Application of ant colony algorithm to optimize waste transport distribution routes in Tegal

Gunawan Gunawan[1], Sri Handayani[2], Sawaviyya Anandianskha[3]

[1,2]Informatics Engineering, STMIK YMI TEGAL, Indonesia
[3]Information System, STMIK YMI TEGAL, Indonesia

A R T I C L E I N F O	ABSTRACT
	Effective and efficient waste management is an essential challenge in developing cities like Tegal City. Optimizing waste transport routes can reduce operational costs and environmental impact. This study aims to implement the Ant Colony Algorithm (ACO) to optimize waste distribution routes in Tegal City. This method was chosen for its proven ability to solve route optimization problems. This study developed a model for the simulation and analysis of waste transportation routes using actual location data from the Integrated Waste Treatment Site (TPST) to the landfill (TPA). The results showed that the implementation of ACO reduced the total mileage from 27.50 km to 21.05 km, a significant reduction that shows the algorithm's efficiency in determining the optimal route. The conclusion of this study confirms that ACO can be effectively used to improve waste transportation operations.

Corresponding Author:

Sri Handayani,
Informatics Engineering,
STMIK YMI TEGAL,
#1 Pendidikan Street, Tegal city, Central Java 52142, Indonesia.
Email: srihandayani211003@gmail.com

1. INTRODUCTION

Rapid population growth makes efficient waste management a significant challenge in major cities worldwide (Ali et al., 2020; Khan et al., 2022; Nanda & Berruti, 2021). Rapid population growth and infrastructure expansion in cities significantly increase the volume of waste, exacerbating the need for an efficient transport system (Bibri et al., 2024; Lu et al., 2021). Limitations in traditional waste-hauling routes often result in high operational costs and significant environmental impacts due to greenhouse gas emissions and excessive fuel consumption (Lamb et al., 2021; Singh et al., 2022). Based on the https://www.tegalkota.go.id/ page , Tegal City produces 250 tons of waste and 30 percent of it is plastic waste, but only 10 percent can be sent to the recycling industry, the rest ends up in TPA (landfill). Efficiency in transporting waste not only has the potential to cause accumulation of waste that can spread disease and increase greenhouse gas emissions, but also reduce the aesthetics and comfort of the city(Ayilara et al., 2020). Efficiency in transporting waste not only has the potential to cause garbage accumulation, which can lead to the spread of disease and increased greenhouse gas emissions but also reduce the aesthetics and comfort of the city (Abubakar et al., 2022; S. Liu et al., 2021).

One of the main problems in waste management in Tegal City is the efficiency of waste transportation routes, which causes delays in waste collection. Non-optimal routes not only increase travel time but also increase carbon emissions from garbage transport vehicles, as opposed to sustainable efforts and carbon footprint reductio (Sar & Ghadimi, 2023). To overcome this problem, the Ant Colony Algorithm (ACO) method can be implemented. ACO works by mimicking the behavior of ants that find the shortest path through the pheromones they leave along the path they travel (Stodola et al., 2022; Zhang et al., 2020).

This study aims to adopt and apply the Ant Colony Algorithm, which takes inspiration from ant behavior in finding the shortest path between the nest and food source, to optimize waste transport routes in Tegal City. This algorithm will be calibrated to consider city-specific variables, like the facilities named TPST (Integrated Waste Management Site) and TPA (Landfill), distance between waste collection points. The Ant Colony algorithm in this study will optimize the travel distance parameters. The success of the algorithm is measured through the reduction of the total distance traveled from the waste transport route, which is expected to contribute to the reduction of carbon emissions and operational efficiency. Measurements were made by comparing the mileage before and after optimization using the Paired Sample T Test to determine the significance of the difference, as well as algorithm convergence analysis to assess speed and stability in achieving the optimal solution (Carrasco et al., 2020; Koul et al., 2022).

Previous research developed a waste collection route optimization model that considers cost and emission factors, aiming to minimize operational costs while reducing greenhouse gas emissions (Hannan et al., 2020). This approach uses mixed linear programming and heuristic algorithms and shows more efficient and environmentally friendly results in a case study in Malaysia. In addition, Gao et al. (2020) proposed a profit optimization and distribution model for the two-echelon collaborative waste collection route problem involving cooperation between waste collection companies and processing facilities; the model considers economic and environmental factors, such as operating costs, profit sharing, and carbon dioxide emissions, using a mixed linear programming approach (L. Liu & Liao, 2021). Developed a task optimization and scheduling model for a distributed cyber-physical system utilizing a modified ant colony algorithm; this approach aims to minimize makespan (overall task completion time) and communication costs between nodes in the system (Yi et al., 2020). In the context of cold chain logistics, the proposed optimization of logistics lines using an improved multiobjective ant colony algorithm; this model considers the factors of transportation costs, delivery times, and product quality in the cold chain supply chain (Zhao et al., 2020). Furthermore, a path-planning optimization method for indoor mobile robots was developed using an adaptive ant colony algorithm (Miao et al., 2021).

Previous research used ACO approaches and mixed linear programming to consider economic and environmental factors, such as operating costs, profit sharing, and carbon dioxide emissions. However, most previous studies have focused only on optimizing garbage collection routes or using other optimization methods, such as linear programming or simple heuristics. This research makes a unique contribution by applying ACO specifically to the optimization of urban waste distribution routes, from the collection process to transportation to the landfill.

This study makes a unique contribution by applying ACO specifically to the optimization of urban waste distribution routes, from the collection process to transportation to landfill. ACO was chosen for its ability to find optimal solutions through a heuristic approach that mimics the natural behavior of ants, which has proven effective in various route optimization applications, and is expected to be more adaptive and efficient than other optimization methods.

2.   RESEARCH METHOD

The research method used in this study is designed to provide a comprehensive and systematic evaluation of the effectiveness of the Ant Colony Algorithm in optimizing waste transportation routes in Tegal City. Here are some steps to take.

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┌─────────┐     ┌──────────────────┐     ┌────────────────────────┐     ┌──────────────────┐
│  Start  │ ──► │  Data Gathering  │ ──► │ Data Pre -pocesing:    │ ──► │ Implementation   │
└─────────┘     └──────────────────┘     │  - Data Cleaning       │     │ Ant Colony       │
                                         │  - Data Normalization  │     └──────────────────┘
                                         └────────────────────────┘              │
                                                                                  ▼
                ┌─────────┐     ┌──────────┐     ┌──────────────────┐
                │   End   │ ◄── │  Result  │ ◄── │ Testing and      │
                └─────────┘     └──────────┘     │ Evaluation       │
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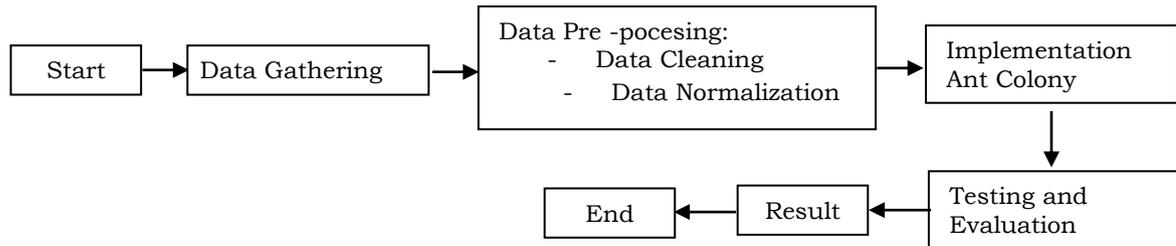
Figure 1. Research Flow

Figure 1 is This research process begins with the "Start" stage, marking the beginning of the research methodology. The "Data Collection" stage involves collecting essential data such as distance between locations and volume of waste. Furthermore, in "Data Pre-processing," the data is cleared of errors and normalized for easy analysis." Implementation Ant Colony" is the stage where the Ant Colony Algorithm is used to design optimal waste transport routes, minimize distances, and improve operational efficiency. After implementation, the "Testing and Evaluation" stage is carried out to evaluate the effectiveness of the resulting route. The evaluation results are then summarized in the "Result" stage, which may also include statistical data analysis. The research process ends with the "End" stage, which marks the completion of all research activities.

2.1 Research Design

This study used an experimental research design to test the effectiveness of the Ant Colony Algorithm in optimizing waste transportation routes in Tegal City. The experimental design was chosen because it allows a controlled and systematic evaluation of the algorithm's performance in a simulated environment (Gad, 2022).

2.2 Data Collection

Data will be collected by accessing the National Waste Information System in 2022 to obtain data on the location and volume of waste in Tegal City. There are 8 data consisting of 7 Integrated Waste Treatment Sites (TPST) and 1 Landfill (TPA). The data is then verified and supplemented with distance information between each location using Google Maps mapping services.

2.3 Pre-processing Data

In pre-processing, only the variables "Facility Name" (TPST and TPA) are preserved from the initial data. Then, TPST Debong Kulon was set as the starting point for the transportation route. The distance between each TPST and TPA location was calculated using Google Maps and added to the dataset.

2.4 Algorithm Configuration

The configuration of the parameters of the Ant Colony Algorithm is carried out, taking into account the characteristics of the route optimization problem and the results of the initial experiments. The parameters used are:

Number of ants (number_of_ants) = 10
Maximum number of iterations (number_of_iterations) = 100
Pheromone evaporation rate (evaporation_rate) = 0.5
Bobot feromon (alpha) = 1
Visibility/distance weight (beta) = 5

        The selection of a relatively small number of ants (10) and a large number of iterations (100) aims to ensure sufficient exploration of the search space without excessively increasing computational complexity (Abualigah et al., 2021). The pheromone evaporation rate (0.5) was chosen to maintain a balance between exploiting existing pheromone traces and exploring new pathways (C. Liu et al., 2023). Visibility/distance weights (beta=5) are given greater values than pheromone weights (alpha=1) to give higher priority to distance minimization in the route decision-making process (Gao et al., 2021).

        These parameters were selected based on initial experiments and previous research using the Ant Colony Algorithm for similar route optimization problems. Choosing the correct values for each parameter allows the algorithm to achieve rapid and stable convergence towards the optimal solution.

2.5 Algorithm Implementation

        Ant Colony is implemented using Python to model waste distribution routes based on pre-prepared data.
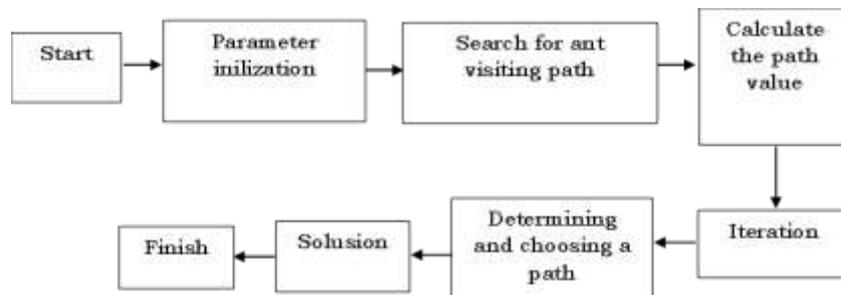

Figure 2. Research Algorithm

        Figure 2 is a flowchart illustrating the steps in the Ant Colony Algorithm to optimize waste transport routes. The process begins with the initialization of parameters that define the basic settings of the algorithm. Then, the ants in the simulation look for a path by following a highly pheromone path, which indicates the effective path that other ants have taken before. Each path taken is assessed based on criteria such as distance or cost. The algorithm iterates, repeating the process of searching and evaluating paths to improve the quality of solutions found continuously. Once the iteration reaches the stop state or finds an optimal solution, the algorithm chooses the best path, and the process is terminated.

        The Ant Colony formula for the probability of an ant k choosing city j from city i can be seen in equation (1).

$$p_{ij}^k = \frac{[\tau ij]^\alpha \cdot [\eta ij]^\beta}{\sum [\eta ij]^\alpha \cdot [\eta ij]^\beta} \tag{1}$$

Where τi is the pheromone intensity on the path of i to j, ηij is a heuristic value (for example, the inverse of a distance), from α and β is a parameter that determines the

influence of pheromones and heuristics. The Ant Colony formula for pheromone updates can be seen in equation (2).

$$\tau ij \leftarrow (1-\rho).\tau ij \ + \ \sum_{k=1}^{m} \Delta\tau_{ij}^{k} \tag{2}$$

Where ρ is the rate of evaporation of pheromones and $\Delta\tau_{ij}^{k}$ Is the amount of pheromone deposited by ants k on track i to j; it is usually inversely proportional to the length of the tour.

2.6 Model Evaluation

The performance of the Ant Colony Algorithm is measured using two primary metrics: Paired Sample T Test and Convergence. The Paired Sample T-Test is used to compare route distances before and after optimization and determine the significance of the difference (Halim et al., 2021). The Paired Sample T Test formula can be seen in equation (3).

$$t = \frac{\bar{d}}{s_d/\sqrt{n}} \tag{3}$$

Where $\bar{d}$ is the average of the differences between the two conditions tested, S_d Is the standard deviation of the difference, and n is the number of data pairs.
Meanwhile, Convergence is examined to evaluate the algorithm's speed in achieving optimal solutions and stability during iteration (Braik, 2021; Zaman & Gharehchopogh, 2022). The Convergence formula can be seen in equation (4).

$$convergence = \frac{1}{N}\sum_{i=1}^{N}\frac{f(x_i)\ -(fx^*)}{f(x^*)} \tag{4}$$

Where $f(x_i)$ is the value of the object function on the i-th iteration, $f(x^*)$ is the optimal value known or best found by the algorithm, and N is the number of iterations taken to achieve convergence.

3.　RESULTS AND DISCUSSIONS

The application of the Ant Colony Algorithm to optimize waste distribution routes in Tegal uses a series of computational steps outlined in the research method. This study applied the Ant Colony Optimization Algorithm to determine the optimal waste distribution route in Tegal City.

Table 1. Dataset

Year	Province	City	Facility Name	Address	Neighborhoods	Subdistrict	Garbage Entry (ton/year)
2022	Central Java	Tegal City	TPST Debong Kulon	Debong Kulon	Debong Kulon	South Tegal	963,60
			TPST Panggung	Jl. Batam 3	Panggung	East Tegal	1835,22
			TPST Bandengsari	Jl. Bandeng	Tegalsari	West Tegal	1927,2
			TPST Keturen	Jl. Ir Juanda	Keturen	South Tegal	963,60
			TPST Kalinyamat Kulon	Kalinyamat Kulon	Kalinyamat Kulon	Margadana	963,60
			TPST Rapi	Jl.Pendidikan	Pesurungan	West Tegal	481,80

		Kidul		
Jaya				
TPST Cleret	Jl.Arum Cleret	Kejambon	South Tegal	2.409
TPA Muarareja	Muarareja	Muarareja	West Tegal	54093

Source: https://sipsn.menlhk.go.id/sipsn/public/home/fasilitas/tpst

Table 1 is the data used in the study obtained from the National Waste Information System in 2022, which includes several data variables such as Year, Province, Regency / City, Facility Name (TPST and TPA), Address, Neighborhoods, Subdistric, Garbage Entry (ton/year).

The initial data obtained was then processed manually by setting the route's starting point at TPST Debong Kulon, and TPST and other landfills were used as the following route. Then, add the distance taken from the starting point to each destination point using Google Maps one by one, as for the data that has been done pre-processing data.

Tabel 2. Research Dataset

Point Strat	TPST or TPA purpose	Distance (KM)
	TPST Panggung	8.7
	TPST Bandengsari	6.6
	TPST Keturen	1.7
TPST Debong Kulon	TPST Kalinyamat Kulon	2.1
	TPST Rapi Jaya	2.6
	TPST Cleret	2.8
	TPA Muarareja	4.3

Table 2 is a data set table used in research and then calculated using the Ant Colony Algorithm. The data is in the form of the name of the TPS used for the Start Point, TPS, and destination TPA, as well as the distance between the initial TPS and the destination TPS and TPA.

Parameter tuning will be used to calculate the Ant Colony Algorithm method.

```
# Algorithm parameters setup
pheromone_matrix = np. Ones (distance_matrix. Shape) /
len(distance_matrix)
number_of_ants = 10
number_of_iterations = 100
evaporation_rate = 0.5
alpha = 1
beta = 2
start_index = 0
end_index = data.columns.get_loc ("TPA Muarareja") - 1
```

Figure 3. Parameter Setting Code

Figure 3 is a code for setting the parameters of the Ant Colony Algorithm used in research on optimizing waste distribution routes in Tegal City. The parameters shown include several essential aspects of the algorithm, such as pheromone matrix initialization (pheromone_matrix), number of ants (number_of_ants), number of iterations (number_of_iterations), evaporation rate (evaporation_rate), as well as alpha and beta parameters that determine the influence of pheromones and distance in decision making by ants. Start_index is set to determine the initial position of ants, while end_index is determined based on the location of the Muarareja landfill. This parameter setting is designed to ensure that the Ant Colony Algorithm can effectively determine the optimal waste distribution route by considering pheromone distance and distribution in a balanced manner.

Algorithm parameter adjustments have been made to implement the algorithm.

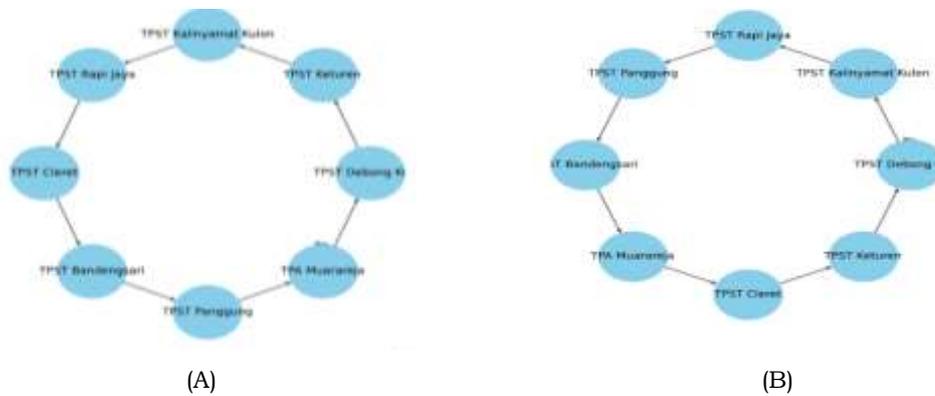(A)   (B)

Figure 4. Route Optimization

Figure 4 shows the result of implementing the Ant Colony Algorithm for optimizing waste distribution routes in Tegal City. The visualization of results is divided into two, namely (A) the route before optimization and (B) the route after optimization. In early conditions, the routes used for garbage transport appear longer and less structured. The route took a less efficient route, visiting several locations such as starting from TPST (Integrated Waste Treatment Site) Debong Kulon - TPST Kalimat Kulon - TPST Rapi Jaya - TPST Panggung - TPST Bandeng Sari - TPA Muarareja - TPST Cleret - TPST Keturen before finally returning to TPST Debong Kulon by reaching a total distance of 27.50 km. Then, after using the Ant Colony Algorithm to optimize the distance, the route traveled was obtained, which started from Debong Kulon - TPST Keturen - TPST Kalimat Kulon - TPST Rapi Jaya - TPST Cleret - TPST Bandeng Sari - TPST Panggung - TPA Muarareja to reach a total distance of 21.05 Km. The initial route before optimization reached a total distance of 27.50 km, while the optimal route produced by ACO was only 21.05 km, showing a reduction of 6.45 km.

The results of the optimization route were then evaluated using two matrices, the Paired Sample T Test and Convergence. The results of the Paired Sample T Test matrix evaluation show that the T-statistic is 115.00024610309937 with a P-value of 3.4287615061525054e-08. This very small p-value indicates that the difference in distance before and after optimization using the Ant Colony Algorithm is statistically significant. This proves that the Ant Colony Algorithm can reliably reduce mileage significantly, justifying the application of this algorithm in the context of optimization of the route under study. Furthermore, the results of the convergence evaluation matrix can be seen more quickly in the figure of Figure 5.
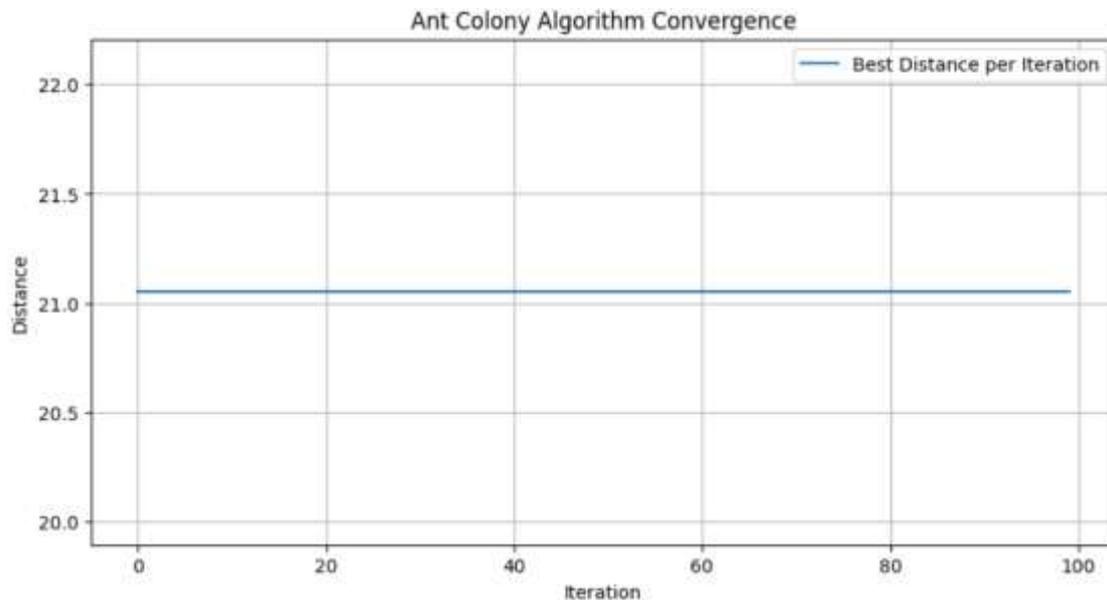
Figure 5. Result of Convergence Evolution

Figure 5 shows the convergence of the Ant Colony Algorithm throughout 100 iterations in route optimization. Convergence Analysis also shows that algorithms can achieve optimal solutions quickly and stably. The convergence graph reveals that the best distance of about 21.05 km was completed in the initial few iterations and maintained until the end of the iteration process.

Practical implementation of the results of this research can be done by integrating the Ant Colony Algorithm into the waste transportation management system in Tegal City. This research uniquely contributes to applying the Ant Colony Algorithm to optimize urban waste distribution routes, from the collection process to transportation to the landfill. Most previous research has focused on optimizing garbage collection routes alone or using other optimization methods such as linear programming or simple heuristics.

The results of the current study showed a significant reduction in total mileage from 27.50 km to 21.05 km, indicating the effectiveness of ACO in optimizing waste transport routes in Tegal City. This is consistent with the findings of (Hannan et al., 2020) and (Gao et al., 2021), which also demonstrated improvements in route optimization using heuristic and mixed linear programming approaches. However, unlike previous studies that focused on cost and emissions, this research specifically addressed the unique geographical and infrastructural conditions of Tegal City, providing a tailored solution for urban waste management.

4. CONCLUSION

This study successfully applied the Ant Colony Optimization (ACO) algorithm to optimize waste collection routes in Tegal City, reducing the travel distance by 6.45 km. The results demonstrate ACO's effectiveness in lowering operational costs and carbon emissions. Practical implications for the city government include cost savings and improved waste collection efficiency due to optimized routes. However, the study's limitations involve using static data and not considering additional constraints. Future research should incorporate dynamic data, account for working hours and vehicle capacity, and compare ACO with other optimization methods. This research significantly contributes to Tegal's waste management policies by providing a more efficient route optimization model.

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