Efficient, Reliable and Sustainable Waste Management

Presented To:

The Department of Environmental Affairs of the State of Optimization

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Introduction

The purpose of this report is to help develop a more efficient, reliable and sustainable waste management system in the State of Optimization. We understand that in order to attract young professionals and to expand economic activity the State of Optimization has three main priorities; to improve quality of life, deploy smart city technologies and to promote sustainable development.

The objective of this project is therefore to identify strategies that leverage modern technologies to develop solutions that are both implementable, resilient, and sustainable. This report will assist the State of Optimization to transition from the current waste management system, which uses open-air dumps that collect waste and burn it from time to time. This is widely recognized to be the worst possible disposal technique from an environmental standpoint.

This report focuses on using a modern system based on sanitary landfills. In addition to the sanitary landfills, we will also explore the possibility of deploying modern waste management systems that use transfer stations for waste compaction. Compaction reduces the size of solid waste, making it easier and less expensive to transport. The two major decisions that the report looks at are how many landfills and transfer stations (if any) to deploy, and where to locate them across the state based on various economic, operational, and environmental considerations.

Based on budget, operational, and feasibility considerations, we will propose a strategy that will allow a seamless transition from the previous waste management system based on open-air dumps to the modern system that uses both waste compaction technology and sanitary landfills, to dispose off waste in a cost-effective and environmentally friendly way.

Methodology/Road Map

Taking into account the uncertainty associated with population and productivity growth, we will look at possible impact of building different number of landfills on distance the waste has to travel and the cost associated with both building new landfills and transporting the waste.

This will be followed by a model that in addition to landfills, also uses transfer stations to compact waste in order to reduce transportation cost. We then analyse the impact of different combinations of different number of landfills and transfer stations on cost of a) transporting waste, b) building landfills and c) building transfer stations. We looked at multiple situations that vary given various budget constraint.

Lastly, we will also try to show the impact of using different technologies that change the rate of compaction and analyse the benefits of that as well. The objective of all the various models discussed above is to minimize cost across all the scenarios.

Our proposed models will allow the decision makers at the State Optimization to identify both the optimal number of landfills and transfer stations to deploy and the location of these landfills and transfer stations given all the factors mentioned above. Our solution proposes a simplified model that can be implemented within a short timeline and this model can further be used to take into consideration further complexities and tailoring the solution for your specific needs and priorities.

Model

We made three models to find the best combinations of construction for landfills and transfer stations:

- Model 1 seeks to determine the optimal number of landfills for total distance by goal programming (Without considering transfer stations and budget)
- Model 2 seeks to determine the optimal number of landfills and transfer stations for total distance by goal programming (Without considering budget)
- Model 3 seeks to determine the optimal budgets for total distance by goal programming

Sets

i = 1, …, 95 : center locations
j = 1, …, 22 : potential sanitary landfill locations
k = 1, ..., 84 : potential transfer station locations
s = 1, ..., 15 : scenarios

Parameters

w_{is} : *forecasted amount of waste generated in center i in scenario s*
dx_{ij} : *distance from center i to landfill j*
dy_{ik} : *distance from center i to transfer station k*
dz_{kj} : *distance from transfer station k to landfill j*
p_s : *probability of scenario s*
T_l : *target number of landfills for goal programming approach*
T_t : *target number of transfer stations for goal programming approach*
T_b : *target budget for goal programming approach*
R : *compaction rate*
Cl : *cost to build a landfill*
Ct : *cost to build a transfer station*
M : *a large number used in constraints*

We consider some assumptions for parameters:

- Each distance parameter is calculated by “grid distance”; the distance between the center location i (x_i, y_i) and the landfill location j (x_j, y_j) is given by $dx_{ij} = |x_i - x_j| + |y_i - y_j|$.
- Each probability of scenario will take place with the same probability; p = 1/15.
- Compaction rate is the ratio of waste left after the compaction; if R = 0.3, an amount of 100 waste becomes to 30. We set R = 0.3 except during the analysis where we change the rate.
- Each cost for building a landfill is the same (we set Cl = 100,000) in any location, and each cost for building a transfer station is the same (we set Ct = 150,000) in any location as well.

<u>Decision variables</u>

l_j : 1 *if a landfill at location j is deployed, otherwise* 0

t_k : 1 *if a transfer station at location k is deployed, otherwise* 0

x_{ijs} : *amount of waste transported from center i to landfill j in scenario s*

y_{iks} : *amount of waste transported from center i to transfer station k in scenario s*

z_{kjs} : *amount of waste transported from transfer station k to landfill i in scenario s*

bx_{ijs} : 1 *if waste generated center i is transported to landfill j in scenario s, otherwise* 0

by_{iks} : 1 *if waste generated center i is transported to transfer station k in scenario s, otherwise* 0

We consider some assumptions for decision variables:

- For all x, all the waste generated in center i will be transported to one landfill j.
- For all y, all the waste generated in center i will be transported to one transfer station k.
- For all z, all the compacted waste in transfer station k will be transported to one landfill i.
- The waste generated in center i will not be separated to multiple landfills or transfer stations.
- The compacted waste in transfer station k must be transferred to landfills and in this case, it may be transferred to multiple landfills.
- We don’t consider other possible factors such as capacity for landfills and transfer stations, or running cost for landfills, transfer stations, and garbage trucks.

Objective functions

Model 1-1: The model seeks to determine the optimal number of landfills for total distance by goal programming

$$Min\ :\ z_{d1}\ = \sum_{s=1}^{15}\sum_{i=1}^{95}\sum_{j=1}^{22} p_s x_{ijs} dx_{ij}\ \ (Expected\ total\ distance\ *\ amount\ waste)$$

Model 1-2: The minimax model based on a specific number of landfills from Model 1-1

$$Min\ :\ Q\ \ (Maximum\ distance\ from\ center\ i\ to\ landfill\ j)$$

Model 2: The model seeks to determine the optimal number of landfills and transfer stations for total distance by goal programming

$$Min\ :z_{d2}\ = \sum_{s=1}^{15} p_s * (\sum_{i=1}^{95}\sum_{j=1}^{22} x_{ijs} dx_{ij} + \sum_{i=1}^{95}\sum_{k=1}^{84} y_{iks} dy_{ik} + \sum_{k=1}^{84}\sum_{j=1}^{22} z_{kjs} dz_{kj})$$

$$(Expected\ total\ distance\ *\ amount\ waste)$$

Model 3: The model seeks to determine the optimal budgets for total distance by goal programming

$$Min :\ z_{d2}\ = \sum_{s=1}^{15} p_s * (\sum_{i=1}^{95}\sum_{j=1}^{22} x_{ijs} dx_{ij} + \sum_{i=1}^{95}\sum_{k=1}^{84} y_{iks} dy_{ik} + \sum_{k=1}^{84}\sum_{j=1}^{22} z_{kjs} dz_{kj})$$

$$(Expected\ total\ distance\ *\ amount\ waste,\ same\ as\ Model\ 2)$$

Constraints

Model 1-1: The model seeks to determine the optimal number of landfills for total distance by goal programming

$$\sum_{j=1}^{22} l_j\ <=\ K_l\ (Target\ for\ number\ of\ landfills\ to\ build)$$

$$x_{ijs}\ =\ w_{is}\ *\ bx_{ijs}\ (for\ all\ i,\ all\ j,\ all\ s,\ amount\ of\ waste\ from\ center\ i\ to\ landfill\ j\ in\ scenario\ s)$$

$$\sum_{j=1}^{22} bx_{ijs}\ =\ 1\ \ (for\ all\ i,\ all\ s,\ for\ each\ center\ i\ the\ waste\ should\ be\ transferred\ to\ one\ j)$$

$$\sum_{i=1}^{95} x_{ijs} \le M l_j\ \ (for\ all\ j,\ all\ s,\ landfill\ j\ should\ be\ built\ if\ waste\ is\ transported\ there)$$

$$x\ (positive)$$

Model 1-2: Minimax model for distance from center to landfill

Add a constraint below to Model 1-1

$$\sum_{i=1}^{95} p_s x_{ijs} dx_{ij} \leq Q \ \ (for\ all\ i)$$ (consider minimizing the maximum total distance for i)

Model 2: The model seeks to determine the optimal number of landfills and transfer stations for total distance by goal programming

$$\sum_{j=1}^{22} l_j \ <= \ K_l \ (Target\ for\ number\ of\ landfills\ to\ build)$$

$$\sum_{k=1}^{84} t_k \ <= \ K_t \ (Target\ for\ number\ of\ transfer\ stations\ to\ build)$$

$$x_{ijs} \ = \ w_{is} \ * \ bx_{ijs} \ (for\ all\ i,\ all\ j,\ all\ s,\ amount\ of\ waste\ from\ center\ i\ to\ landfill\ j\ in\ scenario\ s)$$

$$y_{iks} \ = \ w_{is} \ * \ by_{iks} \ (for\ all\ i,\ all\ j,\ all\ s,\ amount\ of\ waste\ from\ center\ i\ to\ transfer\ station\ k\ in\ scenario\ s)$$

$$\sum_{j=1}^{22} bx_{ijs} \ + \sum_{k=1}^{84} by_{iks} \ = \ 1 \ \ (for\ all\ i,\ all\ s,\ for\ each\ center\ i\ the\ waste\ should\ be\ transferred\ to\ j\ or\ k)$$

$$\sum_{j=1}^{22} z_{kjs} \ = \ r \ * \ \sum_{i=1}^{95} y_{iks} \ (for\ all\ k,\ all\ s,\ for\ each\ transfer\ station\ k,\ all\ reached\ waste\ needs\ to\ leave)$$

$$\sum_{i=1}^{95} x_{ijs} \leq M l_j \ \ (for\ all\ j,\ all\ s, landfill\ j\ should\ be\ built\ if\ waste\ is\ transported\ there)$$

$$\sum_{k=1}^{84} y_{iks} \leq M t_k \ \ (for\ all\ k,\ all\ s, transfer\ station\ k\ should\ be\ built\ if\ waste\ is\ transported\ there)$$

$$\sum_{i=1}^{95} z_{ijs} \leq M l_j \ \ (for\ all\ j,\ all\ s, landfill\ j\ should\ be\ built\ if\ waste\ is\ transported\ there)$$

$$x,\ y,\ z\ (positive)$$

Model 3: The model seeks to determine the optimal budgets for total distance by goal programming

The same as Model 2 except two target constraints are replaced to below

$$Cj * \sum_{j=1}^{22} l_j + Ct * \sum_{k=1}^{84} t_k \ <= \ K_b \ (Target\ for\ budgets\ to\ build\ landfills\ and\ transfer\ stations)$$

Results:

Model 1-1: The model seeks to determine the optimal number of landfills for total distance by goal programming

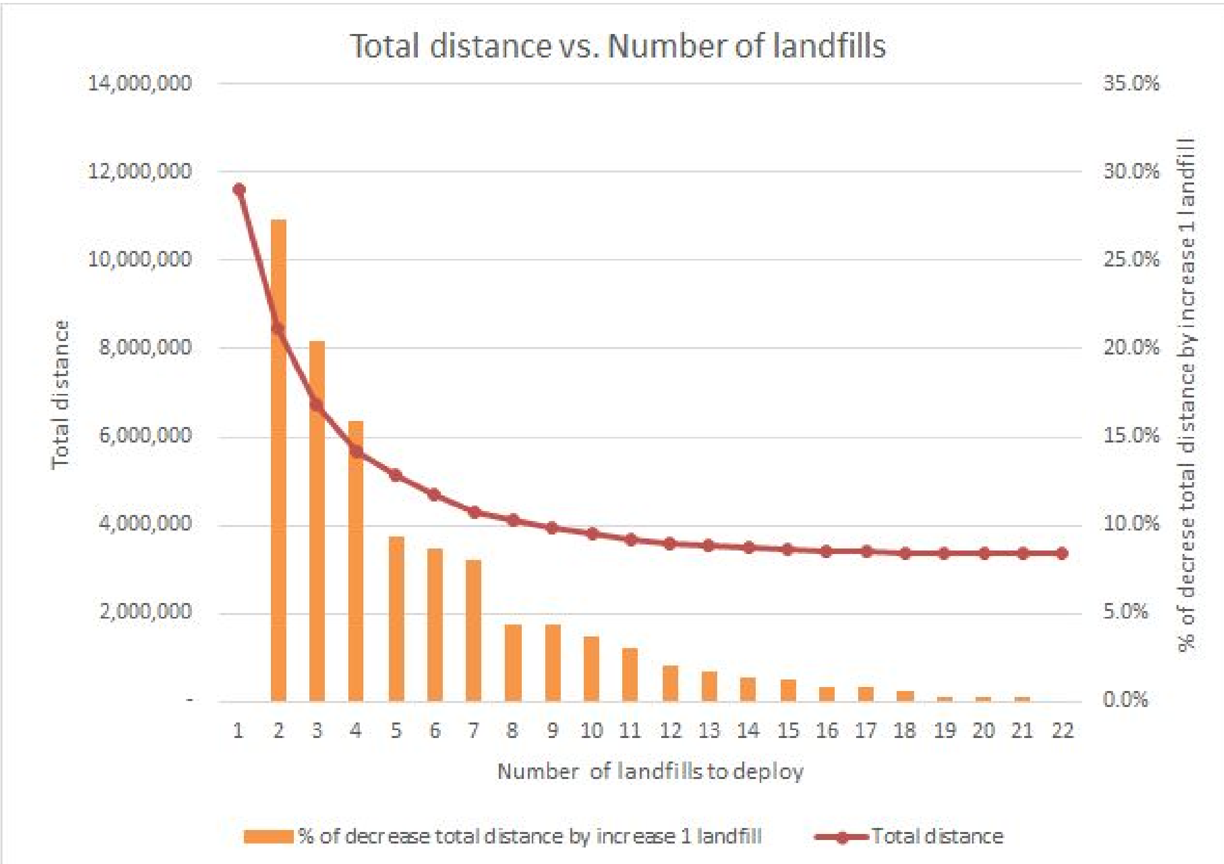

Figure 1: Total distance by changing the number of landfills

As expected, the total expected distance decreases as we increase the number of landfills. However, we can use the percent decrease of the total distance as a better metric to approximate the number of landfills we should deploy. From the graph above, we can observe that the percent decrease of building 8 or more landfills is less than 5 percent. Therefore, it is more efficient to build 7 landfills because if we build any more, the cost of building additional landfills far outweighs the benefits from the percent decrease in total distance.

Model 1-2: Minimax model for distance from center to landfill (Fix landfills = 7)

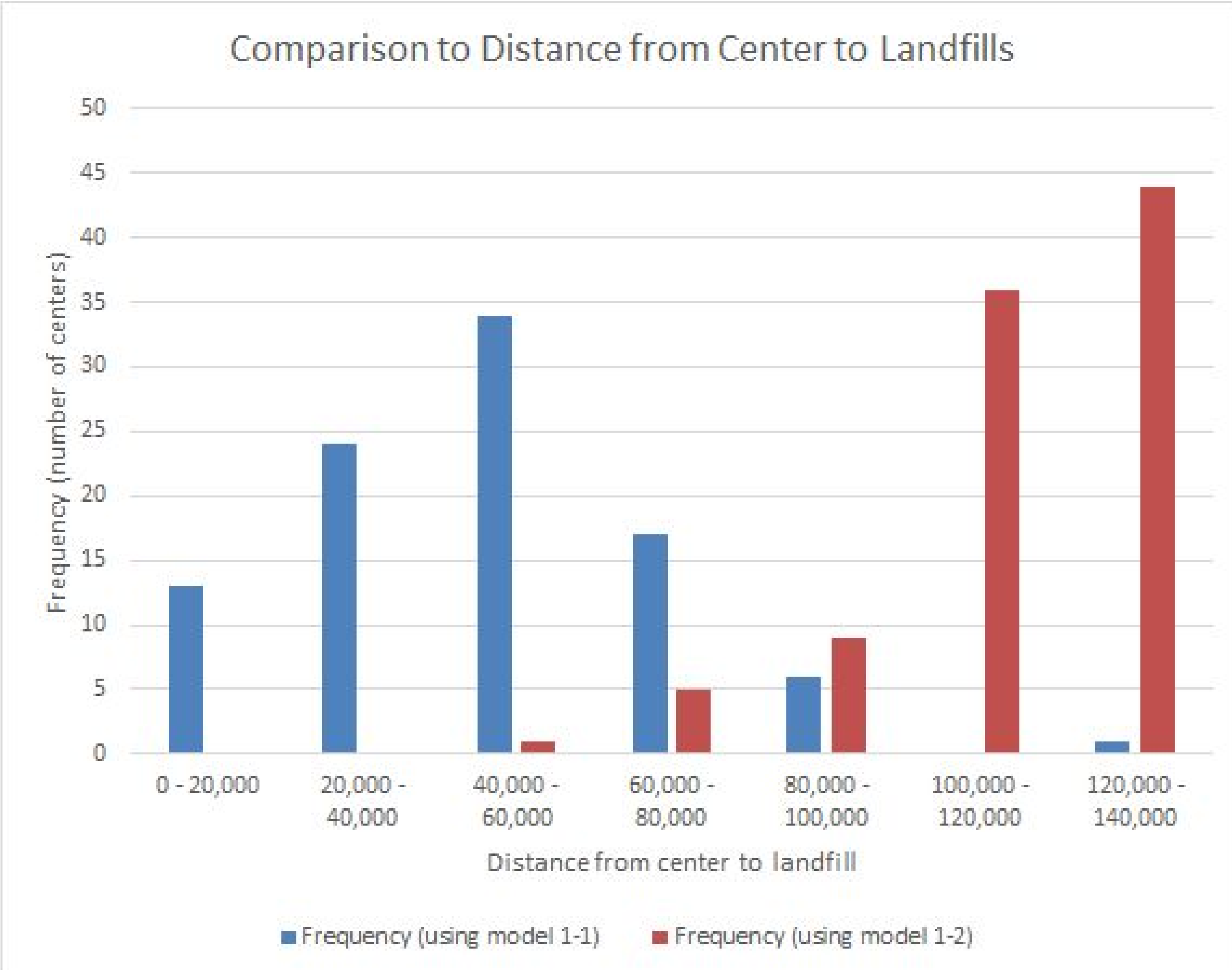

Figure 2: Comparison to distance from centers to landfills

Figure 2 displays that by fixing the number of landfills (i.e. 7), there is a higher frequency of centers that are located further away from landfills when using the minimax technique (model 1-2) in comparison to minimizing the total distance objective (model 1-1). We decided to fix the number of landfills to 7 based on our analysis from Figure 1.

Model 2: The model seeks to determine the optimal number of landfills and transfer stations for total distance by goal programming

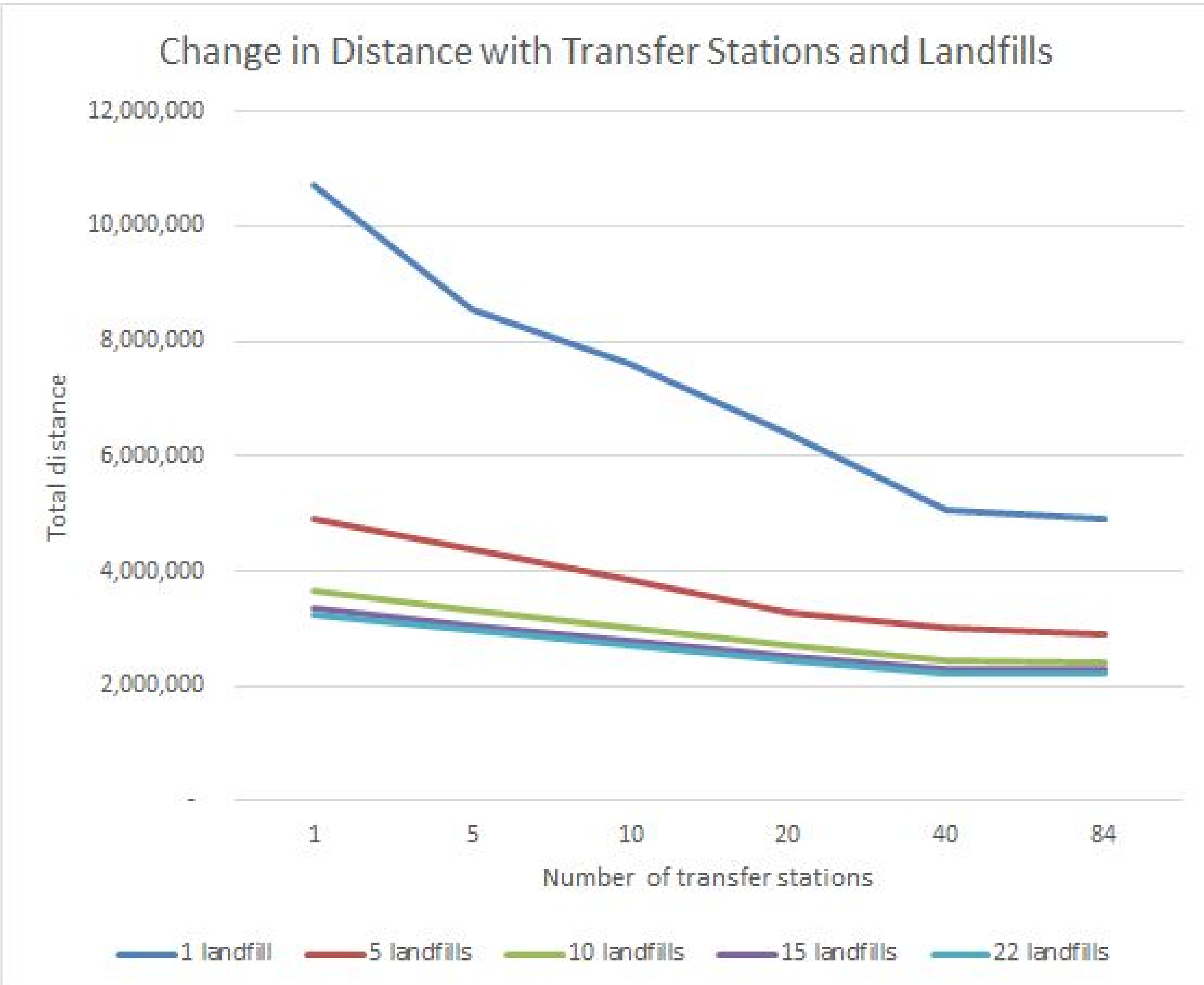

Figure 3: Total distance by changing the number of transfer stations

By increasing the number of transfer stations in each case, the total distance decreases as well. Moreover, by increasing the number of landfills, the total distance decreases as well. Lastly, increasing the number of transfer stations above 40 is inefficient since there is not a large difference in the total distance for landfills greater than 1.

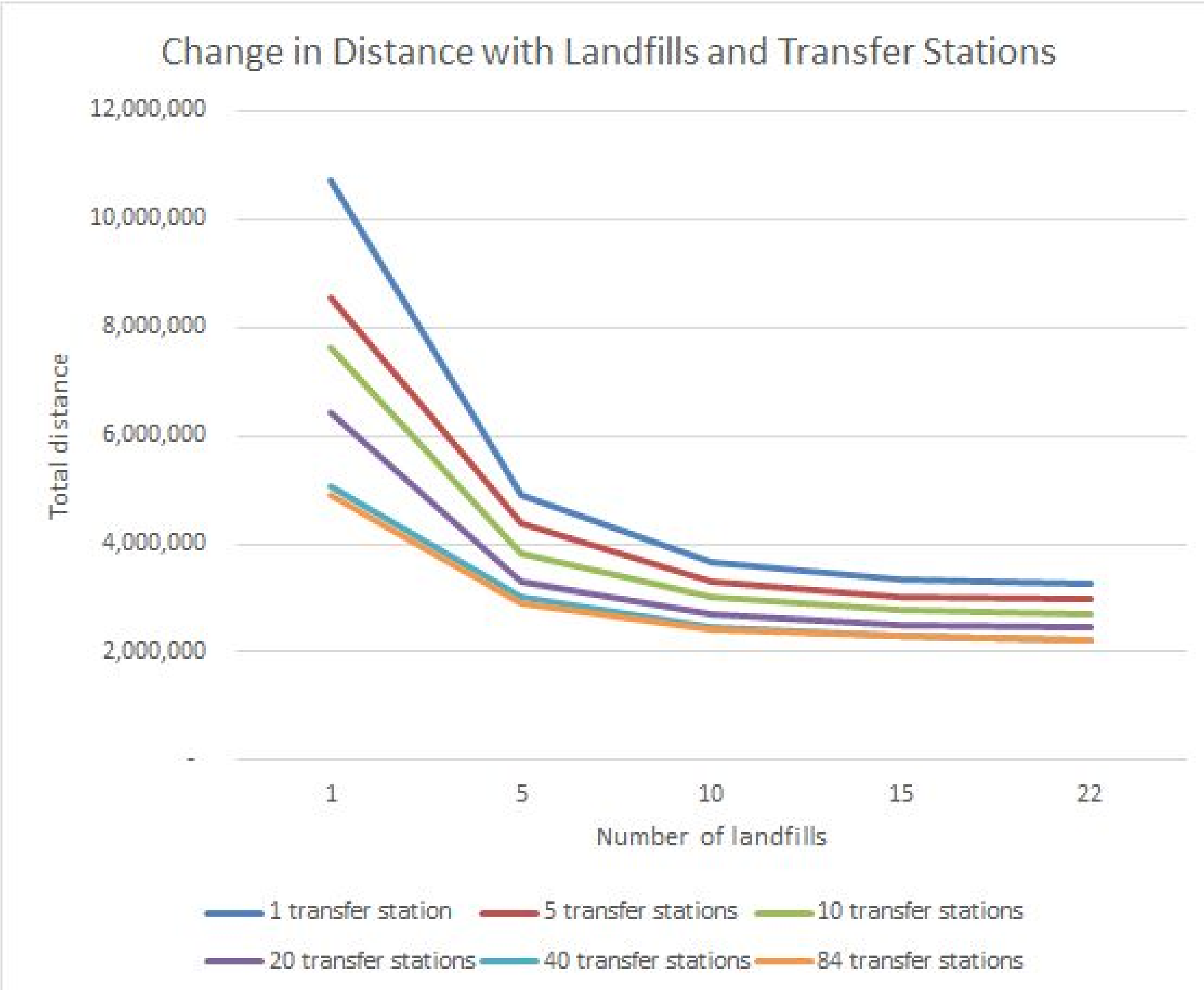

Figure 4: Total distance by changing the number of landfills

In this case, we can confirm that building more than 40 transfer stations can be inefficient because the blue and orange curves are relatively the same (overlapping). The total distance does not really change for the blue and orange curves for all number of landfills.

Model 3: The model seeks for optimal budgets for total distance by goal programming

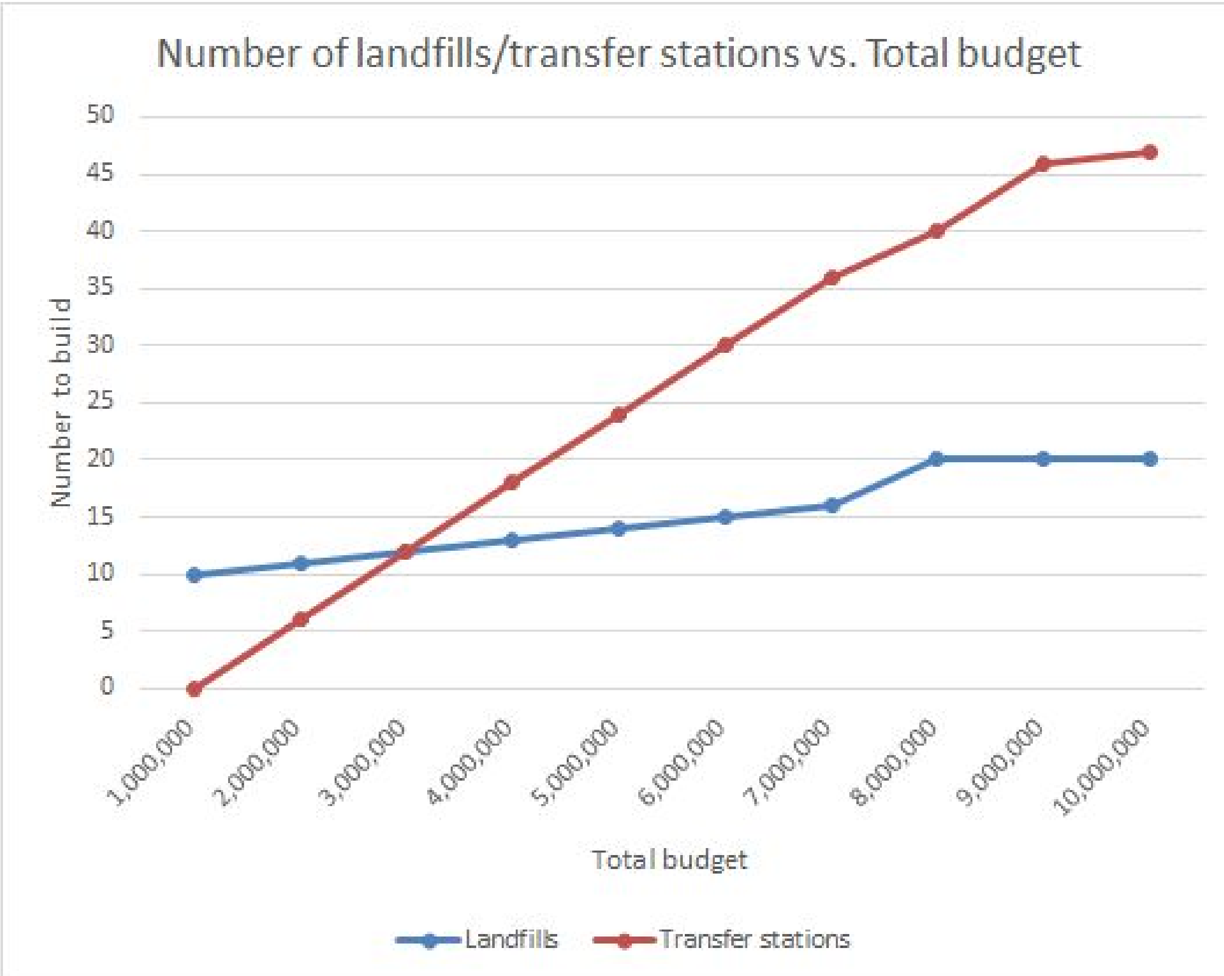

Figure 5: Number of landfills and transfer stations by changing budget

This graph compares how the number of landfills and transfer stations will vary with an increase in budget. The cost is the cost of building a landfill is lower than a transfer station and that shows in the graph. If the state has a low budget then the model builds more landfills than transfer stations and more transfer stations start getting built as the budget increases. It may be noted that increasing the budget from 8 million to 10 million only adds transfer stations and that may be inefficient in terms of cost and benefit. As we mentioned in Model 2 (Figure 3 and 4), building over 40 transfer stations is not efficient by using over 8 million cost.

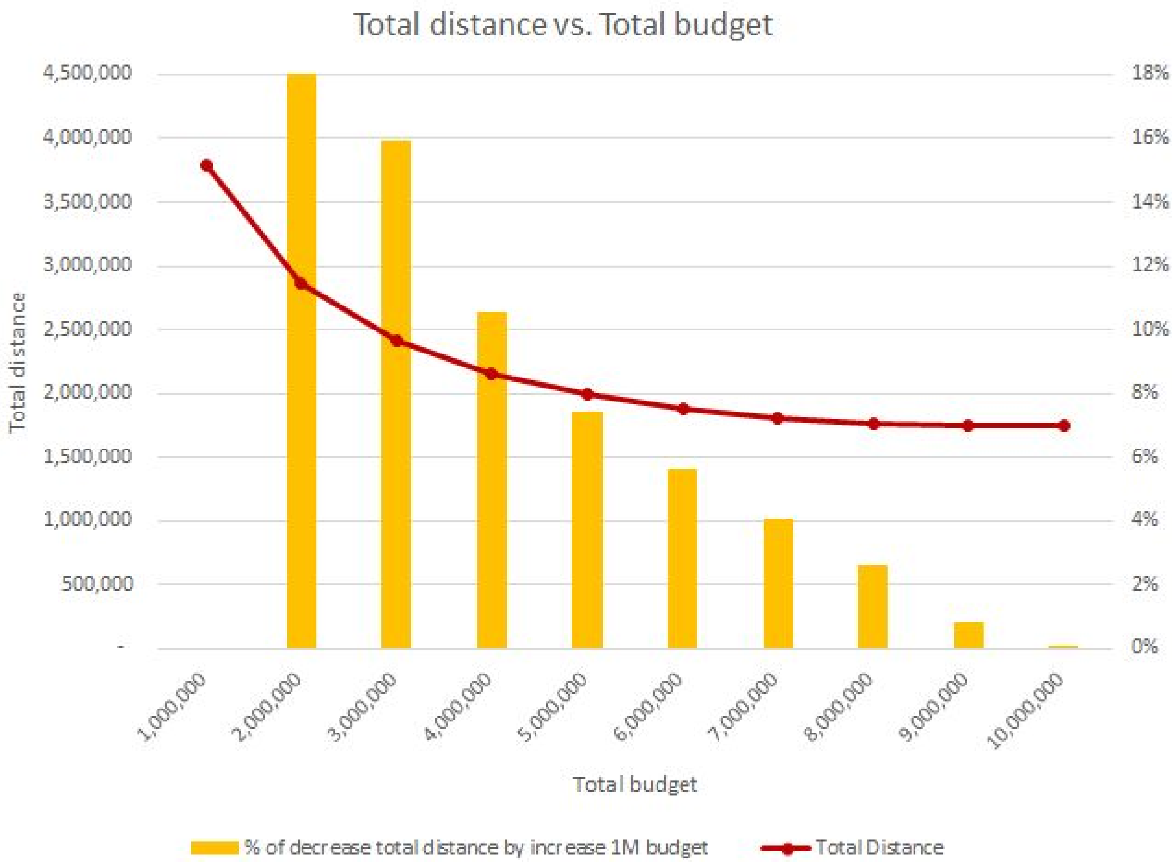

Figure 6: Total distance by changing budget

The infographic shows the relation of distance and budget with the right hand showing how much the decrease in distance is with the increase in every million dollars spent. There is a huge dip in the distance with 3 million budget where 12 landfills and 12 transfer stations are built, which we found from Figure 5. Adding on to the budget further decreases the distance but increasing from 5 million to 6 million only decreases the distance by 6% which might be inefficient. Thus, we recommend that 3 millions or 5 millions for building landfills and transfer stations should be prepared.

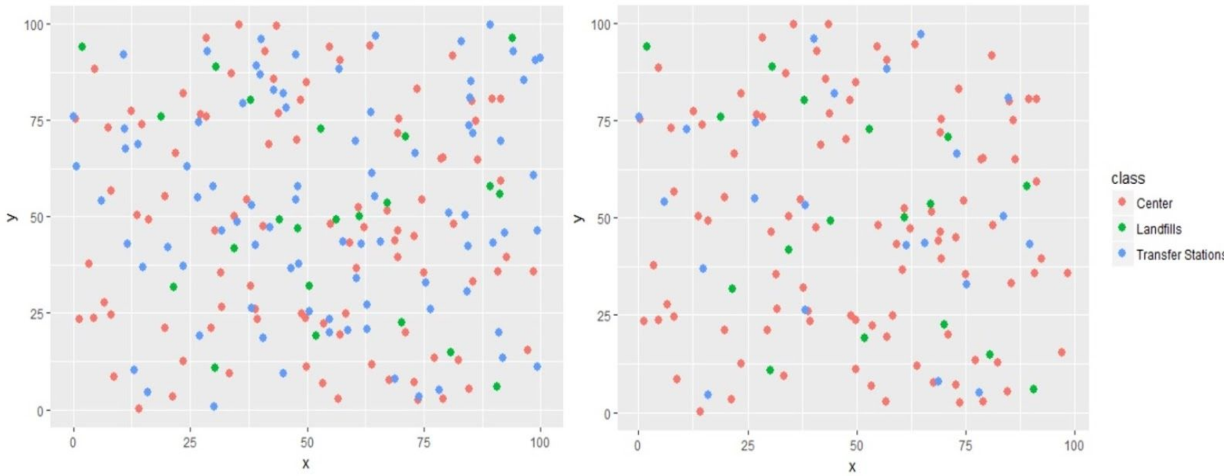

Figure 7: Maps for all potential facilities and selected facilities with budget 5M

This solution with the graphs shows how the how a two dimensional map would look after the model determines how many transfer stations and landfills to build based on the budget decided for the project. In the case of the graphs, a 5 million budget is taken based on the analysis on Figure 5, and the results show how the transfer stations and landfills would be placed (image on right) as compared to an unoptimized solution using all landfills and transfer stations (image on the left). We can see that potential transfer stations on edges will not likely be selected,

Figure 8: Total distance and optimal number of facilities by changing compaction rate

Finally this graph above shows the impact of a different compaction rate and how it affects distance and the number of landfills and transfer stations built. We considered a 5 million budget as one of the optimal budget options as we have done in Figure 7. As the ability of compaction increases the total distance decreases. (Note again: smaller rate is greater, compaction rate 0.1 means 1 waste will be compacted to 0.1). In addition, as we expected, if the compaction ability becomes greater, the optimized solution shows us we should build more transfer station.

Conclusion:

In summary, through our analysis results based on the Figure 1 to 8, the points are below:

1. If we consider only the number of landfills and do not consider transfer stations and budget, building 7 landfills is the optimized solution and recommended
2. If we consider the number of landfills and transfer stations, building over 40 transfer stations is not efficient though transfer stations and compaction ability will work greatly to reduce the expected total distance
3. If we consider landfills, transfer stations, and budget, we recommend that prepare 3 or 5 millions for the budget as optimized solutions. Spend over 8 millions is not efficient as stated 2 above, cost 8 millions means we will build 40 transfer stations.

In this report, we have not considered many possible factors to make the model simple. This means we might be able to improve our model more realistically. There could be many factors to consider, for instance, the capacity of the landfills to store the waste, the capacity to compact the waste at the transfer station in a day, and the construction cost for facilities could vary by locations. Considering these factors will give us the more appropriate solutions for optimizing the number of landfills and transfer stations to deploy where to build them.

However, if we make the model too complexed, it may be difficult to ensure the interpretability. There is one possible assumption that if a landfill is built at a location, the number of neighborhoods will change then it makes the amount of waste changed, which may happen but be over concerned. Similarly, the too simple and broad model may not give the client any useful information. In order to provide helpful information to make a decision, the model needs balanced factors to take into considerations.