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# Optimization of municipal solid waste management system in landfill using response surface methodology (RSM), a case study of Ogbomoso South Local Government

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**ABSTRACT**

***This study assessed solid waste generation and collection in Ogbomoso South Local Government and developed an optimization model for identifying key variables affecting the overall cost of solid waste management and determining their optimal values. Key variables included: the number of solid waste collection trips ($X_1$), the number of personnel ($X_2$), daily fuel consumption ($X_3$), and the weight of solid waste collected per trip ($X_4$). The optimization model was developed using a statistical design of experiments (DOE) with the central composite design (CCD) method. Thirty experimental runs were generated and optimized based on this method. The results indicated that the optimal values were: 47 solid waste collection trips per month ($X_1$), 3 personnel ($X_2$), 18.20 liters of fuel consumption per day ($X_3$), and 6.33 tons of solid waste collected per trip ($X_4$). This optimal configuration resulted in a total cost of ₦162,300. The model was validated using Design Expert software, yielding an objective function with a desirability value of 1, indicating 100% reliability.***

## INTRODUCTION

Waste Management has become a crucial component in advancing environmental sustainability, public health, and the realization of the Sustainable Development Goals of all Nations (Cherubini et al, 2009). Fast-paced urbanization, unrestricted access to goods and services, increasing population, and improved living standards have influenced a sharp increase in waste generation. Globally generated waste is expected to reach over 3 billion tons by 2045 (Mondal *et al.*, 2021; Lou et al, 2022). If not properly managed, the increase in waste will detrimentally affect human health, aggravate pollution, and threaten environmental sustainability for the present and future generations. This has made waste management and threatening issue among policymakers and researchers globally. Concerned with the current case, policymakers worldwide are devising potent strategies to curb this menace. The total volume of waste produced cannot be reduced if the approach to municipal solid waste generation and handling remains the same or deteriorates since population and living standards expand. This calls for a greater need to embrace the various circular economy strategies, including waste sorting, reduction, reuse, and recycling to achieve environmental sustainability (Wang *et al.,* 2021). Waste management services which involve collection of waste and transportation to final disposal are carried out, in most developing countries, by the local authorities, but were stalled by inadequate financial assistance and human resource capacity. These hindered effective waste management services, amounting to serious problems that impair human and animal health and ultimately result in economic, environmental, and biological losses. Some factors affecting effective disposed municipal waste management in Nigeria are poor funding and uncontrolled population, lack of trained/professional waste managers, ineffective monitoring and control, inadequate maintenance culture towards the environment, and lack of modern technology in the implementation of efficient waste management methods (Ojoawo *et al.*, 2012).

Recovering energy from waste can be a better means of managing environmental pollution caused by municipal waste disposal (Cane and Blumfelde-Rutka, 2023; Oladejo et al., 2020). In this regard, recycling is widely accepted as a sustainable municipal SWM (Solid Waste Management) method which is attractive for LGAs because of its potential to reduce disposal costs and waste transport costs, and to prolong the life spans of sanitary landfill sites. To realize the potential benefits of waste recycling, and organizing and managing recycling programs, local governments need to consider appropriate options for recycling programs about financial-economic constraints; the existing situation; regulation; and institutional, environmental, sociocultural, and technical issues. The most important factor among these is how local governments have improved their recycling performance by learning from the successes of other LGAs.

This question must be raised when making a sound decision in the planning stage to ensure that the recycling programs are sustainable over a long period (Govindan et al, 2022; Suttibak and Nitivattananon, 2008).

**Description of Study Area**

The study area is Ogbomoso South Local Government. As a result of the influx of people from rural areas and neighbouring cities, the city experienced tremendous expansion and developed into a metropolis. Ogbomoso (8.133°N 4.250°E) is a city in Oyo state Nigeria. It comprises five local government areas: Orire LG, Ogo Oluwa LG, Surulere LG, Ogbomoso South LG, and Ogbomoso North LG. Ogbomoso as a whole is a predominantly Yoruba-speaking city and was founded in the middle of the sixteenth century by groups of hunters. The town's real physical and economic growth dates back to the 1820s, when various important and powerful towns around Ogbomoso were destroyed in the course of inter-tribal wars. More than 140 communities found refuge in Ogbomoso and most of these people never returned to their former settlements (Abel, 2007).

The establishment of the colonial administration, the advent of the missionaries and the establishment of schools, the expansion of trading activities, and relative peace in Ogbomoso contributed to the rapid growth of the town. The deportation of Indigenous Nigerians by the Ghanaian government in 1969, when many Ogbomoso residents returned home, also affected the development of the town, as many of the returnees established industries. The population grew from 25,000 in 1885 to more than 166,000 by 1991, and the built-up area expanded from 5.8 $km^2$ in 1950 to 10.2 $km^2$ in 1970, to 24.3 $km^2$ in 1995. In 2003, Ogbomoso was estimated to cover 27.5 $km^2$ and it is the second largest city in Oyo state, after Ibadan. There are two local government areas, namely Ogbomoso North and Ogbomoso South, and they have their headquarters at Kinnira and Arowomole, respectively. Together with the contiguous areas of Surulere, Orire, and Ogo-Oluwa, they constitute the Ogbomoso administrative zone in Oyo state. The growth of the city created various urban problems, including inadequate provisions for solid waste management (Abel, 2007).

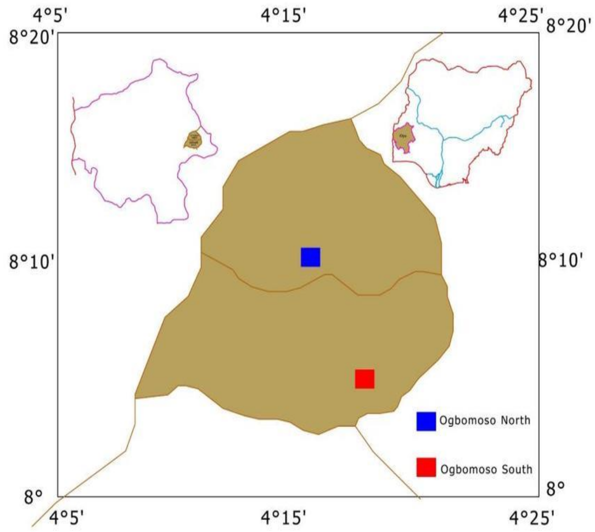


Fig 1.0 Study area map (Ogbomoso South local government)

**MODEL DEVELOPMENT/ DATA COLLECTION**

The overall task of the optimization model was to minimize the total cost of the solid waste collection and segregation process in Ogbomoso South local government using the design of an experiment (DOE) (Munguía-López *et al.*, (2020) and Nadi *et al.*, 2011). The selected variables for the optimization include the number of solid waste collection trips per month ($X_1$), number of manpower per collection vehicle ($X_2$), fuel consumption per day for each collection vehicle ($X_3$) and weight of solid waste collected per trip ($X_4$).

From the data collected from the Ogbomoso South Local Government landfill waste management board, it was observed that there are 2 collection vehicles with 26 trips per month of each vehicle making 52 collection trips in a month, the maximum number of workers per collection vehicle is 5 including the driver, the minimum fuel consumption per day is 16 liters, the maximum weight of solid waste collected per trip is 7 tonnes, the average monthly salary of the solid waste collector per person is N30,000, cost of fuel per liter is N 630 and the cost of vehicle maintenance is presented in Table 1.

**Table 1 - Average monthly cost of vehicle maintenance in 2023**

| S/No | Time (months) | Maintenance cost (N) |
|---|---|---|
| 1 | January | 32,400 |
| 2 | February | 25,000 |
| 3 | March | 32,550 |
| 4 | April | 30,700 |
| 5 | May | 39,350 |
| 6 | June | 52,500 |
| 7 | July | 45,350 |
| 8 | August | 47,200 |
| 9 | September | 42,800 |

The overall cost function for the optimization per month was then formulated as follows.

The objective function of waste collection

$(C_f) = X_1 + N\ 30{,}000\ X_2 + 630\ X_3 + X_4 + N10{,}000$

$$X_1 + X_4 \leq N\ 52{,}500$$

$$X_2 \leq N\ 150{,}000$$

$$X_3 \leq N\ 15{,}750$$

**Design of Experiment/ Process of Optimization**

In other to perform the Optimization, the Statistical design of the experiment using the central composite design method (CCD) was employed (Olanipekun and Oladejo, 2022). The range and level of each of the selected variables are presented in Table 2

For the experimental design and optimization process, Design Expert software was employed. The number of experimental runs using the CCD method was calculated as; ($N = 2^n + 2n + K$), where N is the number of runs, n is the number of variables and K is the center point. Thirty (30) experimental runs were generated and the section of the design matrix is presented in Table 3.3

Table 2 - Range and level of experiment variables affecting solid waste collection

| S/N | Variable name | Range |
|---|---|---|
| 1. | Number of solid waste collection trips per month | 26 – 52 |
| 2. | Number of manpower per collection vehicle | 1 – 5 |
| 3. | Fuel consumption per day for each collection vehicle (liters) | 16 – 25 |
| 4. | Weight of solid waste per trip (tons) | 5 – 7 |

In other generate the cost function matrix, the minimum and maximum vehicle cost maintenance is based on the relationship between the weight of solid collected per trip and the number of collection trips. The cost function was generated based on the following assumptions.

i. The more the weight of the solid waste collected and the bad nature of the road that leads to the dump site the higher the probability of vehicle breakdown and the higher the need for maintenance.
ii. The more the number of collection trips the more the probability of vehicle breakdown and the higher the maintenance cost.

All other assumptions not considered in obtaining the overall cost function matrix were considered as uncertainties which was resolved by the addition of an assumed variable cost Y. For this design, Y was taken as N10,000 per month. Based on the assumptions, the overall cost function matrix was obtained. The maximum cost of maintenance was taken based on the information in table 3.1 as N52,500. The value was adopted as extreme value to represent the total cost of maintenance for a maximum number of trips 52 and maximum weight of solid waste 7 tons which resulted in frequent breakdown of the collection vehicle. In addition, a minimum cost function was adopted as N25,000 which represents the total cost of maintenance for a minimum number of trips 26 and minimum weight of solid waste 5 tons which resulted in the minimum number of breakdowns of the collection vehicle.

Table 2.2 Section of the experimental matrix for solid waste optimization

| Run | Waste collection trips | Manpower (person) | Fuel consumption (litres) | Weight of waste (tonnes) |
|---|---|---|---|---|
| 1 | 26 | 1 | 16 | 5 |
| 2 | 52 | 1 | 16 | 5 |
| 3 | 26 | 5 | 16 | 5 |
| 4 | 52 | 5 | 16 | 5 |
| 5 | 26 | 1 | 25 | 5 |
| 6 | 52 | 1 | 25 | 5 |
| 7 | 26 | 5 | 25 | 5 |
| 8 | 52 | 5 | 25 | 5 |
| 9 | 26 | 1 | 16 | 7 |
| 10 | 52 | 1 | 16 | 7 |
| 11 | 26 | 5 | 16 | 7 |
| 12 | 52 | 5 | 16 | 7 |
| 13 | 26 | 1 | 25 | 7 |
| 14 | 52 | 1 | 25 | 7 |
| 15 | 26 | 5 | 25 | 7 |
| 16 | 52 | 5 | 25 | 7 |
| 17 | 39 | 3 | 20.5 | 6 |
| 18 | 39 | 3 | 20.5 | 6 |
| 19 | 39 | 3 | 20.5 | 6 |
| 20 | 39 | 3 | 20.5 | 6 |

**RESULTS AND DISCUSSION**

Using the cost function equation, the overall cost of solid waste collection was calculated based on the CCD design, and the results obtained are presented in Table 3. The result of Table 3 was adopted as the response (Overall cost function) for optimizing the cost of solid waste management using the numerical optimization method. Evaluation of the design mode reveals that the model possesses a low standard error of 0.25 for both the individual factors and the combined interaction as presented in Table 3.1. The coefficient estimate represents the expected change in response per unit change in factor value when all remaining factors are held constant. The intercept in an orthogonal design is the overall average response of all the runs. The coefficients are adjustments around that average based on the factor settings.

Table 3 Computed Cost of Solid Waste Management

| Run | Cost Consumption |
|---|---|
| 1. | 30,000(1) + 630(16) + 25,000 + 10,000 = 75,080 |
| 2. | 30,000(1) + 630(16) + 52,500 + 10,000 = 102,580 |
| 3. | 30,000(5) + 630(16) + 25,000 + 10,000 = 195,080 |
| 4. | 30,000(5) + 630(16) + 52,500 + 10,000 = 222,580 |
| 5. | 30,000(1) + 630(25) + 25,000 + 10,000 = 80,750 |
| 6. | 30,000(1) + 630(25) + 52,500 + 10,000 = 108,250 |
| 7. | 30,000(5) + 630(25) + 25,000 + 10,000 = 200,750 |
| 8. | 30,000(5) + 630(25) + 52,500 + 10,000 = 228,250 |
| 9. | 30,000(1) + 630(16) + 52,500 + 10,000 = 102,580 |
| 10. | 30,000(1) + 630(16) + 52,500 + 10,000 = 102,580 |
| 11. | 30,000(5) + 630(16) + 52,500 + 10,000 = 222,580 |
| 12. | 30,000(5) + 630(16) + 52,500 + 10,000 = 222,580 |
| 13. | 30,000(1) + 630(25) + 52,500 + 10,000 = 108,250 |
| 14. | 30,000(1) + 630(25) + 52,500 + 10,000 = 108,250 |
| 15. | 30,000(5) + 630(25) + 52,500 + 10,000 = 228,250 |
| 16. | 30,000(5) + 630(25) + 52,500 + 10,000 = 228,250 |
| 17. | 30,000(3) + 630(20.5) + 38,750 + 10,000 = 151,665 |
| 18. | 30,000(3) + 630(20.5) + 38,750 + 10,000 = 151,665 |
| 19. | 30,000(3) + 630(20.5) + 38,750 + 10,000 = 151,665 |
| 20. | 30,000(3) + 630(20.5) + 38,750 + 10,000 = 151,665 |

When the factors are orthogonal the VIFs are 1; VIFs greater than 1 indicate multi-colinearity, and the higher the VIF (Variance inflation factor) the more severe the correlation of factors. As a rough rule, VIFs less than 10 are tolerable, and VIFs above 10 are cause for alarm, indicating coefficients are poorly estimated. Ideal Ri-squared is 0.0, high Ri-squared means terms are correlated with each other, possibly leading to poor models. From the results of Table 3.1, it was concluded that the model is significant since the VIF and Ri-squared values fall within the limit of acceptance coupled with the low values of the standard errors. VIF was observed to be 1.00. The ri-squared value was 0.00 with a standard error of 0.25. The correlation matrix of the regression coefficient is presented in Table 3.2. Lower values of the off-diagonal matrix as observed in Table 3.2 indicate a well-fit model that is strong enough to navigate the design space and accurately calculate the optimized cost of solid waste management while also determining the optimum values of the selected variables

Table 3.1 Model evaluation for optimizing the cost of solid waste management

| S/N | Term | Standard error | VIF | $Ri^2$ | Power |
|---|---|---|---|---|---|
| 1 | A | 0.2500 | 1 | 0.0000 | 96.2% |
| 2 | B | 0.2500 | 1 | 0.0000 | 96.2% |
| 3 | C | 0.2500 | 1 | 0.0000 | 96.2% |
| 4 | D | 0.2500 | 1 | 0.0000 | 96.2% |

Table 3.2 Correlation matrix of regression coefficients for optimizing the cost of solid waste management.

| | Intercept | A | B | C | D |
|---|---|---|---|---|---|
| Intercept | 1.000 | 0.000 | -0.00 | -0.00 | -0.000 |
| A | 0.000 | 1.000 | -0.00 | -0.00 | -0.000 |
| B | -0.000 | -0.00 | 1.000 | -0.00 | -0.000 |
| C | -0.000 | -0.00 | -0.00 | 1.000 | -0.000 |
| D | -0.000 | -0.00 | -0.00 | -0.00 | 1.000 |

In assessing the strength of the model to accurately predict the cost of solid waste management, a one-way analysis of variance (ANOVA) was done, and the result is presented in Table 3.3.

The **Model F-value** of 56956702129.84 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise.

**P-values** less than 0.0500 indicate model terms are significant. In this case, A, B, C, and D are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. Based on the above analysis, it is seen that the selected factors; the number of collection trips (A), number of manpower (B), fuel consumption (C), and Weight of waste (D) all have significant influence on the overall cost of solid waste management.

Table 3.3 Assessment of model significance using analysis of variance (ANOVA)

| Source | SS | dof | MS | F-value | p-value | |
|---|---|---|---|---|---|---|
| Model | 6.07E+10 | 4 | 1.519 E+10 | 5.696 E+10 | <0.0001 | sig |
| A-waste collection trip | 0.0000 | 1 | 0.000 | 0.0000 | 1.0000 | |
| B-Manpower | 5.760 E+10 | 1 | 5.760 E+10 | 2.160 E+11 | <0.0001 | |
| C-Fuel consumption | 1.286 E+08 | 1 | 1.286 E+08 | 4.822 E+08 | <0.0001 | |
| D-weight of waste | 3.025 E+09 | 1 | 3.025 E+09 | 1.134 E+10 | <0.0001 | |
| Residual | 4.00 | 15 | 0.2667 | | | |
| Lack of fit | 4.00 | 12 | 0.3333 | | | |
| Pure Error | 0.000 | 3 | 0.0000 | | | |
| Corr Total | 6.075 E+10 | 19 | | | | |

SS - Sum of Square; MS – Mean Square, dof – Degree of freedom

To validate the level of significance and adequacy of the model based on its ability to optimize the overall cost of solid waste management, the goodness of fit statistics presented in Table 3.4 was employed.

Table 3.4 Goodness of fit statistics for validating model and adequacy

| | | | | |
|---|---|---|---|---|
| Std Dev. | 0.5164 | | $R^2$ | 1.0000 |
| Mean | 1.517E+5 | | Adjusted $R^2$ | 1.0000 |
| CV.% | 0.0003 | | Predicted $R^2$ | 1.0000 |
| | | | Adeq Precision | 5.932E+5 |

The coefficient of determination ($R^2$) of 1.0000 shows the strength of the model and its ability to predict the values of the selected variables that will help optimize the overall cost of solid waste management. Adj R-squared of 1.0000 indicates 100 percent reliability while a predicted R-squared value of 1.0000 indicates a high degree of model prediction accuracy. The reasonable agreement between the Adj R-squared value and the predicted R-squared coupled with a predicted error sum of the square value of 0.0003 shows the significance of the model and its ability to navigate the design space. The model graphs which show the interactions of combined variables on the measured response (cost of solid waste management) were evaluated using the 3D surface plot as presented in Figure 3.0.

The 3D surface plot shown in Figures 3.0 and 3.1 was used to assess the prediction bound for the optimization design model and to evaluate the relative influence of each variable on the overall cost function. From the plots of Figures 3.0 and 3.1, it was observed that the weight of solid waste collected and fuel consumption have a lower influence on cost function than the number of workers and number of collection trips.

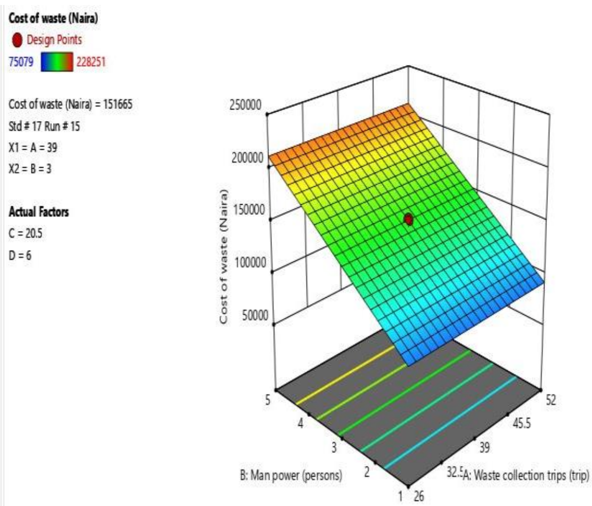


Fig 3.0 Influence of the number of workers per collection vehicle and number of collection trips on the overall cost of solid waste management.

Finally, numerical optimization was performed to ascertain the desirability of the overall model. In the numerical optimization phase, we ask the design expert to optimize the overall cost of solid waste management to determine the optimal value of the number of collection trips (A), number of workers (B), weight of solid waste (C) and fuel consumption (D). The interphase of the numerical optimization model is presented in Figure 3.2.

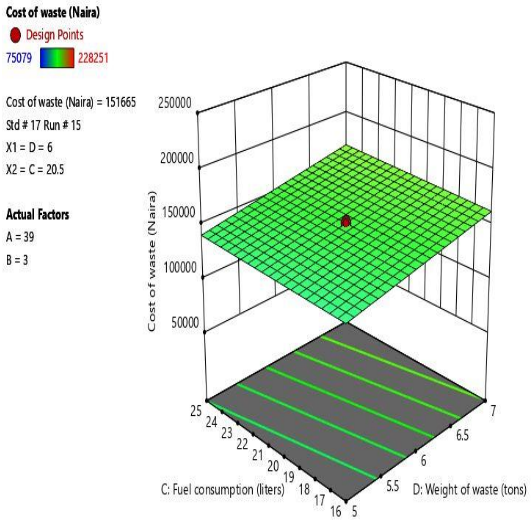


Fig 3.1 Influence of weight of solid waste collected and fuel consumption on the overall cost of solid waste management.

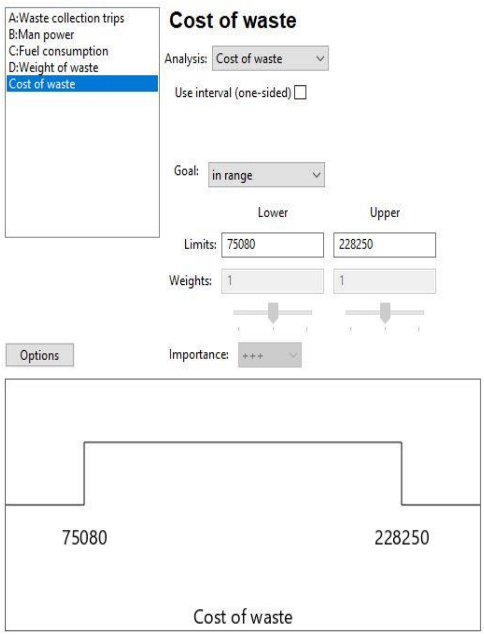


Fig 3.2 Interphase of a numerical optimization model for optimizing the cost of solid waste management

The numerical optimization produces results some of which are presented in Table 3.5

Table 3.5 Optimal Solution of Numerical Optimization Model

| Run | Waste collection trips | Manpower (person) | Fuel consumption (litres) | Weight of waste (tonnes) | Cost of waste (₦) | Desirability |
|---|---|---|---|---|---|---|
| 1 | 47.2 | 2.99 | 18.19 | 6.33 | 162299.2 | 1.00 (selected) |
| 2 | 26.00 | 5.00 | 25.00 | 7.00 | 220000 | 1.00 |
| 3 | 52.00 | 5.00 | 25.00 | 5.00 | 220000 | 1.00 |
| 4 | 26.00 | 1.00 | 25.00 | 7.00 | 100000 | 1.00 |
| 5 | 26.00 | 1.00 | 16.00 | 7.00 | 943300 | 1.00 |

Based on the numerical optimization analysis, the following optimal results were obtained;

i. Number of collection trips (NT) = 47
ii. Number of workers (NW) = 3
iii. Weight of solid waste (C) = 6.33 tons
iv. Fuel consumption (D) = 18.20 liters

These optimal solutions of selected variables resulted in an overall cost of N 162,300 approximately. The solution was selected by a design expert as the optimal solution having a desirability value of 1.000 is 100% reliable. The ramp solution, which is the graphical presentation of the optimal solution, is presented in Figure 3.3.

## CONCLUSIONS AND RECOMMENDATIONS

In this study, the potential of the statistical design of the experiment and response surface methodology in optimizing a given solid waste management system has been evaluated. Results of the analysis have shown that a combination of the design of the experiment and numerical optimization is effective in determining the optimal value of solid waste variables and computing the overall cost function. The result of the one-way analysis of variance shows that the optimization model is highly significant with a p-value < 0.0001.

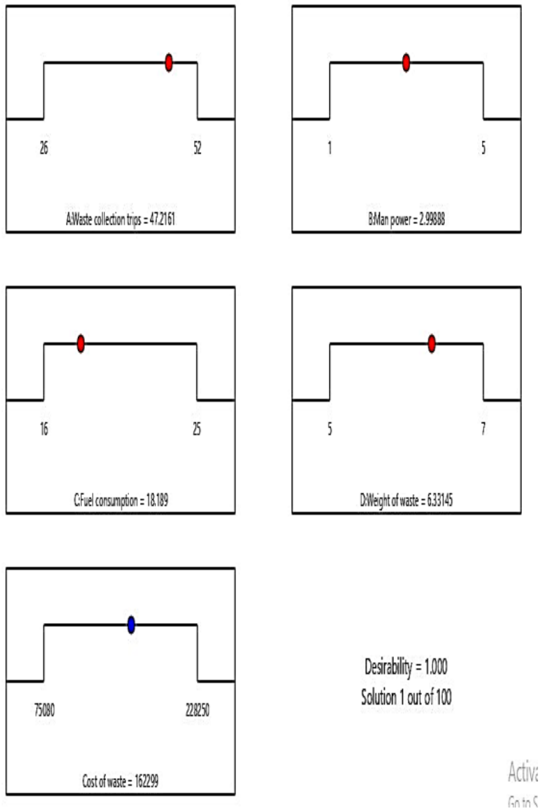


Fig 3.3 Ramp solution of numerical optimization

The accuracy of the model was further established using the goodness of fit statistics in which the computed coefficient of determination ($R^2$) was observed to have a durability value of 1.000 and 100% reliability.

**RECOMMENDATIONS**

It is recommended that if the waste management board in Ogbomoso South Local government can adopt the use of 47 collection trips, 3 number of manpower, 6.33 tons for weight of solid waste collection, and 18.20 liters of vehicle fuel consumption the cost of waste management will be optimal and will be more durable.

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