An International Journal of Optimization
and Control: Theories & Applications
Vol.6, No.2, pp.151-165 (2016) © IJOCTA
ISSN: 2146-0957 eISSN: 2146-5703
DOI: 10.11121/ijocta.01.2016.00277
http://www.ijocta.com

The integrated network model of pipeline, sea and road distribution of petroleum product

Ömer Öztürkoğlu [a] and Oyewale Lawal [b]

[a] Department of Industrial Engineering, Yaşar University, Turkey
Email: omer.ozturkoglu@yasar.edu.tr

[a b] Department of Business Administration, Yasar University, Turkey
Email: oyewale.lawal@stu.yasar.edu.tr

(*Received September 30, 2015; in final form May 10, 2016*)

Abstract. Nigeria ranks high among the community of oil producers both in the world. It is, therefore, paradoxical that Nigeria, with such profile in Organization of Petroleum Exporting Countries (OPEC) statistics finds it difficult to optimize its supply distribution while spending so much money on transportation and distribution. This paper thus reviews the petroleum product supply and distribution systems in the country. Thus, we develop a single period, single product deterministic mathematical model to effectively distribute the product to the end user through the most effective channel to the interest of the economy of the country. In our model, we first consider a perfect condition in the petroleum industry irrespective of the production crises and conflicts like pipeline vandalism, communal instability. We then consider different scnearios that presumes several breakdown cases in pipeline connection to anaylze the survivability of the network of petroleum distribution.

Keywords: Distribution logistics; network model; pipeline; petroleum product.
AMS Classification: 90C90; 90B10; 90B06

1. Introduction

All around the world, petroleum distribution enjoys transportation options which include road transportation (by trucks), rail transportation and sea transportation. Pipeline transportation has become the most viable means among these options in a long time. This could be either from exploration site to refinery or from refinery to supplying depots. This attractive means of transportation influences the oil market logistics positively: one of which includes, effective delivery of petroleum product to the required point, accidents or traffic adversity that might arise from road transportation are avoided and most importantly, transportation cost are considerably lowered when compared to other means of transportation.

The safety and reliability of petroleum is also assured via pipeline transportation as compared to road or rail transportation where product adulteration is possible on transit. Health and environmental hazards that arises from open movement of petroleum products are also avoided when transported through the pipeline. Researchers have also shown that there are lesser chances of spillage in pipeline transportation compared to other means of transporting petroleum products [1].

Although the risks of carrying petroleum products through pipelines are very rear but when they occur, they are more fatal compared to other means of transportation thus incurring great casualty. Since pipelines that transport petroleum products are submerged in the earth, there are possibilities of spillage which might arise from pipeline rapture or corrosion. These then have contact with the under-earth drinking water supply making it contaminated for consumption.

Corresponding Author. Email: omer.ozturkoglu@yasar.edu.tr

Multiple break-downs in the pipeline network also cause product delivery delay, causing industrial down tool for the period of break down. This also affects the economy in the negative sense.

Operational and personal pressure miscalculation that might arise from pipeline transportation always has adverse effect on the environment and wildlife. Predominant failure that arises from pipeline transportation and mostly caused by corrosion, welding and material failure which might warrant evacuation is also another difficult and expensive task. This is predominant in regions within USA and Canada. Malfunction within the pipeline network are most times difficult and expensive to manage whereby the products leak unnoticed. Pipeline vandalism is another disadvantage of pipeline transportation of petroleum product; this is predominant in the sub-Sahara Africa cases. Because of this, in this paper we focus on one of the biggest petroleum produces in Africa, Nigeria.

Nigeria is a country with abundance of natural resources and most of which are of economic quantity. One of its natural resources that are readily available for trade and with high market demand is petroleum (crude oil). Exploration of crude oil have increased compared inception; production have also increased to close to a billion barrel in the year 2006. Similarly, Nigeria exported a relatively higher volume (hundreds of millions of barrels) of crude oil resulting in a corresponding increase in oil revenue making Nigeria practically abandoning other sources of revenue generation. The increasing revenue trend thus portrays Nigeria in a very good position for steady development through revenue availability for infrastructure and sustainable micro economics management. But in spite of these, the nation still wallows in decayed infrastructure and weak institutions through corrupt leadership and technological negligence.

Nigeria Oil industry has been suffering due to inadequate funding in the infrastructures, weak government policies; pipeline surveillance inefficiency and mismanagement have contributed immensely to the incessant distribution problem of the petroleum products for decades [2]. That's why, Auwal and Mamman [3] mentioned that the petroleum market in Nigeria is very sensitive; however authors claim that market players will find an opportunity to access facilities such as pipelines, depots etc. to maximize supplies to customers due to deregulation. Additionally, Ehinomen and Adeleke [4] discussed that privation of the distribution of the petroleum product in Nigeria both creates job opportunities and increase the effectiveness and the efficiency in the distribution of the product. Ehinomen and Adeleke [4] also pointed out that state-owned facilities such as pipelines, depots and refineries, storage facilities are poorly managed, hence it causes a low utilization of the facilities, inadequate distribution and increase in treasury loss. Therefore, in recent decades, there have been incessant shortages of products, long queues at gas stations due to product shortages and ineffective distribution mechanism. Hence, this paper aims to optimize the distribution of petroleum products in the downstream supply industry in Nigeria assuming that the sector is deregulated and operated by private companies.

It was evaluated that the network density and pipeline connectivity for the distribution of petroleum finished products are low thus creating room for inefficiency in the supply of these products to the eventual end users through the necessary intermediate actors [5]. Therefore, the model we develop in this study is aimed to provide answers to several questions such as "which pipeline connections are crucial for the network and what should be their capacity", "what should be the capacity of depots" and "which pipeline connections can be treated as back-up connections when a sabotage is occurred in the network."

Recently, An et al. [6] reviewed previous research about biofuel and petroleum supply chain in details and divided them into three categories: strategic, tactical and operational. This review shows that many of the research has been done in tactical level and dealt with capacity and planning of refineries and production plants, inventory, flows of product as well as scheduling multi-products. Catchpole [7] is one of the earliest study that discussed how to use a linear program to determine the optimal flow of fuel between refineries and distribution centers. However, due to computational difficulties in that time, they did not develop a model and implemented. Later on, Klingman et al. [8] developed a multi-period mathematical model to solve the planning and distribution of petroleum of product in the network of Citgo. Authors also considered the exchange contracts between nodes. Recently, Herran et al. [9] presented a non-linear model to determine the optimal sequence of products that flow through a multi-product pipeline. They solved their model for difference scenarios after they linearized their model. Additionally, Oyewale and Ozturkoglu [10] presented a deterministic linear program for the optimal distribution of petroleum products both among depots, suppliers and downstream customers in Nigeria. In this paper, we extend Oyewale and Ozturkoglu [10]'s model to evaluate the survivability of the network. Throughout the optimization, we also aim to efficiently supply the petroleum product across all nodes involved in the supply chain to affect product availability. This also serves the purpose of transportation cost reduction. After the optimal solution is obtained, different scenarios would also be analyzed to check the cost deviation in event of pipeline or flow breakage at some points in the flow network which might be as a result of pipeline vandalization, ethnic crises or other form of disruption.

2. Integrated network model

There are several assumptions that accompany the model. The model is a single-period, deterministic mathematical model. The model assumes that the transportation cost on a given route is directly proportional to the distance between two nodes.

There are assumed to be five different types of facilities in a distribution network of petroleum product. These are petroleum supply countries, import seaports, in-country refineries, and depots/pump stations and filling stations. In our model, filling stations are customers of the network. However, because there are thousands of them available in the network, we assume to that a customer point is located in the centroid of each state, and the demand of each state is calculated with respect to the accumulated demand of filling stations in that state. Depots/pump stations are points from where petroleum product is supplied to the end customer through road transportation. While depots/pump stations are connected to refineries and import seaports through a pipeline network in general, goods are transferred between import seaports and supply countries via sea transportation. Hence, considering the available route among these facilities we construct a network consisting of nodes and edges.

All facilities except for customer zones are defined as nodes in a set N where $i \in N$ represents the i^{th} facility in the network. In this set, i represents depot/pump station nodes from 1 to p, seaport nodes from $p+1$ to q, refinery nodes from $q+1$ to r, and supply country nodes from $r+1$ to u. Customer zones are also defined as nodes in a set K where $k \in K$ and there are s number of states in total. R is also a set of defined routes that vessel $e \in E$ might travel. Therefore, the parameters and decision variables are as defined in Table 1.

Table 1. Model parameters and decision variables.

Parameters	
d_{ij}	distance between node i and node j (km)
c_{ij}	unit cost of transferring of product from node i and node j (\$/km-barrel)
tc_{ik}	unit trucking cost of transporting from node i and state k (\$/km- barrel)
m_{ij}	a matrix that indicates if there is a road or pipeline connection between node i and node j ($\in \{0,1\}$)
p_{ij}	pipeline capacity between appropriate node i and node j (barrel)
D_k	total demand of the product in state k (barrel)
V_e	capacity of vessel e (barrel)
T_{eij}	cycle time of vessel e on route i and j (time/cycle)
S_i	Supply capacity of node i (barrel)
w	working period (time)
Variables	
X_{ij}	quantity of product transferred from node i and node j (barrel)
Y_{ik}	quantity of product transported from node i and state k (barrel)
N_{eij}	Number of trips that vessel e make through route nodes $i-j$
δ_{ij}	1, if connection from i to j; otherwise it is 0

$$\min \quad Z = \sum_{i \in N} \sum_{j \in N, i \neq j} X_{ij} \cdot c_{ij} + \sum_{i=1}^{p} \sum_{k \in K} Y_{ik} \cdot tc_{ik} \tag{1}$$

Subject to

$$\sum_{j=1,i\neq j}^{p} X_{ij}\cdot m_{ij} + \sum_{k\in K} Y_{ik} \leq \sum_{j\in N,i\neq j} X_{ji}\cdot m_{ji} \qquad \forall i = 1 \ldots p \tag{2}$$

$$\sum_{j\in N,i\neq j} X_{ij}\cdot m_{ij} - \sum_{j\in N,i\neq j} X_{ji}\cdot m_{ji} \leq S_i \quad \forall i = (p+1) \ldots m \tag{3}$$

$$X_{ij}\cdot m_{ij} \leq p_{ij} \quad \forall i = 1 \ldots r, \forall j = 1 \ldots p \tag{4}$$

$$\sum_{i=1}^{p} Y_{ik} \geq D_k \quad \forall k \in K \tag{5}$$

$$\sum_{i=p+1}^{q-2}\sum_{j=i+1}^{q} N_{eij}\cdot T_{eij} = w \quad \forall e \in E \tag{6}$$

$$X_{ij}\cdot m_{ij} \leq \sum_{e\in E} N_{eij}\cdot V_e \qquad \forall\, i,j = p+1 \ldots q, i \neq j \tag{7}$$

$$X_{ij} \leq M\cdot\delta_{ij} \quad \forall i,j = 1,..,p; i \neq j \tag{8}$$

$$X_{ij} \geq \delta_{ij} \quad \forall i,j = 1,..,p; i \neq j \tag{9}$$

$$\delta_{ij} + \delta_{ji} \leq 1 \quad \forall i,j = 1,..,p; i \neq j \tag{10}$$

$$X_{ij}, Y_{ik}, N_{eij} \geq 0, \delta_{ij} \in \{0,1\}\, \forall i,j \in N, \forall k \in K, \forall e \in E \tag{11}$$

In formulating the model, the objective (Z) in Eq. (1) is to minimize total cost of transportation of petroleum product from supplying countries and local refineries through depots involving pipeline network to the states. The first part of the objective function presents total sea and pipeline transportation cost occurred before the products are distributed to states. Hence, the second part is related to total trucking cots to meet customer demands in states.

Because depots/pump stations are transhipment nodes, Eq. (2) maintains the equilibrium in the pipeline network such that total flow out from pump stations should be less than or equal to total flow into pump stations. Eq. (3) also enhances the equilibrium in the rest of the network in which total capacity of the refineries, supplying countries and seaport cannot be exceeded. Eq. (4) is the pipeline capacity constraint for a given period under the assumption that there is no vandalism or outage. Eq. (5) guarantees that demand of states should be satisfied by pump stations. Eq. (6) is used to calculate the number of trips that a vessel can make in a given period. We assume that a vessel visits only one location in a trip after it is loaded. As soon as it deposits all products to a location, it goes back to the beginning to be loaded. Hence no tour is allowed for vessels. Therefore, in Eq. (7), amount of products shipped among seaports cannot exceed vessel capacities. Eq. (8)-(10) provides that only one way of the pipeline flow can be allowed within the planning horizon if there is any two way flow available among the pump stations. In Eq. (8), M is a relatively big number. Eq. (11) is the non-negativity and binary constraint. Therefore, the model is a mixed-integer linear programming (MILP) model.

3. Case study: Nigerian petroleum distribution network

We implemented our model to the petroleum network in Nigeria. The data used in this case study is obtained from local sources that summarize Nigerian petroleum industry reports, analysis and expert knowledges. Most of them are not accessible in digital formats, however, some of the data are obtained from NEITI [11] by refining the appropriate tables. Even though it is not rare to face with network breakdown or pipeline vandalism in Nigeria, we first assume that the network runs properly without any shortage. In order to determine if there is any scarcity in the network in terms of depot or pipeline capacities, we assume that depots and pipelines have infinite capacity. It is a single period model; hence the working period in the model is assumed to be one week. The supply chain distribution of the petroleum industry in Nigeria is represented as a network of nodes in Figure 1. In Figure 1, the dotted lines represent sea transportation, the single line represents pipeline transportation while the thick line represents trucking transportation. Names of the locations represented by nodes are given in Table 2.

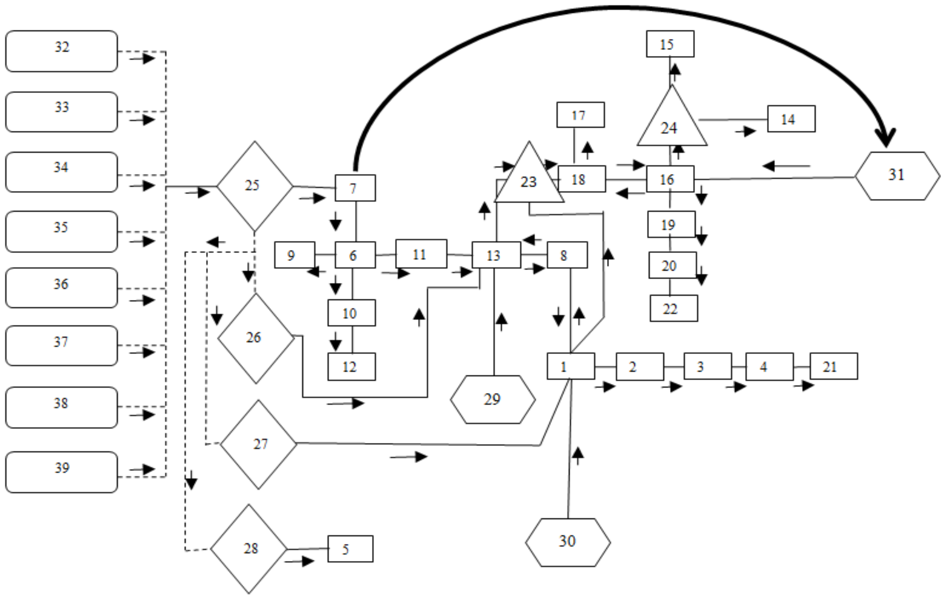

Figure 1. Representation of supply chain network of petroleum industry in Nigeria.

Table 2. Location names of nodes in Figure 1.

Node	Depot	Node	Depot	Node	Depot	Node	Suppliers
1	P.Harcourt	12	Ilorin	23	Auchi P/S	32	India
2	Aba	13	Benin	24	Suleja P/S	33	France
3	Enugu	14	Kano		**Seaport**	34	Italy
4	Makurdi	15	Gusau	25	P.Lagos	35	S/Korea
5	Calabar	16	Kaduna	26	P.Delta	36	Netherland
6	Mosimi	17	Minna	27	P.Harcourt	37	Singapore
7	Atlascove	18	Suleja	28	P.Calabar	38	Portugal
8	Warri	19	Jos		**Refinery**	39	Ivory
9	Ejigbo	20	Gombe	29	Warri		
10	Ibadan	21	Yola	30	P.Harcourt		
11	Ore	22	Maiduguri	31	Kaduna		

In Figure 1, nodes 1 through 24 are designated to represent the depot/pump stations that are connected by pipelines which are owned and operated by Nigerian government. Table A.1. in Appendix shows the distances between connected pair of nodes and the transportation cost per barrel of petroleum flowing between these pair of nodes. This data is obtained from Fantini [12]. The pipeline transportation cost is calculated by using a formula obtained from local industry experts. This formula is given in Eq. (12). The first part of the equation is related to weekly fixed maintenance and deterioration cost of pipelines per barrel under the assumption of 100% utilization of the pipelines. The second part is variable transportation cost with respect to the distance of a barrel of product flow through the pipeline. Pipeline transportation cost

$$c_{ij} = 0.5 + (1.5\ x \frac{d_{ij}}{1000}) \qquad (12)$$

The depots/pump stations are used to meet demand of filling stations in states via road transportation. Although there are tens of thousands of filling stations in states, we take the center of mass of each state as the demand node. Hence, we determine that 37 customer zones in the network and their total demands are obtained from NNPC [13] (see Table A.2. in Appendix for details). All of the depots/pump stations can serve any of these states by trucks. We assume that there are enough number of trucks available in the network. The connections between states and depots are not represented on the network diagram for clarification reason. However, trucking costs among the depots and state centers are given in Table A.3. in Appendix.

Nodes 25 to 28 are the local seaport nodes. These seaports are used to feed pipeline network with the imported products. As seen in Figure 1, after imported petroleum products arrive to Port Lagos, they are either transferred to the depots through pipeline network, or transferred to other local ports via sea vessels. The types of vessels that are available to use among local ports, and their capacities are given in Table 3. Additionally, average cost of shipping one barrel of product via vessels between ports are also given in Table 4, assuming that the type of vessel does not affect the transportation cost. Table 4 also shows how long a vessel travels between Port Lagos and other ports in a trip. Hence, seaport and depot/pump station nodes serve as transhipment nodes connecting the supply and demand nodes.

Table 3. Available vessels (barges) and their capacities.

Vessel Name	Capacity (barrel)
Desire I	25368
Desire II	36440
Dera I	32482
Dera II	22809
Marvel I	40483
Praise I	20745
Praise II	20813
Mnemosyne	37472
Saje 460	76139
Hera	49568
Kirikiri	56076
Demetra	18689
S215	88533
Rhea	37515
Hestia	56076
Energy 7001	27177
Energy 6503	24711

Table 4. Transportation cost and average trip cycle time from and back to Port Lagos.

	Transportation Cost				Cycle time (days)
Local seaports	**Port Lagos**	**Port Calabar**	**Port Delta**	**Port Harcourt**	**From/To Port Lagos**
Port Lagos	0,00	0,11	0,05	0,09	---
Port Calabar	0,11	0,00	0,06	0,04	4,64
Port Delta	0,05	0,06	0,00	0,04	3,155
Port Harcourt	0,09	0,04	0,04	0,00	4,145

Table 6. Capacities of suppliers and their distances to Lagos Port.

Country	Distance (Nautical mile)	Supply Capacity (barrel/week)	Transportation Cost (USD/barrel)
India	7,826.5	2,221,212	2.15
France	4,758.0	932,463	1.04
Italy	3,763.0	1,445,206	1.31
S/Korea	10,574.5	752,346	2.90
Netherland	4,260.5	2,680,545	1.17
Singapore	8,166.0	1,780,667	2.25
Portugal	3,276.0	167,727	1.90
Ivory Coast	457.0	71,001	0.13

Nodes 29 through 31 are refinery nodes where local petroleum product is produced and supplied to the depots/pump stations through pipeline network. The weekly capacities of these refineries are given in Table 5. In the case of scarcity in local supply or need of petroleum product due to excessive demand, products are imported from petroleum product supplying countries. Nodes 32 to 38 represent these suppliers. The estimated supply capacities of these countries and their distances, as well as shipping cost, to Port Lagos (node 25) are given in Table 6.

Table 5. Capacities of refineries.

Refinery	Supply Capacity (barrel/week)
Warri	131250
P.Harcourt	220500
Kaduna	115500

4. Scenario analysis and results

The mathematical model for the case study is coded using AMPL and solved by using IBM ILOG CPLEX Optimization Studio version 12.6. The optimum flows of the petroleum product that minimizes total transportation cost under ideal case are depicted in Figure 2. The ideal case refers that there is no breakage, vandalism or leakage during the transportation. The surplus, which is the difference between total inflow and total outflow, at the depots refer to the amount of products sent to the appropriate states to meet customer demands.

Therefore, the optimal solution presents what the capacity of depots and pipeline connections should be to minimize total supply chain cost of the petroleum product in Nigeria. For example, the depot at Port Harcourt (node 1) and its pipeline connection with the refinery at Port Harcourt (node 30) should be able to handle about 220,500 barrels of product. In other words, this refinery should be able to produce at least this amount of products. Additionally, it is seen that several of the depots such as depots at Ejigbo (node 9), Ore (node 11) and Maiguduri (node 22), a refinery at Kaduna (node 31), and a local Port Hartcourt are inactive in the optimal solution. However, it doesn't mean that they are useless in real life. Because of the variabilities in the production and the distribution, these nodes could be utilized as back-up or support units and play important role in smooth flow of goods to meet customer demands. Especially, in the case of vandalism or breakdown in the network which is very common in Nigeria, they are indeed actively used nodes in real life, according to our knowledge.

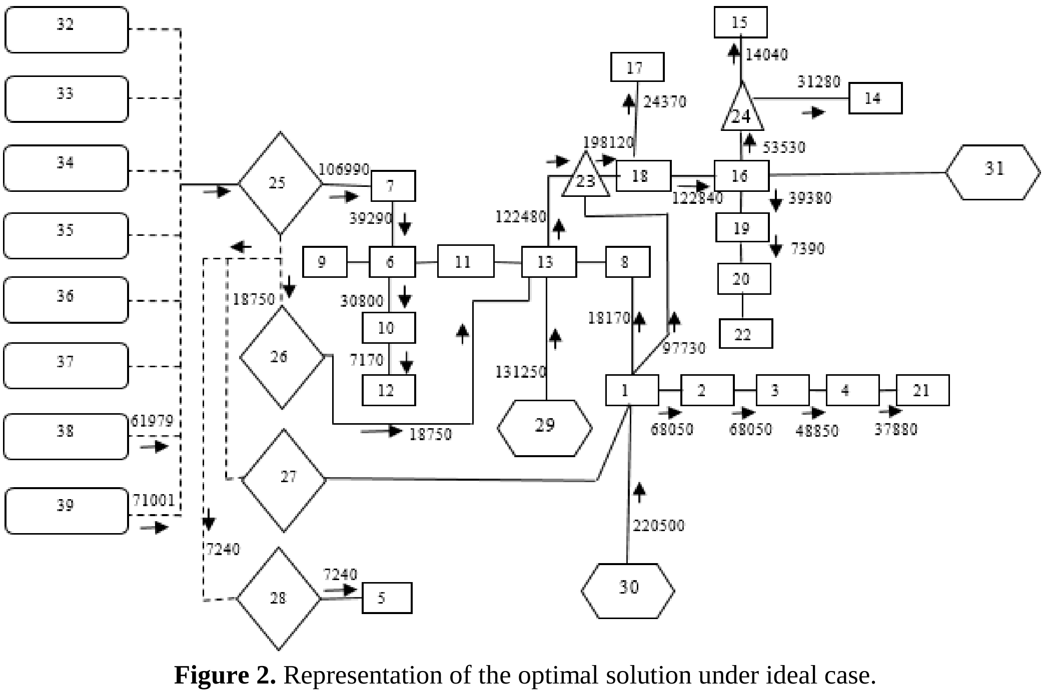

Figure 2. Representation of the optimal solution under ideal case.

The solution also shows that node 1 (depot at Port Harcourt) and node 25 (Port Lagos) have maximum flow connections (degree) in the network. In case of any problem in these connections, one can easily say that there will be a problem in flow of goods in the network. Because we run our model under ideal condition previously, we also want to show managers the survivability of their network. The term survivability refers to the ability of the network to meet customer demands in case a problem occurs in the connections. The survivability of the network is very important not only in pipeline networks but also in telecommunication networks.

Therefore, network designers always consider back-up nodes to alleviate the negative effects of breakdowns of shortages in networks.

To show the survivability of the petroleum network in Nigeria, we develop several important scenarios considering the important connections in the network and optimal flows in the ideal solution. These scenarios are described in Table 7. For example, scenario 1 represents that the pipeline connection between nodes 1 and 8 is out of work for the working period. Additionally, scenario 4 assumes that either pipeline connection between nodes 1 and 30 is broken or refinery at node 30 is out of work (no supply from this refinery).

Table 7. Several possible scenarios of breakages in the connections.

Scenarios	Breakage in connections	Reason of chosen
Scenario 1	1 – 8	Importance of node 1
Scenario 2	1 – 23	Importance of node 1 and high flow in ideal solution
Scenario 3	1 – 2	Importance of node 1
Scenario 4	30 – 1	Importance of node 1 and high flow in ideal solution
Scenario 5	25 – 7	Importance of node 25 and high flow in ideal solution
Scenario 6	18-16	High flow in ideal solution

Table 8. Scenarios and their total costs.

Cases	Total Cost (USD)	% Cost Increment
Base Scenario	1,773,019.8	---
Scenario 1	1,775,563.6	0.1
Scenario 2	1,822,212.2	2.8
Scenario 3	1,923,592.4	8.5
Scenario 4	1,959,818.5	10.5
Scenario 5	2,090,903.1	17.9
Scenario 6	1,933,835.4	9.1

Our mathematical model can easily be adjusted to reflect these scenarios by modifying the values in matrix m_{ij} which represents the availability of node connections. Currently, we assume that m_{ij} can take value of 1 or 0. Thus, we assign 0 to the value of m_{18}, $m_{1,23}$, m_{12}, $m_{30,1}$, $m_{25,7}$, and $m_{18,16}$ one at a time by recovering the value of the previously changed connection. We then evaluate both the changes in the network solution and the changes in the total cost comparing to the ideal solution. Table 8 shows the percentage increment in cost in these scenarios. The results show that the network is survivable in any of these scenarios with an additional distribution cost.

Even though the network is survivable in scenario 5, total distribution cost of the network increases about 11%, which is the second most costly scenario after scenario 4, compared to the ideal solution. We present the optimal solution for this scenario in Figure 3. The main reason of this result is that the supply capacity of the local refinery is not used due to lack connection to the distribution network. Therefore, the model buys the amount of product that the local refinery supplied (220,500 barrels) from supplying countries. Additionally, Port Hartcourt (node 27) becomes active to keep feeding node 1 and also its connected nodes to meet customer demands in states. Hence, this scenario shows that node 27 can play an important role as support units to keep the network surviving. In this scenario, it is also interesting to see that pipeline connections 1-8 and 1-23 become inactive due to lack of supply from node 31. Instead, the reduced flow to nodes 8 and 23 are met from node 13 that receives more goods from Port Delta (node 26). As a result, all of the local ports play an important role to keep product flowing in the network due to increasing amount of imported goods in this scenario.

Except for the connection between nodes 1 and 8, if any of the connections of node 1 falls down, it causes a dramatic increment in the cost of distributing goods. For example, the scenario 4 causes 10.5% increment in total distribution cost. An interesting result among the scenarios occurs in scenario 1. Interestingly, breakage in the connection 1-8 in scenario 1 almost does not change the ideal solution (see Figure 4). When we analyze the network solution for this scenario, we see that the model decides to use connection 13-8, which is not used in the ideal solution, to support node 8 to meet relevant customer demand in states. Hence, 18,170 barrels of products transferred from node 13 node 8 instead of from node 1 to 8. Additionally, to compensate the reduced flow to node 23 (from 122,480 in the ideal to 104,310), the model increases the flow from node 1 to node 23. The rest of the network is the same as the ideal solution in this scenario. As a result, this scenario shows that node 13-8 keeps the network surviving with a cheap cost. Because of the similar discussions and the length of the manuscript, we decide not to present solutions for the other scenarios. The reason why we choose to present scenarios 5 and 1 are due to inclusion of the local refinery in connection to breakage and similar solution to the ideal case, respectively.

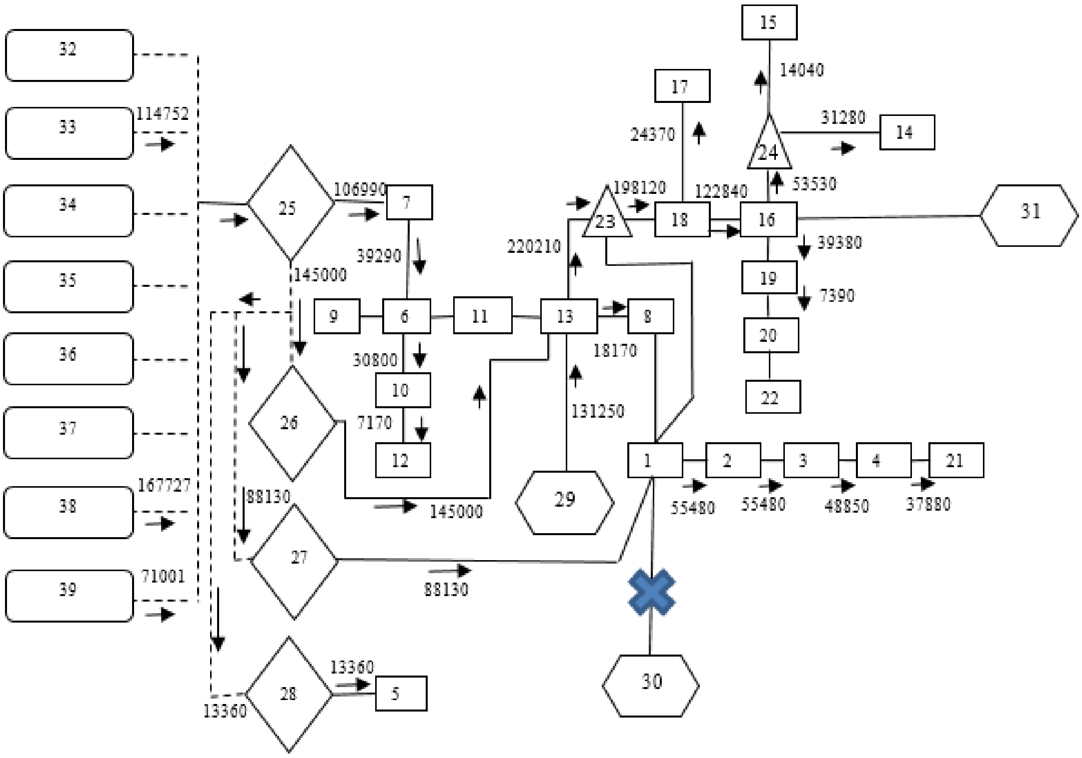

Figure 3. Representation of the solution for scenario 4.

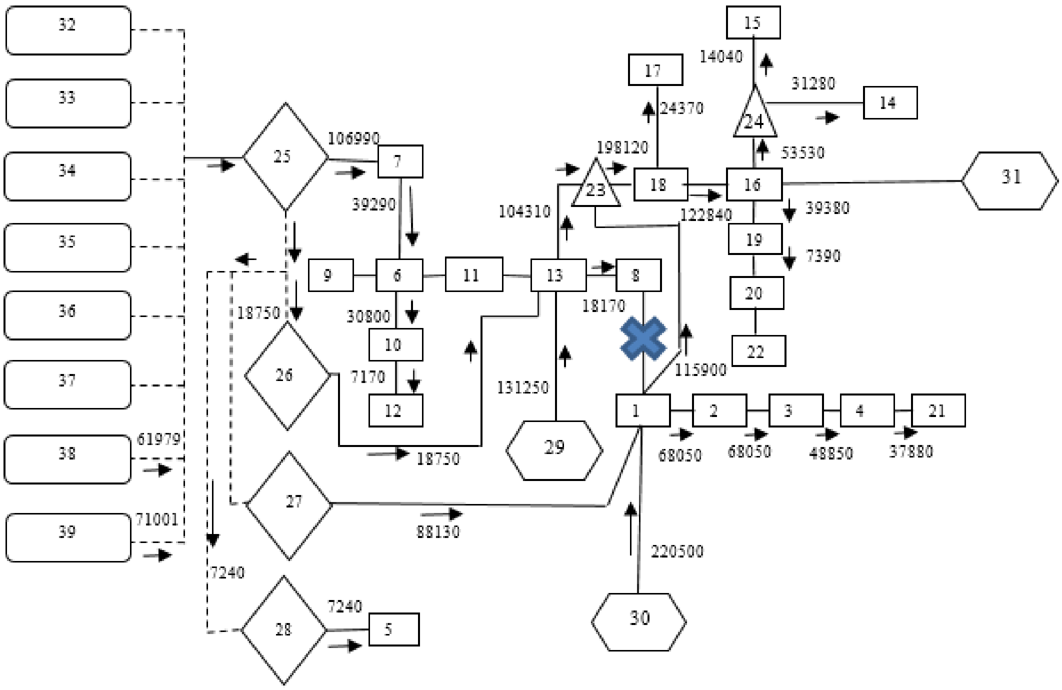

Figure 4. Representation of the solution for scenario 1.

5. Conclusion

The result of this study emphasizes on the most economical distribution of petroleum product in the downstream of the Nigerian petroleum industry to the target customers considering minimization of total transportation cost.

A resource saving is an important objective in the industry today, every progressive industry wants to procure as much saving as possible despite their interest of completing required production which the petroleum industry is not an exemption. A model of such a network would save a lot of resources, especially in an underdeveloped country such as Nigeria. Furthermore, this kind of model is liable to reasonable manipulation relative to more data availability while it still serves as a saving mechanism to transportation of petroleum product and enhancing prompt delivery as required.

From this case study, it is advisable to evacuate dormant nodes and pipeline from this network to save enough resources that would be useful in other sector of life in the Nigerian economy, thus saving transportation and distribution cost and reduces or eradicates petrol station long unnecessary queues due to product unavailability. For future direction, we are planning to develop a simulation model to investigate the potential effects of stochastic pipeline breakage on the distribution of petroleum products and on total distribution cost. Additionally, we plan to consider repair time for breakages of in the network.

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Ömer Öztürkoğlu is an Assistant Professor in Industrial Engineering at Yaşar University, Izmir, Turkey. He teaches related courses to Logistics Facilities, Warehousing, and Production and Operations Analysis. His research interests are designing warehouses and modeling logistics network problems. His papers have been published in EJOR and IIE Transactions.

Lawal Oyewale is a Ph.D. student in Business Administration at Yaşar University. He got his MSc. Degree from Industrial Engineering department at Yaşar University. He has a bachelor degree in Chemical Engineering from Nigeria.

Appendix

Table A.1. Pipeline distances and transportation cost between connected nodes (OPEC, 2012).

Pipeline connections (node-node)	Distance (Km)	Pipeline transportation cost (USD/barrel)
25-7	9.7	0.51
7-6	117.5	0.67
6-9	46.7	0.57
6-10	280.0	0.91
10-12	272.0	0.90
6-11	152.9	0.72
11-13	110.0	0.66
13-8	90.1	0.63
13-23	106.2	0.66
23-18	521.4	1.27
18-17	80.5	0.62
18-16	165.0	0.74
16-18	165.0	0.74
16-24	103.0	0.65
24-14	259.1	0.88
24-15	263.9	0.89
16-19	265.5	0.89
19-20	1335.8	2.49
20-22	1335.8	2.49
8-1	218.9	0.82
1-8	218.9	0.82
1-2	156.1	0.73
2-3	54.7	0.58
3-4	268.8	0.90
4-21	756.4	1.62
26-13	4.8	0.50
27-1	33.8	0.55
28-5	16.1	0.52
29-13	8.1	0.51
30-1	23.7	0.53
31-16	17.7	0.52
1- 23	328.3	0.99
31-16	9.4	0.51

Table A.2. State demand of petroleum product (NNPC, 2012).

No	State	Demand (barrel/week)
1	Abuja	50,910
2	Abia	3,850
3	Adamawa	22,950
4	Akwa Ibom	3,900
5	Anambra	10,350
6	Bauchi	25,450
7	Bayelsa	4,240
8	Benue	5,690
9	Borno	7,080
10	Cross River	7,240
11	Delta	18,170
12	Ebonyi	2,220
13	Edo	12,230
14	Ekiti	4,310
15	Enugu	6,630
16	Gombe	7,390
17	Imo	4,720
18	Jigawa	5,260
19	Kaduna	29,930
20	Kano	26,020
21	Katsina	8,210
22	Kebbi	7,290
23	Kogi	12,360
24	Kwara	7,170
25	Lagos	52,080
26	Nasarawa	9,730
27	Niger	17,080
28	Ogun	15,620
29	Ondo	10,980
30	Osun	8,490
31	Oyo	23,630
32	Plateau	6,540
33	Rivers	19,840
34	Sokoto	6,030
35	Taraba	5,280
36	Yobe	7,850
37	Zamfara	8,010

Table A.3. Trucking cost from depots to the center of states.

Depors\States	Abuja	Abia	Adamawa	Akwa ibom	Anambra	Bauchi	Bayelsa	Benue	Borno	Cross river	Delta	Ebonyi	Edo
Aba	6,8	0,5	9,4	0,9	2,0	9,2	1,7	4,5	13,0	3,4	2,5	2,0	3,1
PH	7,2	1,2	10,0	1,5	2,3	10,4	1,4	5,1	13,6	4,0	2,2	2,6	3,4
Enugu	4,4	1,6	8,0	2,4	0,9	7,5	3,0	2,8	11,6	2,0	3,2	0,9	2,7
Makurdi	3,1	4,3	6,6	5,1	3,3	4,7	5,7	0,7	10,3	2,5	5,6	2,8	5,1
Calabar	6,9	1,7	9,4	1,2	3,4	9,3	3,4	4,5	13,0	1,6	4,2	2,0	4,7
Warri	6,1	3,0	11,5	3,5	2,5	10,4	1,6	5,9	15,1	5,4	0,3	4,2	1,5
Benin	5,1	3,1	10,9	3,9	1,9	9,4	2,5	5,3	14,5	4,8	1,2	3,6	0,5
Auchi	3,6	3,1	9,6	3,9	2,0	7,9	3,7	3,9	13,5	3,9	2,7	2,8	1,0
Mosimi	7,0	6,7	13,5	7,5	5,5	11,4	6,1	7,7	17,0	8,4	4,8	7,1	4,1
Atlascove	7,9	7,4	14,4	8,2	6,2	12,0	6,8	8,7	17,7	9,1	5,5	7,9	4,8
Satellite	7,9	7,4	14,4	8,2	6,2	12,0	6,8	8,7	17,7	9,1	5,5	7,9	4,8
Ibadan	7,2	7,6	14,6	8,4	6,4	11,0	7,0	8,9	16,6	9,4	5,7	8,1	5,0
Ore	5,5	4,3	12,1	5,1	3,1	9,8	3,7	6,5	15,7	6,0	2,4	4,8	1,7
Ilorin	5,0	6,3	12,4	7,2	5,2	9,4	6,3	6,7	14,4	7,7	5,0	6,6	6,6
Kaduna	2,0	7,8	7,9	8,6	6,3	4,3	8,8	5,3	9,3	7,1	7,8	7,2	6,1
Kano	4,6	10,4	6,8	11,2	8,9	3,6	11,4	7,3	7,4	9,1	10,4	9,9	8,7
Minna	1,7	7,1	9,7	7,9	5,5	6,2	8,0	5,0	11,1	6,8	7,0	6,5	5,3
Suleja	0,6	6,1	8,7	6,9	4,6	5,2	7,1	3,9	10,2	5,7	6,1	5,6	4,4
Zaria	2,9	8,8	7,8	9,6	7,2	4,2	9,7	6,6	8,7	8,4	8,7	8,2	7,0
Gusau	4,9	10,7	9,7	11,5	9,1	6,2	11,6	8,5	10,5	10,3	10,6	10,1	8,9
Jos	2,6	7,6	5,5	8,5	6,7	2,0	9,0	4,1	7,0	5,9	9,0	6,2	7,3
Gombe	5,6	10,2	2,5	11,0	9,7	2,1	12,3	7,2	3,9	8,1	12,1	8,9	10,4
Yola	8,2	9,0	0,2	9,8	9,0	4,9	11,1	6,0	5,0	7,0	11,3	7,7	10,8
Maiduguri	8,8	12,0	4,3	12,7	12,0	4,5	14,0	8,9	0,6	9,9	14,2	10,7	13,7

Table A.3. Trucking cost from depots to the center of states (Continued).

Depors\States	Ekiti	Enugu	Gombe	Imo	Jigawa	Kaduna	Kano	Katsina	Kebbi	Kogi	Kwara	Lagos
Aba	4,8	2,0	10,9	0,9	12,4	8,4	10,9	11,8	12,0	4,4	7,1	7,4
PH	5,3	2,8	11,5	1,2	12,8	9,1	11,3	11,7	12,6	5,1	7,7	7,2
Enugu	3,5	0,1	9,1	1,7	10,5	6,4	8,9	9,8	10,2	2,7	6,3	7,0
Makurdi	4,6	2,8	6,4	4,4	7,5	5,1	6,7	8,5	10,6	2,8	7,6	8,2
Calabar	6,4	2,9	10,7	2,5	12,1	9,2	11,7	12,6	12,9	5,5	8,7	9,0
Warri	3,2	3,4	12,1	2,4	11,8	7,7	10,2	11,1	10,5	4,1	5,6	5,4
Benin	2,1	2,8	11,1	2,5	10,8	6,7	9,2	10,1	9,4	3,1	4,5	4,3
Auchi	1,7	1,9	9,6	2,5	9,3	5,2	7,7	8,6	9,3	1,6	4,4	5,2
Mosimi	3,1	6,4	13,0	6,1	11,8	7,9	10,2	10,3	8,1	4,9	3,2	0,8
Atlascove	3,8	7,1	13,7	6,9	12,5	8,6	10,9	11,0	8,8	5,9	3,9	0,1
Satellite	3,8	7,1	13,7	6,8	12,4	8,6	10,9	11,0	8,8	5,9	3,9	0,2
Ibadan	3,5	7,3	12,6	7,0	11,4	7,5	9,8	10,0	6,5	5,7	2,9	2,6
Ore	1,7	4,0	11,4	3,7	11,1	6,9	9,6	10,5	8,4	3,4	3,5	2,9
Ilorin	1,6	5,4	10,5	5,8	9,2	6,4	7,7	7,2	5,6	3,5	0,7	3,1
Kaduna	5,7	6,0	5,4	7,7	4,4	0,3	2,8	3,3	6,2	3,7	5,0	8,4
Kano	8,4	8,6	4,3	10,3	1,6	3,8	0,4	1,6	7,0	6,3	7,3	10,7
Minna	3,6	5,3	7,2	6,9	6,3	3,3	4,8	5,2	4,8	2,9	3,3	6,7
Suleja	4,1	4,3	6,2	6,0	5,9	2,2	4,4	4,8	7,0	2,0	4,0	7,4
Zaria	6,7	7,0	5,3	8,6	3,3	2,1	1,7	2,2	5,4	4,6	5,6	9,0
Gusau	7,7	8,9	7,2	10,5	4,5	4,0	3,6	2,2	4,2	6,5	5,7	9,1
Jos	7,0	5,9	3,0	7,7	4,2	1,4	2,8	4,7	8,8	4,9	6,9	10,3
Gombe	10,1	8,9	0,1	11,0	4,4	4,4	4,0	5,8	11,5	8,0	10,0	13,4
Yola	11,0	8,4	2,7	9,8	7,0	7,0	6,6	8,5	14,1	9,5	12,6	14,3
Maiduguri	13,3	11,3	3,4	12,8	4,8	7,6	6,2	8,0	13,3	11,2	13,2	16,6

Table A.3. Trucking cost from depots to the center of states (Continued).

Depors\States	Nasarawa	Niger	Ogun	Ondo	Osun	Oyo	Plateau	Rivers	Sokoto	Taraba	Yobe	Zamfara
Aba	5,3	9,1	7,3	4,7	5,5	6,4	7,6	0,7	13,4	6,9	11,9	11,8
PH	6,5	9,7	7,4	4,6	5,6	7,3	8,2	0,4	13,8	7,5	12,5	12,2
Enugu	3,5	7,2	6,9	4,3	5,1	6,0	5,8	2,7	11,5	5,5	10,5	9,8
Makurdi	2,9	7,7	8,0	6,7	5,8	6,8	3,1	5,4	10,1	4,1	8,1	8,5
Calabar	6,0	10,0	8,9	6,3	7,1	8,0	7,3	2,4	14,2	6,9	11,8	12,6
Warri	5,8	7,6	5,3	2,7	3,6	4,4	8,9	2,0	12,3	8,9	13,8	11,1
Benin	4,9	6,5	4,2	1,6	2,5	3,3	8,3	3,0	11,2	8,4	12,8	10,1
Auchi	3,4	6,4	5,1	2,4	2,8	3,9	6,4	3,6	10,3	7,1	11,3	8,6
Mosimi	6,7	5,2	0,8	2,0	1,7	1,4	11,3	6,5	9,9	11,0	14,8	8,5
Atlascove	7,6	5,9	0,8	2,7	2,4	2,1	12,0	7,3	10,6	11,9	15,5	9,2
Satellite	7,6	5,9	0,6	2,7	2,4	2,1	12,0	7,2	10,6	11,9	15,5	9,2
Ibadan	7,5	4,8	2,0	2,8	2,2	0,4	10,9	7,4	9,6	12,1	14,4	8,2
Ore	7,9	5,4	3,2	0,3	1,4	3,0	9,5	4,2	10,6	9,6	13,2	8,8
Ilorin	7,2	2,7	3,0	2,7	1,6	2,0	8,8	6,7	7,8	9,9	12,2	6,0
Kaduna	4,2	3,8	8,4	6,8	7,0	7,3	4,4	8,7	5,4	7,6	7,3	3,7
Kano	5,8	5,9	10,6	9,4	9,2	9,6	5,0	11,3	5,2	8,7	5,0	3,5
Minna	4,0	2,3	6,7	4,9	4,4	5,6	5,5	7,9	7,0	8,1	8,9	4,3
Suleja	2,8	4,0	7,4	5,1	5,3	6,3	4,5	7,0	6,9	7,0	8,0	5,3
Zaria	5,0	4,2	9,0	7,8	7,5	7,9	4,5	9,6	4,3	7,7	6,2	2,6
Gusau	7,0	3,4	9,1	8,7	7,6	8,0	6,4	11,5	2,4	9,7	8,0	0,8
Jos	2,5	6,3	10,2	8,0	8,2	9,2	0,5	8,7	6,8	5,2	4,8	5,2
Gombe	5,5	7,9	13,3	11,2	11,3	12,3	3,2	12,0	9,6	4,4	2,8	7,9
Yola	6,8	10,5	14,4	12,2	12,1	14,0	4,3	10,8	12,2	3,2	3,8	10,5
Maiduguri	8,7	11,0	16,6	15,1	14,5	15,5	6,8	13,8	11,6	6,2	1,5	10,0