International Journal of Computer Applications (0975 – 8887)
Volume 186 – No.24, June 2024

Best-Fit Strategy for Optimal Location of Petroleum Filling Stations using Genetic Algorithm and Geographical Information System

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ABSTRACT
A petroleum filling station is a type of facility used for the sales or dispensing of petroleum products such as Premium Motor Spirit (PMS), Automated Gas Oil (AGO), Dual Purpose Kerosene (DPK), Lubricating Oil (LubOil) and Liquefied Petroleum Gas (LPG) amongst others, to automobiles and other users. Best fit location of facilities is a decision-making problem. The proper location of public and private facilities within a city is one of the demands required by town planners and urban planning development agencies. Apart from reduced property values and, the added threat of accidents and fire disasters, the poor location of facilities also comes with other considerable hazards to the environment and its inhabitants. The proposed approach for the optimal location of petroleum filling stations is a best-fit strategy using Genetic Algorithms (GA) and Geographical Information Systems (GIS). A multi-objective function was formulated taking into consideration the requirements of the regulatory body - the Department of Petroleum Resources (DPR) and consumer demand. The genetic algorithm models were implemented using MATLAB while data analysis was carried out in ArcGIS version 10 and Microsoft Excel. The model was tested using locations of filling stations in Akure, Ondo State, Nigeria as a case study. It was observed that only 34% of the existing filling stations in the Akure metropolis were found to satisfy the minimum spacing requirement set by the DPR. The model was able to re-allocate filling stations that do not meet the requirements of the DPR. It was also, able to propose the coordinates for a new petrol filling station.

Keywords
Petrol, filling station, facility location, optimization, Genetic Algorithm (GA), Geographical Information Systems (GIS), Optimal allocation, Minimum spacing, Multi-objective, K-nearest Neighbor (KNN), Spatial analysis, facility planning

1. INTRODUCTION
Facilities are defined as situated structures which can be public or private property that serve a specific purpose [3]. There are many types of facilities, including hospitals, churches, mosques, schools, filling stations, recreational parks, motor parks, monuments, government and residential buildings. The location of a facility is crucial, as it impacts its surrounding environment [12]. Choosing a bad location can negatively affect both the environment and the people living nearby. This challenge is known as the facility location problem. Several factors influence facility location, such as optimal distance to users, the facility's capacity, population density, and minimizing costs[12]. Finding the best solution to this problem is vital for decision-makers. Facilities should be positioned to serve the growing needs of the population effectively.

A recent surge in the global demand for petroleum products has been attributed to the attendant growth in the number of vehicles on the roads and the expansion of the transportation industry[17] [7] [15]. The optimal siting of petroleum filling stations is crucial in minimizing customer travel distances and ensuring service accessibility. By employing a data-driven approach to station placement, total operational costs can be minimized. Furthermore, this strategic allocation contributes significantly to environmental sustainability by reducing air pollution associated with excessive vehicle travel in search of fuel[13] [9]. The current advancements in Geographic Information Systems (GIS) and the growing adoption of genetic algorithms within computer science have spurred the development and application of numerous optimization strategies that leverage the combined capabilities of these technologies.[14] [1].

The upstream sector and the downstream sector constitute the petroleum industry [16]. The former encompasses all activities such as the exploration, production, and delivery of petroleum products for export whereas the latter involves logistics and transportation of crude and refined oil between the terminal and its users. Thus, filling stations are within the downstream sector. A petroleum filling station or petrol station as referred to in some literature, is a type of facility used for the sale or dispensing of PMS, AGO, DPK, Lub oil, and LPG

2. LOCATION ANALYSIS
Gaining insights into how and where people live, and how facilities are situated have been a major problem area of investigation by urban and city planners. The location problem arises when it is to be decided where to locate a facility [18] [19] [20]. The issue of location is the challenge of identifying the most favourable position for facilities within a two-dimensional space containing points of demand, with the condition that each demand point must be within a specified distance from at least one facility [21][22]. The facility location problem has extensive applications across various domains. Solving this task involves employing both conventional and heuristic approaches. Location analysis refers to the procedure of extracting valuable information from the geographic aspects of business data including datasets with coordinates for demand locations, travel cost matrices, and supply values. This data, especially generated by either socio-economic or demography often contains geographical information which allows for more dimensions of analysis through visual means [23]. Location analysis can be carried out using real-time geographical data or historical geographical data. Location analysis can be applied to urban planning and disaster/emergency prevention. This

research dwells in the area of finding the optimal facility locations in urban areas, leveraging location analysis techniques to optimize allocation/sitting of filling stations in an urban metropolis, in line with facility location standards by using location analysis in conjunction with a genetic algorithm search method.

2.1 Petroleum Filling Station History

The American Heritage Dictionary (2011) defines a petrol station as a facility that dispenses gasoline and oil for motor vehicles. Additionally, it may encompass the capability to perform repairs and maintenance on automobiles This energy source needs an effective distribution. Nigeria's reliance on petroleum has grown steadily starting from the 1980s. This is reflected in energy usage records, where petroleum products accounted for a significant and rising share of the country's total energy use: 53% in 2006, 67.3% in 2007, and 68.5% in 2011 [2, 5]. The history of filling stations dates back as far as the origin of the automobile because the basic role of the petrol station is to source the energy requirements of users. The earliest car entered the market in 1895 while the first filling station opened in 1905[4].

2.2 Department of Petroleum Resources (DPR)

A pivotal function of the DPR is records management on the industry's operations, in particular, records about petroleum reserves, production, export, licenses, and leases. Allocation of areas for specific purposes either for residential, industrial, recreational, or socio-economic purposes is invested in town planners. DPR approves and licenses refineries, petrochemicals, fertilizer plants, jetties, depots, and retail channels. It also ensures the conformity of downstream oil, gas, and pipeline facilities It is responsible for issuance of import/export permits and clearance for petroleum products. It also implements government policies on upstream and downstream matters. The DPR issues certificates and supervises filling station operations.

2.3 Town Planning in Nigeria

One of the concerns of every government is to ensure a high-quality environment where inhabitants can live, work, and recreate, likewise to sustain the physical development of its people to ensure harmony in the environment [10]. This requirement thus, is the main pillar upon which the objectives of physical planning are formulated. Some literature refers to town planning as physical planning. Most researchers reason that there is an erroneous interpretation of “town planning” as being restricted to towns alone but by town, it means any region of the country as an entity. For the sake of this study, the former will be used throughout the remainder of this work.

2.4 Genetic Algorithm

Genetic algorithms (GAs) mimic natural selection to iteratively improve a population of candidate solutions (chromosomes) for optimization problems [25]. Unlike single-guess methods, GAs maintain a diverse population, enabling exploration of the entire solution space and discovery of multiple optima [26]. Solution fitness is based on an objective function, with fitter individuals more likely to be selected for reproduction via crossover and mutation (Albadr et. al., 2020). This process creates offspring with potentially better traits, leading the population to converge towards the optimal solution(s) over generations. GAs' versatility extends to multi-objective problems, where specialized Multi-Objective GAs (MOGAs) handle competing objectives through adapted fitness assignment techniques [27, 28]. This work demonstrates the application of a MOGA to a specific problem, showcasing the effectiveness of GAs in complex optimization scenarios.

2.5 GIS Location Analysis

A Geographic Information System gathers, presents, controls, and analyses geographic information. It is the technology that connects geography with data, not only does it connect the two but it also generates insights from its analysis which powers millions of decisions requiring spatial thinking problems. The origin of spatial analysis in epidemiology can be traced back to the 1854 cholera outbreak in London, England[8]. Faced with a disease of unknown origin, physician John Snow pioneered its use by mapping the locations of cholera cases. This groundbreaking approach helped identify the source of the outbreak and revolutionized our understanding of disease transmission (John., 2015).

GIS solves crucial problems about location, patterns, and trends, combining geography, statistics, and other fields to analyze spatial data. The basic operations of GIS come down to four simple ideas:

i. Create geographic data
ii. Manage data.
iii. Analyze data
iv. Display on a map

3. METHODOLOGY

3.1 Area Covered by the Study

Akure in Nigeria, a South Western city in the tropical rainforest is selected for this research. It is located between latitude 7.2571° N and longitude 5.2058° E which is about 355 meters above sea level. Its GPS coordinates are further expressed as 7° 15' 2.7756" N and 5° 12' 36.9576" E. Akure is the capital of Ondo State with a population of over half a million spanning 991 km2. The residential areas include Oke-Ijebu, Oke-Aro, Ijoka, and Irowo with a population density of over 200. Ijapo, Alagbaka Estate, and Igbatoro have between 80±20 population density.

3.2 Data Collection and Processing

For this study, data was gathered in the field to identify the spatial location of functional petrol stations in Akure. A Google satellite Esri imagery of Akure metropolis and maps from the Department of Surveying and Geo-infromatics, the Federal University of Technology Akure, were obtained. A street map of the Akure metropolis containing adjoining roads was sourced, scanned, and exported to ArcMap environment. The data was geo-referenced using the “map to image”. Quickbird 2013 image of the area was used as a slave image. Major landmarks in the map were used as reference points. Secondary data obtained from field observation were input into a Microsoft Excel application containing the station’s coordinates. The records contained the longitude and latitude readings of the filling stations. The coordinate data are then converted to shape files with the same coordinates in the Arc Catalog environment. The shape files were then imported into ArcMap environment of ArcGIS 10.3 and used in the geo-referencing and digitalization of the mappings.

3.3 Pattern Analysis Using K-Nearest Neighbour Technique (kNN)

Pattern and spatial analysis were used to determine petroleum filling station location pattern(s) within the Akure metropolis, which employed the use of spatial statistics tools in ArcMap environment. In determining the DPR standard requirement of a minimum of 400m distance between filling stations, the nearest neighbor analysis was used to compute the nearest neighbor index (Euclidean distance).

3.4 Genetic Algorithm-Based Model for Optimal Allocation of Filling Station

A genetic algorithm is a nature-inspired framework that takes after the natural selection of species or objects. It is a problem-solving algorithm that finds optimal solutions to search problems. The following terms are synonymous with this search technique; Gene, Chromosome, Individual, Population, Crossover, Mutation, and other terms.

3.5 Genetic algorithm-based methodology for optimal allocation of filling stations

Selecting the best-fit strategy for optimal allocation of filling stations in Akure based on some considerations is carried out using Euclidean distance. In this methodology, spatial locations of facilities (filling stations) and demands (automobiles) are considered in the model. This is done by converting the Excel file containing the coordinates for both facilities and demand points into a shape file ArcGIS. After inputs of the model and setting parameters, GIS data is viewed as maps using the sharp map viewer tool in the ArcGIS environment. Then genetic algorithm technique processes all the GIS data. The best locations are deduced from a map presenting all important location information as a text/CSV file.

3.6 Objective Function of Model

Most location-allocation problems achieve optimization by either minimizing distance or transportation time or cost. In this research, the objective is to maximize the distance between stations and the average capacity of stations. Instead of implementing more than one objective function, all are converted to a single multi-objective function solution. The resultant objective function is a function of the fitness value. Thus, the lower the value of function F, the higher the fitness value becomes.

$$\text{Fitness value} = \frac{Consant}{Objective\_function} \quad (1)$$

In solving the first objective, a multi-objective optimization function was formulated taking into consideration the requirements of the regulatory agency and consumers. The first objective function (Eqn 3) is to minimize the distribution of filling stations considering the minimum distance between them. The second objective function (Eqn 4) ensures that for any given road axis, the average capacity of sited stations is greater than the demand of consumers (which is the total capacities of automobiles plying the route). These two functions are merged into a multi-objective function (Equation 2) where the first one takes a higher priority. Thus, the approach used in this research is to convert the multiple objectives into one single objective using weights and summation. The multi-objective function was adapted from the work in Arifin (2010) where consideration was only based on the distance between the facilities.

The solution to multi-objective function for filling station location is given as

$$MinF(d,s,A,c) = \left[F_1(d,s) + F_2(s,A,c)\right] \quad (2)$$

where

$$MinF_1 = \sum_{i=1}^{Ns}\sum_{j=1}^{Nr} d_{ij} s_i \quad (3)$$

$$MinF_2 = \sum_{i=1}^{Ns}\sum_{j=1}^{Na}\sum_{i,j=1}^{Nr} \frac{s_i c_i}{A_j c_j} \quad (4)$$

Subject to the following constraints:

$$d_{ij} \geq 400 \text{ meters} \quad (5)$$

$$\frac{s_i c_i}{A_j c_j} \geq 1 \quad (6)$$

$$c_i \geq c_j \quad (7)$$

where

Ns is number of filling stations

Nr is number of road/routes

Na is number of automobiles (or demand) on a given route j

d_{ij} is distance from i to j

s_i is filling station at point i

c_i is capacity of a filling station at point i

c_j is capacity of demand (automobile) at point j

A_j is Automobile at point j

3.7 Output of Model

There are two types of output in the model. One creates an optimal location via the shape file that the GIS software can use for processing and evaluation. The other contains all the population chromosomes sorted in order of fitness as the output of the genetic algorithm.

The model solves variants of location problems such as to

i. relocate stations from existing locations; find candidate locations of stations in view of present ones; and to
ii. meet demand coverage requirements.

4. IMPLEMENTATION AND RESULTS

4.1 Input to the Model

The two inputs into the model include (i) each station's capacity and a set of coordinates; and (ii) the population density of the location and a set of user demand for the product.

4.2 Tools for Map Display and Genetic Algorithm Modelling

SharpMap, an open-source tool was used to display potential facilities and demand on the map. The optimal location outputs of the GA was displayed by SharpMap. For the GA, MATLAB R2017a was used to implement the model. The optimal location shape file was created with NetTopologySuite.

4.3 Analysis of Petroleum Filling Station Locations in Akure

The analysis of the stations in the Akure metropolis was carried out in ArcGIS environment using the proximity operation tool. This feature considered the distribution of Petroleum filling stations and analysed the minimum distance between them. K-nearest neighbour using Euclidean distance metric was used to calculate the distance between the nearest petroleum petrol stations. Observation shows that 32% of the petrol stations within the Akure metropolis satisfy the minimum spacing requirement set by the regulatory agency.

The results show that the distribution of facilities in Akure followed an uneven linear pattern along major roads with only 13% of the facilities along minor roads and 87% of petroleum filling stations located along major roads. From the result, more than half of evaluated stations were located less than 400m distal from the nearest neighbour (Appendix II). Moreover, the result shows that the most distal neighbouring station was 6771.9m away. It further indicates that 32% of the Filling stations conform to the 400-meters distance to their neighbours by road. However, about 68% of the Filling stations failed to observe the 400-meter minimum distance to their neighbours. Fig 1 shows the distribution with areas shaded yellow represent distances between 0 – 200m while red shades represent distances between 200 – 400m respectively.

The uneven distribution of filling stations is due to the traffic flow on the major road, proximity to parks and commercial outlets, and competition between petroleum marketers and exit roads.

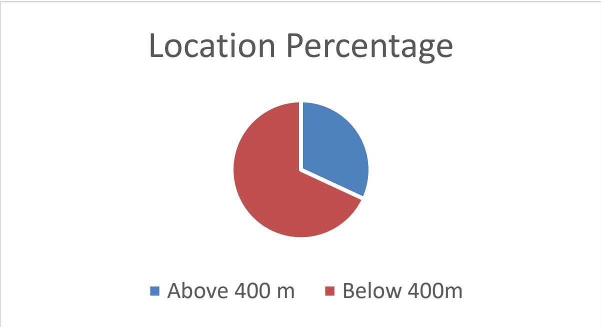

Fig 1: Chart showing location percentage of the distribution of filling station

4.4 Output of Model

The output from the Genetic Algorithm that was generated using MATLAB which represents the optimized coordinate, stores all chromosomes in population sorted by fitness order in text file format. It was used as an input to ARCGIS for the locating of the filling station on the map. The output created the optimal location in the shape file to be used in the GIS software for processing and investigation.

4.4.1 APPLICATION OF THE DEVELOPED MODEL FOR LOCATION AND RE-ALLOCATION OF FILLING STATIONS

Fig 2 displays the login page where the administrator gains access to the system. Fig 3 shows the main interface where the coordinates can be uploaded. The "Import facility coordinates" button gives access to the user to upload the coordinates of the existing filling station within a metropolis. The "Plot facility map" button displays the graphical location of the existing coordinate location so that users can have an insight into the .

already existing location of the filling stations. The "Optimised location and map" button performs the tasks of locating and re-allocating the filling station considering based on existing data. The new coordinate that is generated from the optimised location is saved in Excel format to serve as an input to the ArcGIS to plot an optimised Map as shown in Fig 8 and the new coordinate table in Appendix III. Based on the model, 70% of filling stations in the Akure metropolis were reallocated to achieve optimum location requirements as stated in the objective function. The "Recommend New Location" button recommends a suitable or next best-fit location for the new petrol filling station.

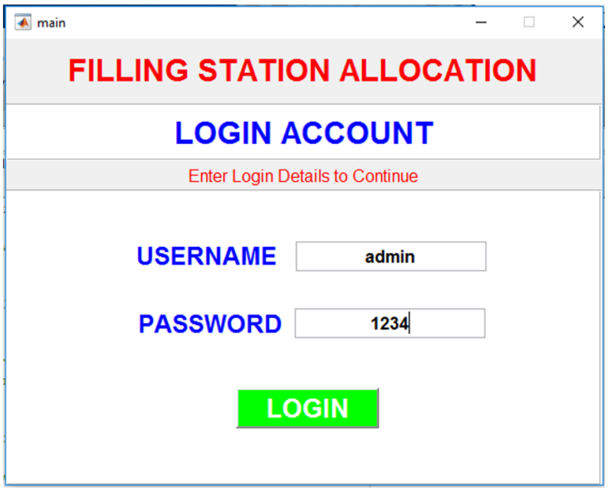

Fig 2: Login Page

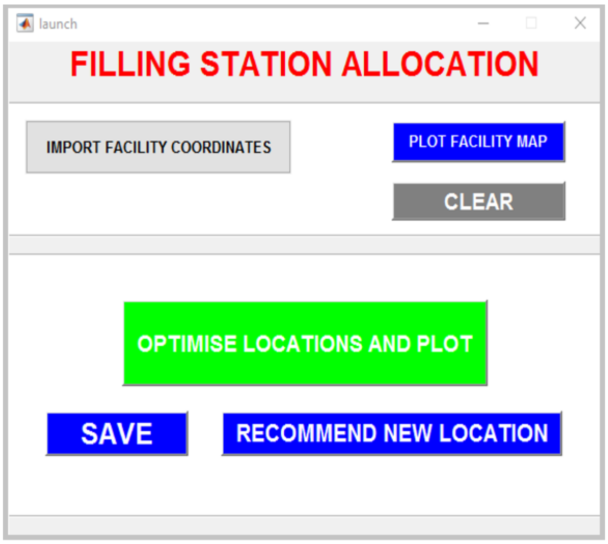

Fig 3: Main Interface

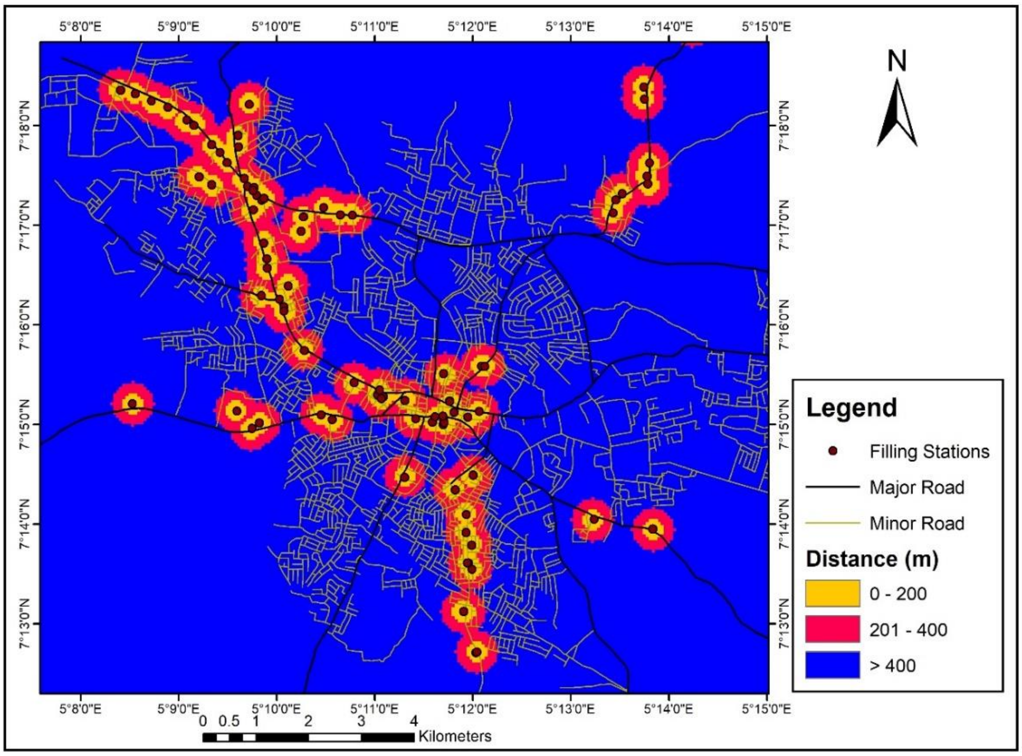

Fig 4: Facility data of Akure main road network with filling station location

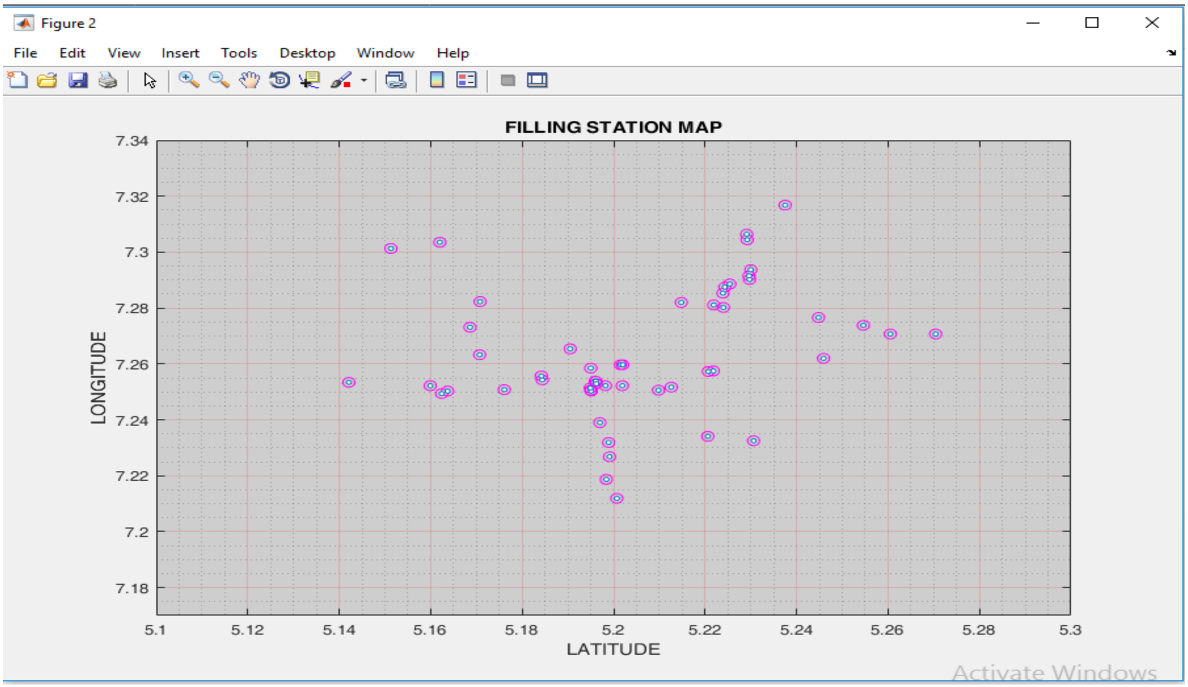

Fig 5: Graph showing original location of the filling

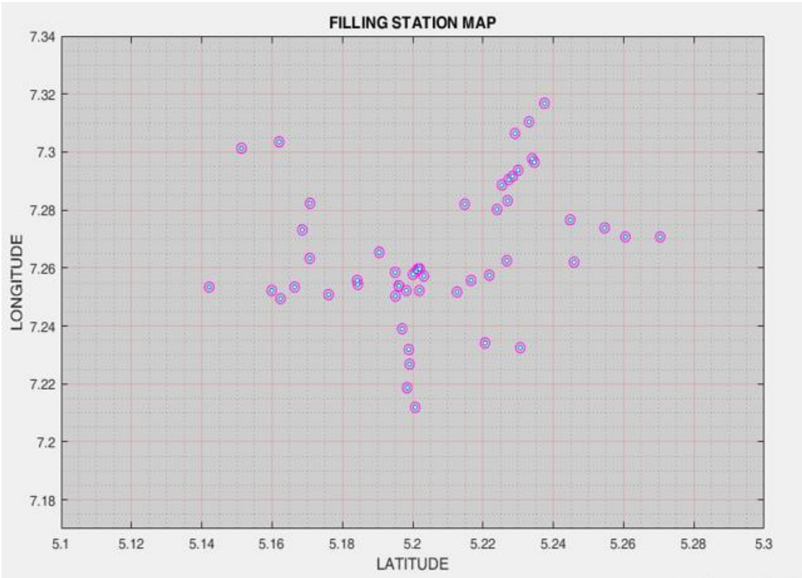

Fig 6: Graph showing Optimised Location.

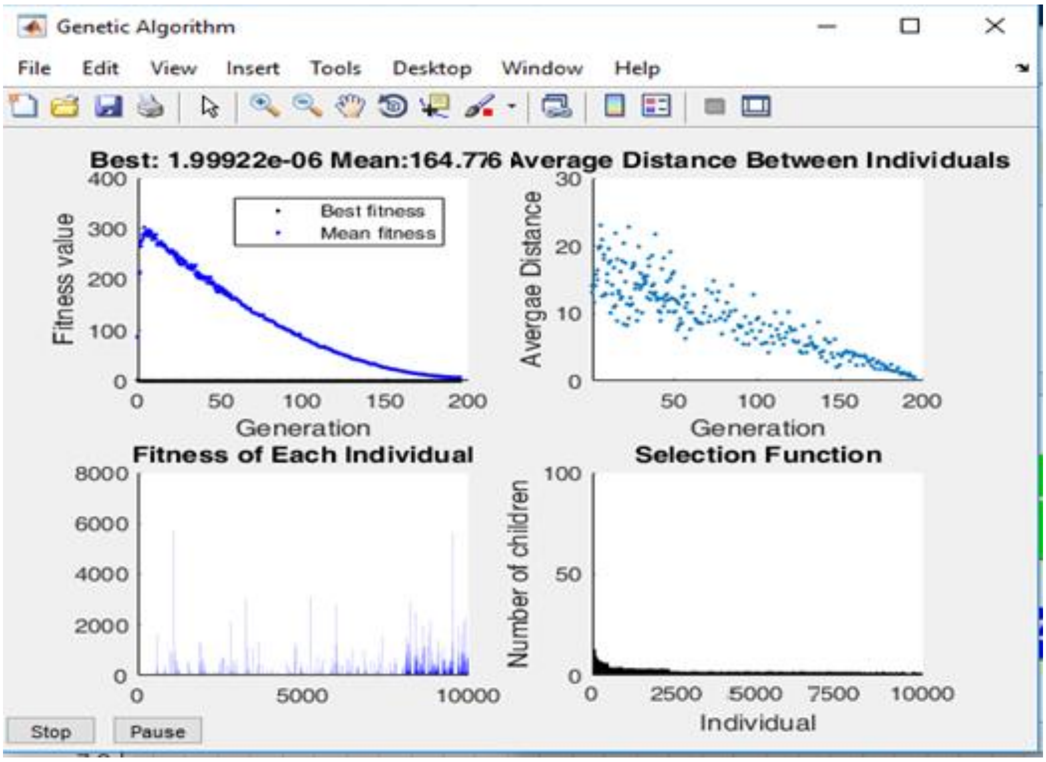

Fig 7: Genotype fitness based on Euclidean distance.

The output (new coordinate) from the genetic algorithm serves as input into ArcGIS to display the optimized location on the map. Fig 7 shows the output from best parameter settings from the best-fit allocation model using a road network. In the model, the red circle represents optimal filling stations satisfying the (>=400m) requirement, while the yellow circles represent distances below 200m. The black dots show the optimal filling stations. Black lines are the major roads while the grey lines represent the minor roads. Fig 8 shows the fitness value which converges at 200 generations (iterations). The fitness curve shows top fitness values up to that generation. Fig 8 shows the best-fit filling station allocation strategy in Akure from the model viewed in ArcGIS.

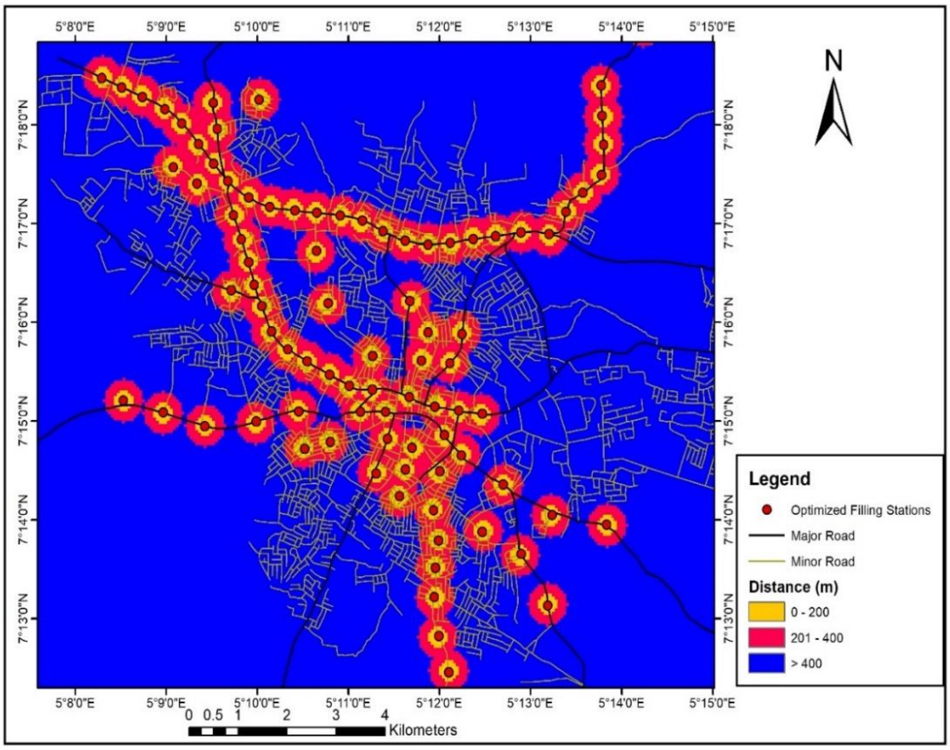

Fig 8: Optimal Filling Station Allocation in Akure city using GA viewed in ArcGIS

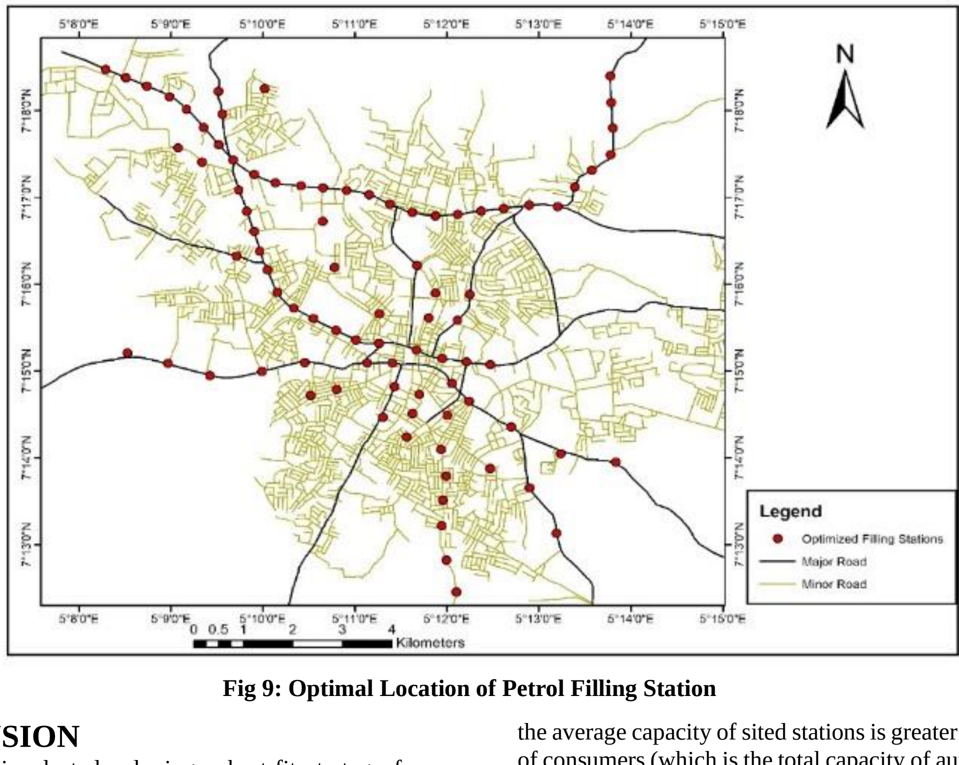

Fig 9: Optimal Location of Petrol Filling Station

5. CONCLUSION

This research is aimed at developing a best-fit strategy for filling station location-allocation problem using metaheuristic solutions. The methodology adopted in this work is the formulation of a multi-objective optimization function while taking into consideration the minimum distance between stations and the demand of petroleum by consumers The first objective function is to minimize the distribution of filling stations considering the minimum distance between them. The second objective function ensures that for any given road axis, the average capacity of sited stations is greater than the demand of consumers (which is the total capacity of automobiles plying the route). These two functions are merged into a multi-objective function. Integration of genetic algorithm with GIS data was carried out. To overcome the challenge of preparing GIS data for genetic algorithm indexing of (filling stations) coordinate points was instead of geographic points. The street map was imported into ArcMap environment of ArcGIS and geo-referenced using map to image geo-referencing method.

From the results, the uneven distribution of filling stations is due to traffic flow on the major roads, proximity to motor parks and commercial outlets; competition between petroleum marketers; and exit roads. Future research will be extended to accommodate raster data rather than vector data of coordinates as input to the model. Also, more factors (constraints) that affect the distribution of filling stations will be included in the objective function to make the model more robust.

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