

Optimizing Green Vehicle Routing Problem for Halal and Non-Halal Products using Salp Swarm Algorithm

Dana Marsetiya Utama, Aisyah Leilani Salsabilah *

Department of Industrial Engineering, University of Muhammadiyah Malang, Malang, 65144, Indonesia

* Corresponding Author: aisyahleilanisalsabilah@gmail.com

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ABSTRACT

Modern distribution systems must clearly distinguish between halal and non-halal items, particularly in areas with sizable Muslim populations and rising awareness of halal integrity. Consumer confidence may suffer, halal principles may be broken, and cross-contamination may result from failing to maintain this separation. This research uses the Green Vehicle Routing Problem (GVRP) approach, which is solved with the Salp Swarm Algorithm (SSA), to develop a joint distribution optimization model for halal and non-halal products in an effort to address these issues. With complete separation and adherence to halal logistics regulations, this methodology aims to reduce Total Distribution Cost (TDC), which comprises fuel expenses, carbon emissions, and operating costs. The SSA method is combined with Large Rank Value (LRV) to convert continuous solutions into practical and feasible route sequences. Simulation results using synthetic data from 20 customer locations show that increasing the population size and SSA iterations consistently reduces the TDC value until stable convergence is achieved. The model also proves to be robust to changes in fuel costs, emissions, and vehicles without altering the route structure. Overall, the results of the research show that the SSA-based GVRP model is capable of providing efficient and sustainable halal logistics solutions. The novelty of this research lies in the explicit integration of halal and non-halal segregation with the SSA-based GVRP optimization framework in a single sustainable distribution system.

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1. Introduction

The issue of separation between halal and non-halal products has become a critical concern in contemporary distribution systems, especially in countries with large Muslim populations and increasing consumer awareness of the halal status of the products they consume (Ziegler et al., 2022). In this context, non-compliance with the principle of segregation of halal and non-halal products not only has the potential to cause cross-contamination that damages product integrity, but can also lead to serious violations of halal principles that are strictly regulated in religious laws and regulations (Okpala & Korzeniowska, 2023). The consequences of these violations include lawsuits, damage to a company's reputation, and a significant decline in consumer confidence (Dwi Agustina Kurniawati & Rochman, 2023; Mo et al., 2023). This trust is a key element in the operational continuity and sustainability of the halal industry. Therefore, the urgency of developing a halal logistics system is not only driven by operational efficiency, but also closely related to ethical considerations, regulatory

compliance, and the sustainability of the halal industry, which is currently experiencing rapid growth globally (Dwi Agustina Kurniawati & Rochman, 2023; Vienazindienė et al., 2021). The integrity of halal logistics is a non-negotiable foundation in the modern supply chain, as it concerns not only meeting market preferences but also the moral and social responsibility of companies in providing distribution services that are transparent, accountable, and in line with the religious values embraced by consumers (Azizan et al., 2024).

Efficient and sustainable logistics distribution is a major concern in modern supply chain systems, especially in the context of increasing awareness of environmental issues (Utama et al., 2023) and compliance with halal principles (Ab Rashid & Bojei, 2019). The Green Vehicle Routing Problem (GVRP) is a strategic approach designed to optimize distribution routes by considering two crucial aspects simultaneously, namely logistics efficiency and reduction of environmental impact through minimization of mileage, fuel consumption, and carbon emissions (Dewi & Utama, 2021; Fang et al., 2022). The application of GVRP is becoming increasingly relevant as global pressure on the industry to adopt environmentally friendly logistics practices as part of its sustainability commitment increases (Sabet & Farooq, 2022). However, most previous studies have focused on optimizing costs, travel time, and distribution efficiency for fresh or agricultural products, without explicitly integrating the separation of halal and non-halal products into integrated distribution systems (Miao et al., 2023; Rahim et al., 2023). In fact, in the context of Muslim communities that have specific requirements for product halalness, the inability of logistics systems to ensure total segregation can lead to cross-contamination, sharia violations, and a decline in consumer trust. Therefore, there is an urgent need to develop distribution strategies that not only maximize logistics efficiency and environmental sustainability but also strictly ensure the separation of halal and non-halal products at every stage of distribution, from routes and vehicles to delivery times (Kurniawati et al., 2023). The integration of sustainability principles and halal compliance is an important foundation in creating a modern logistics system that is adaptive to market demands and religious values (Febriyanti et al., 2022; Sihotang, 2024).

The Salp Swarm Algorithm (SSA) is a metaheuristic approach that demonstrates high performance in solving complex optimization problems involving many constraints, thanks to its ability to balance the exploration and exploitation processes during solution search (Garside et al., 2024). This advantage makes SSA a competitive alternative to classical algorithms such as Genetic Algorithm or Ant Colony Optimization, which tend to get stuck on local solutions (Abualigah et al., 2024). In the context of logistics, SSA has been successfully implemented to solve various variants of the Vehicle Routing Problem (VRP), particularly those emphasizing route efficiency (Pham et al., 2025) and emission reduction (Son Pham et al., 2024). However, the application of SSA in distribution systems that simultaneously handle halal and non-halal products is still very limited. Most previous studies have focused only on the technical aspects of route optimization without explicitly considering the need for product segregation based on religious values and sharia compliance. The lack of integration of halal and non-halal segregation into the SSA-based GVRP framework creates a significant gap in the literature. Therefore, this research presents an innovative contribution by being one of the first studies to incorporate the principle of halal-non-halal segregation into a GVRP model optimized using SSA, thereby enriching the literature on sustainable halal logistics from both a methodological and practical application perspective (Fathima et al., 2024; Xiong & Chia, 2024).

The main gap in the literature lies in the absence of a distribution optimization model that comprehensively integrates the segregation of halal and non-halal products into the GVRP framework using the SSA approach. Although various algorithms have been used in the context of distribution route optimization, very few studies have explicitly addressed the challenge of simultaneously distributing these two product categories separately, whether in terms of vehicles, routes, warehouses, or delivery times (Dwi Agustina Kurniawati & Rochman, 2023; Kurniawati et al., 2024). This research aims to fill this gap by developing and testing an SSA-based distribution optimization model specifically designed to ensure complete segregation between halal and non-halal products, while minimizing overall mileage and operational costs (Afifah & Abduh, 2024). The main contribution of

this research is the presentation of a holistic model that not only considers technical and sustainability aspects but also accommodates cultural and religious factors in a single integrated optimization framework. This approach is particularly relevant for multi-category distribution companies facing pressure to improve efficiency without compromising compliance with halal regulations. The validity and effectiveness of this model are reinforced through literature-based case scenarios that illustrate its broad potential application in contemporary logistics practices, particularly in regions with high sensitivity to halal issues.

2. Method

2.1. Assumptions and Problem Definition

Based on this research, some assumptions are observed as follows: (1) Each vehicle is dedicated to one type of product (halal/non-halal), (2) Each vehicle departs and returns to the warehouse, (3) Vehicles are prohibited from making split deliveries, and (4) All vehicles have the same capacity. Some notations are also used to define Total Distribution Cost, as shown below.

H	: Maximum number of vehicles dedicated to halal product distribution
h	: Distribution of halal products
I	: Number of retailers
i	: Node i
j	: Node j
C_f	: Fuel cost (Rp/liter)
C_e	: Carbon emission cost (Rp/liter)
Fc_{ij}	: Fuel consumption for unloaded vehicles
Cv_H	: Halal transportation cost
r_{ij}	: Distance traveled from node i to node j (km)
V_{ij}	: Average vehicle speed (km/h)
St_i	: Service time at node i (h)
X_{ijH}	: Binary variable, 1 if there is a halal product traveling from node i to node j
NH	: Maximum number of vehicles dedicated to non-halal product distribution
n	: Distribution of non-halal products
Cv_{NH}	: Non-halal transportation cost
Y_{ijNH}	: Binary variable, 1 if there is a non-halal product traveling from node i to node j
X_{0jh}	: Ensures that every halal vehicle delivery route starts at the depot (warehouse)
$X_{i,I+1,h}$	: Ensures that every halal vehicle delivery route ends at the depot (warehouse)
Y_{0jn}	: Ensures that every non-halal vehicle delivery route starts at the depot (warehouse)
$Y_{i,I+1,n}$	: Ensures that every non-halal vehicle delivery route ends at the depot (warehouse)
dh_i	: Halal product demand of retailer i (units)
dn_i	: Non-halal product demand of retailer i (units)
Q	: Vehicle capacity (Kg)
p	: Delivery route
X_{iph}	: Delivery route sequence constraint from node i for a halal vehicle
X_{pjh}	: Delivery route sequence constraint up to node i for a halal vehicle
Y_{ipn}	: Delivery route sequence constraint from node i for a non-halal vehicle
Y_{pjn}	: Delivery route sequence constraint up to node i for a non-halal vehicle

The GVRP mathematical model was developed to determine the optimal route for vehicles distributing products to a number of customers with the aim of minimizing total costs and reducing carbon emissions. This model consists of an objective function and a set of constraints, such as vehicle capacity, one visit to each customer, and a prohibition on the formation of sub-tours. The objective function of the proposed model is formulated in Eq. (1). This function is used to minimize the total distribution cost of halal and non-halal products.

$$\sum_{h=1}^H \sum_{j=1}^{I+1} \sum_{i=0, i \neq j}^I \left(((C_f + C_e) x F c_{ij}) + \left(C v_H x \left(\frac{r_{ij}}{v_{ij}} + S t_i \right) \right) \right) x X_{ijh} + \quad (1)$$

$$\sum_{n=1}^{NH} \sum_{j=1}^{I+1} \sum_{i=0, i \neq j}^I \left(((C_f + C_e) x F c_{ij}) + \left(C v_{NH} x \left(\frac{r_{ij}}{v_{ij}} + S t_i \right) \right) \right) x Y_{ijnH}$$

$$\sum_{h=1}^H \sum_{j=1, i \neq j}^{I+1} X_{ijh} = 1; \quad i = 0, 1, 2 \dots I \quad (2)$$

$$\sum_{h=1}^H \sum_{j=1, i \neq j}^I X_{ijh} = 1; \quad j = 0, 1, 2 \dots I \quad (3)$$

$$\sum_{n=1}^{NH} \sum_{j=1, i \neq j}^{I+1} Y_{ijn} = 1; \quad i = 0, 1, 2 \dots I \quad (4)$$

$$\sum_{n=1}^{NH} \sum_{j=1, i \neq j}^I Y_{ijn} = 1; \quad j = 0, 1, 2 \dots I \quad (5)$$

$$\sum_{j=1}^{I+1} X_{0jh} = 1; \quad h = 1, 2, \dots, H \quad (6)$$

$$\sum_{i=0}^I X_{i, I+1, h} = 1; \quad h = 1, 2, \dots, H \quad (7)$$

$$\sum_{j=1}^{I+1} Y_{0jh} = 1; \quad n = 1, 2, \dots, N \quad (8)$$

$$\sum_{i=0}^I Y_{i, I+1, h} = 1; \quad n = 1, 2, \dots, N \quad (9)$$

$$\sum_{j=1}^{I+1} \sum_{i=1, i \neq j}^I d h_i X_{ijh} \leq Q; \quad h = 1, 2, \dots, H \quad (10)$$

$$\sum_{j=1}^{I+1} \sum_{i=1, i \neq j}^I d n_i Y_{ijn} \leq Q; \quad n = 1, 2, \dots, N \quad (11)$$

$$\sum_{i=0, i \neq p}^I X_{iph} - \sum_{j=1, p \neq j}^{I+1} X_{pjh} = 0; \quad p = 1, 2, \dots, I; h = 1, 2, \dots, H \quad (12)$$

$$\sum_{i=0, i \neq p}^I Y_{ipn} - \sum_{j=1, p \neq j}^{I+1} Y_{pjn} = 0; \quad p = 1, 2, \dots, I; h = 1, 2, \dots, N \quad (13)$$

$$X_{ijh} \in \{0, 1\}; \quad i = 0, 1, 2 \dots, I; j = 1, 2, 3 \dots, I + 1; i \neq j; h = 1, 2, \dots, H \quad (14)$$

$$Y_{ijn} \in \{0, 1\}; \quad i = 0, 1, 2 \dots, I; j = 1, 2, 3 \dots, I + 1; i \neq j; n = 1, 2, \dots, N \quad (15)$$

The proposed model combines the following constraints. Eq. (2) and Eq. (3) stipulate that each node (retailer) i is visited exactly once by vehicle h dedicated to the distribution of halal products. Eq. (4) and Eq. (5) stipulate that each node (retailer) i is visited exactly once by vehicle n dedicated to the distribution of non-halal products. For the distribution of halal products, Eq. (6) ensures that each delivery route of vehicle h starts at the depot (warehouse), while Eq. (7) ensures that each delivery route of vehicle h ends at the depot (warehouse). Eq. (8) and Eq. (9) have the same purpose for the distribution of non-halal products. Eq. (10) and Eq. (11) limit the load of vehicle h and vehicle n to their respective capacities. Eq. (12) and Eq. (13) limit the delivery route sequence for vehicles h and

n, respectively. Finally, Eq. (14) and Eq. (15) represent the binary and non-negative decision variables X_{ijh} and Y_{ijn} .

2.2. Salp Swarm Algorithm (SSA)

This research uses the Salp Swarm Algorithm as a metaheuristic algorithm to solve the Green Vehicle Routing Problem. SSA is based on the behavior of salps that form swarms when navigating and searching for food in the sea, with a leader and follower mechanism that moves in a coordinated manner (Garside et al., 2024). In this research, the main parameters used include population size (N), maximum number of iterations, lower bound (lb), upper bound (ub), distance between points, halal and non-halal demand, fuel cost, emission cost, and transportation cost. Fig. 5 shows the stages of solving GVRP using SSA, from initialization to solution evaluation.

The pseudocode shown in Fig. 1 can be used to illustrate the Salp Swarm Algorithm's (SSA) sequential process. The iterative process of initializing the salp population, assessing fitness, adjusting leader and follower positions, and implementing boundary constraints until convergence is attained is described by this pseudocode.

```

Initialize the salp population  $x_i (i = 1, 2, \dots, n)$  considering  $ub$  and  $lb$ 
while (end condition is not satisfied)
    Calculate the fitness of each search agent (salp)
     $F$  = the best search agent
    Update  $c_1$  by Eq. (17)
    for each salp ( $x_i$ )
        if ( $i==1$ )
            Update the position of the leading salp by Eq. (16)
        else
            Update the position of the follower salp by Eq. (19)
        end
    end
    Amend the salps based on the upper and lower bound of variables
end
return  $F$ 

```

Fig. 1. Pseudocode of the Salp Swarm Algorithm

To update the position of the leader, the following Eq. (16) is proposed:

$$x_j^i = \begin{cases} F_j + c_1 ((ub_j - lb_j) c_2 + lb_j) c_3 \geq 0,5 \\ F_j - c_1 ((ub_j - lb_j) c_2 + lb_j) c_3 < 0,5 \end{cases} \quad (16)$$

Where x_j^i denotes the position of the first salp (leader) in the j^{th} dimension, F_j is the food source, ub_j and lb_j represent the upper and lower bounds of the search space, and c_1, c_2, c_3 are random numbers.

The coefficient c_1 is the most critical parameter balancing exploration and exploitation, as defined in Eq. (17).

$$c_1 = 2e^{-\left(\frac{4i}{L}\right)^2} \quad (17)$$

Where i is the current iteration and L is the maximum number of iterations.

For the follower salps, the position is updated using Newton's law of motion as expressed in Eq. (18).

$$x_j^i = \frac{1}{2}at^2 + v_0t \quad (18)$$

Since the optimization is conducted in discrete iterations, and assuming $v_0 = 0$, the simplified form of the follower update becomes Eq. (19).

$$x_j^i = \frac{1}{2}(x_j^i + x_j^{i-1}) \quad (19)$$

These equations simulate the chain movement of salps in the search space and enable the algorithm to dynamically adjust its position toward the global optimum while maintaining exploration balance.

Fig. 2 illustrates the salp swarm represented in a two-dimensional matrix, where each row shows the position of individual salps in the solution space (Garside et al., 2024). These positions are still continuous values, so they need to be converted into discrete sequences to form travel routes. For this purpose, the LRV method is used, which has been proven effective in converting continuous representations into discrete solutions in routing problems (Ananda et al., 2024). LRV works by sorting the salp position values from largest to smallest, then translating them into a sequence of customer visits. Fig. 3 illustrates the process of converting continuous positions into discrete sequences using LRV.

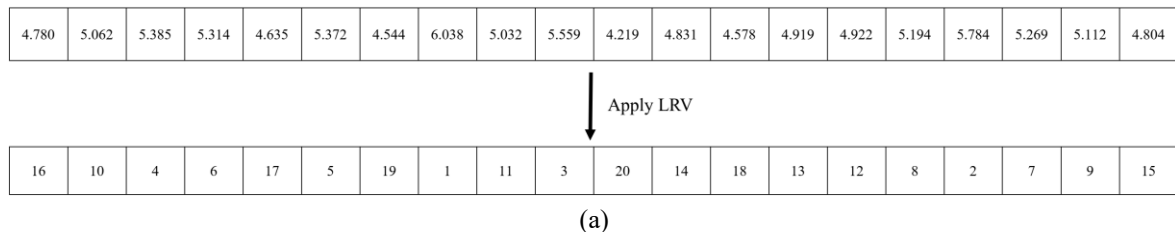
Once the visit sequence is obtained, the next step is to arrange the distribution route by considering vehicle capacity and the separation of halal and non-halal products. Thus, each solution produced is not only mathematically valid but also complies with the principle of segregation. This route arrangement process is shown in Fig. 4, where the LRV sequence is mapped into a feasible distribution route. With this approach, each solution generated is not only mathematically valid but also complies with the halal segregation principle, which is key in a combined distribution system (Kurniawati et al., 2023; Mo et al., 2023).

The LRV method is applied to each salp in each SSA iteration. In this way, SSA can balance exploration and exploitation capabilities in the search for optimal solutions. At the same time, LRV ensures that the solution results can be converted into routes that can be applied to halal and non-halal distribution systems. The integration of the two enables an efficient, adaptive solution search that meets halal logistics requirements (Agrawal et al., 2022; Wu et al., 2022).

$$\begin{aligned} \text{Population}_h &= \begin{bmatrix} 5.266 & 5.103 & 5.015 & 4.884 & 5.725 & \dots & 4.849 \\ 5.371 & 4.995 & 4.775 & 5.178 & 5.464 & \dots & 5.035 \\ 5.269 & 5.112 & 5.032 & 4.919 & 6.038 & \dots & 5.062 \end{bmatrix} & \text{Population}_{nh} &= \begin{bmatrix} 4.786 & 5.179 & 5.048 & 4.335 & 5.363 & \dots & 4.475 \\ 5.651 & 3.945 & 5.035 & 4.646 & 4.844 & \dots & 5.425 \\ 4.791 & 5.255 & 5.072 & 5.320 & 5.381 & \dots & 5.511 \end{bmatrix} \end{aligned}$$

(a)
(b)

Fig. 2. Population. (a) Halal. (b) Non-Halal



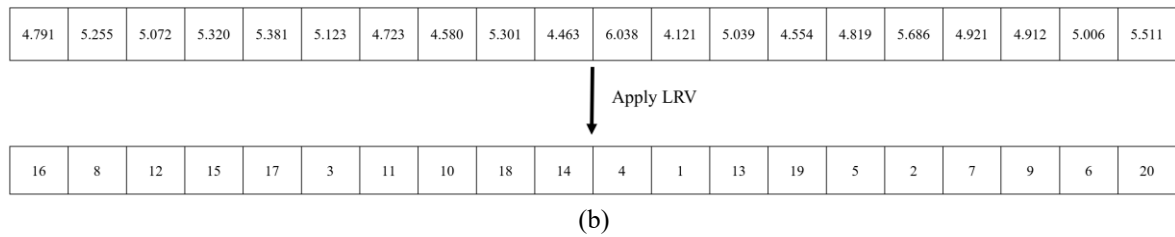


Fig. 3. Representation of LRV. (a) Halal Travel Sequence. (b) Non-Halal Travel Sequence

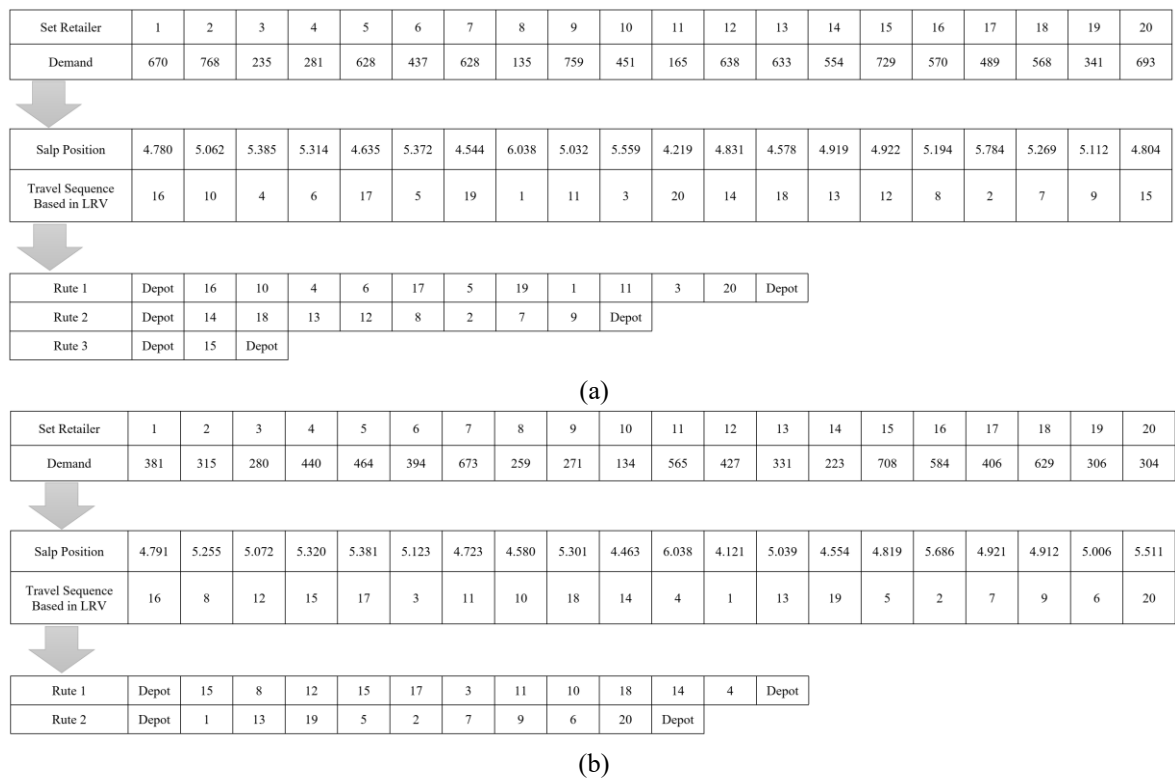


Fig. 4. Route Arrangement (a) Halal Route. (b) Non-Halal Route

2.3. Data Collection

Using scenarios based on synthetic data that represented actual conditions, the research's data came from random numerical data that was simulated from a distribution system for halal and non-halal products. According to Fig. 6, there is a single DC and twenty client points that need to be attended to. Every customer has various needs, which are distinguished by the kinds of halal and non-halal products. The Colt Diesel Double (CDD) Truck is the vehicle that is utilized, and its maximum vehicle capacity is 5.000 kg per vehicle per day. A distance matrix, with values ranging from 3.4 km to 58.8 km, is used to compute the distance between places. For the vehicle being used, the cost of fuel is Rp13.350 per liter and the cost of carbon emissions per liter is Rp1.227. Furthermore, the maximum driver working time is eight hours per day, and the daily vehicle maintenance cost is Rp31.250. In this research, vehicle routes are optimized using the Salp Swarm Algorithm approach based on overall expenses, which include pollution, fuel, and operating time. To discover the best route solution, a number of algorithm parameters are simulated in different circumstances, including the number of iterations and the size of the SSA population. MATLAB software will be used to run this technique with 1.000 iterations and 1.000 populations.

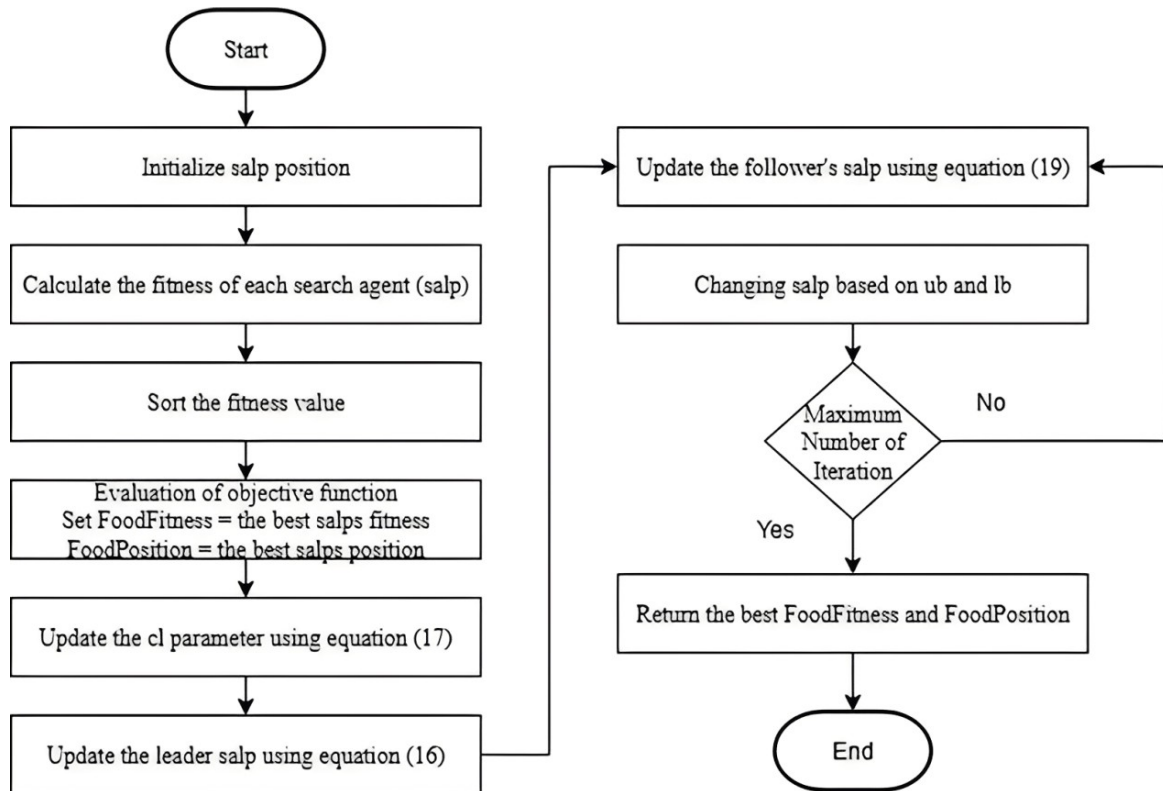


Fig. 5. Flow Chart of Salp Swarm Algorithm

	DC	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
DC	0	10.30	44.05	47.21	3.41	36.15	28.64	17.49	68.90	36.85	43.21	44.40	28.25	45.62	3.43	2.03	21.27	35.76	41.41	36.79	14.05
1	10.30	0	53.18	58.80	27.46	43.70	55.29	45.55	67.91	68.90	51.04	16.46	61.16	19.67	38.97	39.61	69.27	12.71	3.99	11.16	60.07
2	44.05	53.18	0	7.95	36.28	6.95	40.84	8.91	8.79	39.26	38.68	42.09	28.11	41.04	37.73	13.82	57.66	62.19	10.61	45.52	47.00
3	47.21	58.80	7.95	0	38.07	66.00	23.87	56.03	45.21	14.63	55.99	12.81	22.29	63.54	44.35	69.39	66.82	13.84	19.63	57.15	40.30
4	3.41	27.46	36.28	38.07	0	36.35	18.81	32.86	48.72	54.92	36.57	64.20	10.45	66.14	11.31	34.83	47.99	28.46	66.27	60.51	54.21
5	36.15	43.70	6.95	66.00	36.35	0	44.74	42.61	52.46	47.82	54.59	66.24	43.37	13.14	25.21	41.56	58.02	2.70	7.96	4.12	64.42
6	28.64	55.29	40.84	23.87	18.81	44.74	0	17.12	39.80	31.96	24.12	57.90	46.85	69.94	8.27	25.06	4.16	0.42	47.17	2.45	13.24
7	17.49	45.55	8.91	56.03	32.86	42.61	17.12	0	22.94	7.70	44.02	33.03	11.81	67.93	51.77	3.86	53.54	17.61	53.21	53.03	55.18
8	68.90	67.91	8.79	45.21	48.72	52.46	39.80	22.94	0	64.97	22.10	45.76	2.40	16.75	58.00	44.94	12.48	11.96	25.30	16.45	49.72
9	36.85	68.90	39.26	14.63	54.92	47.82	31.96	7.70	64.97	0	38.77	32.06	66.84	31.81	45.82	27.39	31.89	51.95	60.89	29.81	44.63
10	43.21	51.04	38.68	55.99	36.57	54.59	24.12	44.02	22.10	38.77	0	18.14	58.02	50.89	68.36	62.14	14.32	38.67	0.10	20.85	31.80
11	44.40	16.46	42.09	12.81	64.20	66.24	57.90	33.03	45.76	32.06	18.14	0	22.42	7.68	69.49	11.28	57.37	10.47	17.93	62.88	34.92
12	28.25	61.16	28.11	22.29	10.45	43.37	46.85	11.81	2.40	66.84	58.02	22.42	0	4.25	11.62	26.46	10.34	60.88	9.00	29.52	58.13
13	45.62	19.67	41.04	63.54	66.14	13.14	69.94	67.93	16.75	31.81	50.89	7.68	4.25	0	43.28	68.70	53.38	53.51	4.61	16.45	31.65
14	3.43	38.97	37.73	44.35	11.31	25.21	8.27	51.77	58.00	45.82	68.36	69.49	11.62	43.28	0	33.41	49.89	36.71	1.23	63.76	54.75
15	2.03	39.61	13.82	69.39	34.83	41.56	25.06	3.86	44.94	27.39	62.14	11.28	26.46	68.70	33.41	0	15.28	17.48	45.48	41.87	64.90
16	21.27	69.27	57.66	66.82	47.99	58.02	4.16	53.54	12.48	31.89	14.32	57.37	10.34	53.38	49.89	15.28	0	3.60	1.36	41.06	34.60
17	35.76	12.71	62.19	13.84	28.46	2.70	0.42	17.61	11.96	51.95	38.67	10.47	60.88	53.51	36.71	17.48	3.60	0	51.91	7.46	19.43
18	41.41	3.99	10.61	19.63	66.27	7.96	47.17	53.21	25.30	60.89	0.10	17.93	9.00	4.61	1.23	45.48	1.36	51.91	0	43.47	19.61
19	36.79	11.16	45.52	57.15	60.51	4.12	2.45	53.03	16.45	29.81	20.85	62.88	29.52	16.45	63.76	41.87	41.06	7.46	43.47	0	43.14
20	14.05	60.07	47.00	40.30	54.21	64.42	13.24	55.18	49.72	44.63	31.80	34.92	58.13	31.65	54.75	64.90	34.60	19.43	19.61	43.14	0

Fig. 6. Distance Matrix

3. Results and Discussion

3.1. Effect of SSA on Total Distribution Cost

The results in Table 1 show that increasing the number of iterations and population consistently reduces the total distribution cost. This confirms that the effectiveness of the Salp Swarm Algorithm is greatly influenced by the balance between exploration and exploitation in finding

optimal solutions (Bustos-Rivera et al., 2023; Chakraa et al., 2023). Conceptually, the greater the values of the iteration and population parameters, the higher the SSA's ability to avoid local solutions and produce stable convergence (Tirkolaei et al., 2022). Table 2 explains that the SSA-GVRP-HNHPD model is capable of efficiently handling problems with large data using MATLAB, demonstrating the potential for real application of SSA in complex and sustainable halal logistics systems (Badi et al., 2024; Salehi et al., 2022).

Table 1. The Effect of SSA on Total Distribution Costs (IDR)

N	Iteration					
	100	200	400	600	800	1000
100	7.255.000	7.244.200	6.705.800	6.827.200	6.316.300	6.571.800
200	6.722.600	7.480.900	6.997.800	6.657.400	6.647.100	6.484.900
400	6.769.800	6.489.100	7.404.700	6.048.900	7.246.300	6.960.800
600	6.421.000	7.560.800	7.149.400	7.280.200	5.780.300	6.143.600
800	6.206.400	5.917.500	6.079.800	5.355.800	6.985.800	5.673.800
1000	7.268.300	6.887.900	5.605.000	6.611.200	6.506.200	5.209.500

Table 2. Numerical Experiment Results with SSA-GVRP-HNHPD

Type of Product	Route	Fuel Cost	Emission Cost	Vehicle Cost	Distribution Cost	Total Distribution Cost
Halal	1-17-11-5-7-18-6-20-2-12-4-21-1	1.171.900	107.710	1.378.600	2.658.210	5.209.500
	1-15-19-14-13-9-3-8-10-1					
	1-16-1					
Non-Halal	1-17-9-13-16-18-4-12-11-19-15-5-1	1.195.600	109.890	1.245.800	2.551.290	
	1-2-14-20-6-3-8-10-7-21-1					

3.2. Sensitivity Analysis

Fig. 7 shows that an increase in fuel costs significantly increases the Total Distribution Cost for both halal and non-halal products. while the number of Sub-Routes remains relatively stable. These results indicate that the Salp Swarm Algorithm is capable of maintaining cost efficiency despite fuel fluctuations. Compared to Ant Colony Optimization (ACO), which tends to converge quickly but often gets stuck in local solutions. SSA demonstrates better stability because the salp chain mechanism allows for broader global exploration (Álvarez et al., 2024; Bustos-Rivera et al., 2023). These findings are consistent with the research, which emphasizes the importance of balancing distance and cost, but this research shows that SSA can optimize both simultaneously.

Fig. 8 shows that an increase in emission costs raises the TDC without significantly affecting the route structure. This confirms that SSA is capable of balancing economic efficiency and environmental sustainability. Compared to Genetic Algorithm (GA), which requires crossover and mutation mechanisms to adjust emission penalties. SSA is able to directly adjust emission cost weights through an adaptive fitness function (Utama, Fitriani, et al., 2022). This finding expands on the results showing that SSA is more efficient in the context of halal logistics systems because it maintains route segregation without drastically increasing costs.

Fig. 9 shows that an increase in vehicle costs has a significant impact on TDC, but the Sub-Route remains stable. This condition indicates that SSA can optimize routes by considering fleet limitations without changing distribution patterns (Bustos-Rivera et al., 2023). These results improve on the research, where GA showed good performance on single capacity but was less efficient for a multi-

fleet system. In contrast, SSA has higher flexibility because it does not require complex random operators and is capable of producing rapid convergence with minimal parameter variation.

Fig. 10 compares the initial conditions and distribution cost efficiency results for the halal product segment. A significant decrease in TDC occurred without changing the number of Sub-Routes, indicating that SSA is effective in optimizing partial costs without disrupting the overall distribution system balance (Kurniawati et al., 2023). These findings complement the research, which focused on cost segmentation efficiency but did not consider algorithmic adaptability. In this context, SSA proved to be superior to classical deterministic and heuristic approaches because it is able to adjust search parameters according to the dynamics of complex halal distribution systems.

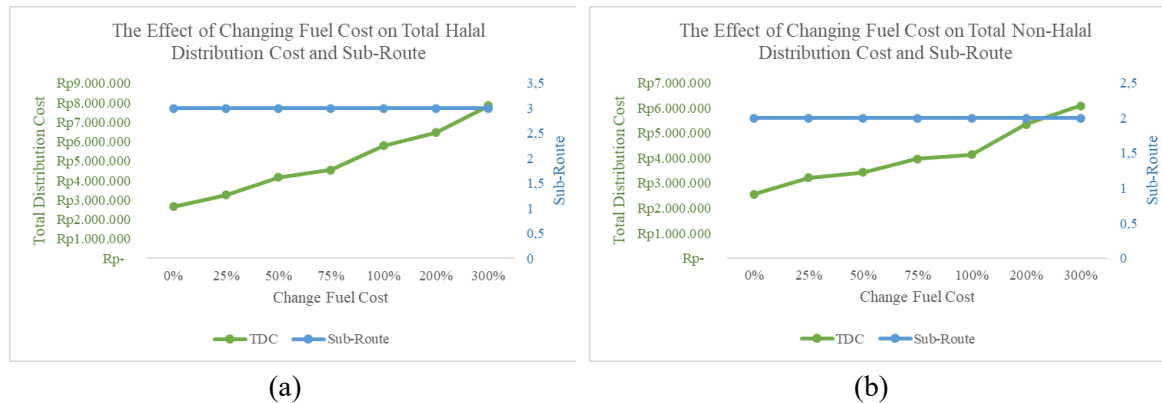


Fig. 7. The Effect of Fuel Cost Changes on Total Distribution Cost and Sub-Route. (a) Halal Product. (b) Non-Halal Product.

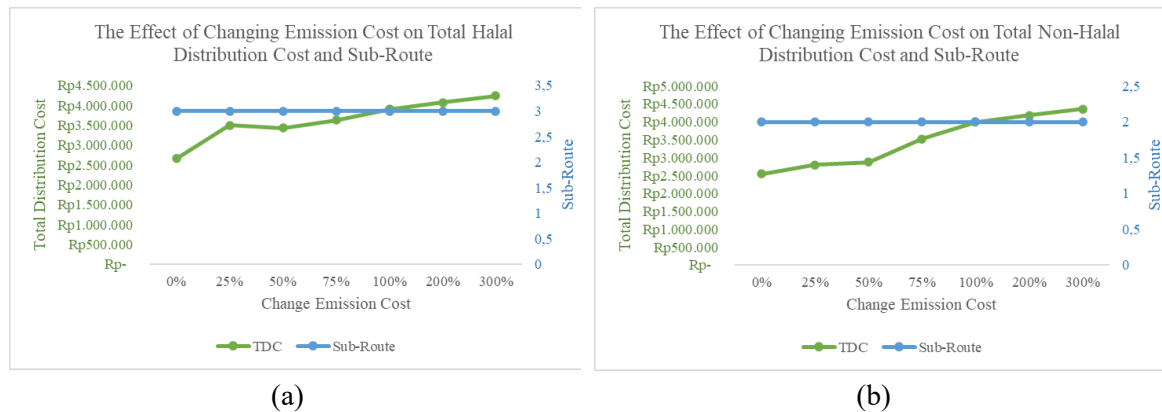


Fig. 8. The Effect of Emission Cost Changes on Total Distribution Cost and Sub-Route. (a) Halal Product. (b) Non-Halal Product

When halal and non-halal segregation requirements are taken into consideration, the research findings demonstrate that SSA generates more stable solutions with lower distribution costs (Utama, Fitriani, et al., 2022). SSA is superior to other algorithms in a number of ways. For instance, Genetic Algorithm (GA) necessitates intricate crossover and mutation processes, whereas Ant Colony Optimization (ACO) tends to converge rapidly but is prone to local solutions (Alvarez et al., 2024). These results are in line with research that demonstrates SSA's efficacy in solving optimization problems with numerous constraints (Chakraa et al., 2023; Utama, Safitri, et al., 2022).

SSA's primary benefit is its capacity to strike a balance between exploration and exploitation, which enables it to adapt to both halal and non-halal distribution systems (Angarita-Zapata et al.,

2021). SSA can transform continuous solutions into discrete routes that take product segregation and truck capacity into account by integrating the LRV approach (Vienazindienė et al., 2021). However, SSA's sensitivity to parameters is also its weakness. Solutions are typically less than ideal for low populations and iterations. Additionally, SSA has not been compared to the most recent hybrid algorithms, like the Jellyfish Algorithm or Hybrid Whale Optimization, which have been shown in multiple studies to be effective in solving transportation-related problems (Utama, Safitri, et al., 2022; Utama, Widjonarko, et al., 2022).

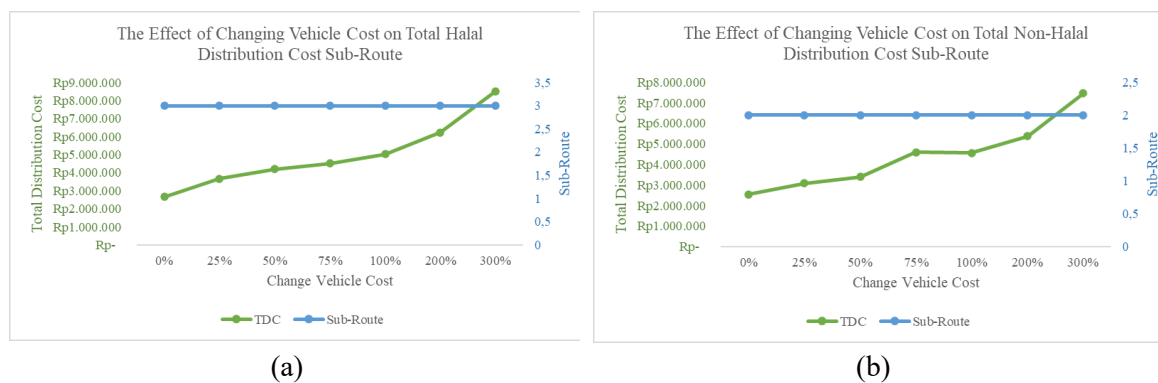


Fig. 9. The Effect of Vehicle Cost Changes on Total Distribution Cost and Sub-Route. (a) Halal Product. (b) Non-Halal Product.

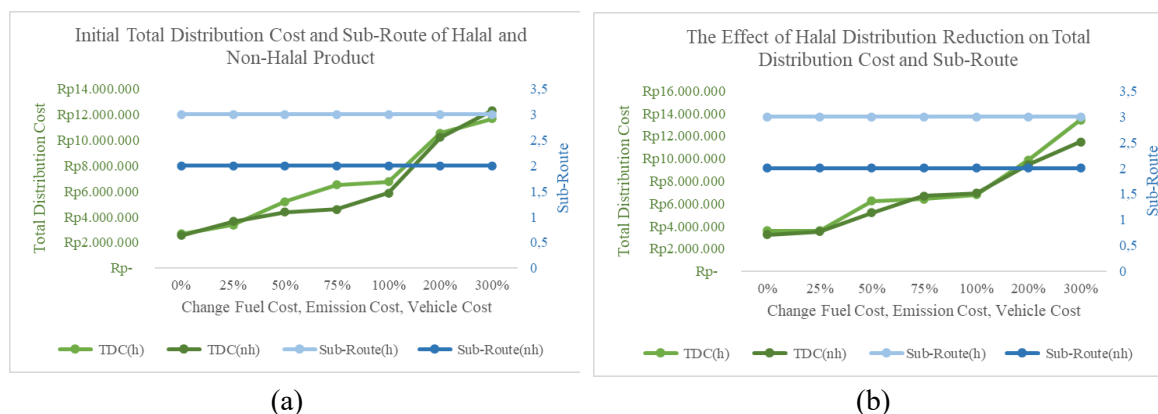


Fig. 10. The Effect of Changes in Fuel Costs, Emission Costs, And Vehicle Costs on Total Distribution Costs and Sub-Routes. (a) Initial Costs. (b) Reduction In Halal Distribution Costs.

The literature on halal logistics which previously mostly relied on deterministic models, is strengthened by this research. This research differs from others that just concentrate on cost and distribution time efficiency without taking halal compliance into account by incorporating halal and non-halal segregation into the SSA-based GVRP framework (Liu, 2024). Furthermore, as the presented model takes emission costs into account as part of the TDC, these findings are consistent with research that emphasizes sustainability dimensions (Chen et al., 2021). Thus, this research supports sustainable halal logistics practices 44 in addition to the advancement of route optimization theory.

4. Conclusion

This research develops a combined distribution model for halal and non-halal products based on the Salp Swarm Algorithm integrated with the Large Rank Value method. Simulation results show that SSA can significantly reduce Total Distribution Cost while ensuring complete segregation between halal and non-halal products. Conceptually, this research is one of the first studies to integrate

halal-non-halal segregation into the Green Vehicle Routing Problem framework using the SSA approach. The contribution of this research is both theoretical and practical. From a theoretical perspective, this research enriches the literature on halal logistics optimization by presenting an adaptive metaheuristic model that takes into account religious, technical, and sustainability aspects. From a practical standpoint, this model can be used by multi-category distribution companies to improve efficiency while maintaining compliance with halal principles. However, this research still has limitations, namely that it has not been compared in depth with other hybrid algorithms and has not been tested for implementation using real field data. Further research could develop an SSA-based hybrid model and test its application in more complex industrial scenarios.

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