Cost

5.3.1 Validation of the Trip-based Formula Results Against the Shipping Cost per Liter

Before conducting the optimization using the point-to-point approach with the trip-based cost formula, we first validate whether this formula can accurately generate the shipping cost per liter for routes that are already known and specified in the Ministry Decree. We perform a t-test on 522 BUBBN–BUBBM pairs for which the official shipping cost per liter is available. The details of the validation are presented in the following paragraph.

Table 11 Route and yearly shipment allocation result of scenario 2.

No	Route	Yearly Shipment (KL)	No	Route	Yearly Shipment (KL)
1	BUBBN 1 - BUBBM 21 - BUBBN 1	256,256	28	BUBBN 11 - BUBBM 21 - BUBBN 11	67,926
2	BUBBN 2 - BUBBM 9 - BUBBN 2	5,770	29	BUBBN 11 - BUBBM 31 - BUBBN 11	14,799
3	BUBBN 2 - BUBBM 10 - BUBBN 2	48,372	30	BUBBN 13 - BUBBM 4 - BUBBN 13	113,256
4	BUBBN 2 - BUBBM 11 - BUBBN 2	115,189	31	BUBBN 13 - BUBBM 16 - BUBBN 13	212,852
5	BUBBN 2 - BUBBM 20 - BUBBN 2	796,115	32	BUBBN 13 - BUBBM 17 - BUBBN 13	4,616
6	BUBBN 2 - BUBBM 42 - BUBBN 2	135,923	33	BUBBN 13 - BUBBM 21 - BUBBN 13	50,052
7	BUBBN 2 - BUBBM 45 - BUBBN 2	24,939	34	BUBBN 14 - BUBBM 16 - BUBBN 14	307,983
8	BUBBN 2 - BUBBM 48 - BUBBN 2	5,385	35	BUBBN 14 - BUBBM 51 - BUBBN 14	150,000
9	BUBBN 3 - BUBBM 21 - BUBBN 3	251,885	36	BUBBN 15 - BUBBM 5 - BUBBN 15	128,174
10	BUBBN 4 - BUBBM 6 - BUBBN 4	126,109	37	BUBBN 15 - BUBBM 6 - BUBBN 15	73,488
11	BUBBN 4 - BUBBM 21 - BUBBN 4	149,568	38	BUBBN 15 - BUBBM 11 - BUBBN 15	414,835
12	BUBBN 5 - BUBBM 5 - BUBBN 5	184,747	39	BUBBN 15 - BUBBM 19 - BUBBN 15	27,709
13	BUBBN 5 - BUBBM 21 - BUBBN 5	269,232	40	BUBBN 15 - BUBBM 25 - BUBBN 15	75,782
14	BUBBN 6 - BUBBM 12 - BUBBN 6	39,727	41	BUBBN 16 - BUBBM 21 - BUBBN 16	79,839
15	BUBBN 6 - BUBBM 13 - BUBBN 6	97,286	42	BUBBN 16 - BUBBM 29 - BUBBN 16	225,483
16	BUBBN 6 - BUBBM 39 - BUBBN 6	216,265	43	BUBBN 17 - BUBBM 39 - BUBBN 17	164,511
17	BUBBN 7 - BUBBM 12 - BUBBN 7	60,717	44	BUBBN 18 - BUBBM 31 - BUBBN 18	241,193
18	BUBBN 7 - BUBBM 24 - BUBBN 7	19,731	45	BUBBN 18 - BUBBM 41 - BUBBN 18	733,673
19	BUBBN 7 - BUBBM 49 - BUBBN 7	19,996	46	BUBBN 18 - BUBBM 47 - BUBBN 18	33,464
20	BUBBN 8 - BUBBM 2 - BUBBN 8	105,532	47	BUBBN 19 - BUBBM 36 - BUBBN 19	164,897
21	BUBBN 8 - BUBBM 15 - BUBBN 8	51,744	48	BUBBN 19 - BUBBM 42 - BUBBN 19	19,996
22	BUBBN 8 - BUBBM 22 - BUBBN 8	207,015	49	BUBBN 20 - BUBBM 36 - BUBBN 20	361,233
23	BUBBN 9 - BUBBM 14 - BUBBN 9	2,419	50	BUBBN 20 - BUBBM 44 - BUBBN 20	63,517
24	BUBBN 9 - BUBBM 24 - BUBBN 9	236,525	51	BUBBN 20 - BUBBM 7 - BUBBN 20	101,380
25	BUBBN 9 - BUBBM 32 - BUBBN 9	70,210	52	BUBBN 21 - BUBBM 32 - BUBBN 21	482,185
26	BUBBN 9 - BUBBM 37 - BUBBN 9	424,519	53	BUBBN 21 - BUBBM 35 - BUBBN 21	251,885
27	BUBBN 9 - BUBBM 41 - BUBBN 9	198,369	54	BUBBN 22 - BUBBM 39 - BUBBN 22	353,294

Table 12 Statistical t-Test for shipping costs estimated using the proposed formula and those stated in the Ministerial Decree.

	Ministry Decree's	Formula
Mean	481.0235507	630.1358564
Variance	48891.53665	205537.3291
Observations	552	552
Pearson Correlation	0.347357162	
Hypothesized Mean Difference	0	
df	551	
t Stat	-8.149799986	
P(T<=t) one-tail	1.23147E-15	
t Critical one-tail	1.647623772	
P(T<=t) two-tail	2.46294E-15	
t Critical two-tail	1.964278689	

Among the 552 supply–delivery point pairs for which shipping costs were available from the Ministerial Decree, 58% of the trip-based formula estimates were higher than the shipping cost/liter from Ministry Decree, with an average difference of 41%, as illustrated in Figure 2. This result suggests that the proposed formula tends to produce more conservative estimates, indicating that it is not overly optimistic and is thus suitable for estimating shipping costs when official data are unavailable. Further supporting this finding, a statistical t-test was conducted, with the resulting t-statistic (-8.149), as presented in Table 12, falling well

outside the critical value threshold (1.96). This outcome confirms a statistically significant difference between the formula-based estimates and the shipping costs specified by the Ministerial Decree. Accordingly, in Scenarios 3 and 4, the shipping cost formula was applied to estimate costs for new routes that were not included in the Ministerial Decree. The validation results confirmed that the formula provides a reliable basis for estimating missing shipping costs.

5.3.2 Route Optimization

We performed the optimization model as outlined in Section 4.1 using Microsoft Excel (Mac version) with

OpenSolver and CBC. The computation time was approximately 1 seconds resulting 67 routes. The complete results for each route presented in Appendix 4. As an example, consider Route 3: BUBBN 1 – BUBBM 47 – BUBBN 1. There are three components of the trip-based cost, as specified in Equations (1) to (5). Based on the information provided in Tables 1 and 2, along with the distance matrix and monthly allocation details in the Appendix 1 and Appendix 2, the following data apply:

Route 3: BUBBN 1 – BUBBM 47 – BUBBN 1, monthly demand: 2,393 KL, parcel size: 1,196.3 KL, selected vessel type: BL, number of trips per month: 2, and distance: 0 nautical miles. The voyage time with and without parcels is calculated as: $2(0 / (9 \times 24)) = 0$. The remaining operational component (e.g., port stay, loading/unloading) amounts to 7 days. Since the distance is zero, the bunker consumption is assumed to be 14.8 KL. Thus, the cost components are calculated as follows:

- Vessel Charter Fees (VF) = $7 \times 2,500 \times 15,000 = \text{IDR } 262,500,000$
- Bunker Costs (BC) = $14.8 \times 1,000 \times 14,000 = \text{IDR } 207,200,000$
- Port Charges (PC) = $\text{IDR } 168,736,500$
- Thus, the Trip-based Cost (TC) from BUBBN 1 to BUBBM 47 and back to BUBBN 1 using vessel BL is: TC = $\text{IDR } 638,436,500$ (or 0.64 billion IDR)
- The monthly number of trips (MT) is MT = $[2,393 / 1,196.3] = 2$ trips

Thus, the Monthly Transportation Cost (MTC) is: $\text{MTC} = 2 \times 638,436,500 = \text{IDR } 1,276,873,000$. Finally, the Yearly Transportation Cost (YC) for this route is: $\text{YC} = 12 \times 1,276,873,000 = \text{IDR } 15,322,476,000$. By performing this calculation for all 67 routes, we obtained a total yearly transportation cost of $\text{IDR } 2,841,526,655,162$.

5.3.3 Vessel Selected

Based on the clustering analysis, the required vessel type for each route was identified in Table 13. A detailed breakdown of vessel assignments across the 67 routes is provided. In total, the operations involved 178 trips across all vessel types.

5.4 Scenario 4: Multi-Point with Trip-Based Cost

Following the mathematical model in Section 4.2 and flowchart presented in Figure 1, we utilized the input route results from Section 5.3 and consolidated feasible routes in accordance with the previously described algorithm. Through this process, we identified 62 routes, consisting of multipoint (consolidated) routes, split delivery routes, and point-to-point routes similar to those described in Section 5.3. These results are explained in detail in the following subsections.

5.4.1 Route Optimization

Route optimization was conducted based on the model formulated in Section 4.2, utilizing enumeration techniques implemented in Python. The computational time for each BUBBN was consistently under two seconds. A total of 62 optimized routes were generated, with the complete results presented in Appendix 4. To illustrate the calculation process, we highlight two examples: Route 9: BUBBN 2 – BUBBM 5 – BUBBM 2 (point-to-point with split delivery) and the consolidated Route 9&10: BUBBN 2 – BUBBM 5 – BUBBM 11 – BUBBN 2 (multi-point).

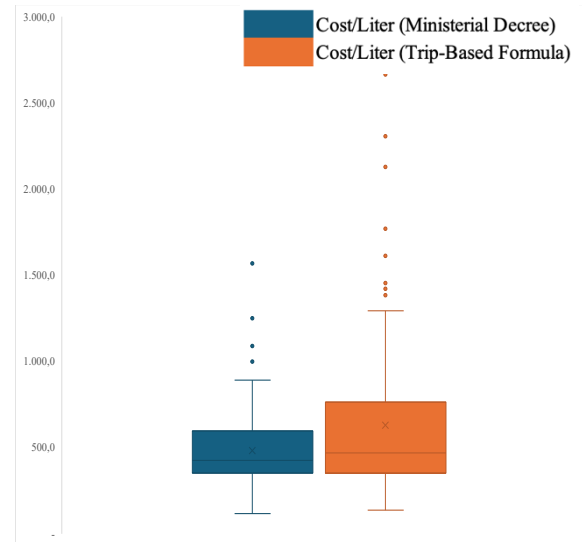


Figure 2 Comparison between shipping costs estimated using the proposed formula and those stated in the Ministerial Decree.

Table 13 Vessel type selected in each BUBBN cluster in scenario 3.

	BL	SI	SII	GP
Cluster 1	7	5	12	3
Cluster 2	6	3	7	3
Cluster 3	2	7	1	0
Cluster 4	2	1	0	0
Cluster 5	4	2	0	2

Route 9 (Scenario 3): BUBBN 2 → BUBBM 5 → BUBBN 2, monthly demand: 27,958 KL, parcel size: 3,944 KL, selected vessel type: SI, number of trips per month: 7, Distance: 0 nautical miles. The voyage time during sailing is calculated as $2 \times (0 / (9 \times 24)) = 0$ days, while the operational activities (e.g., port stays, loading/unloading) amount to 7 days. Since the sailing distance is zero, bunker consumption is assumed to be 14.8 KL. The resulting trip-based cost components are:

- Vessel Charter Fees (VF): $7 \times 4,250 \times 15,000 = \text{IDR } 446,250,000$
- Bunker Costs (BC): $14.8 \times 1,000 \times 14,000 = \text{IDR } 207,200,000$
- Port Charges (PC): $\text{IDR } 168,736,500$

Thus, the Trip-based Cost (TC) is TC = $\text{IDR } 822,186,500$ (or approximately 0.82 billion IDR). The Monthly Transportation Cost (MTC) is: $\text{MTC} = 7 \times 822,186,500 = \text{IDR } 5,755,305,500$. The Yearly Transportation Cost (YC) is: $\text{YC} = 12 \times 5,755,305,500 = \text{IDR } 69,063,666,000$

Consolidated Route 9&10, Route: BUBBN 2 → BUBBM 5 → BUBBM 11 → BUBBN 2, Consolidated shipment volume: $3,944 + 4,772 = 8,736$ KL, Selected vessel type: SII, Number of trips per month: $\min \{27,958/3,944; 9,546/4,772\} \approx 2$, Distance: 258 nautical miles. The voyage time with sailing is: $2 \times (258 / (10 \times 24)) \approx 1.08$ days, and the operational activities at ports amount to 11 days. The estimated bunker consumption is 32.69 KL. The trip-based cost components are:

- Vessel Charter Fees (VF): $12.08 \times 8,000 \times 15,000 = \text{IDR } 1,449,600,000$

- Bunker Costs (BC): $32.69 \times 1,000 \times 14,000 = \text{IDR } 457,660,000$
- Port Charges (PC): $2 \times 168,736,500 = \text{IDR } 337,473,000$

Thus, the Trip-based Cost (TC) for this consolidated route is TC = IDR 2,244,733,000 (or approximately 2.24 billion IDR). The Monthly Transportation Cost (MTC) is: $\text{MTC} = 2 \times 2,244,733,000 = \text{IDR } 4,489,466,000$. The Yearly Transportation Cost (YC) is: $\text{YC} = 12 \times 4,489,466,000 = \text{IDR } 53,873,592,000$. After consolidation, only five trips per month remain for Route 9 using the SI vessel type. The adjusted yearly transportation cost is: $\text{YC} = 5 \times 12 \times 822,186,500 = \text{IDR } 49,331,190,000$. Thus, the combined yearly cost for the consolidated Route 9&10 and the split delivery adjustment for Route 9 is: Total = IDR 53,873,592,000 + IDR 49,331,190,000 = IDR 103,204,782,000. This cost is lower than the total cost under the point-to-point approach (Scenario 3) for Route 9 and Route 10 separately, which amounts to IDR 103,689,942,000.

By applying this consolidation and split approach to all BUBBNs serving multiple BUBBNs, a total of 62 optimized routes were identified, including both point-to-point and multi-point consolidations. The resulting total yearly transportation cost across all routes is: IDR 2,692,421,353,909, -

5.4.2 Vessel Selected

Based on the clustering analysis, the required vessel type for each route was identified in Table 14. A detailed breakdown of vessel assignments across the 62 routes is provided in Appendix 4. In total, the operations involved 154 trips across all vessel types.

Table 14 Vessel type Selected in each BUBBN cluster in scenario 4.

	BL	SI	SII	GP
Cluster 1	5	5	9	4
Cluster 2	5	5	6	3
Cluster 3	2	7	1	0
Cluster 4	2	1	0	0
Cluster 5	3	1	1	2

5.5 Discussions

Now we elaborate all the scenario total yearly cost as shown in Table 15. The comparative analysis of cost savings across the four scenarios demonstrates the significant benefits of optimization, both when using shipping costs per liter based on the Ministry Decree and when adopting a trip-based cost formula. Scenarios that incorporated routing optimization consistently outperformed the baseline, with Scenario 4 achieving the highest overall savings. Specifically, Scenario 4 optimized using a trip-based cost formula reduced logistics costs by 18.02% compared to the traditional Scenario 1, which relied on static per-liter costs without routing adjustments. Even when comparing scenarios using the same Ministry Decree cost basis, optimization efforts such as those in Scenario 3 yielded notable savings of up to 13.47%.

These findings highlight that integrating vessel routing optimization, whether under regulatory cost structures (Scenario 2) or trip-based formulas, leads to substantial improvements in shipment consolidation, vessel utilization, and overall cost efficiency in maritime biodiesel distribution.

Importantly, the results also indicate that although the trip-based cost formula may statistically produce higher shipping costs per liter, it still enables greater total cost efficiency. This validates that the proposed strategy of optimizing routes and vessel selection, combined with multi-point distribution and shipment consolidation, is crucial for achieving sustainable and cost-effective maritime logistics operations.

Table 15 Comparison of each scenario.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Scenario 1	0.00%	7.78%	13.47%	18.02%
Scenario 2	7.78%	0.00%	6.17%	11.09%
Scenario 3	13.47%	6.17%	0.00%	5.25%
Scenario 4	18.02%	11.09%	5.25%	0.00%

6. THEORETICAL AND PRACTICAL IMPLICATION

The study provides several important theoretical and practical implications, which are outlined as following sub-section.

6.1 Theoretical Implication

This study offers several theoretical contributions to the logistics and transportation literature. First, it extends classical transportation and fleet assignment models by integrating dynamic multi-point consolidation and heterogeneous vessel selection mechanisms, addressing the limitations of traditional static routing frameworks. Second, the proposed model introduces a flexible vessel reassignment mechanism, allowing vessel types to be reselected dynamically during consolidation, while maintaining original vessel assignments for any split deliveries. Third, the study applies split delivery strategies in a maritime archipelagic context, offering a novel perspective beyond the conventional land-based applications and capturing the unique logistical challenges present in Indonesia's biodiesel distribution network. Finally, by incorporating the trip-based cost formula into the optimization framework, the study demonstrates that although the formula may statistically yield higher cost per liter, mathematical optimization enables strategic reconfiguration of delivery plans, resulting in overall cost efficiency improvements. These contributions collectively reinforce the importance of optimization-driven decision-making in enhancing the effectiveness of complex maritime logistics systems.

6.2 Practical Implication

This study also provides important practical implications for maritime logistics operations, particularly in the distribution of bio-based diesel fuel across archipelagic regions. First, it offers a flexible consolidation strategy that allows shipping operators to dynamically group multiple delivery points, thereby reducing the total number of trips and achieving significant cost savings. Second, by introducing a mechanism for vessel reassignment during consolidation, the model enables operators to optimize vessel utilization, choosing either a new or existing vessel based on cost minimization, which improves operational flexibility. Third, the incorporation of a split delivery strategy ensures that delivery commitments can still be met even when consolidated shipments cannot fully accommodate all

demands, thus maintaining service reliability without sacrificing efficiency. Finally, the integration of the trip-based cost formula within an optimization framework demonstrates that rigorous mathematical modeling can transform rigid cost structures into opportunities for enhanced logistical efficiency. Furthermore, by incorporating actual vessel types, load factors, and routing strategies, the trip-based formula provides a more precise and operationally relevant basis for estimating shipping costs per liter, applicable to both existing distribution routes and the development of new ones.

7. CONCLUSIONS AND FURTHER RESEARCH

This study provides compelling evidence that optimizing the bio-based diesel fuel distribution network through a trip-based cost formula substantially enhances transportation efficiency compared to the traditional static cost-per-liter approach. This study expands on Ransikarbum *et al.* (2024) by incorporating split deliveries and addressing maritime-specific complexities. Based on the research questions posed, several key conclusions are drawn. First, shipment allocation optimization under the point-to-point models significantly reduced annual transportation costs relative to the unoptimized baseline. Second, although the trip-based cost formula resulted in higher per-liter costs for 58% of shipment pairs, statistical analysis confirmed its reliability, reinforcing its value for realistic and flexible cost estimation in maritime logistics. Third, dynamically matching vessel types to parcel sizes proved critical; despite generating more route combinations, this strategy markedly reduced total transportation costs compared to static vessel assignment. Fourth, implementing a point-to-many strategies with split deliveries and dynamic vessel selection achieved remarkable cost savings, exceeding 18% compared to the current model, underscoring the transformative potential of adaptive, consolidation-based strategies for Indonesia's archipelagic supply chain. These findings advocate a decisive shift toward more dynamic, optimized frameworks to ensure the future resilience and sustainability of maritime fuel logistics.

While this study offers important insights into optimizing bio-based diesel fuel distribution, several simplifying assumptions present opportunities for future research. First, vessel availability was assumed to be unlimited across all vessel types, enabling flexible assignment based solely on parcel size. In practice, vessel availability is often constrained by operational schedules, maintenance, and charter limitations. Future models could incorporate dynamic vessel availability constraints, enhancing realism and applicability. Second, consolidation strategies in this study were limited to shipments originating from the same BUBBN location. However, future research could explore inter-BUBBN consolidation, where shipments from different supply points are combined to maximize vessel utilization and further reduce costs. Developing models that account for inter-supplier coordination and complex consolidation scenarios would provide a richer understanding of optimization potentials in archipelagic logistics systems.

CONFLICTS OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENTS

Data will be made available on request.

REFERENCES

- Amaliah, B., Fatichah, C., & Suryani, E. (2022). A supply selection method for better feasible solution of balanced transportation problem. *Expert Systems with Applications*, 203, 117399.
- Arevalo-Ascanio, R., De Meyer, A., Gevaers, R., Guisson, R., & Dewulf, W. (2024). Location-routing problem for integrated supply chain network design with first and last mile: a critical literature review. *Operations and supply chain management: an international journal*, 17(2), 206-219.
- Archetti, C., & Speranza, M. G. (2008). The split delivery vehicle routing problem: A survey. In *The vehicle routing problem: Latest advances and new challenges* (pp. 103-122). Boston, MA: Springer US.
- Archetti, C., Bianchessi, N., & Speranza, M. G. (2014). Branch-and-cut algorithms for the split delivery vehicle routing problem. *European Journal of Operational Research*, 238(3), 685-698.
- Avci, M., & Topaloglu, S. (2016). A hybrid metaheuristic algorithm for heterogeneous vehicle routing problem with simultaneous pickup and delivery. *Expert Systems with Applications*, 53, 160-171.
- Christiansen, M., Fagerholt, K., Nygreen, B., & Ronen, D. (2013). Ship routing and scheduling in the new millennium. *European Journal of Operational Research*, 228(3), 467-483.
- Fazi, S., Fransoo, J. C., Van Woensel, T., & Dong, J. X. (2020). A variant of the split vehicle routing problem with simultaneous deliveries and pickups for inland container shipping in dry-port based systems. *Transportation Research Part E: Logistics and Transportation Review*, 142, 102057.
- Harrath, Y., & Kaabi, J. (2018). New heuristic to generate an initial basic feasible solution for the balanced transportation problem. *International Journal of Industrial and Systems Engineering*, 30(2), 193-204.
- Hennig, F., Nygreen, B., Furman, K. C., & Song, J. (2015). Alternative approaches to the crude oil tanker routing and scheduling problem with split pickup and split delivery. *European Journal of Operational Research*, 243(1), 41-51.
- IEA (International Energy Agency). (2022). "An Energy Sector Roadmap to Net Zero Emissions in Indonesia." Retrieved April 20, 2025 from <https://iea.blob.core.windows.net/assets/b496b141-8c3b-47fc-adb2-90740eb0b3b8/AnEnergySectorRoadmaptoNetZeroEmissionsinIndonesia.pdf>
- IESR (Institute for Essential Services Reform). (2023). "Indonesia Energy Transition Outlook (IETO) 2023." Retrieved April 20, 2025 from <https://iesr.or.id/en/pustaka/indonesia-energy-transition-outlook-ieto-2023/#:~:text=IETO%202023%20arrives%20just%20as,toward%20clean%20energy%20last%20year>
- Kabadurmus, O., & Erdogan, M. S. (2023). A green vehicle routing problem with multi-depot, multi-tour, heterogeneous fleet

- and split deliveries: a mathematical model and heuristic approach. *Journal of Combinatorial Optimization*, 45(3), 89.
- Kementerian Energi dan Sumber Daya Mineral. (2023). "Laporan Kinerja Tahun 2023." Retrieved April 20, 2025 from <https://www.esdm.go.id/assets/media/content/content-laporan-kinerja-kementerian-esdm-tahun-2023.pdf>
- Lysgaard, J., Letchford, A. N., & Eglese, R. W. (2004). A new branch-and-cut algorithm for the capacitated vehicle routing problem. *Mathematical programming*, 100(2), 423-445.
- LEMIGAS Oil and Gas Testing Center, Ministry of Energy and Mineral Resources. (2024). "Group Discussion and Interview in determining shipping cost/liter of bio-based diesel fuel."
- Ministerial Decree of Energy and Mineral Resources No. 158.K/EK.05/DJE.S/2024
- Mor, A., & Speranza, M. G. (2022). Vehicle routing problems over time: a survey. *Annals of Operations Research*, 314(1), 255-275.
- Ozfirat, P. M., & Ozkarahan, I. (2010). A constraint programming heuristic for a heterogeneous vehicle routing problem with split deliveries. *Applied Artificial Intelligence*, 24(4), 277-294.
- Panda, A., Das, C. B., Midnapore, P., Bengal, W., Mahavidyalaya, T., & Bengal, W. (2014). Capacitated transportation problem under vehicles. *Camo Journal*, 16(1), 73-91.
- Rajaei, M., Moslehi, G., & Reisi-Nafchi, M. (2022). The split heterogeneous vehicle routing problem with three-dimensional loading constraints on a large scale. *European Journal of Operational Research*, 299(2), 706-721.
- Ransikarbum, K., Kritchanchai, D., Chanpuypetch, W., & Niemsakul, J. (2024). Central hospital location and distribution planning using integrated K-means and vehicle routing algorithm in the healthcare chain. *Operations and Supply Chain Management: An International Journal*, 17(2), 299-315.
- Sabbagh, M. S., Ghafari, H., & Mousavi, S. R. (2015). A new hybrid algorithm for the balanced transportation problem. *Computers & Industrial Engineering*, 82, 115-126.
- Šedivý, J., Průša, P., Čejka, J., & Bartuška, L. (2022). Utilization of the Capacitated Vehicle Routing Problem with the Capacity Limitation of Nodes in Water Transportation. *NAŠE MORE: znanstveni časopis za more i pomorstvo*, 69(3), 149-158.
- Singh, S., & Gupta, G. (2014). A new approach for solving cost minimization balanced transportation problem under uncertainty. *Journal of Transportation Security*, 7(4), 339-345.
- Tian, X., Guan, Y., & Wang, S. (2023). A decision-focused learning framework for vessel selection problem. *Mathematics*, 11(16), 3503.
- Yoshizaki, H. T. Y. (2009). Scatter search for a real-life heterogeneous fleet vehicle routing problem with time windows and split deliveries in Brazil. *European Journal of Operational Research*, 199(3), 750-758.
- Zhang, H., Li, Q., & Yao, X. (2025). An efficient local search algorithm for split delivery vehicle routing problem with three-dimensional loading. *Memetic Computing*, 17(2), 1-37.
- Zolfani, S. H., Görçün, Ö. F., Kundu, P., & Küçükönder, H. (2022). Container vessel selection for maritime shipping companies by using an extended version of the Grey Relation Analysis (GRA) with the help of Type-2 neutrosophic fuzzy sets (T2NFN). *Computers & Industrial Engineering*, 171, 108376.

Artya Lathifah is a lecturer at the Department of Industrial Engineering, Universitas Indonesia. She earned her Ph.D. in Industrial and Information Management from National Cheng Kung University, Taiwan, in 2023, where she was recognized as an Outstanding Ph.D. Student and a Phi Tau Phi Honor Member. She later continued as a postdoctoral researcher at the same institution. Her research focuses on operations management, game theory, and technology adoption in supply chains, with publications in journals such as the *European Journal of Operational Research*, *Decision Support Systems*, *International Journal of Production Economics*, *Research in Transportation Business & Management*, and others.

Komarudin is the Head of the Industrial Engineering Department at the Faculty of Engineering, Universitas Indonesia. He received his Ph.D. from Vrije Universiteit Brussel, Belgium, with a research focus on optimization and mathematical programming for industrial applications. His work has been published in leading journals, including the *European Journal of Operational Research*, *Annals of Operations Research*, and the *Journal of the Operational Research Society*. He is also actively engaged in professional organizations, notably serving as the Regional Coordinator for Jakarta in the Association of Indonesian Industrial Engineering Higher Education Providers (BKSTI).

Danang Sismartono is a PhD student at the Department of Industrial Engineering, University of Indonesia. He is also a professional in oil and gas techno-economic and works at the Oil & Gas Testing Center LEMIGAS, Ministry of Energy and Mineral Resources. His research has been published in journals including the *Indonesian Journal of Energy*, *Scientific Contribution Oil and Gas*, and *Bioresource Technology Report*. Currently he is conducting research related to the optimization of energy commodity distribution, energy policy, CCS/CCUS and new and renewable energy economics modelling.

Muhammad Dliya'ul Haq joined the Department of Information Management at the National Sun Yat-sen University in the fall semester of 2022. Besides, he is a visiting scholar at the Department of Computer Information Systems, J. Mack Robinson College of Business, Georgia State University, United States. His research interests include AI-enabled service innovation, the adoption of information technology, electronic commerce, social commerce, virtual communities, and digital marketing. His research has appeared in *Journal of Retailing and Consumer Services*, *Electronic Commerce Research and Applications*, *Journal of Destination Marketing & Management*, *Marketing Intelligence and Planning*, *Research in Transportation Business & Management*, *Tourism and Hospitality Research*, and others.

Nurul Lathifah is a faculty member at the Department of Industrial Engineering, Universitas Indonesia. She holds degrees from Universitas Islam Indonesia and Universitas Gadjah Mada. Her research focuses on behavioral operational research, system simulation, and agent-based modeling, with publications in journals such as the *Journal of Risk Research*, particularly on misinformation detection during the COVID-19 pandemic.

Herbert Wibert Victor Hasudungan is an Energy Economics and Policy Analyst at the Directorate General of New, Renewable Energy and Energy Conservation, Ministry of Energy and Mineral Resources, Indonesia. He earned his Ph.D. in Energy Economics from the University of Dundee, UK. His research focuses on the intersection of economics, energy, and environmental policy, applying CGE models to evaluate carbon taxation and renewable energy subsidies. His work has appeared in journals such as the Bulletin of Indonesian Economic Studies, Rivista di Studi sulla Sostenibilità, Scientific Contributions Oil and Gas, and the Central European Journal of Economic Modelling and Econometrics.