Waste Removal Simulation

Introduction

This report models a waste removal company that utilizes one truck to collect waste from farms and transport it to waste drop-off sites. The road system connecting these entities is represented as a network with edge weights indicating road lengths. The waste removal simulation is modeled using a discrete, agent-based approach. The scenario under consideration consists of waste sites, farms, and a truck responsible for collecting waste and delivering it to the farms. The goal is to optimize the waste removal simulation by trying to minimize fuel consumption and maximize waste collected. This is done by implementing different strategies for the truck's movement and collection decisions.

Model

In the waste removal simulation, we have implemented three primary strategies: Random Strategy, Greedy Fuel Strategy, and Greedy Waste Strategy. Each strategy follows a set of overarching rules, and are mainly separated in teh tasks that they do based on teh assumption we assign to them. Table 1 summarizes the rules for all strategy.

Rule	Explanation
Movement	Trucks can travel between farms, wait at current farms, visit waste drop-off sites, or return to headquarters.
Waste Capacity	Trucks have a finite capacity for carrying waste, and once full, they need to unload the waste at a waste drop-off site.
Fuel Capacity	Trucks have a finite fuel supply and need to return to the company headquarters to refuel when running low on fuel.
Waste Pickup	If the truck is at a farm and its waste capacity is not full, it collects waste.
Waste Disposal	If the truck is at a waste site and it has waste to dispose of, it disposes of the waste.
Fuel	The truck consumes fuel at each time step based on its movement
Consumption	decisions.

Table 1. Summary of Rules

In addition to the rules governing the waste removal simulation, certain assumptions play a vital role in shaping the performance and behavior of each strategy. These assumptions help simplify the model while providing a framework to analyze the strategies under different conditions. Table 2 outlines the overarching assumptions applicable to all strategies and highlights the strategy-specific assumptions that impact each strategy's performance and decision-making process.

Overall Assumptions		
Assumption	**Explanation**	**Argument for Reasonability**
Fixed Waste Site and Farm Locations and Waste Production Rate	Waste sites and farms have fixed locations, and waste production rate does not change over time.	In many real-world scenarios, waste site and farm locations are relatively stable, and waste production rate changes slowly over time, making this a reasonable approximation for short-term simulations. Even thought the waste rate isn't changing the waste added is picked form a normal distribution ensuring that there is some variance in the amount of weaste added to each farm per time step making it more realistic.
Constant Waste and Fuel Capacities for the Truck	The truck's waste and fuel capacities do not change throughout the simulation.	This simplification allows for a more manageable model and is often true for real-world trucks over short periods of time.
Truck Number	There is only 1 truck to make it easier to see which strategy	This makes the simulation simpler and easy to handle

	would work best as multiple trucks will make the simulation will make the simulation more complicated.	and we can potentially look to find an optimum strategy for this one truck and then scale up the number of trucks and apply the strategy to them, thus allowing for real-world application.
Minimum Spanning Trees	I used Minimum Spanning Tree to ensure there is only one path to and from a particular node.	The idea was based on long highways where there is just one clear path and the farms or waste sites located on the side, thus making it more like real-world scenarios.
Fuel Refill Location	The garbage truck can only refuel at company headquarters, thus ignoring the need for gas stations.	This makes the simulation simpler and it was also highlighted in the instructions.
Waste Disposal Sites	The garbage truck can only dispose of waste at waste disposal sites, and not at the headquarters, thus giving each location or node type a specified task.	This allows for each location to have a unique role, which can be seen in the real-world
Constant Fuel Consumption Per Unit Distance	The truck's fuel consumption is constant for each unit of distance traveled.	In many real-world scenarios, fuel consumption varies relatively little over short distances, making this a reasonable approximation.
Deterministic Truck Movement	The truck's movement is not affected by random factors such as traffic or weather conditions.	This simplifies the model and allows for easier comparison of strategies, although it may not capture real-world variability.
Random Strategy-Specific Assumptions		

Ignorance of Wastte Capacity	The truck moves randomly, regardless of whether its waste capacity is full or not.	This assumption provides a baseline scenario to compare against more sophisticated strategies. In certain situations with low waste availability or when fuel consumption is not a major concern, the random movement could provide a reasonable approximation of a less-informed decision-making process. Additionally, it helps to explore the impact of unoptimized decision-making on the system's performance.
Greedy Fuel Strategy-Specific Assumptions		
Movement to the Nearest Farm	The garbage truck travels to the nearest farm and stays there until its waste capacity is reached. It then moves to the nearest waste site to dispose of it and moves back to the next nearest farm, repeating the process. The overarching rule of returning to the headquarters for fuel efficiency is still maintained.	This assumption offers a simplified approach to optimize fuel consumption by minimizing the distance traveled. It is a reasonable approximation when fuel efficiency is the primary concern, and the waste distribution among farms is relatively even. It may not provide the most optimal solution in all situations but serves as a starting point for understanding the impact of fuel consumption-focused decision-making on the system's performance.
Greedy Waste Strategy-Specific Assumptions		

Movement to the Farm with Highest Waste	The garbage truck locates the farm with the highest waste and travels there. After reaching its maximum waste capacity, it moves to the nearest waste site to dispose of the waste and then returns to collecting from the farm with the highest waste at that time step. The overarching rule of returning to the	This assumption prioritizes waste collection by targeting farms with the most significant waste accumulation. It is a reasonable approximation when maximizing waste collection is the primary goal, and the distribution of waste among farms is uneven. While it may not be optimal
	headquarters for fuel efficiency is still maintained.	in terms of fuel consumption, it serves as a useful approach for understanding the impact of waste-focused decision-making on the system's performance.

Table 2. Summary of Assumptions

After understanding the rules and assumptions that guide the waste removal simulation, it is essential to consider the parameters that affect the behavior and performance of the strategies. These parameters define the complexity of the scenario and the truck's capabilities, which can be adjusted to evaluate the efficiency of each strategy under various conditions. Table 3 provides an overview of the key parameters involved in the simulation, along with a brief description of their impact on the model:

Parameters	**Explaination**
num_waste_sites	Number of waste sites in the simulation, affecting the complexity of the problem.
num_farms	Number of farms in the simulation, also influencing the complexity of the scenario.
max_truck_cap	Maximum waste capacity of the truck, determining how much waste the truck can carry at once.
max_fuel_cap	Maximum fuel capacity of the truck, which influences how far the truck can travel.

max_time_steps	Maximum number of steps allowed for the simulation.
fig_on	Simple boolean checker to indicate whether we want the animation to display or not.

Table 3. Summary of Paramters

In order to evaluate the performance of the waste removal strategies implemented in the simulation, we need to analyze the output measurements. These measurements help us understand the effectiveness of each strategy in the given scenario, allowing for better decision-making in real-world applications. Table 4 provides a summary of the output measurements and their explanations.

Output Measurement	Explaination
Total Waste Collected	This measurement represents the total amount of waste collected by the garbage truck during the simulation. It is an indicator of the efficiency of the waste collection process, allowing for the comparison of waste collection performance across different strategies.
Total Fuel Consumed	This measurement represents the total amount of fuel consumed by the garbage truck during the simulation. It is an indicator of the efficiency of the fuel consumption process, allowing for the comparison of fuel consumption performance across different strategies.

Table 4. Summary of Output Variables

By analyzing these output measurements, we can draw insights into the performance of each strategy under various conditions and evaluate their effectiveness in the waste removal simulation. **Test Cases**

The provided test results offer a comprehensive demonstration that the implemented code is functioning correctly and producing the expected behavior for the waste collection and fuel consumption optimization problem. By considering various test scenarios, we can analyze the performance of the three strategies – Random Strategy, Greedy Fuel Strategy, and Greedy Waste Strategy – and evaluate their effectiveness.

From the test cases, we can make the following observations:

1. For the general case (test1), the Greedy Waste Strategy performs the best in terms of waste collection, collecting significantly more waste than the other two strategies. This is expected, as the Greedy Waste Strategy focuses on maximizing waste collection.
2. For the low waste capacity, high fuel capacity scenario (test3), the Greedy Fuel Strategy performs better in terms of waste collection and fuel consumption. This indicates that the Greedy Fuel Strategy is effective when the truck has a low waste capacity and a high fuel capacity.
3. In cases with invalid inputs, the code provides appropriate error messages, ensuring that the simulation only runs with valid parameters.
4. In scenarios with no farms and waste sites (test5), no waste is collected, and no fuel is consumed, as expected.
5. In the case of equal numbers of waste sites and farms (test12), the Greedy Waste Strategy performs the best in terms of waste collection, while the Greedy Fuel Strategy consumes the least fuel.
6. In the high waste sites, low farms scenario (test13), the Greedy Waste Strategy still performs the best in terms of waste collection, indicating that it is effective in scenarios with different proportions of waste sites and farms.

These results and the other test cases demonstrate that the implemented code is correctly modeling the waste removal simulation. The strategies perform as expected under various conditions, and the simulation effectively measures and compares their performance. This indicates that the code is working correctly and producing the expected behavior for the modeled scenario.

Analysis

Emperical

The empirical analysis to figure out a good waste disposal strategy meant trying different strategies which have been discussed above.

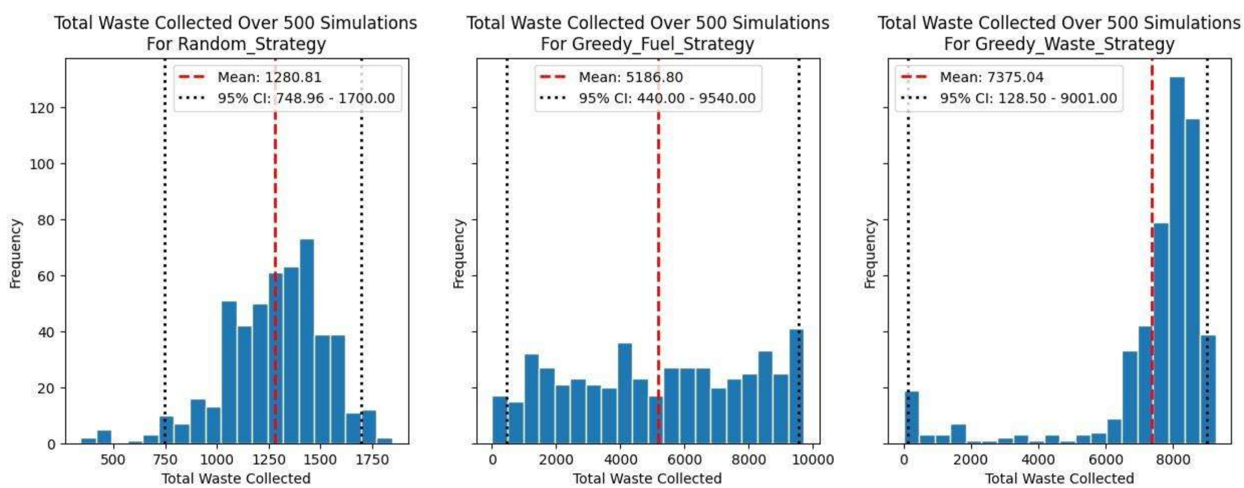

Figure 1. Total Waste Collected over 500 simulations for different Strategies.

Based on the simulation results from the three different strategies as seen in figure 1, it is evident that the Greedy Waste strategy outperforms the Random strategy and the Greedy Fuel strategy in terms of total waste collected after 500 simulations.

The Random strategy has a mean of 1280.81, and its 95% confidence interval is 748.96 1700, showing a mostly normal distribution with a slight left skew. The Greedy Fuel strategy has a mean of 5186.80 and a 95% confidence interval of 440 - 9549, exhibiting a mostly uniform distribution. The Greedy Waste strategy has the highest mean of 7375.04, with a 95% confidence interval of 128.50 - 9001.00, and a mostly left-skewed distribution.

Considering the results, I would recommend employing the Greedy Waste strategy as the best course of action, as it consistently leads to a higher amount of waste collected compared to the other two strategies. This strategy focuses on prioritizing the collection of waste at locations where waste generation is highest, which has proven to be more effective in this scenario.

Regarding the remaining uncertainty in the results, the 95% confidence intervals for all three strategies still show some uncertainty, with the Greedy Fuel strategy exhibiting the highest level of uncertainty due to its wide confidence interval. To reduce the width of these confidence intervals and increase the confidence in our results, we could perform more simulations or increase the number of simulation steps. Conducting additional simulations will provide a better understanding of the strategies' performance, which in turn will allow for more accurate and reliable decision-making.

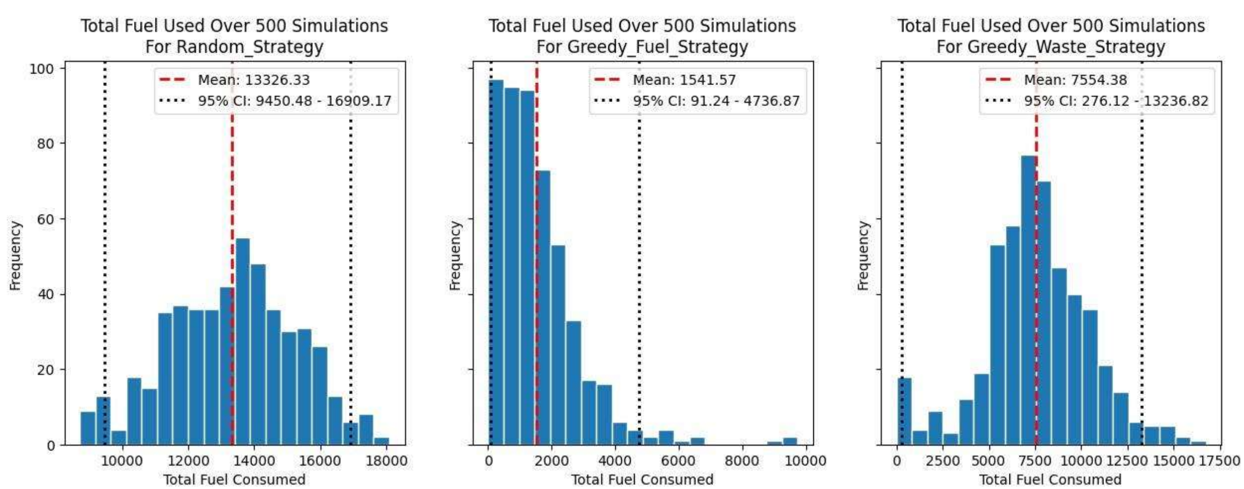

Figure 2. Total Fuel Consumed over 500 simulations for different Strategies.

In addition to the total waste collected, it is important to consider the total fuel consumed after 500 simulations for each strategy. Analyzing the fuel consumption can provide insights into the efficiency and sustainability of each strategy.

The Random strategy has a mean fuel consumption of 123,326.33, with a 95% confidence interval of 9,450.48 - 16,909.17, showing a mostly normal distribution. The Greedy Fuel strategy has the lowest mean fuel consumption of 1,541.57 and a 95% confidence interval of 91.24 - 4,736.87, displaying a mostly right-skewed distribution. The Greedy Waste strategy has a mean fuel consumption of 7,554.38, with a 95% confidence interval of 276.12 - 13,236.82, and a mostly normal distribution.

Taking both total waste collected and total fuel consumed into account, the Greedy Fuel strategy seems to be the best overall option, as it collects the decent about of waste while having really low fuel consumption. However, the Greedy Waste strategy should also be considered, especially in situations where we only priortize waste collection. While the Greedy Fuel strategy collects less waste compared to the Greedy Waste strategy, it consumes significantly less fuel, making it more environmentally friendly and cost-effective in terms of fuel consumption.

The 95% confidence intervals for the fuel consumption analysis also indicate some uncertainty in the results, with the Greedy Fuel strategy showing a wider confidence interval and higher uncertainty. To further improve confidence in our results, we could perform more simulations or increase the number of simulation steps. This would help narrow down the confidence intervals and provide more reliable information for decision-making.

Theoretical

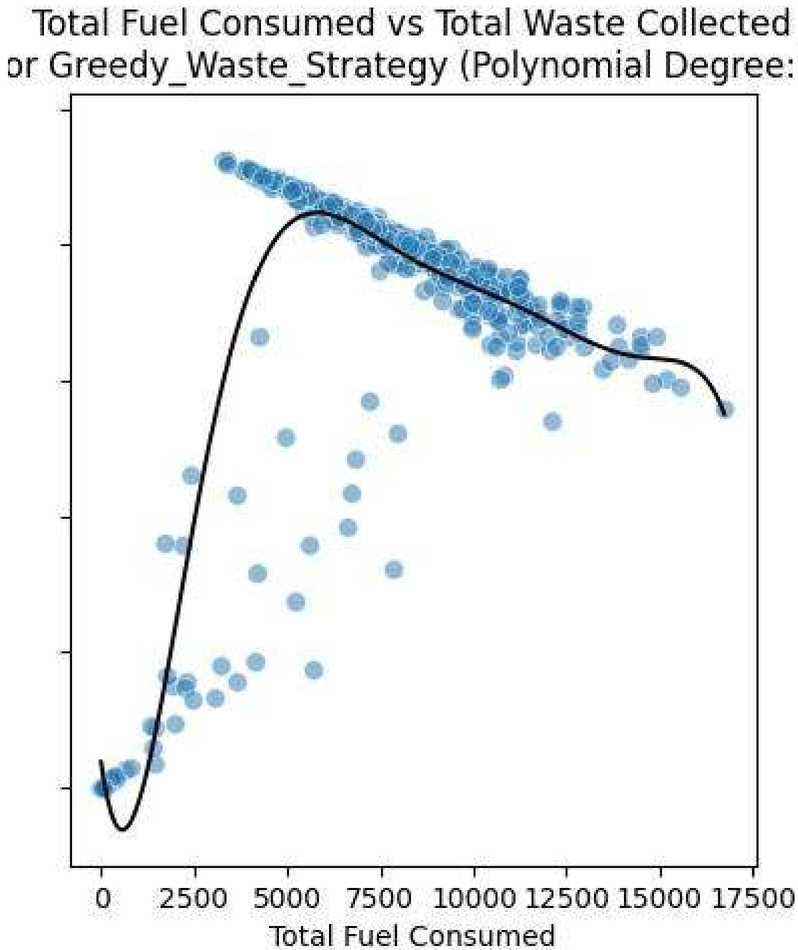

Figure 3. Fuel Consumed VS Waste Collected.

Based on the observation in figure 3. Initially, as more fuel is consumed, the waste collection rate increases, suggesting that the trucks are effectively targeting areas with higher waste density. This results in an efficient and productive waste collection process.

However, after a certain point, the plot shows that increasing fuel consumption leads to a decrease in waste collected. This behavior can be explained by the trucks revisiting areas that have already been mostly cleared of waste. As fuel consumption increases, the trucks are forced to travel longer distances to reach the remaining waste, leading to a decrease in efficiency.

Additionally, the trucks may be spending more time navigating through areas with lower waste density, further contributing to the diminishing returns.

The mathematical analysis of the model supports these observations by highlighting the diminishing returns effect and the limitations of the Greedy Waste strategy. Theoretical results emphasize the importance of considering the trade-offs between fuel consumption and waste collection, which helps to inform the most efficient operating regions in the parameter space.

Based on this analysis, it becomes evident that although the Greedy Waste strategy is effective in collecting waste initially, it is not the most sustainable choice in the long run. Balancing fuel consumption with waste collection efficiency is essential to maintain a cost-effective and environmentally responsible waste management system.

Final Thoughts

Our extensive analysis of the three waste collection strategies - Random, Greedy Fuel, and Greedy Waste - demonstrates that the Greedy Fuel strategy is the most recommended approach for waste collection operations. While the Greedy Waste strategy collects the most waste overall, it also consumes more fuel than the Greedy Fuel strategy. Considering the increasing importance of environmental sustainability and the rising cost of fuel, we recommend employing the Greedy Fuel strategy, as it optimizes fuel efficiency while still collecting a substantial amount of waste.

The Greedy Fuel strategy has a significantly lower mean fuel consumption compared to the other strategies, with a right-skewed distribution that highlights the potential for even greater fuel savings. Although the total waste collected is lower compared to the Greedy Waste strategy, the trade-off in fuel efficiency and environmental impact make it the preferred choice. We advise waste disposal companies to implement the Greedy Fuel strategy for waste collection, as it strikes a balance between cost-effectiveness, environmental responsibility, and reasonable waste collection performance.