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A Hybrid Particle Swarm Optimization – Travelling Salesman Problem for Efficient Multi Depot Vehicle Routing

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Abstract

The Fast-Moving Consumer Goods (FMCG) industry faces increasing demand to optimize distribution networks to reduce costs. The company seeks to establish a proper redistribution route network, optimize truck allocation, and minimize warehouse operations, administration, and transportation costs while adhering to capacity and volume constraints. To achieve this, the study formulates the problem as a Multi-Depot Vehicle Routing Problem (MDVRP) with 3 depots. The proposed model with the addition of a particle swarm algorithm yields a substantial cost reduction of 21.41% compared to the existing system, demonstrating the potential of hybrid metaheuristic algorithms for addressing complex logistics challenges in the FMCG industry.

Keywords: Multi-depot vehicle routing problem; K-Means Clustering; Gravity model; Particle Swarm Optimization; Travelling Salesman Problem

Introduction

The Vehicle Routing Problem (VRP) first introduced by Dantzig and Ramser (1959) is a class of problems concerning the distribution of goods between depots and final users. Marc Goetschalckx (2011) defines the Vehicle Routing Problem (VRP) as the optimization of routes for a fleet of vehicles where each vehicle, starting and ending at a depot, must visit multiple customers to fulfil their demands. The challenge lies in minimizing the total distance travelled while ensuring all customers are served exactly once and vehicle capacity constraints are satisfied. The cost is calculated to be directly proportional to the total distance travelled by all vehicles; therefore, by finding the shortest distance, the VRP minimizes the transportation cost.

The Multi Depot Vehicle Routing Problem (MDVRP) is an extension of the VRP that incorporates multiple depots, where vehicles depart from a depot and return to the same depot after delivering, which allows for more complex and realistic distribution scenarios. If a company operates a main factory, central warehouse, or main branch alongside multiple depots to fulfil customer demand, the resulting distribution problem is categorized as a Multi-Depot Vehicle Routing Problem (MDVRP). A fleet of vehicles is assigned to each depot, operating out of and returning to their respective depots to serve designated customers. For MDVRP, demand points are typically customers, retailers, or distribution centres that need to receive products from the depots, and they are typically clustered around the depots. There are controllable variables for MDVRP such as the number of vehicles, vehicle capacity, number of depots, number of clusters, and type of the goods. On the other hand, there are non-controllable variables such as the travelling distance, number of demand points, travelling time period, road and weather conditions, human resources and traffic rules and regulations. The size of the problem

https://doi.org/10.54389/JXSH5934

mainly depends on the number of demand points.

This case study presents a comprehensive approach to optimize vehicle routing for ABC (Pvt) Ltd., a Sri Lankan Fast-Moving Consumer Goods (FMCG) company with nine agents operating in two regions, serving 5483 clients across 25 demand points, using eleven distribution vehicles. By addressing the complex MDVRP using a heuristic approach, we aim to improve the efficiency of their distribution network. Unlike the single-depot vehicle routing problem (SDVRP) employed by Jayarathna et al. (2022), our approach leverages multiple depots and Particle Swarm Optimization (PSO) to enhance operational efficiency and reduce costs.

Materials and Methods

This research aimed to assess the profitability of MDVRP for an FMCG company and a model using various inputs, including the number and volume of demand points was developed focussing on minimizing travel distance, warehouse operation costs, administration costs, and transportation costs. A combination of mathematical modelling and optimization techniques was used to identify the most effective solution. To optimize the distribution network, we employed a multi-step approach. As shown in Figure (1), Initially, K-Means clustering was used to group showrooms into clusters based on their geographical locations. And then, the gravity model was applied to determine the optimal locations for the central depot within each cluster. Next, a heuristic method (Clarke & Wright, 1964) was used to construct initial routes, followed by the introduction of Particle Swarm Optimization (PSO) algorithm to the Traveling Salesman Problem to minimize the total distance travelled.

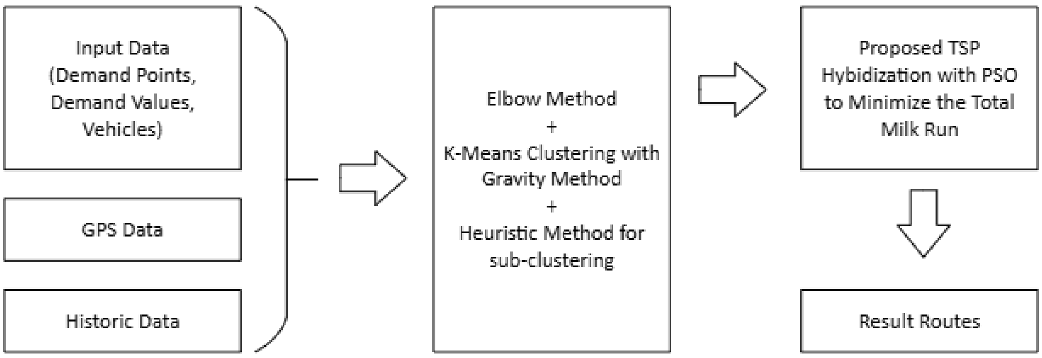

Figure 1. MDVRP Problem

Secondary Data

Our analysis builds upon the dataset used by Jayarathna et al. (2022) to explore the impact of using a centralized delivery strategy.

Model

Following the approach of Jayarathna et al. (2022) to design a cost-effective mathematical model focussing on transportation from the central warehouse to the merchants, the logistic distribution problem is defined as a complete directed graph $G=(V,E)$ where $V=\{V_0, V_1, V_2, \ldots, V_n, V_{(n+1)}\}$ is the set of nodes, representing geographically dispersed customers and is the collection of routes $E=\{(i,j) \mid i,j \in V, i \neq j\}$. is the total number of demand points in the distribution. A tour of the cluster starts and ends at the node V_0.

Suppose the i^{th} depot, with demand points (customers) has D vehicles in their fleet, each with capacity Q_k, where $k \in \{1,2,3,\ldots,D\}$ Then, each customer in $V \setminus \{V_0\}$ has a positive demand q_j^i such that,

$$\sum_{j=1}^{n_i} q_j^i \leq Q_k \qquad 1$$

K-Means Clustering

Let R be the total number of depots, $d^{ir}_{V_jV_k}$ be the distance traveled from client V_j to client V_k in the r^{th} cluster at i^{th} depot and d^{ir} be the total distance travelled in the r^{th} cluster at i^{th} depot. The distance matrix is symmetric, $d^{ir}_{V_jV_k} = d^{ir}_{V_kV_j}$, all $j,k \in \{0,1,2,\ldots,n_i\}, i \in \{1,2,\ldots,R\}, j \neq k$. The main distribution depot manages transportation facilities and assigns vehicles to routes based on the transportation plan. Vehicles start and end their routes at the depot.

To cluster the pool of demand points, the Elbow Method (Thorndike, 1953) was employed. This method identifies the optimal number of clusters by minimizing the total within-cluster variation (WSS) which measures the compactness of clusters. Thus, we can use the following algorithm to define optimal clusters, using k-means clustering for different values of k as shown in figure (2).

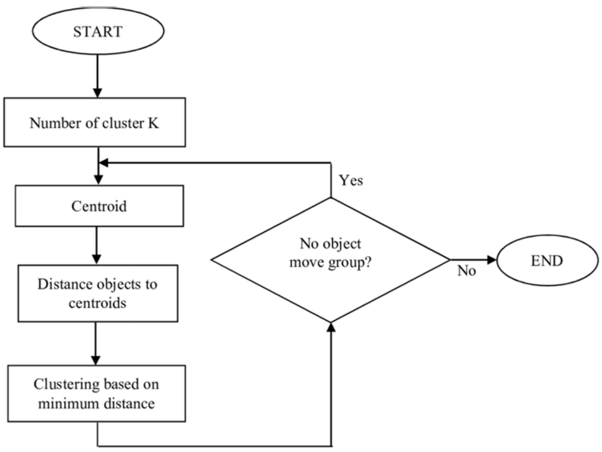

Figure 2. K-Means clustering flow chart

Identification of sub clusters by heuristic method

The Clarke-Wright (1964) algorithm, a well-known heuristic for vehicle routing problems, was used to cluster clients based on their individual demand and the capacity of available vehicles, ensuring that each cluster's total demand did not exceed the capacity of a single vehicle. This heuristic procedure involves the following steps:

- The optimal location for the central depot, V_0, was determined using the gravity model formula proposed by Anderson (2011). The nearest client, V_1, to the central depot was identified based on the minimum distance.
- From the remaining clients, the nearest client, V_2, to V_1 was identified. To determine V_2 if belonged to the same cluster as V_1, the distances $d_{V_0V_2}$ and $d_{V_1V_2}$ were compared and if $d_{V_0V_2} \geq d_{V_1V_2}$, V_1 and V_2 were assigned to the same cluster. Otherwise, they were assigned to different clusters.
- This process continued to identify subsequent clients and assign them to appropriate clusters based on distance comparisons.
- Once all clients were clustered, the total cost of fuel and maintenance for each sub-cluster was calculated using the cost formula.

Proposed new metaheuristic technique based on the Particle Swarm Optimization (PSO) algorithm

PSO is a metaheuristic algorithm inspired by the social behaviour of bird flocking, introduced by James Kennedy and Russel Eberhart (1995). It efficiently explores the solution space by iteratively updating a swarm of particles (potential solutions). Key Steps:

1. Clients are initially clustered based on vehicle capacity and individual demand.
2. PSO Initialization is done by creating a swarm of particles, each representing a potential route for a cluster.
3. Each particle's route length is evaluated.
4. Particle velocities are updated based on their own position, the best position found by the particle, and the best position found by the swarm.
5. Particles are moved to new positions based on their updated velocities.
6. Steps 3-5 are repeated until a stopping criterion is met (e.g., maximum number of iterations).

The PSO algorithm uses a swap operator to explore different route combinations. This operator involved exchanging the positions of clients within a route. By applying various swap sequences, the algorithm could efficiently search for shorter routes.

Total Transportation Cost

The total transportation cost calculation considered factors such as fuel consumption, vehicle maintenance, and driver wages, within each cluster, under the assumptions:

- Each demand must be satisfied, and each customer is served only once.
- The depot owns enough homogenous vehicles. Each vehicle must depart from the depot and after having served its customer it must return to the depot.
- Time window constraints (Taner et al., 2012) are not considered. i.e., the study only provides a simplified view of the problem or may not capture the full complexity of the real-world real-time situation.

We calculated the total cost of each sub-cluster by considering the warehouse operation and administration costs along with the transportation costs as detailed in Jayarathna et al. (2022).

Limitations of the model

1. Distance estimation done using Google Maps.
2. Assumption of straight-line distances between points, disregarding potential detours and obstacles.
3. Lack of consideration for external factors like time constraints, vehicle conditions, weather, traffic conditions, and driver behaviour that can influence delivery routes and times.
4. Sole focus of the study is on inter-cluster transportation, ignoring potential intra-cluster optimization.
5. Assumption of static demand, neglecting fluctuations in demand over time.
6. Absence of consideration for reverse logistics.

Results and Discussion

The ABC company with nine consignment distributors in Colombo and Gampaha, with five in the Colombo region and four in the Gampaha region, uses decentralized distribution strategies for distributing FMCG products among 5483 clients in Colombo and Gampaha.

Multi Depot Clustering Process by Using the K means Clustering and Gravity Model

Table 1. Annual Demands of ABC Company Products in Colombo and Gampaha Region (Jayarathna et al., 2022)

Demand Points	Demand value (LKR)	Latitude	Longitude
Dehiwala	109,839,943.34	6.83667	79.8439262
Panadura	50,534,312.42	6.7291202	79.8944164
Nugegoda	30,837,303.75	6.8656182	79.8706401
Boralasgamuwa	32,881,664.51	6.8365293	79.8897056
Battaramulla	107,556,545.54	6.9001015	79.9029844
Maharagama	79,324,049.21	6.8502516	79.9073489
Kottawa	51,370,635.27	6.8690953	79.9797876
Homagama	30,820,660.27	6.8451342	79.9887083
Malabe	34,619,046.57	6.9043629	79.9479226
Angoda	43,510,655.99	6.9333996	79.9161694
Piliyandala	54,879,871.97	6.7896893	79.9012898
Kaduwela	6,624,608.59	6.9299975	79.9733482
Maradana	261,063,935.94	6.926745	79.8605224
Wattala	168,494,022.45	6.989402	79.885278
Wellawatta	31,208,418.96	6.8738385	79.8611775
Gampaha	53,352,830.66	7.083605	80.006455
Kelaniya	22,525,756.47	6.9559081	79.9169459
Kadawatha	61,080,181.62	7.0097642	79.942525
Ja-Ela	17,784,276.89	7.0742115	79.8937204
Negambo	142,750,892.67	7.1963407	79.829926
Yakkala	28,513,346.82	7.0877703	80.0232392
Meerigama	47,583,630.89	7.253295	80.1096746
Weliweriya	7,770,027.05	7.0346322	80.019072
Ragama	6,554,858.77	7.0306524	79.9232021
Kochchikade	13,327,673.99	7.2628576	79.8634837

The 5483 clients in the Colombo and Gampaha regions were subdivided into 25 clients' main demand points by clustering them based on their geographical positions as shown in Table 01. These demand points were then clustered into three groups by identifying optimal central warehouse locations according to their geographical locations. Initially, three depots (Balummahara, Rathmalana, Angoda) were randomly chosen as shown in Table 02, and their distances to all demand points were calculated.

Table 2. First Multi Depot Distance Arrangement

Demand Points	Distance Measure from demand point to selected depots - km			Allocated cluster
	Balummahara (1)	Rathmalana (2)	Angoda (3)	
Panadura	56.7	12.3	27.8	2
Nugegoda	38.7	7.2	12.0	2
Boralasgamuwa	39.0	2.9	15.2	2
Battaramulla	32.4	10.8	12.2	3
Maharagama	36.7	6.3	6.1	2
Kottawa	26.6	16.1	13.2	3
Homagama	32.4	15.4	16.7	2
Malabe	23.4	16.6	6.0	3
Piliyandala	42.2	5.7	21.4	2
Kaduwela	19.2	21.9	6.2	3
Maradana	26.1	14.8	8.6	3
Wattala	19.2	24.5	11.5	3
Wellawatta	38.4	7.3	14.6	2
Gamapaha	4.1	48.1	22.2	1
Kelaniya	18.4	20.5	3.6	3
Kadawatha	10.0	33.1	22.6	1
Ja-Ela	16.2	36.5	24.6	1
Negambo	28.2	53.5	40.2	1
Meerigama	28.9	75.7	51.7	1
Weliweriya	6.5	43.4	21.3	1
Ragama	14.6	40.5	16.1	1
Kochchikade	31.2	57.3	45.4	1
Yakkala	6.1	48.2	27.3	1
Dehiwala	51.5	1.5	16.3	2
Angoda	23.3	17.1	0	3

Then, the accurate locations of the centroids were found using the Gravity Model (Anderson, 1979),

$$X = \frac{\sum_i^n d_i * x_i}{\sum_i^n d_i} \; , \; Y = \frac{\sum_i^n d_i * y_i}{\sum_i^n d_i}$$

Where (x_i, y_i) is the given location coordinates with the demand point (longitude & latitude), is the demand values (from Table 01) associated with demand point, and is the unknown location coordinate of the new depot.

Table 3. Iteration 1 - Cluster 1 Calculations for Gravity Model

Cluster 1 - Balummahara					
Demand Point	**Demand Value**	**Latitude**	**Longitude**		
Gampaha	53,352,830.66	7.083605	80.006455	377930378	4268570845
Kadawatha	61,080,181.62	7.0097642	79.942525	428157670.4	4882903946
Ja-Ela	17,784,276.89	7.0742115	79.8937204	125809736.1	1420852045
Negambo	142,750,892.67	7.1963407	79.829926	1027284059	11395793198
Meerigama	47,583,630.89	7.253295	80.1096746	345138112	3811909187
Weliweriya	7,770,027.05	7.0346322	80.019072	54659282.48	621750354
Ragama	6,554,858.77	7.0306524	79.9232021	46084933.54	523885302.2
Kochchikade	13,327,673.99	7.2628576	79.8634837	96796998.33	1064394474
Yakkala	28,513,346.82	7.0877703	80.0232392	202096052.7	2281730373
Total	= 378,717,619.36			= 2,703,857,123	= 30,171,789,626

Table (3) above shows the gravity model calculations for the Balummahara cluster (cluster 1) and similarly, we calculated the new depot coordinates for cluster 2 and cluster 3 and obtained the following new depots:

- Coordinates:(7.1232,79.9242), Location: Kotugoda
- Coordinates:(6.825661878,79.88689352), Location: Rathmalana
- Coordinates:(6.933821111,79.89261703), Location: Kotikawatta

We continued this process up to 3 iterations and the number of demand points for each cluster remains the same between the 2nd and 3rd iterations, which indicates that the clustering algorithm has converged. A Gravity Model was used in order to find the exact geographical locations of the depots (Table 4).

Table 4. 3rd Iteration - The Exact Location of the three centroids Found by Gravity Model

Cluster Name	**Coordinate of the Exact Place**	**Name of the Exact Place**
Cluster 1-Minuwangoda	(7.16759488,79.9305206)	Minuwangoda
Cluster 2-Rathmalana	(6.82566188,79.8868935)	Rathmalana
Cluster 3-Welewatta	(6.9407288,79.8968728)	Welewatta

Table 5. 3rd Iteration - Depot Allocation

Depots Allocation	**Number of Demand Points for Each Depot**
Minuwangoda	7
Rathmalana	8
Welewatta	10

Using heuristic model (Jayarathna et al., 2021), 7 sub clusters were formulated. Once we put the set of data in each cluster to the proposed method of TSP hybridized with PSO Algorithm the shortest path which minimizes the total route cost was calculated. The final global best value is the answer for the best route (after iterating 100 times). As shown in Table 6, the total milk run was calculated using the distance of each shortest path.

Table 6. Total Milk Run Travelled in Each Sub Cluster

Depot	Sub Cluster	Shortest Path (Global Best)	Monthly Demand volume	Total Milk Run
Minuwangoda	1	Minuwangoda - Ja-ela – Gampaha – Yakkala – Weliweriya – Mirigama – Kochchikade - Minuwangoda	46	100.9 km
	2	Minuwangoda – Negambo - Minuwangoda	35	22 km
Rathmalana	3	Rathmalana – Dehiwala – Boralasgamuwa – Maharagama – Nugegoda – Wellawatta - Rathmalana	77	25.2 km
	4	Rathmalana – Piliyandala – Panadura - Homagama-Rathmalana	28	54.6 km
Welewatta	5	Welewatta - Angoda – Kelaniya – Wattala - Ragama -Kadawatha - Welewatta	75	40.9 km
	6	Welewatta - Maradana-Welewatta	72	12.0 km
	7	Welewatta - Battaramulla - Malabe - Kaduwela – Kottawa - Welewatta	58	44.6 km

In the existing system, the delivery is done weekly. The capacity of a truck used in this proposed method is 77 cubic meters in volume. As shown in Table 6, the demand per month for each subcluster is less than 77 , therefore, with the new system, the delivery is done once a month by using a truck for each sub cluster at a reduced cost. Here, trucks are charged a fixed fee for the first 50 kilometers and an additional Rs.200 per kilometer thereafter. Tables 7-9, show the total transportation cost calculations for the proposed system per each depot.

Table 7. Total Distance Travelled in Each Two Clusters - Minuwangoda Depot

Description	Distance Travelled	Fixed Transportation Cost of the Cluster (Rs)	Additional Distance Travelled	Additional Transportation Cost (Rs.200 per 1 km)
Cluster 01	100.9	35,000	50.9	10,180
Cluster 02	22.0	35,000	0	0
Total Distance travelled in Cluster(km)	111.9			
Fixed Transportation Cost (Rs)	70,000			
Additional Distance Transportation Cost (Rs)	10,180			
Total Transportation cost of the proposed system (Rs)	80,180			

Table 8. Total Distance Travelled in Each Two Clusters - Rathmalana Depot

Description	Distance Travelled	Fixed Transportation Cost of the cluster (Rs)	Additional Distance Travelled	Additional Transportation cost (Rs.200 per 1 km)
Cluster 03	25.2	35,000	0	0
Cluster 04	54.6	35,000	4.6	920
Total Distance travelled in Cluster (km)	79.8			
Fixed Transportation Cost (Rs)	70,000			
Additional Distance Transportation Cost (Rs)	920			
Total Transportation cost of the proposed system (Rs)	70,920			

Table 9. Total Distance Travelled in Each Three Clusters - Welewatta Depot

Description	Distance Travelled	Fixed Transportation Cost of the cluster (Rs)	Additional Distance Travelled	Additional Transportation cost (Rs.200 per 1 km)
Cluster 05	40.9	35,000	0	10,180
Cluster 06	12.5	35,000	0	0
Cluster 07	44.6	35,000	0	0
Total Distance travelled in Cluster(km)		98		
Fixed Transportation Cost (Rs)		105,000		
Additional Distance Transportation Cost (Rs)		0		
Total Transportation cost of the proposed system (Rs)		105,000		

For each depot, the Tables 10 – 15 below gives the administration costs for the 3 depots, the warehouse cost for the 3 depots, the difference between the labor costs for the proposed and existing system, monthly costs for the existing system, the total calculated cost for the existing system, and the calculated difference in total costs for the proposed and existing systems.

Table 10. Total Insurance for Good, Other Expenses and Other Staff Service Salaries

Depots	Quantity Volume	Insurance for Goods	Total Cost for Insurance (Rs)	Other Expenses (Rs)	Supporting Staff Service Salary (Rs)	Total Cost (Rs)
Minuwangoda	81	1,300	105,300	3,400	7,000	115,700
Rathmalana	105	1,300	136,500	3,400	7,000	146,900
Welewatta	205	1,300	266,500	3,400	7,000	276,900
Total Cost for all three depots					**800,900**	

Table 11. Warehouse Cost (SQF = Square feet)

Warehouse Rent	Minuwangoda		Rathmalana		Welewatta	
	Quantity	Cost(Rs)	Quantity	Cost(Rs)	Quantity	Cost(Rs)
	5500 SQF	250,000	7500 SQF	350,000	10000 SQF	375,000

Table 12. Labor Cost Difference Between Labors in Existing System and Proposed System

	Salary(Rs)	Existing System		Proposed System	
		Number of Employees	Total Cost	Number of Employees	Total Cost
Area Manager	85,000	2	170,000	1	85,000
Warehouse Manager	80,000	0	0	3	240,000
Accountant	70,000	2	140,000	1	70,000
Assistant Accountant	55,000	2	110,000	2	110,000
IT Officer	50,000	2	100,000	1	50,000
Logistic Officer	50,000	2	100,000	1	50,000
Assistant Logistic Officer	35,000	4	140,000	2	70,000
Clerk	20,000	2	40,000	3	60,000
Sales Ref	30,000	18	540,000	6	180,000
Forklift Drivers	28,000	9	252,000	6	168,000
Porters	25,000	27	675,000	6	150,000
Store Porters	25,000	9	225,000	3	75,000
Driver	32,000	10	320,000	0	0
Total		**89**	**2,812,000**	**41**	**1,308,000**

Table 13.Total Monthly Cost of the Existing System

Description	Total Cost (Rs)	Total Cost per Week (Rs)	Total Cost per Month (Rs)
Total transportation cost for agent point to retail maker	11*12,500 = 137,500	137,500	550,000
Total number of lorries = 11, total volume capacity per week () = 123			
Torry insurance	11*4190 = 46,090	46,090	184,360
Insurance for goods (per cubic meter)	123*1300 = 1,562,100	159,900	639,600
Total safety stock cost	87,000		87,000
Transportation cost of goods delivery from CWH to agent points		87,500	350,000
Salary & wages			2,812,000
Total cost per month			**4,535,960**

Table 14. Total Transportation, Warehouse Operation and Administration Cost

Description	**Cost Value (Rs.)**
Total Distribution Cost	256,100
Warehouse Rent Cost	975,000
Holding Cost	125,000
Total Insurance for goods and other expenses	800,900
Total salaries	1,308,000
Electricity	100,000
Total Cost	3,565,000

Table 15. A Comparative Study of the Existing Method and Proposed Method

Total Transportation, Warehouse Operation and Administration Cost for Existing System	Rs.4,535,960	
Total Transportation, Warehouse Operation and Administration Cost for Proposed System	Rs.3,565,000	
Total Cost Saving through new heuristic compared to the Existing Model	Rs.970,960	**(21.41%)**

Conclusions

The research successfully demonstrated the effectiveness of a multi-depot distribution strategy in optimizing the supply chain operations of ABC (Pvt) Ltd. By employing K-means clustering and the gravity model, optimal locations for three central warehouses were identified. Furthermore, the distribution routes were refined, and the transportation costs were minimized using a combination of heuristic methods and Particle Swarm Optimization.

The proposed multi-depot distribution system significantly outperformed the existing decentralized model in terms of cost reduction and efficiency. By consolidating distribution activities into three warehouses, the number of agents was reduced from nine to three, and the number of people engaged in the distribution process was reduced from 89 to 41, resulting in a substantial decrease in labour costs from Rs. 2,812,000 to Rs. 1,308,000. The overall cost of transportation, warehouse operations, and administration declined from Rs. 4,535,960 to Rs. 3,565,000, representing a total savings of Rs. 970,960 (21.41%). These findings clearly demonstrate the superior cost-effectiveness of the multi-depot distribution strategy compared to the decentralized approach. The findings emphasize the importance of strategic warehouse location and efficient route planning in achieving supply chain optimization.

Future research could explore the impact of real-time demand and cost variations to further enhance the distribution network.

Acknowledgement

We would like to express our deepest gratitude to the Head of the Department of Mathematics and Statistics at SLIIT, Prof. Sarath Peiris and Dr. Juman Abdeen, Senior lecturer, Department of Mathematics, Faculty of Science, University of Peradeniya for their expertise and encouragement in writing this paper.

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