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Vehicle Routing Problem Optimization for Rebar Material Distribution using the Symbiotic Organisms Search Method

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Abstract

The success rate of construction projects depends on subcontractors and material suppliers, especially in ensuring the material delivery to avoid delays and cost overruns. The Vehicle Routing Problem (VRP) addresses transportation management to minimize the distribution costs. This study presents a comparative analysis of three VRP scenarios: the existing case, the Capacitated Vehicle Routing Problem (CVRP), and the Capacitated Vehicle Routing Problem with Time Windows (CVRPTW). The Symbiotic Organisms Search (SOS) method is used to solve the VRP of a building materials supplier in Sulawesi, Indonesia in delivering rebar to 19 locations over 12 weeks while considering the vehicle capacity and the time window constraints. The results show that the SOS method effectively handles the rebar distribution problems with these constraints. The CVRP scenario achieves a total cost saving of Rp 23,263,278 (26.15%), while the CVRPTW scenario saves Rp 6,732,942 (7.57%).

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INTRODUCTION

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Construction projects involve various stakeholders including architects, designers, main contractor, subcontractors, and material suppliers [1]. The success rate of these projects heavily depends on the performance of subcontractors and material suppliers, especially in ensuring the material delivery to avoid the delays and cost overruns. This delivery process relies on several key factors, including the transportation system, infrastructure, resources availability, and the effective communication among stakeholders [2]. However, the main challenges in the material distribution involve the design of the supply chain network and organizing the transportation processes. These efforts aim to minimize the transportation costs, ensure consistent material availability, and reduce the production expenses, and it is often called the Vehicle Routing Problem (VRP) [3].

VRP is a mathematical model for solving the transportation management problems introduced by Dantzig and Ramser in 1959 to model how the group of trucks could efficiently serve the oil demands from multiple gas stations originating from a central hub with a minimum traveling distance [4]. VRP problems are classified into the static and dynamic types, where the static problems assume constant parameters, such as travel time, demand, and costs. The Dynamic Vehicle Routing Problem (DVRP) overcomes the limitations of the static VRP by accommodating the changes in customer demand and travel time, which are variable in real-world scenarios [5]. Since then, various factors influencing the problem have been identified, leading to the development of multiple VRP variants based on the specific constraints encountered in each optimization scenario. The examples of VRP variations include the Capacitated Vehicle Routing Problem (CVRP) which considers the vehicle capacity constraints [6] and the VRP with Time Windows (VRPTW), where both the customers and vehicles operate within specified time frames or working

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hours, requiring the services and operations to occur only within these certain periods [7]. Additionally, other variants have been developed to address various constraints, such as the multiple depot VRP and the VRP with pick-up and delivery requirements [8]. These VRP variants are closely linked to the real-world scenarios, with the goal of reducing the total distribution costs while maintaining high-quality distribution services [9]. The VRP is mathematically, a combinatorial optimization problem, where the number of possible solutions to the problem increases exponentially with the number of customers to be served [10,11]. The vehicle route selection process enables the selection of any combination of customers to assign the delivery route for each vehicle. Since there is no known polynomial algorithm to find the optimal solution in each instance, the problem of vehicle routing is considered Nondeterministic Polynomial Time Hard (NP-Hard) [11,12]. Figure 1 provides a general overview of the VRP problem.

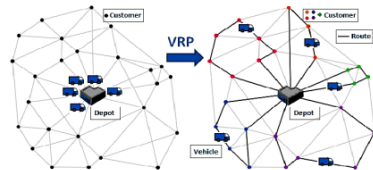


Figure 1. General Overview of VRP Problem

The VRP seeks to identify the optimal routes for multiple vehicles based on the customer demands by minimizing the total transportation costs. Solving the VRP often requires the material distributors to manually assign and adjust the delivery routes of each vehicle, which can be time-consuming. The optimization algorithms or metaheuristic methods can help identifying the best combinations of the delivery route for each vehicle, with the goal of determining the best transportation routes for multiple customers to obtain the lowest cost. The metaheuristic methods have been widely applied across various optimization problems in the construction industry. In construction site planning, the bio-inspired optimization methods have been used to improve the layout of site facilities, enhancing spatial efficiency and reducing overall project costs [13]. In project scheduling problem, the Symbiotic Organisms Search (SOS) algorithm has proven effective for resource leveling under multiple objective criteria, offering a robust solution to balance the workloads and timelines [14]. Similarly, in geotechnical engineering, the metaheuristic methods have been employed to optimize the design of counterfort retaining walls with shear key, resulting in more efficient and cost-effective structural designs [15]. Based on these facts, many studies have also used the metaheuristic methods as an optimizer for the VRP optimization problems. Ho et al. used the hybrid Genetic Algorithm (GA) to minimize the total delivery time for multi-depot VRP [16]. Khoudja et al. compared the performance of the Particle Swarm Optimization (PSO) and Variable Neighborhood Search (VNS) to solve the VRP with dynamic requests [17]. Zhang et al. implemented the hybrid Ant Colony Optimization (ACO) to minimize the total distribution costs and maximize the overall customer satisfaction of multi-objective VRPTW [18]. These studies demonstrated that the metaheuristic methods can effectively solve the VRP optimization problems.

This research employs an optimization algorithm based on the swarm intelligence, specifically the Symbiotic Organisms Search (SOS) to examine and solve the VRP problem of a building materials supplier in delivering the steel rebar to multiple stores. Some challenges that faced by the company are such as a large number of stores located in diverse regions, geographically dispersed areas, and the need to optimize the vehicle capacity for efficient use. The study focuses on single-objective optimization, aiming to optimize the vehicle routes for the rebar delivery from a single distributor to multiple material store locations while considering the customer demand, the number of vehicles, the vehicle capacity, and the delivery time constraints.

METHODS

Symbiotic Organisms Search (SOS) Method

Symbiotic Organisms Search (SOS) method is a population-based algorithm inspired by the interactions of organisms within an ecosystem, known as symbiosis. It was developed by Cheng and Prayogo and has proven to be effective in solving various mathematical problems [19,20]. This method simulates the interactions among organisms within an ecosystem as they compete, grow, and survive. It incorporates the three fundamental types of symbiotic relationships: the mutualism phase, where both species benefit; the commensalism phase, where one species benefits without harming the other; and the parasitism phase, where one species gains at the expense of the other [21]. Unlike many

competing methods, SOS does not need any parameter tuning, which enhances its performance stability [22]. The SOS method begins with an initial population called an ecosystem. In this ecosystem, a group of organisms emerges randomly in the search space. Each organism represents a solution to the optimization problem. Additionally, each organism has a fitness value reflecting its level of adaptation to the problem's objective. The organisms adapt according to the objective, and the optimization processes continue based on the number of organisms and specified iterations.

Vehicle Routing Problem: Variables, Constraints, and Objective Function in Optimization

The VRP model can be described in the form of a graph $G(A, V)$. V in Equation 1 is a set of nodes where each node represents the customer location to be served and a central depot. A in Equation 2 is a set of arcs where there are pairs of nodes connecting connections between nodes i and j with a distance d in the set in Equation 3. Each customer has a demand called D according to the set in Equation 4. M_m in Equation 5 represents a set of vehicles and capacities available for the material delivery. Each vehicle M_m has a maximum capacity cap_m , limiting the amount of materials that can be carried.

$$V = \{v_0, v_1, v_2, \dots, v_n\} \quad (1)$$

$$A = \{(v_i, v_j): v_i, v_j \in V\} \quad (2)$$

$$d = \{d_{0,1}, d_{1,2}, d_{2,3}, \dots, d_{i,j}\} \quad (3)$$

$$D = \{D_0, D_1, D_2, \dots, D_n\} \quad (4)$$

$$M_m = \{m_1, m_2, \dots, m_m\} \quad (5)$$

where:

v_n = nodes for customer and depot

$d_{i,j}$ = distance from node i to j

D_n = demand of customer i

m_m = vehicle number m

i = initial node index

j = destination node index

m = vehicle index

0 = depot index

n = index of sum

The variables used in the VRP optimization process are the customer locations and vehicles, constrained by the upper bounds (UB) and lower bounds (LB). These upper and lower bounds are determined based on the number of locations and vehicles specified by the distributor company. These variables will be separated by the program into two parts, one for the sequence of the number of locations and the other for the sequence of vehicle indices. The variables will determine the distribution cost of building materials based on the operational costs of the vehicles and wage costs specified by the company. The variables, upper bounds, and lower bounds used in this study can be seen in Equation 6 to 8.

$$R = \{r_1, r_2, r_3, \dots, r_m\} \quad (6)$$

$$LB = 0 \quad (7)$$

$$UB = dmax \quad (8)$$

where:

r_m = number of locations and the m -th vehicle.

$dmax$ = sum of location and vehicle

The constraints are needed to limit the objective function values so that they do not exceed the specified requirements. The constraints used in this study are presented in Equation 9 to 15. Subsequently, these constraints will eliminate the objective function values that exceed the limits, ensuring they do not become the optimal solution.

- Each vehicle must return to the depot.

$$\sum_{i=1}^N X_{i0,m} = 1 \quad (9)$$

- Each node can only be visited once for each route.

$$\sum_{m=1}^M \sum_{i=1}^N \sum_{j=1}^N X_{ij,m} = 1 \quad (10)$$

- After visiting a node, the vehicle must move to the next node.

$$\sum_{m=1}^M \sum_{i=1}^N X_{ip,m} = \sum_{m=1}^M \sum_{i=1}^N X_{ip,m} \quad (11)$$

- Limiting vehicle capacity and adjusting it to the customer demand.

$$\sum_{i=1}^M \sum_{j=1}^N X_{ij,m} \times D_j = Dm_{ij,m} \quad (12)$$

$$\sum_{i=1}^N Dm_{0i,m} \leq cap_m \quad (13)$$

- Limiting the number of available vehicles.

$$\sum_{m=1}^M X_{ij,m} \leq veh_m \quad (14)$$

- Time window constraints for the material delivery.

$$a_j \leq t_{ij} \leq b_j - tl_{ij} \quad (15)$$

where:

D_j = customer demand from node i to j
 $Dm_{ij,m}$ = capacity that the m -th type of vehicle can accommodate from node i to j
 cap_m = maximum vehicle capacity
 veh_m = maximum number of vehicles
 p = index of the destination node
 t_{ij} = arrival time of the vehicle at the node
 h_{ij} = working days of the vehicle for each route taken
 tl_{ij} = loading and unloading time at the node
 $[a_j, b_j]$ = time window for delivery at node j

The objective function in Equation 16 is implemented by minimizing the total delivery cost. The costs considered in this study include the fuel costs and the wage costs for each vehicle. The fuel and wage costs are determined based on the company's policy.

$$\text{Minimize } \sum_{m=1}^M \sum_{i=0}^N \sum_{j=0}^N X_{ij,m} \times fc_m + \sum_{m=1}^M \sum_{i=0}^N \sum_{j=0}^N h_{ij} \times vc_m \quad (16)$$

where:

fc_m = fuel cost of the vehicle
 vc_m = wage cost of the vehicle

RESULTS AND DISCUSSION

Case Study

The case study used in this research involves a building materials distributor company located in Sulawesi, Indonesia. The distributor delivers the steel rebar material to 30 stores located in 19 different locations. The data obtained from this case study includes the information about the distributor and store locations, the customer purchase history of steel rebar material, the store operating hours, the types and capacities of vehicle, as well as the original routes commonly used by the distributor. This research is a single-object optimization with the goal of optimizing the delivery routes of each vehicle in distributing the rebar based on the number of vehicles, vehicle capacities, delivery time constraints. The optimization results in this study are based on a single run and were implemented on a computer equipped with a Ryzen 7 5800H 3.2 GHz processor and 16 GB RAM.

The distances between stores were obtained using the Google Waypoint Application Programming Interface (GWAPI), which retrieves the distances between points from Google Maps. Details of the distances between locations or nodes can be seen in Table 1. In this table, index 1 represents the material depot, and the other 18 indices represent the customer locations. For example, the distance from node 1 (depot) to node 3 is 6.49 km, and the distance from node 3 to node 1 (depot) is 5.51 km. This difference in traveling distance may happen because the distance for departure and return can be different according to Google Maps.

Table 1. Distance between Locations or Nodes (in km)

	1	2	3	4	5	6	7	8	9	10
1	0	8.37	5.51	38.49	21.39	32.56	34.9	73.4	116.4	126.3
2	8.2	0	11.92	43.42	26.33	41.91	44.25	66.48	109.4	119.3
3	6.49	13.13	0	33.31	16.21	37.07	39.41	77.91	120.9	130.8
4	38.09	46.46	31.6	0	17.1	49.49	37.06	93.85	136.8	146.7
5	21	29.37	14.5	17.1	0	32.39	24.52	76.75	119.7	129.6
6	32.24	40.05	35.18	48.48	31.38	0	12.02	72.92	115.9	125.8
7	35.53	43.34	38.48	37.06	24.52	9.49	0	80.45	123.4	133.3
8	74.03	64.7	76.97	93.79	76.69	77.23	79.57	0	43.02	52.91
9	117	107.7	120	136.8	119.7	120.3	122.6	43.08	0	9.9
10	126.9	117.6	129.9	146.7	129.6	130.1	132.5	52.98	9.9	0
11	160.5	153.4	166.9	199.9	182.8	192.1	194.4	99.56	56.48	46.58
12	227.3	220.2	233.7	266.7	249.6	258.9	261.2	155.6	112.5	102.6
13	160.9	153.8	167.3	200.3	183.2	192.5	194.8	141.1	115.4	105.5
14	187	180	193.4	226.4	209.3	218.6	220.9	167.2	141.5	131.6
15	277.3	270.3	283.8	316.7	299.6	308.9	311.3	257.5	231.8	221.9
16	317.8	310.8	324.3	357.2	340.1	349.4	351.8	298	272.3	262.4
17	345.8	338.8	352.3	385.3	368.2	377.5	379.8	326	300.4	290.5
18	363.3	356.3	369.8	402.7	385.6	394.9	397.3	343.5	317.8	307.9
19	392	385	398.5	431.4	414.3	423.6	426	372.2	333.4	323.5

Distance between Locations or Nodes (in km) – Continued

	11	12	13	14	15	16	17	18	19
1	160.8	227.6	161.2	187.3	279.2	319.4	347.4	364.9	393.6
2	152.6	219.4	153	179.1	271	311.2	339.3	356.7	385.5
3	168	234.8	168.4	194.5	286.4	326.6	354.6	372.1	400.8
4	199.6	266.4	200	226.1	317.9	358.2	386.2	403.7	432.4
5	182.5	249.3	182.9	209	300.9	341.1	369.1	386.6	415.3
6	172.3	258.2	191.8	217.9	309.8	350	378	395.5	424.2
7	194.7	261.5	195.1	221.2	313.1	353.3	381.3	398.8	427.5
8	99.49	157.2	141	167.1	259	299.2	327.2	344.7	373.4
9	56.47	114.2	115.3	141.4	233.2	273.5	301.5	319	335.1
10	46.58	104.3	105.4	131.5	223.3	263.6	291.6	309.1	325.2
11	0	62.4	63.46	89.57	181.4	221.7	249.7	267.2	283.3
12	60.68	0.0	62.87	72.69	164.6	204.8	232.8	242.2	223.2
13	63.59	62.9	0	26.18	118.1	158.3	186.3	203.8	232.5
14	89.69	72.7	26.18	0	91.87	132.1	160.1	177.6	206.3
15	180	163.0	116.5	90.35	0	41.7	69.72	87.2	115.9
16	220.5	203.5	157	130.9	40.51	0	28.42	45.9	74.6
17	248.6	231.6	185.1	158.9	68.52	28.41	0	18.72	47.43
18	266	242.2	202.5	176.3	85.99	45.88	18.72	0	43.71
19	281.6	223.2	231.2	205.1	114.7	74.59	47.43	43.72	0

The detailed information about the rebar demands for each customer and the delivery routes from the company was obtained. The purchasing history data was processed and transformed into a weekly delivery schedule, which later be input into the program. Table 2 presents the rebar purchasing history data from the 19 locations for 12 weeks period or 3 months. The rows represent the number of weeks, and the columns represent the quantity of rebar purchased in kg. Based on the interviews conducted, the average operating hours for the customer stores are from 8:00 AM to 5:00 PM. These 8-9 working hours will become the time window constraint in this study.

The company operates 10 vehicles for the rebar delivery, consisting of two types: 7 units of type 1 vehicle with a capacity of 4000 kg and 3 units of type 2 vehicle with the capacity of 2200 kg. Based on the interview results, the fuel cost is Rp 680/km for type 1 vehicle and Rp 450/km for type 2 vehicle. All vehicles are assumed to travel at a speed of 40 km/h. In addition to the fuel expenses, each vehicle also incurs wage costs, which include the daily wages of the driver and assistants required for the delivery and operation. The daily wage for one driver is Rp 150,000, and for one assistant, it is Rp 100,000. A type 1 vehicle requires 1 driver and 3 assistants accumulating a total daily wage cost of Rp 450,000. Meanwhile, type 2 vehicle requires 1 driver and 2 assistants accumulating Rp. 350,000 in daily wage cost. The details for each vehicle type can be seen in Table 3.

Table 2. Rebar Purchasing History Data (in kg)

Week/Node	1	2	3	4	5	6	7	8	9	10
1	0	2239	14812	0	0	4720	3619	3642	0	0
2	0	0	0	0	0	0	0	1451	0	0
3	0	1333	19214	0	75	0	9237	0	0	947
4	0	1747	0	0	0	0	9178	6137	237	0
5	0	533	0	0	0	0	947	0	250	0
6	0	95	95	4737	508	0	5798	0	0	0
7	0	0	0	0	0	0	2368	2368	0	0
8	0	142	0	0	2052	0	4312	0	0	0
9	0	0	8734	0	0	0	7905	1865	0	0
10	0	488	1480	0	0	1599	0	533	0	2665
11	0	1442	0	0	878	0	5595	0	0	0
12	0	637	0	0	290	0	6972	0	0	2013

Rebar Purchasing History Data (in kg) – Continued

Week/Node	11	12	13	14	15	16	17	18	19
1	2303	0	0	0	4613	0	1480	0	1251
2	0	0	4607	38	3656	0	0	0	8618
3	0	0	625	0	995	0	0	1850	0
4	0	0	0	0	0	0	711	1599	0
5	0	0	0	0	1673	0	0	0	7675
6	0	0	0	2132	1990	0	0	1421	1351
7	0	0	0	3162	2487	0	0	0	0
8	0	0	0	0	1332	0	497	0	0
9	0	533	1895	0	1232	0	0	1876	0
10	0	0	533	0	2280	13360	1480	0	534
11	0	8011	0	0	0	0	0	0	0
12	0	799	947	0	0	0	0	0	2949

Table 3. Detailed Vehicle Information

Vehicle Type	Capacity (Ton)	Unit	Fuel Cost (fc) - Rp/km	Wage Cost (vc) - Rp/day
1	4	7	680	450,000
2	2.2	3	450	350,000

Table 4. Existing Original Routes from the Distributor Company

Vehicle/Week	1	2	3	4	5	6
1	[1, 17, 19, 1]	[1, 19, 1]	[1, 13, 15, 1]	[1, 17, 18, 1]	[1, 19, 1]	[1, 15, 18, 19, 1]
2	[1, 15, 1]	[1, 19, 1]	[1, 10, 18, 1]	[1, 8, 1]	[1, 19, 1]	[1, 14, 19, 1]
3	[1, 11, 15, 1]	[1, 19, 15, 1]	[1, 7, 1]	[1, 8, 9, 1]	□	[1, 7, 1]
4	[1, 8, 1]	[1, 13, 1]	[1, 7, 1]	[1, 7, 1]	□	[1, 5, 7, 1]
5	[1, 7, 1]	[1, 13, 14, 15, 1]	[1, 5, 7, 1]	[1, 7, 1]	□	[1, 4, 1]
6	[1, 6, 1, 3, 1]	□	[1, 3, 1, 3, 1]	□	□	□
7	[1, 3, 1]	□	[1, 3, 1, 3, 1]	□	□	□
8	[1, 3, 1]	[1, 8, 1]	[1, 3, 1]	[1, 7, 1]	[1, 7, 1]	[1, 3, 4, 1]
9	[1, 3, 1, 3, 1]	□	[1, 3, 1]	[1, 2, 1]	[1, 2, 1]	[1, 2, 1]
10	[1, 2, 1, 2, 3, 6, 1]	□	[1, 2, 1]	□	[1, 9, 15, 1]	□

Existing Original Routes from the Distributor Company – Continued

Vehicle/Week	7	8	9	10	11	12
1	[1, 14, 15, 1]	[1, 15, 17, 1]	[1, 13, 15, 18, 1]	[1, 16, 1]	[1, 12, 1]	[1, 13, 19, 1]
2	[1, 8, 1]	[1, 7, 1]	[1, 8, 12, 18, 1]	[1, 16, 1]	[1, 12, 1]	[1, 10, 12, 1]
3	[1, 7, 1]	[1, 5, 7, 1]	[1, 7, 1]	[1, 16, 1]	[1, 7, 1]	[1, 7, 1]
4	□	□	[1, 7, 1]	[1, 16, 19, 17, 1]	[1, 5, 7, 1]	[1, 5, 7, 1]
5	□	□	[1, 3, 1]	[1, 13, 15, 1]	□	□
6	□	□	[1, 3, 1]	[1, 8, 10, 1]	□	□
7	□	□	□	□	□	□
8	[1, 15, 1]	[1, 2, 1]	[1, 3, 1]	[1, 6, 1]	[1, 12, 2, 1]	[1, 2, 1]
9	□	□	□	[1, 3, 2, 1]	□	□
10	□	□	□	□	□	□

Table 4 presents the delivery routes for 10 vehicles over the 12 weeks period. Vehicles 1-7 are type 1, and vehicles 8-10 are type 2. The routes show the sequence of nodes visited by the vehicles, starting and ending from and to the depot with node index 1. Empty cells ([]) indicate no rebar delivery assignment in that week for the respective vehicle. Based on the existing original routes made by the company, the total distribution cost of the rebar material in 12 weeks period is Rp 88,947,476 consisting of Rp 15,447,476 for the fuel cost and Rp 73,500,000 for the wage cost. The total distance covered is 23550.1 km. Each vehicle route includes details such as the load capacity, total distance, travel time, and equivalent working days (8 working hours/day). As an example, Table 5 shows the delivery route details from the first week (week 1). Vehicle 1 departs from the depot (node 1), delivers 1480.29 kg to customer 17, delivers 1250.84 kg to customer 19, and back again to the depot (node 1) with total travel distance of 786.88 km in 26 hours over around 4 working days. Some vehicles, like vehicle 6 and 10, make multiple trips in a week, returning to the depot between deliveries. This approach is also used in the optimization scenarios to resemble the real-world conditions.

Table 5. Delivery Route Details for Week 1 (Existing Original Routes)

Week	Vehicle	Route	Customer	Loaded Capacity (kg)	Total Distance (km)	Travel Time (hours)	Working Day (days)
1	1	[1,17,19,1]	17	1480.29	786.88	26	4
			19	1250.84			
	2	[1,15,1]	15	4000	556.49	26	4
			11	2303.32			
	3	[1,11,15,1]	15	612.57	619.54	26	4
			8	3641.50			
	4	[1,8,1]	7	3619.30	70.43	4.095	1
			6	4000			
	5	[1,7,1]	3	4000	76.8	5.773	1
			3	4000			
	6	[1,6,1,3,1]	3	4000	12	3.496	1
			3	2200			
	7	[1,3,1]	3	2200	24	3.929	1
			3	2200			
	8	[1,3,1,3,1]	2	2000	195.77	7.515	1
			3	211.74			
	9	[1,2,1,2,3,6,1]	6	720.19			
			6	720.19			
Total				38679.13	2501.34	110.767	19

Optimization Result

This study examines the two optimization scenarios ⁴¹ to minimize the total delivery costs ³ for rebar material: the Capacitated Vehicle Routing Problem (CVRP) and the Capacitated Vehicle Routing Problem with Time Windows (CVRPTW), both solved using the SOS metaheuristic method. The CVRP optimization case assumes no delivery time window constraint, while the CVRPTW optimization case includes the delivery time window constraint, adding complexity to the problem. The SOS method runs using 200 organisms and 100 iterations, with the computational time between 16 to 35 hours.

CVRP Optimization Result

Table 6 shows the optimum CVRP delivery routes with the total rebar material distribution cost of Rp 65,684,200, comprising Rp 14,784,200 in fuel cost and Rp. 50,900,000 in wage cost. The delivery routes cover 22257.14 km. Compared to the existing original routes, this yields a cost saving of Rp 23,263,276 (26.15%) and 1292.96 km less traveling distance (5.49%). These savings are achieved by maximizing the vehicle capacity and removing the working hours and time window constraints. Table 7 presents the detailed route information assigned from the first week. In this scenario, Vehicle 2 departs from the depot (node 1), delivers 1480.286 kg of rebar to customer 17, 1250.841 kg to customer 19, and 1268.873 kg to customer 15 before returning to the depot (node 1). The vehicle travels 786.88 km with travel time of 21.005 hours. Compared to the existing original route, the delivery to customer 15 is an addition. However, the total distance remains unchanged, as the program identifies more optimal combinations of delivery routes. The route requires 2 fewer working days due to the absence of time constraints.

After comparing the routes of the optimum CVRP scenario and existing original routes, it can be concluded that the program finds more optimal routes with fewer working days in the CVRP scenario. By maximizing the vehicle

capacity without exceeding limits, all rebar orders are delivered very well. However, the lack of working hours and time window constraints makes the results less applicable to real-world scenarios. To improve the results applicability, the time window constraint will be added, leading to the optimization in the second case, CVRPTW.

Table 6. Optimum Delivery Routes for the CVRP Scenario

Vehicle/Week	1	2	3	4	5	6
1	[1,2,11,8,1]	[1,19,15,1]	[1,3,1]	[1,8,7,1]	[1,15,2,7,1]	[1,4,5,1]
2	[1,17,19,15,1]	[1,19,1]	[1,18,15,13,2,1]	[1,9,17,18,2,1]	[1,9,19,1]	[1,18,19,15,1]
3	[1,8,3,1]	[1,15,14,13,1]	[1,3,1]	[1,7,1]	∅	[1,5,7,1]
4	[1,3,1,7,1]	∅	[1,3,5,7,1]	∅	∅	∅
5	[1,3,1]	[1,8,1]	[1,3,1]	[1,7,1]	∅	∅
6	[1,3,1]	∅	[1,7,1]	∅	∅	∅
7	[1,15,2,1]	[1,19,1]	[1,2,10,3,1]	[1,2,8,1]	[1,19,15,1]	[1,15,14,2,3,4,1]
8	[1,3,6,1]	∅	[1,7,1]	∅	∅	∅
9	[1,6,1]	∅	[1,7,1]	∅	∅	∅
10	[1,3,1,6,1]	[1,13,8,1]	[1,3,1]	[1,7,1]	∅	[1,7,1]

Optimum Delivery Routes for the CVRP Scenario – Continued

Vehicle/Week	7	8	9	10	11	12
1	[1,8,7,1]	[1,7,1]	[1,3,1]	[1,16,1]	[1,12,5,7,1]	[1,7,1]
2	[1,15,14,1]	[1,17,15,2,5,1]	[1,18,15,13,1]	[1,16,1]	[1,2,12,1]	[1,19,13,2,1]
3	∅	∅	[1,3,1]	[1,16,17,19,15,1]	[1,7,1]	[1,7,1]
4	∅	∅	[1,7,1]	[1,3,6,1]	∅	∅
5	∅	∅	[1,7,1]	[1,2,10,8,3,1]	∅	∅
6	∅	∅	∅	∅	∅	∅
7	[1,14,8,1]	[1,5,7,1]	[1,13,12,8,3,1]	[1,16,1]	[1,12,1]	[1,2,12,10,5,7,1]
8	∅	∅	∅	∅	∅	∅
9	∅	∅	∅	∅	∅	∅
10	∅	∅	[1,3,7,1]	[1,15,13,2,1]	∅	∅

Table 7. Optimum Delivery Route Details for Week 1 (CVRP Scenario)

Week	Vehicle	Route	Customer	Loaded Capacity (kg)	Total Distance (km)	Travel Time (hours)	Working Day (days)
1	1	[1,2,11,8,1]	2	1583.074	334.56	9.697	2
			11	2303.325			
			8	113.602			
			17	1480.286			
	2	[1,17,19,15,1]	19	1250.841	786.88	21.005	3
			15	1268.873			
			8	3527.901			
	3	[1,8,3,1]	3	472.099	156.86	5.255	1
			3	4000			
	4	[1,3,1,7,1]	7	3619.299	82.43	4.601	1
			3	4000			
	5	[1,3,1]	3	4000	12	1.633	1
	6	[1,3,1]	3	4000	12	1.633	1
	7	[1,15,2,1]	15	3343.697	557.67	15.275	2
			2	656.303			
	8	[1,3,6,1]	3	139.640	74.82	2.604	1
			6	2060.360			
	9	[1,6,1]	6	2200	64.8	2.353	1
			3	2200			
	10	[1,3,1,6,1]	3	459.827	76.8	2.807	1
			6	459.827			
	Total				38679.126	2158.82	66.8627

CVRPTW Optimization Result

Table 8 presents the optimum CVRPTW routes with a total rebar material distribution cost of Rp 82,214,534, including Rp 15,514,534 for the fuel cost and Rp 66,700,000 for the wage cost. The total travel distance is 23052.92 km. Compared to the existing original routes, there is a traveling distance saving of 497.18 km (2.11%). However, the fuel costs are nearly the same due to the increased use of the type 1 vehicles compared to the existing original

routes. This occurs because the CVRPTW scenario results in more usage of type 1 vehicles. Meanwhile, the optimization in the CVRPTW scenario reduces the wage costs by 9.25%, saving equivalent to 20 working days and lowering the operational expenses. As illustrated in Table 9, the detailed routes data and visualizations for the first week of the CVRPTW scenario are shown. In this example, Vehicle 5 follows a similar route to the CVRP results of vehicle 2 but in a different delivery order. The vehicle 5 departs from the depot (node 1), delivers the rebar material 1250.841 kg to customer 19, 1480.286 kg to customer 17, and 1268.873 kg to customer 15 before returning to the depot (node 1). The vehicle travels 786.89 km with a traveling time of 26 hours. The adjusted sequence reduces the working days and wage costs, demonstrating the program's ability to optimize the delivery time within the specified time windows.

Table 8. Optimum Delivery Routes for the CVRPTW Scenario

Vehicle/Week	1	2	3	4	5	6
1	[1,11,8,1]	[1,19,14,15,1]	[1,3,1]	[1,8,2,7,1]	[1,15,2,7,1]	[1,4,5,1]
2	[1,3,1,7,1]	[1,13,8,1]	[1,3,1]	[1,7,1]	□	[1,7,1]
3	[1,3,1]	□	[1,3,5,7,1]	□	□	□
4	[1,3,1]	□	[1,7,1]	□	□	□
5	[1,19,17,15,1]	[1,19,1]	[1,18,15,13,10,1]	[1,17,18,9,8,1]	[1,19,1]	[1,19,18,14,1]
6	[1,15,11,1]	[1,19,1]	[1,10,2,3,1]	[1,8,1]	[1,19,9,15,1]	[1,14,15,2,3,4,1]
7	[1,8,2,3,1]	[1,15,13,1]	[1,3,1]	[1,7,1]	□	[1,5,7,1]
8	[1,3,1,6,1]	□	[1,3,1]	□	□	□
9	[1,6,1]	□	[1,7,1]	□	□	□
10	[1,3,6,1]	□	[1,7,1]	□	□	□

Optimum Delivery Routes for the CVRPTW Scenario – Continued

Vehicle/Week	7	8	9	10	11	12
1	[1,8,7,1]	[1,7,1]	[1,3,1]	[1,16,1]	[1,12,5,7,1]	[1,7,1]
2	[1,15,14,1]	[1,17,15,2,5,1]	[1,18,15,13,1]	[1,16,1]	[1,2,12,1]	[1,19,13,2,1]
3	□	□	[1,3,1]	[1,16,17,19,15,1]	[1,7,1]	[1,7,1]
4	□	□	[1,7,1]	[1,3,6,1]	□	□
5	□	□	[1,7,1]	[1,2,10,8,3,1]	□	□
6	□	□	□	□	□	□
7	[1,14,8,1]	[1,5,7,1]	[1,13,12,8,3,1]	[1,16,1]	[1,12,1]	[1,2,12,10,5,7,1]
8	□	□	□	□	□	□
9	□	□	□	□	□	□
10	□	□	[1,3,7,1]	[1,15,13,2,1]	□	□

Table 9. Optimum Delivery Route Details for Week 1 (CVRPTW Scenario)

Week	Vehicle	Route	Customer	Loaded Capacity (kg)	Total Distance (km)	Travel Time (hours)	Working Day (days)
1	1	[1,11,8,1]	11	1647.022	334.37	9.693	2
			8	2352.978			
	2	[1,3,1,7,1]	3	4000	82.43	6.463	1
			7	3619.299			
	3	[1,3,1]	3	4000	12	3.496	1
			3	4000			
	5	[1,19,17,15,1]	19	1250.841	786.89	26	4
			17	1480.286			
			15	1268.873			
	6	[1,15,11,1]	15	3343.697	619.67	30.23	4
			11	656.303			
			8	1288.525			
	7	[1,8,2,3,1]	2	2239.376	156.51	5.411	1
			3	472.099			
	8	[1,3,1,6,1]	3	2200	77	4.669	1
			6	459.827			
	9	[1,6,1]	6	2200	65	3.539	1
			3	139.640			
	10	[1,3,6,1]	3	139.640	75	4.466	1
			6	2060.360			
Total				38679.126	2220.29	97.462	17

Optimization Result Comparison: Existing Original, CVRP, and CVRPTW

Table 10 provides a comparison between the existing original delivery routes and the optimum results from both the CVRP scenario and CVRPTW scenario. The evaluation includes the total traveling distance, travel time, equivalent working days, and total distribution costs. The existing original routes cover 23550.1 km of traveling distance with a total travel time 987.82 hours over equivalent 170 working days for 10 vehicles. The overall expenses are Rp 88,947,476 which includes Rp 15,447,476 for the fuel cost and Rp 73,500,000 for the wages. Through CVRP optimization scenario, these results are reduced to 22257.14 kilometers of traveling distance, 635.89 hours of travel time, and equivalent 116 working days for 10 vehicles, with the total distribution cost of Rp 65,684,200, comprising Rp 14,784,200 for the fuels and Rp 50,900,000 for the wages. In comparison, the CVRPTW optimization scenario results in 23052.95 kilometers of travel in 924.51 hours across equivalent 150 working days for 10 vehicles, with the total rebar material distribution cost of Rp 82,214,534, including Rp 15,514,534 for the fuel cost and Rp 66,700,000 for the wage cost.

Table 10. Comparison of the Existing Original Route, CVRP Scenario, and CVRPTW Scenario

Route Scenario	Total Distance (km)	Travel Time (hours)	Total Working Day (days)	Operational Cost		
				Fuel Cost (fc)	Wage Cost (vc)	Total Cost
Existing Original	23550.10	987.82	170	Rp 15,447,476	Rp 73,500,000	Rp 88,947,476
CVRP	22257.14	635.889	116	Rp 14,784,200	Rp 50,900,000	Rp 65,684,200
CVRPTW	23052.95	924.51	150	Rp 15,514,534	Rp 66,700,000	Rp 82,214,534

The CVRP optimization scenario reduces the traveling distance by 1291.96 km, travel time by 351.93 hours, and equivalent 54 working days for 10 vehicles, resulting in a cost saving of Rp 23,263,276 (26.15%). This includes a 4.29% decrease in the fuel costs and a 30.75% reduction in wage expenses. On the other hand, CVRPTW offers a more realistic scenario with savings of 497.15 km of traveling distance, 63.31 hours of travel time, and equivalent 20 working days for 10 vehicles, and a total distribution cost reduction of Rp 6,732,942, or 7.57%. Despite a slight 0.43% increase in the fuel costs, the CVRPTW scenario is better suited for real-world conditions, making it a more practical choice for the distributor company.

In the first week, as shown in Table 11, a detailed analysis of the rebar material deliveries to nodes or locations 15, 17, and 19 highlights the differences between the existing original routes, CVRP scenario, and CVRPTW scenario. The current original routes use 2 vehicles but fail to optimize the delivery routes and vehicle capacity. In contrast, the CVRP scenario improves the delivery routes by assigning part of the orders to customer 15, optimizing the vehicle capacity. Furthermore, the CVRPTW optimization scenario not only maximizes the vehicle capacity but also reduces the equivalent working days by adjusting the delivery sequence.

Table 11. Comparison of the Optimum Rebar Material Delivery Route Details for Week 1

Route Scenario	Vehicle	Route	Customer	Loaded Capacity (kg)	Total Distance (km)	Travel Time (hour)	Working Day
Existing Original	1	[1,17,19,1]	17	1480.286	786.88	26	4
			19	1250.841			
			15	4000			
CVRP	2	[1,17,19,15,1]	17	1480.286	786.88	21.005	3
			19	1250.841			
			15	1268.873			
CVRPTW	5	[1,19,17,15,1]	19	1250.841	786.89	26	4
			17	1480.286			
			15	1268.873			

CONCLUSIONS

Based on the optimization results of the Capacitated Vehicle Routing Problem (CVRP) scenario and the Capacitated Vehicle Routing Problem with Time Windows (CVRPTW) scenario using the Symbiotic Organisms Search (SOS) method, it can be concluded that the SOS method is effective in addressing the challenges in the rebar material distribution, considering both the vehicle capacity constraint (CVRP) and time windows constraint (CVRPTW). The CVRP optimization scenario results show the delivery routes that maximize the vehicle capacity, while the CVRPTW scenario not only optimizes the vehicle capacity but also takes the delivery time windows constraint into account. As a result of the optimization, the CVRP scenario achieves a total distribution cost saving of Rp 23,263,278, or approximately 26.15%, while the CVRPTW scenario saves around Rp 6,732,942, or about 7.57%. These cost savings significantly enhance the operational efficiency and distribution of the building materials, especially the steel rebar.

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