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Optimization of Gas Flow Network using the Traveling Salesman And the Nearest Neighbors Algorithms

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Abstract

The overall goal of this paper is to develop a general formulation for an optimal infrastructure layout design of gas pipeline distribution networks using algorithm developed from the application of two industrial engineering concepts: the traveling salesman problem (TSP) and the nearest neighbor (NN). The focus is on the optimization of pipe length and the selection of satisfactory pipe diameters (based on economics and market availability) to minimize the length of pipe used. A computer model is developed for the optimization of pipeline lengths. The formulation was based on well-known equations for the pressure loss at every node. The mathematical model embedded in the C#NET code was developed in a Window environment so as to make the solution user-friendly. Validation of the solution is done for layout design by manual selection of optimal path.

1.0 Introduction

A pipeline network design contains pipes, reservoirs, pumps, valves of different types, which are connected to each other to provide product (gas) to the consumer. It is an essential component of urban infrastructure and requires considerable investment. Pipeline gas distribution delivers more gas easily to more people thus encouraging more gas consumption and curbing wastage.

The problem of optimal design of a distribution network has various aspects that must be considered; e.g., hydraulics, reliability, material availability, quality of the delivered products, delivery pressure, demand patterns and infrastructure layout. [1]

In this paper an approach to the design and optimization of cost-effective network design using industrial engineering concepts, the Traveling Salesman Problem (TSP) and the Nearest Neighbour (NN), The objective function is the minimization of the total length of pipeline used. As cost is directly related to total length, the economic implication is obvious.

The most reliable route for the TSP is used with penalties attached to each route based on some desirable or undesirable factors [2]. The reliability is associated with reduced cost. This accounts for the additional expense incurred on the more undesirable routes.

The TSP was essentially used to solve the routing aspect of the infrastructure layout. A heuristics is used to get a good approximation that falls within the feasible solutions, which quickly yields an effectively short route. The resultant route (arcs) is dependent on the start node.

The objective function is the minimization of total distance traveled and the costs associated with each network are: (1) Cost. This is assigned based on the weight associated with each arc. (2) Weight: This is defined as the relative difficulty in reaching an end node from a start node.

The steps of the procedure are given as follows. Each location is considered as a node, the pipelines are the arcs. The nodes and the arcs make up the network.

Let N be the set of nodes of the network such that

$N = \{1, 2 \ldots n\}$

C_k = set of nodes that have been connected at iteration k.

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$\bar{C}_k$ = set of nodes yet to be connected after iteration k

Step 0 At the start of the iteration all values are set to their minimum values.

That is $c_k = 0, \quad \overline{c_k} = N$ and K=0

Step 1: After the first iteration, when a node ***i*** is selected.

$C_1 = 1 \quad , \overline{c_i} = N - 1$ and K=1

Problem Statement

Natural gas produced from gas fields, miles away from consumption point, must be transported through pipelines to delivery points.

This paper develops techniques for solving the design of optimal network structures, given x, y, z coordinates of consumer points and flow requirements in order to minimize the sum of investment and operation costs. The techniques incorporate procedures for globally optimizing pipeline length and use a heuristic procedure for generating low-cost structures.

Constraint Handling

The constraints in the problem can be grouped into the following: (1) hydrodynamic, (2) minimum head (3) physical or geographical (4) commercial and (5) computing/software limitations.

Hydrodynamic Constraints

There are two hydraulic constraints, namely: (1) discharge and (2) energy.

From the continuity equation the discharge into each consumer node must be equal to that leaving the node. Exceptions are the storage nodes (tanks and reservoirs). For *n* nodes in the network, this constraint can be written as [3]

$$\sum_{i=1}^{n} Q_i = 0 \qquad (1)$$

where

Q_i the discharges into or out of the i^{th} node.

The total head loss around any loop must add up to zero or is equal to the energy delivered by a pump, if there is any.

$$\sum h_f = E_p \qquad (2)$$

where:

$h_f =$ the head loss due to friction in a pipe and

$E_p =$ the energy supplied by a pump.

Head and flow constraints:

Historically, several methods have been used to compute head loss. These include the Hazen Williams equation and the Hardy cross methods. In the Hazen Williams's formulation [4],

(FSS units): $V = 1.318\, C_{hw}\, R_h^{0.63}\, S^{0.54}$ (3)

(SI units): $V = 0.849\, C_{hw}\, R_h^{0.63}\, S^{0.54}$ (4)

where R_h is the hydraulic radius, S is the head loss per unit length, and C_{hw} is the roughness coefficient.

The head loss in any pipe is a function of its diameter, length and hydraulic properties; and must be equal to the difference in the nodal heads. The equation relating frictional head loss and flow velocity is non-linear and can be written [4-5]:

$$h_f = f \frac{L}{D} \frac{v^2}{2g} \qquad (5)$$

where:

h_f = head loss due to friction in a pipe
L = length, m
D= diameter, m
v = velocity, m/s
f = friction factor
g = gravity correction factor, $10 m/s^2$

Pipe diameter size constraints:

According to Afshar [6-7] the diameter constraints can be expressed mathematically as:

$$d_{\min} \le d_i \le d_{\max} \qquad (6)$$

where:

d = pipe diameter and i = the ith node

Market Constraints:

The minimum head requirement at the consumer-nodes is taken as a constraint for the choice of pipe diameters.

Pipe Length

There is a problem of connecting all node-points that make up the layout of the gas transmission system. When the terrain is irregular there is a further complication.

Physical or geographical Constraints (Terrain and Area Extents Constraint)

The terrain over which the pipelines pass is an important factor for obvious reasons. Terrain determines such factors as the number of, and need for, booster stations. The rate of corrosion and deterioration of materials are also influenced by the terrain and rain fall.

Composition of Natural Gas

The initial composition, pressure and temperature conditions determine the fluid that can be expected from a reservoir; but at the surface, temperature and pressure during production determine the state of the hydrocarbon gas.

Computer Model

A computer model is developed. The model is designed to run in the window environment in order to make it user-friendly. The program execution is simple and consists of the following steps:

(1) The user would scan a map of the location.

(2) The scanned map is introduced into the programme by simply opening the file from its location.

(3) Click on the scanned maps to insert nodes in area of interest The program automatically picks the x, y- coordinate of the inserted points.

(4) Supply additional information as requested by the program. This information includes the z- co-ordinate of each node.

The produced image is fed into another module of the program to yield the optimal path using the TSP and NN algorithm.

(5) By running the second module, an optimal path would be obtained and drawn on the graphical user interface (GUI).

(6) Select three diameters for diameter assignment. This reflects the market constraints and availability. The program calculates the expected head loss for these selections and displays information. Final selection rests on human preference.

Modular programming is now used to design the program into modules. Each module is a stand-alone independent of the other and solved as one aspect of the problem.

The second module processes the information received from the first module and accepts the map**.** It allows user to input x, y and z- co-ordinates to points on the map. The inter-nodal distance is calculated by:

$$\text{Distance} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \qquad (7)$$

Information on nodal co-ordinates is saved in in the program folder.

Analysis for head-loss starts with the user selecting three diameters from the selection panel. The selection panel represents the market constraints (as commercial pipes can only be purchased in a finite number of pipe diameter sizes).

The user's selection represents the availability and economic constraints as all commercial sizes may not be available due to project finance or other factor beyond the engineer's. The available sizes would be used by the program to determine the diameter placements. For each pipe diameter selected the head loss is calculated based on the head loss equation.

The results are displayed and the user can make the final judgment based on all the available information. Thus the user is able to make sound investment and operational decisions.

Assignments of Weights

Assignment of weight is done to reflect the penalties incurred in moving from one node to another. Information needed to assign weights effectively are the elevation of each node, the distance from one node to another and the relief of the area.

Penalties reflect the relative difficulty to get from one node to another. These difficulties are a function of the geography of the expected route. The presence of rivers, water ways and structural relief are of great importance in the assignment of a weight to any possible arc. As much as possible, water ways and road networks are avoided due to cost and safety consideration.

The total penalties on an arc are the weight for the arc. It is a common practice to use the maximum constraint violation for calculating the penalty cost. The penalty cost is calculated according to a fitness equation. Afshar et al [6] used the relation, as stated below:

$$\min C_P = \sum_{i=1}^{m} C_i L_i + \sum_{i=1}^{m} \propto_i \left(q_i - q_{\min}\right)^2 + \sum_{k-1}^{n} \propto_k \left(H_k - H_{\min}\right)^2 \qquad (8)$$

where α_l and α_k are the pipe flow and nodal head penalty parameters with large values when corresponding constraints are violated and zero values, if otherwise

The proper setting of the penalty parameters is very important to the solution as a low value of the penalty parameters could lead to a constraint violating solution, while a high value of the parameters would result in rejecting some of the constraint violating solutions.

Case Study: Esan West Local Government Area

To demonstrate the capability of the computer code a solution is proffered for the optimization of gas pipeline in an area of Nigeria, known as Esan West Local Government Area. in the present day Edo state of the Federal Republic of Nigeria. Edo states is located in the SW part of the country. The climate is generally dry and arid with most of the seasonal rains in May to September. Nine settlements, chosen randomly are considered.

To calculate weights/penalties between nodes, we need distances between settlements, elevation of each settlement, and the differences in elevation between settlements as follows:

Table 1: Coordinates and Penalties of Nine Selected Locations

S/N	Settlement	X	Y	Pena lties alties
1	Egoro-Amede	240	60	3
2	Eguare-Egoro	162	82	3
3	Ekpoma	321	122	6
4	Idumebo	224	111	3
5	Ihumudan	284	107	3
6	Ileh	449	111	6
7	Irrua	354	169	6
8	Iruekpen	99	97	6
9	Uke	188	153	0

Table 2: Distances, in Metres, between the Settlements

	Egoro-Amede	Eguare-Egoro	Ekpoma	Idumebo	Ihumudan	Ileh	Irrua	Irukpen	Uke
Egoro-Amede	0.0	95.23	364.23	403.56	355.87	408.81	557.77	289.40	318.36
Eguare-Egoro	95.23	0.00	341.88	356.63	324.82	477.08	528.83	210.22	261.18
Ekpoma	364.23	341.88	0.00	109.68	39.92	151.34	193.71	244.76	145.43
Idumebo	409.56	356.63	109.68	0.00	78.20	226.99	196.19	195.76	11.28
Ihumudan	355.87	324.82	39.92	78.20	0.00	183.41	207.29	210.54	117.61
Ileh	408.81	477.08	151.34	226.99	183.41	0.00	153.02	393.82	294.59
Irrua	557.77	528.83	193.71	196.19	207.29	153.02	0.00	389.15	288.16
Irukpen	289.40	210.22	244.76	195.76	210.54	393.82	389.15	0.00	116.43
Uke	318.36	261.18	145.43	11.28	117.61	294.59	288.16	116.43	0.00

Assuming a direct relationship between weight and cost, each settlement is linked to the next closest settlement to itself, to optimally minimize the elevation change (which influences the pressure loss) and the distance apart (using the TSP and NN algorithms) to produce a network.

Table 3: Elevations of Settlements

Settlement		Elevation
1	Egoro-Amede	850
2	Eguare-Egoro	900
3	Ekpoma	1200
4	Idumebo	1250
5	Ihumudan	1200
6	Ileh	1280
7	Irrua	1385
8	Iruekpen	1100
9	Uke	1150

The elevation of each node is obtained from the map of **Fig. 1**.

Table 4: Difference in Elevation between Settlements

	Egoro-Amede	Eguare-Egoro	Ekpoma	Idumebo	Ihumudan	Ileh	Irrua	Irukpen	Uke
Egoro-Amede	0	50	350	400	350	430	535	250	300
Eguare-Egoro	50	0	300	350	300	380	485	200	250
Ekpoma	350	300	0	50	0	80	185	200	50
Idumebo	400	350	50	0	50	30	135	244.76	100

Ihumudan	350	300	0	50	0	80	185	100	50
Ileh	430	380	80	30	80	0	105	195.76	130
Irrua	535	485	185	135	185	105	0	150	235
Irukpen	250	200	100	150	100	180	285	210.54	50
Uke	300	250.50	50	100	50	130	235	100	0

The proposed route in order to minimize the pressure losses due to change in elevation becomes:

Egoro-Amede to Eguare-Egoro to Iruekpen to Ihumudan to Ekpoma to Idumebo to Ileh to Irrua to Uke.

Taking a 50m = 1 weight then for

Egoro-Amede to Eguare-Egoro = 95.23/50 = 1.9046 and 50/50 = 1. Therefore, weigh from Egoro-Amede to Eguare-Egoro is 1.9046 +1 = approximately 3. Similar calculation is done for each inter-node. The penalties are tabulated in Column 3 of **Table 1**.

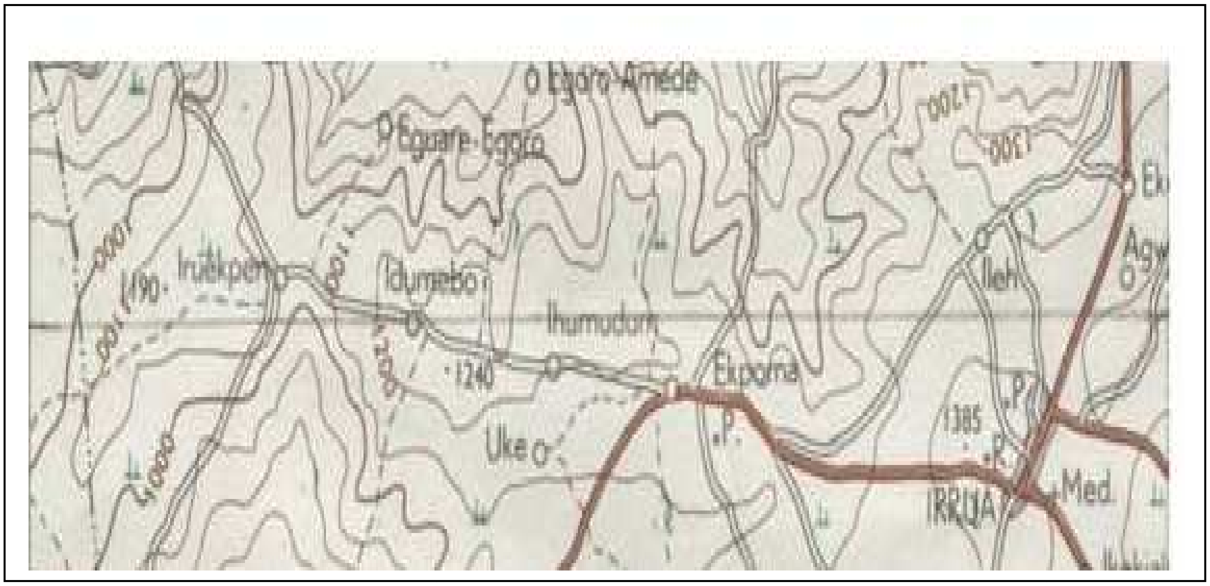

Fig. 2: Political Map of Esan West L.G.A. showing the different Wards

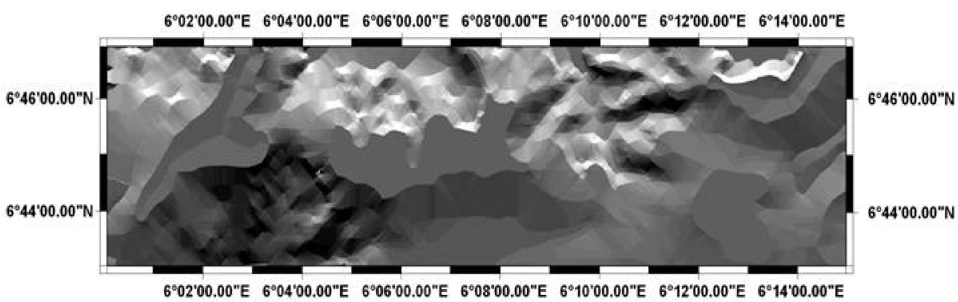

Fig. 3: Topographical Map of study area

When information in **Tables 1 to 4** is run the recommended path to be followed is shown in **Fig. 3**.

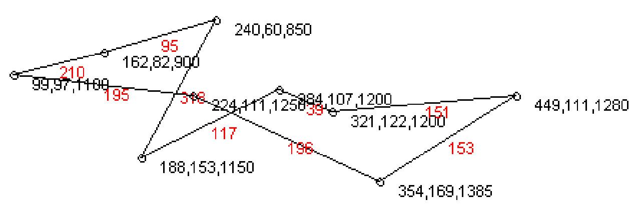

Fig. 3: Computer Output showing Recommended Network Path

Validation

The distances between nodes are calculated manually using Eq. 7 using the NN algorithm and the results are found to be in agreement with those used for obtaining the route in Fig. 3.

Difficulty Associated with Each Proposed Route

By an assessment of the difficulty associated with each of the proposed segment of the pipe line route an understanding of the factors that may increase the cost for the pipeline construction in a particular settlement on the designated route may be obtained. These include the presence of rivers, human settlement, e.t.c. This information is obtained by studying the drainage pattern, road network and other relevant maps of the area. The single dominant factor that was observed to influence the project cost is expected to be need for (and number of) compressor stations (occasioned by the terrain and the respective elevation).

Conclusion

This project focused on the determination of the optimal routing of pipelines based on minimization of pipe length and elevation differential under steady- state, single phase flow in small diameter pipelines using the TSP and NN algorithms. The following conclusions were apparent from the study:

1. The TSP and NN algorithms are efficient and effective with computer simulation.
2. It is possible to optimize networks with any kind of hydraulic facilities theoretically. In practice, however, the integration of an optimal method and geographical information system would improve planning and solve design problems. This approach is worth further investigation as it has great practical importance.
3. Points connected by the network yield less head loss possible due to adequate weight selection.
4. The model can be applied to any area since it is efficient for the practical case selected for this study.
5. Although only length selection was minimized, it is mentioned that since length implies cost a minimization of length implies a minimization of overall cost of the project.

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