Selection of Optimum Petroleum Pipeline Routes Using A Multi-Criteria Decision Analysis and GIS Least-Cost Path Approach

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Abstract- Optimal pipeline planning is an emerging problem of the environment and economic development in uneven terrain areas that requires the most sophisticated scientific methods of path analysis. During the planning of the most suitable routes for the pipeline, the topography, proximity to the road, settlement, water resources, protected sites and other critical landmarks have always acted as an important role as a constraint. With the Application of Analytical Hierarchical Process, the suitability analysis to derive the relative preferences of the different factors affecting the route is achieved. The Least-Cost Path Analysis (LCPA) method provides designers a way to find the cheapest technique to connect two locations within a cost surface, which can be computed by combining multiple criteria, and therefore by accounting for different issues (environmental impact, economic investment, etc.). This analysis used topography and functions related to the slope, land use, and the cost data layers. The study found that the pipeline should be kept away from the unnecessary slopes. LCPA model is developed from the accumulated cost surface obtained from the criteria and their applied weightages derived from the pairwise comparison of the decision-makers' preferences. Finally, suitable cost-effective pipeline routes namely the pipeline from the refinery at Tema in the Greater Accra Region to Saltpond in the Central Region (Tema to Saltpond pipeline), from Saltpond in the Central region to Badukrom in the Western region (Saltpond to Badukrom Pipeline), from Saltpond in the Central region to Anyinam in the Eastern region (Saltpond to Anyinam Pipeline) and finally from Anyinam in the Eastern region to Kubease in the Ashanti regions (Anyinam to Kubease Pipeline) were created in ArcGIS 10.4.

Index Terms- Geographic Information System (GIS), Pipeline, Least-Cost Path, Multi-Criteria Decision Analysis (MCDA), Bulk Road Vehicles (BRVs).

I. Introduction

Formerly, stakeholders in the Petroleum distribution industry for the most part centered more around selecting the shortest and most direct pipeline route for the distribution of petroleum products. This is primarily to save costs on construction and other capital expenditure reasons [1]. However, several other factors apart from cost have to be considered in the route selection process. Geophysical, environmental, political, economic, social, and regulatory factors all have significant influences on the route selection process [2].

Pipeline systems are very important for transporting gas, oil, and petroleum products because they are the most cost-effective way of moving fluid products over long distances [3]. The significant impact of these transported resources on the national economy and security makes it imperative to device reliable and affordable methods to transport them [1]. Pipeline transport is most predominant around the world and in the USA nearly two-thirds of the ton-miles of oil get transported annually through a network of more than two million kilometers of pipelines, in some of the toughest terrains [4]. Determination of the shortest and most uninterrupted and efficient route is a primary objective to minimize fuel travel time and capital expenses since the distances between the source of petroleum products and their destination for energy transitions can traverse hundreds of miles with meandering terrain [5].

Pipelines are the most efficient, cost-effective, and environmentally friendly means of fluid transport [6], [7]. Transmission or trunk pipelines are examples of engineering marvel requiring high project cost and long development periods and operating life. Hence careful planning of their route can save on cost, time, and operating expenses, ensure longer operational life, and help prevent environmental fallouts. Geographic Information System technology and the methodology of the least-cost path-finding are still at a probing stage. Some studies already conducted highlight a similar trend of methodology enforced in its executions as it is also implemented in this paper; for instance, a study conducted by Saha established that the computer-assisted methodology of route planning is quick in correlation with the regular manual practice [8]. Feldman, Sandra C., et al. in their study done in the Caspian Sea, the least-cost path resultant was 21% longer than the straight-line path between the source point and destination point, but it gives rise to a reduction in construction costs by 14% [9]. In the least-cost path pipelines analysis to the Langkawi Island, Malaysia two scenarios are presented; one based on a lesser value to paddy and the other based on a lesser value to rubber. The resulting least-cost pipeline route to Temoyong was from the Limbong reservoir was 9.12 km for scenario 1 and Kuah town was from the Ulu Melaka reservoir 6.3 km from scenario 2. The study revealed that GIS can evaluate suitable alternatives and visualize the results thus providing options to the decision-makers [10]. S. Suleiman et al. by the use of (GIS) grid-based approach generated three alternative routes with length 31.96km,27.93km, and 27.23km. The shortest path comes out to be 27.73km which is obtained based on the equal impact of land use/land cover, land slope, and soil class of the area [11]. Hence it can be concluded that geographic information system (GIS) optimal path analysis is proved to be well suited in optimal route location in a short period of time which is economical, it also provides the ability to the consultants to provide several alternatives and compare such alternatives.

A Multicriteria Decision Analysis is based on using the best approach to analyze multiple ways of arriving at a solution, looking at the impact on cost, environmental, and social impact. The AHP method is accepted as a powerful tool for MCDA to solve complex decision problems [12]. Analytical Hierarchy Process (AHP) is a quantitative method for ranking decision-making alternatives by developing a numerical score to rank each decision alternative based on how well each alternative meets the decision maker's criteria [13]. The AHP is a decision-making approach developed by Saaty in 1980. The process aids in the solution of complex multiple criteria problems in several application domains. In AHP, one constructs hierarchies, then makes judgments or performs measurements on pairs of elements [14], [15], concerning a control element to obtain ratio scales which are then incorporated into the whole structure to select the best alternative [16].

According to [7] there are three basic steps for considering decision problems using AHP which includes;

1) Construction of a structural hierarchy.
2) Establishment of comparative judgments
3) Synthesis of priorities.

In this modern development era the growth of cities will equally spike up the request for petroleum products. However, Ghana's Petroleum Products distribution operations lack behind in its transportation (pipeline routes) and available storage facilities which go further down to obstruct the safe transportation and consistent storage of oil and gas products, there are some pipelines inside the country but not problematic on account that they run from the refinery to Akosombo. Furthermore, the availability of these pipelines running through to Akosombo though is no longer enough now not only to prevent products shortage but also to stop these Bulk Road Vehicles (BRVs) from transporting from the Oil Refinery to other transport points since the operation of these BRVs greatly contribute to the frequent accidents and congestions on our highways.

The southern and mid part (being the Western, Central, Ashanti, and some part of the Brong-Ahafo Regions) of the country lack proper engineered pipeline transportation system. Hence as stated above the operation of these BRVs is mostly utilized in the distribution of petroleum products which mostly are not efficient, safe, and convenient in transporting the products. According to the 2010 world population census it's stated from the census data collected in Ghana that the final results from the regional breakdown shows, Greater Accra (16.3%) and Ashanti (19.4%) regions had the greater share of the population while upper East (4.2%) and Upper West (2.8%) regions had the smaller share of the population [17]. This is to conclude that, the southern and mid parts of the country have the largest occupancy ratio as compared to the Northern part of the country. Therefore, the consumption of petroleum products is very high since there are major factories, companies, agricultural, fisheries, and other commercial operations which require high patronage of various petroleum products.

The total available storage capacities as of 2019 for petroleum products currently for Ghana are as shown in (figure 1) below. But these are not enough to serve the whole country especially the western-Central Regions and some part of the Ashanti and Brong-Ahafo Regions where consumption of petroleum products is high. This calls for an extensive pipeline network and storage facilities to help in the distribution of refined petroleum products to consumers across the nation.

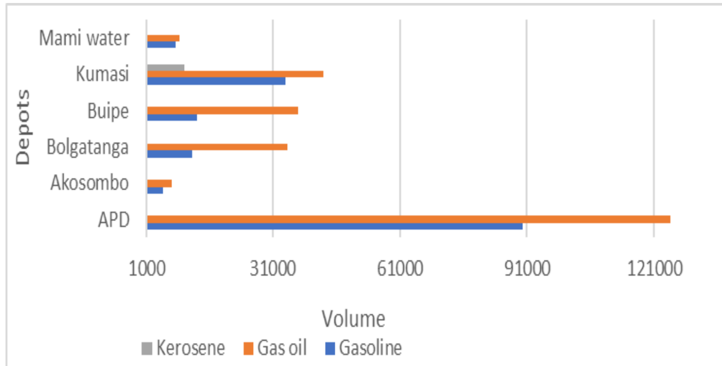

Figure 1. Existing Storage capacity

Therefore, this study pursuits to address a progressive choice using GIS in the direction of substituting the manual strategy in pipeline routing to improve the least-cost pipeline path. Being one of the scientific-analytical technology, Geographic Information System (GIS) could integrate, store and analyze the spatial correlation between diverse layers of spatial data to define areas of suitability interest and enact a critical approach to develop a pipeline route with the least-cost path GIS techniques [6], [18]. The term cost involves two things; time and expenditure. The time explains the duration consumed for planning a route and it is essentially the ability to consolidate and plan the time spent on activities involved in determining the best routes from start to finish. The result of the least costly time increased the effectiveness and quality of the outcome. On the other hand, the least-cost expenses explain the fact that the route should have limited overheads in terms of crossing physical and man-made hurdles within the vicinity of the study area. This helps to keep the project on its tracks. Hence the problem is aimed to solve with GIS-based Multi-criteria Decision Analysis (MCDA) to reach the optimal pipeline route.

II. CURRENT RESEARCH

Over the last decade, numerous attempts have been made to automate the route- planning process using Geographic Information Systems (GIS) technology and Multi-Criteria Decision Analysis (MCDA) [5]. A review of several papers put forward that these methodologies are still being at a probing stage. Yildrirm and Tomuralioglu in 2011, comparing the path-finding method for oil and gas pipeline traditional procedure prove that the designed path by using GIS is 14% cheaper than the path coupled with the traditional technique and also confirms GIS software as more user friendly than other software [19]. During the study conducted in Turkey on Optimization Model for pipeline routing based on GIS and MCDA approach suggested at the end of the study that the route defined using raster network analysis techniques over the developed model reduces project cost by 23%, pollutes the environment at a lower level, and is more appropriate from a sociological perspective [20]. In some studies, current routes have been optimized and the cost of routes selected by using conventional methods (economic, social, and time costs) are compared with the costs of the routes selected by using GIS-based models [21]. The application of AHP in oil and gas pipeline route selection has yielded tremendous results since it has transformed traditional qualitative analysis to comprehensive qualitative and quantitative analysis, constructs a trade-off between various factors, and greatly reduces subjective factors [22], [23]. Also to save time, money, effort, and fuel consumption during Selection of Road Alignment Location in Kano-Nigeria, GIS and Analytical Hierarchy Process (AHP) model results show that the Hybrid theme LCP is the most economical, suitable, and has the shortest travel distance of 37.31km [24]. An optimal oil pipeline route was generated using GIS analysis and spatial modeling incorporating multicriteria decision with environmental, engineering, technical, and social factors being the key criteria [25].In comparing the existing pipeline routes to the proposed pipeline routes for Keystone XL, Nebraska state USA the least-cost paths accurately detail routes that are amazingly similar and effective in providing a path from the documented source and destination points within Nebraska [26]. In addition to these researches conducted by [3], [6], [27], [28], a variety of other studies have been performed to choose the most suitable route between many routes or corridors which replaces the traditional approach of route selection. Different implementations have been carried out in these studies using GIS techniques. Some routing experiments were also performed using only one or a few of the important factors influencing a selection of a pipeline path.

III. THE STUDY AREA AND DATASET

The study area as shown in (**figure 2)** falls within the mid to the Southern parts of Ghana. Namely the Brong-Ahafo, Ashanti, and Central and Western Regions. The average elevation is relatively low, mostly between sea level and about 305 meters (1,000 feet) [29]. Ghana has five major geographical regions. In the southern part of the country are the low plains, part of the belt that extends along the entire coastal area of the Gulf of Guinea. In Ghana, the climate is tropical, with a dry season in winter and a rainy season in summer due to the African monsoon. The rainy season in the south lasts from May to September in the north, from April to October in the center, and from April to November in the south. On the contrary, along the east coast, the rainy season is shorter and goes from April to June, with a break in July and August, and a slight recovery in September and October [30].

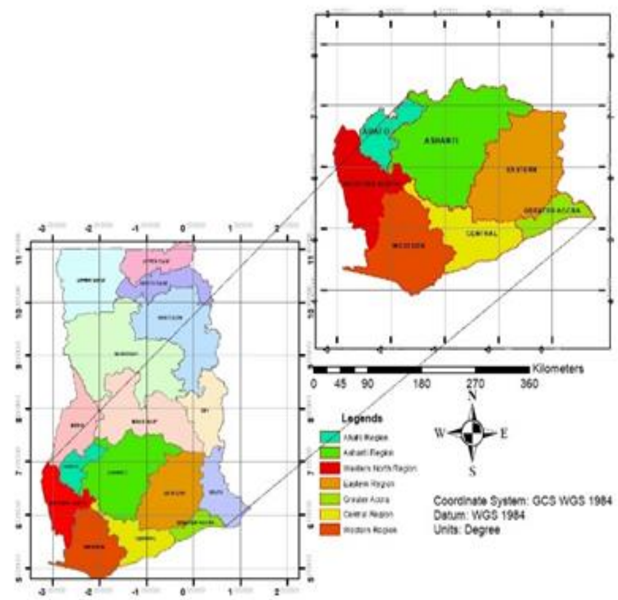

Figure 2. The Study Area

Data used

The spatial dataset was organized using ArcGIS 10.4 for data processing. All the available datasets mention was in a vector data model, and are later converted into the raster model. The datasets were organized in layers for convenient data processing which involved derivation of relevant parameters from selected datasets.

1) Slope_ DEM layer
2) Land use Layer
3) Water Resources layer
4) Linear features e.g. Main roads and railways lines
5) Geological layer
6) Settlement layer
7) Protected sites layer

Soil type layer

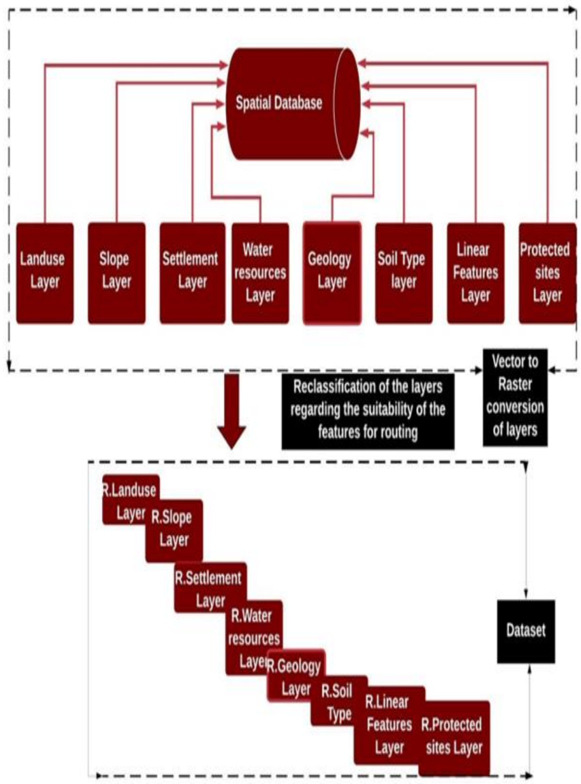

Figure 3. The workflow of Dataset.

Data Processing

Derivation of Relevant Parameters from Selected Datasets

Raster datasets were derived from vector datasets using the ArcGIS Spatial Analyst and conversion tools as follows;

1) Euclidean distance from the linear features (main roads, railways), protected sites, Settlements, and water resources are derived.
2) The slope raster dataset was derived from the elevation data.
3) Other routing criteria such as the geology, soil type, and land-use layers were converted to raster.

The source and destination point raster included Tema Oil Refinery (TOR), Saltpond, Anyinam, Badukrom, and Kubease as shown in the map display below (**figure 4).**

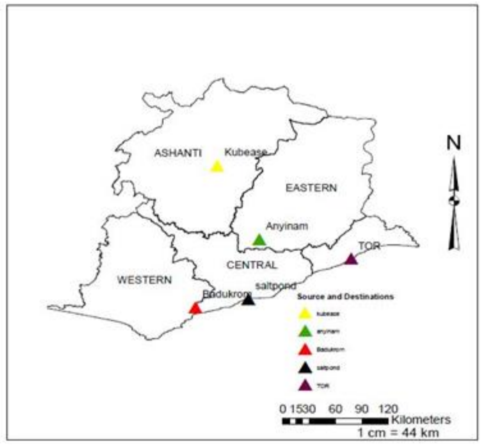

Figure 4. Facility Centres.

IV. LEAST COST PATH ANALYSIS

Steps to Find the Optimal Routes

In application, the best Optimal route is found for a petroleum product pipeline. The steps to produce such a path are outlined below. The path is performed using ArcGIS 10.4 Spatial Analysis Module.

1) Create Source, Destination
2) Create Cost Datasets
3) Generate A Thematic Cost Map (Classify and Weighting)
4) Perform Cost Weighted Distance
5) Create Direction Datasets
6) Perform Shortest Path with Distance and Direction Datasets
7) The least-cost path developed.

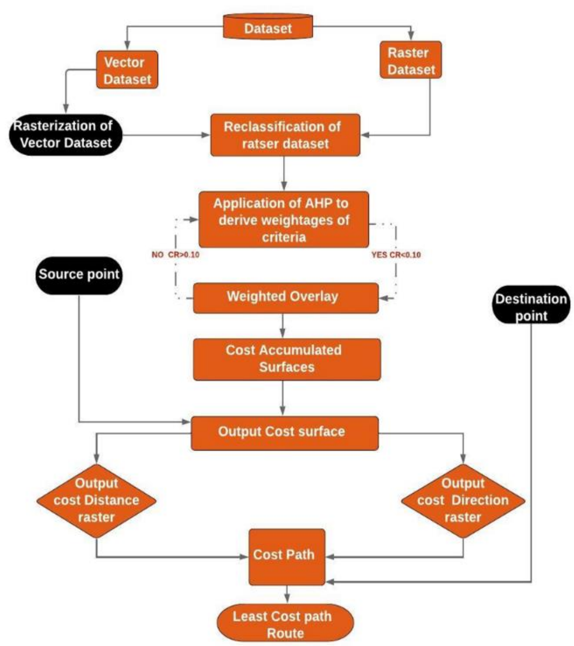

Figure 5. Methodology WorkFlow.

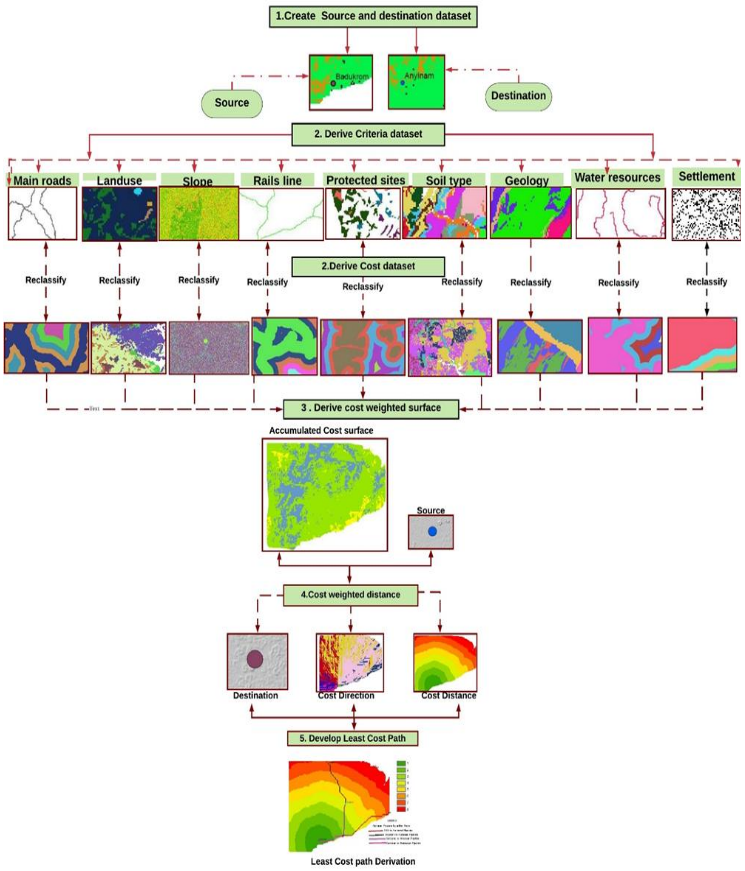

Figure 6. Least-cost path Result.

V. RESULTS OF EXPERIMENT

The LCPA modeling technique is a cost-effective method in GIS which gives the least-cost paths for the pipeline, roads, and all other linear features. The LCPA as a spatial function of the GIS was used to generate the best route using a 750m elevation (contour) data layer. The contour data layer was converted into a Digital Elevation Model (DEM) to produce a slope data layer. The slope was considered to be 0 to 74° in determining the least-cost path for the pipeline route to the southern corridors of Ghana. The results of the LCPA is shown in (**figure 6)** above.

Considering the commencement points of the route and the pixel size as shown in **step 3 in (figure 6)**, the accumulated total cost surface was generated over the weighted cost surface, according to the working principle of the raster-predicated network analysis algorithm. This data set on the route transition was predicated on values determined for each pixel. The cost distance function (or cost weighted distance) utilizes the source and accumulated cost surface and engenders an output raster where each cell is assigned a value that is the least accumulative cost of traveling from each cell back to the source. The cost-weighted distance function produces the two costs raster surfaces as shown in **step 4 in (figure 6)** i.e. the cost weighted distance raster and the cost weighted direction raster (back-link raster) [28].

The cost distance raster surface suggests the least accumulated cost surface for each cell to the proximate source point however, it does not illustrate how to arrive there. The output back-link or direction raster offers a road map to find the route to take from any cell, along with the cheapest path, back to the proximate source. The algorithm for calculating the direction of the raster to each cell to establish the code is identical to the neighboring cells is the best way back to the nearest integer numbered 0 to 8 [31], [32]. The value 0 is used to represent the source locations. If the least costly path is to pass from the existing cell location to the lower right diagonal cell, the existing cell will be allotted 2; if traveling directly down or south, the existing cell would receive the value 3 and so forth as shown in (**figure 7)** [33].

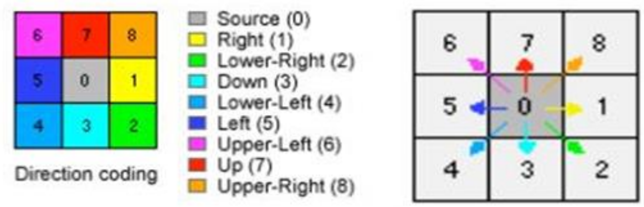

Figure 1 Cost backlink coding

The last to develop the least cost Path taking the resulted Distance and Direction Raster Layers as inputs with the Destination Layer and calculates the Shortest Path between the Source and Destination as shown in **step 5 (figure 6)**.

VI. DISCUSSION

Table 1. **Comparison of cost-determining factors between pipeline routes Feature**

Feature Attributes		Slope (degree)	Length (km)	Crossing of road	Crossing of rails
Existing highway routes	Tema-Saltpond	6.8	144	1	8
	Saltpond-Badukrom	4.2	69	0	2
	Saltpond to Anyinam	8.9	87	0	1
	Anyinam to Kubease	10.15	133	2	3
Least-Cost path routes proposed (pipeline)	Tema-Saltpond	2.2	133	1	1
	Saltpond-Badukrom	2.7	63.73	0	0
	Saltpond to Anyinam	2.8	76	1	0
	Anyinam to Kubease	8.15	106	1	2

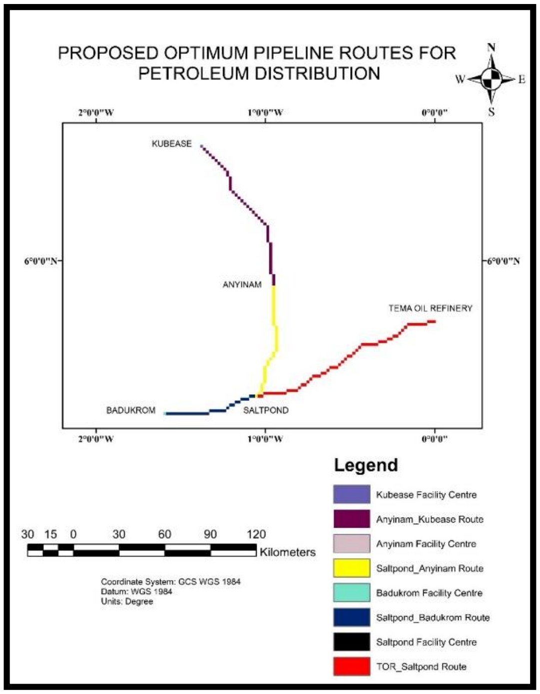

Figure 8. Pipeline Routes Proposed.

With the advanced application of Geographic Information System, it is possible to compute the shortest route of linear features with associated costs which ineluctably can reduce the cost and time of project execution and hence the operating expenses. GIS provides a variety of analytical functions that are capable of superseding manual and traditional methods of route planning. The integration of GIS and the Spatial Multi-criteria decision support system offers a baseline for multiple kinds of decision making where a variant nature of criteria and stakeholders can be catered successfully.

From the analysis of this study, the generated least-cost paths shown **in (figure 8)** are found to be more convenient than the existing highway routes taken by the BRVs in the distribution of Petroleum Products. However, when judging it in terms of factors that determine the cost of construction, the least-cost-paths are better than the existing highway routes since it crosses fewer steep areas and its lengths are shorter than the existing routes as shown **in (table 1).**

The comparison of the important factors in determining the pipeline routes are summarized in (**Table 1)**. From the table above the existing highway routes commonly used by Bulk Road vehicles (BRVs) have long traversing distance as compared to the developed optimal pipeline routes. Taking for instance the highway route from the Refinery in Tema to Saltpond in the central region has a length of 144 km and with an increase in the crossing of waters resources. Comparing it to the Pipeline route from the refinery to Saltpond, the length of crossing flatter areas is maximum for least-cost-path, being 133km as compared to the existing 144 km highway route. Again, the effect of crossing water resources is highly minimized for the route. Also, taking the highway route from Saltpond to Badukrom in the Western Region has a length of 69km with a slope of 4.2˚. However, the least cost pipeline path developed has a shorter length of 63km with no effect on the crossing of water resources along its path and a flatter slope of 2.7˚. Saltpond to Anyinam highway route in the Eastern Region has a length 87km on the other hand a developed least cost pipeline route of length 76km from the same source to the same destination point with a slope of 2.8 ˚ as compared to the highway steeper slope of 8.9 ˚. The last developed least cost pipeline route from Anyinam to Kubease in the Ashanti region has a length of 106km passing through a less stepper slope terrain with a limited crossing of water resources and other features of important as compared to the highway route of length 133km.In summary these developed least-cost paths have the highest suitability to routing cutting the cost of patronage of Bulk Road Vehicles(BRVs) traversing on the highways with a longer travel distance and at a high cost of management and maintenance of these BRVs. These pipelines destination points namely, Saltpond in the central region, Badukrom in the Western region, Anyinam in the Eastern Region and finally Kubease in the Ashanti region serve as facility storage centers which will link and boast distribution within the regions, thereby cutting down the cost and time of transportation of petroleum products being it kerosene, gas oil or gasoline by BRVs within the study area.

From **table 1** discussions, it can be therefore be stated that the pipeline routes fulfill the top priorities which are the safety and cost in the route design process.

VII. CONCLUSION

The pipeline routing criteria are identified and input into GIS. Spatial Analyst tool in ArcGIS 10.4 is utilized in the least-cost path analysis and a Multicriteria Decision Analysis method; the Analytical Hierarchical Process is applied to determine the weightages of criteria. The GIS-developed routes are not only by far shorter than the subsisting highway routes utilized by the BRVs but also reduces the expenses incurred on oil marketing companies to transport the petroleum products and again the routes cross most of the flatter slope areas which contributes to truncation in pipeline construction cost. The developed routes have the best suitability to public consequently solving the frequent occurrences of contingency on our highway caused by the traversing of Bulk Road conveyances carrying petroleum products from the refinery to the sundry facility centers. In conclusion, the GIS approach is no doubt a more structured and consistent method than contemporary routing method because all the routing criteria and corresponding level of consequentiality in affecting pipeline construction cost are not only designated and documented limpidly but can withal be monitored to engender more routes according to different sets of weightages desired. This approach of using GIS and AHP method for route analysis further confirmed the works done by most researchers finding optimal route path for linear structures being road, rails, transmission line among others and also determining suitable sites for setting up physical structures of economic and environmental importance such as that of a sewage treatment plant. This study from the onset has faced so many problems from data acquisition, down to processing and analysis. These problems almost limited the amount and quality of information gathered for this study. Among the setbacks is the unwillingness of some stakeholders to provide information about the study and the bureaucracy involved in getting the required data. The study recommends further studies on the determination of impacts of varied and additional physical, socioeconomic, and political parameters on finding optimal route location using the

Least Cost Path (LCP) approach. Furthermore, the legal framework of the pipeline industry must be tightened since it is porous and much attention is not given to the pipeline industry.

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