International Refereed Journal of Engineering and Science (IRJES)
ISSN (Online) 2319-183X, (Print) 2319-1821
Volume 5, Issue 7 (July 2016), PP.55-62

Logistics of Off-Shore Transportation of Compressed Natural Gas

Dr. Diplo. Muhammad Akram Khan[1], Prof. Dr. Andrzej Osiadacz[2]
[1](*Gas Engineering Department, Warsaw University of Technology, Warsaw, Poland*)
[2](*Gas Engineering Department, Warsaw University of Technology, Warsaw, Poland*)

Abstract: -Thenatural gas is becoming a very attractive source of energy, with its share in global consumption expected to increase dramatically over the next two decades. However, the gas markets are normally far away from production fields. There are many possible technologies of transporting gas from production fields to consumers but off-shore transportation of Compressed Natural Gas has emerged as an outstanding alternative to Liquefied Natural Gas.
To make a marine CNG project economically attractive, it is very necessary to optimize the transportational expenses. In this paper, a decision-based scheme is developed to improve the competitiveness and efficiency of marine CNG shipping. The main focus is to minimize the total transportation distance from one production source to multiple recipients. The reduction in distance, in turn, minimizes the transportational cost. This goal has been achieved by using Milk-Run pattern of CNG distribution and Dijkstra’s Algorithm has been applied to calculate the shortest distance from one production source to several recipients. The calculations show that the proposed algorithm efficiently minimizes the travel distance up to 30%. This algorithm has been successfully tested at Sakhalin-II natural gas production field in Russia.
The Milk-Run scheme of CNG distribution involves a large number of iterations and complex calculations. To make the work quicker and easier, a C++ tool has been developed in this project.
Keywords: -Dijkstra’s Algorithm, Logistics, Marine CNG, Milk-Run Scheme, Optimization.

I. INTRODUCTION

The worldwide consumption of natural gas is increasingrapidly. Besides the U.S., Europe, Korea and Japan historically, the leaders in natural gas consumption and whose demand will continue to increase significantly, the fast evolving large Asian economies such as China and India will definitely become new players in this rapidly expanding market. The dominant exporter of natural gas is and will be by far Russia, with its leading position in proved reserves (1,680 Tcf, about 50,000 Bcm) and production (over 23 Tcf, about 650 Bcm). [1].

There are many possible technologies of transporting gas from production fields to consumers elsewhere as a fuel or as a chemical feedstock in a petrochemical plant, where gas is converted into valuable products. The methods for transportation of natural gas include Pipelines (PNG), Liquefied Natural Gas (LNG), Compressed Natural Gas (CNG), Gas to Hydrates (GTH), Gas to Liquids (GTL), Gas to Commodity (GTC) such as glass, cement or iron and Gas to Wire (GTW) i.e. electricity.

The CNG transportation is not new, nor is the technology being introduced to it, but what is new is the application of modern technologies into a CNG marine based system and the increased volumes of CNG proposed to be transported. The competitive advantage of marine CNG routes over other non-pipeline gas transportation processes is that they require simple technology and very small investment. These could be the options for handling niche markets for gas reserves which include stranded, associated gas and cannot be flared or re-injected, or small reservoirs which cannot otherwise be economically exploited. Above all, the marine CNG still figures economically attractive over shorter voyages (up to ~ 4000 km) and medium volumes of gas. [2]. Recent advances in containment systems are poised to provide marine CNG with the best opportunity to be resurrected as a major enabler of new and previously stranded hydrocarbons by becoming an important optimization tool to petroleum well performance.

For several decades, both optimization algorithms and mathematical models have played a vital role in solving thousands of optimization problems in the everyday life. Discrete and continuous models, along with heuristic and exact methods have been created which have greatly improved the activities of an institution or a company (whether it’s lucrative/profitable or not).The natural gas industry is no exception. Because of problems such as environmental aspects, safety and financial reasons, a large number of mathematical models have been created and rigorously tested to solve many of the processes related to the exploration, refining, processing, transportation, storage, sales and consumption etc. of natural gas. Millions of dollars might be saved per year by optimizing gas transmission systems or their schemes, infrastructure and their schedules of everyday operations. This paper is a small effort in minimizing the Operational Expenses (OPEX) of a marine CNG project.

II. MARINE CNG DISTRIBUTION SCHEMES

There are numerous methods to distribute natural gas with the help of marine CNG transportation. The main difference lies upon relation to the type of corresponding way, which depends mainly on demand size at each receiving point, and as well as their relative geographical locations. The two well-known schemes are so-called hub and spokes and the milk run pattern. [3]. The first is good for places with a relatively big consumption demand and can be better handled by the medium-sized vessels and also by developing a storage terminal on the hub and receiving points. On contrary, the milk-run pattern is forced to run, when demand of natural gas consumption is very slow. The transportation will be done with the help of a small ship in a repeatedly cyclic method. In this case, the creation of storage facility at each receiving is compulsory in order to provide the desired amount of gas to be consumed until another CNG ship visits the reception end.

The other major difference between the two methods is that, when a single CNG production source supplies gas to multiple recipients, the Milk-Run (M-R) Pattern distributes the CNG in a much efficient way; while, if there are more than one CNG production sources and the number of recipients is greater than production sites, the Hub-and-Spoke (H-a-S) Pattern is the best solution. [4].

Study Case - (Milk-Run Pattern)

Suppose there is one production source and five different recipients with relatively smaller quantities of CNG demand. Our goal is to minimize the total transportation distance, which should minimize the total transportation costs.

minimize $\sum_{e_j \in E} c_{ij} x_j$, for $i = 1,2,3 \ldots . n$ (1)

$\sum_{\left\{e_j \in \frac{E}{\mathrm{end}\left(e_j\right)} = v\right\}} x_j$ for $x_j = 0,1,2,3 \ldots . n$ (2)

For, $v \in V$, $e \in E$ (3)

Here, the set of nodes is denoted by $V = \{v_1, v_2, \ldots . v_n\}$, where m is the number of edges, n, is the number of nodes, and E as a set of edges, $E = \{e_1, e_2, \ldots . . e_n\}$, and e_j is the j^{th}-edge. Let $G = VE$ be a certain network.

We define the cost vectorfor $j \in E$, where the element $c_{i,j}$ is the penalty cost for the $i - th$ objective function of edge e for $i = 1,2,3 \ldots . n$ and all costs are non-negative. We define the cost vector $\left(c_{1j}, c_{2j} \ldots . c_{i,j}\right)$for which the element is the cost of penalty for the $i -$ thtarget feature edges e for $i = 1,2,3 \ldots .$ nand all loads are non-negative. In addition, let start(e) and end(e) be the start and end nodes for an e, and $s \in V$, means the start node and $t \in V$ means the end node in this network. And let $x_j \in 0,1,2,3 \ldots n$, be the binary variable where, $0,1,2, \ldots n$ express the existence of edge e_j.

The distance from the production source to the recipients is as follows:

a) From Production source to first recipient T_1 is 200 nautical miles (nm),
b) From Production source to second recipient T_2 is 100 nm,
c) From T_1 to T_2 is 50 nm;
d) From T_1 to T_4 is 250 nm;
e) From T_2 to T_3 is 500 nm;
f) From T_2 to T_4 is 400 nm;
g) From T_3 to T_4 is 100 nm;
h) From T_3 to T_5 is 150 nm; and
i) From T_4 to T_5 is 300 nm.

This scheme is graphically shown below:

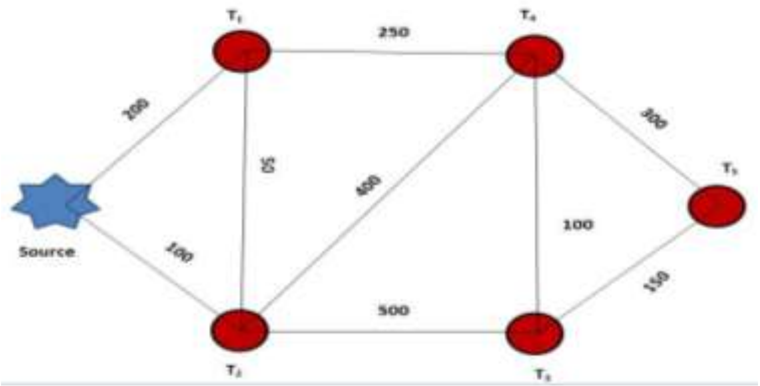

Fig. 1: CNG Distribution, amongsingleproductionsourceandmultiplerecipients

Usually, the total distance which a ship has to cover to complete its one cycle is (200+250+300+150+500+100) 1500 nm.

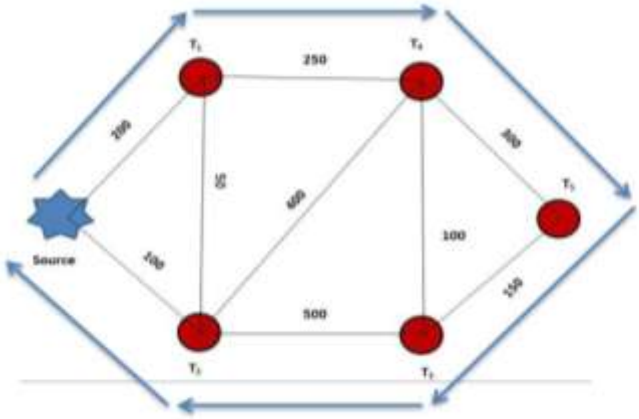

Fig. 2: ordinarymethodof CNG distribution

Theship's connecting and disconnecting time at each recipient is 1.5 hours respectively. In this way, the total connection and disconnection time during one cycle is 18 hours (1080 minutes). If the ship is sailing with the speed of 18 knots, to find out the total time taken by the ship we use the following formula:

$$60\,.\,D = S.T \tag{4}$$

Where,
D – Distance (nautical miles - nm);
S – Speed (knots); and
T- time (minutes).
60 is used to ensure that time is calculated in minutes.

$$60\,.\ 1500 = 18.T$$
$$T = 5000$$
$$\text{Total Time} = 5000 + 1080 = 6080 \text{ minutes}$$

Therefore, the total time needed to transport gas from production source to all recipients is 6080 minutes or 4 days and 22 hours.

Now, let's apply Dijkstra's Algorithm and compare the results with our previous calculations.

Dijkstra's Algorithm

Step I- Initialization

a) Assign the zero value to source node $v_1$and label it as constant;
b) Assign to all other nodes a value of ∞ and mark them as Temporary. [The condition of all other nodes is (∞, t).];
c) Assign the node v_1 as the present node.

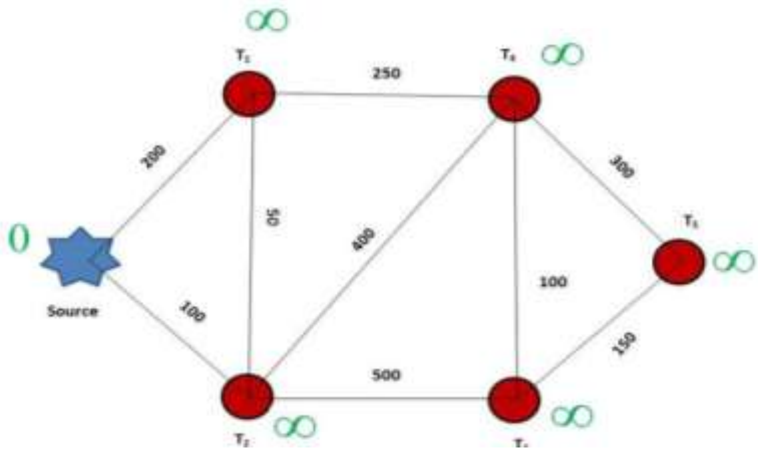

Fig. 3: Dijkstra's algorithm - I

Step II – Update distance value and node assignment

a) Let i – the index of the present node;
b) Find the set J of nodes with temporary marks where can we travel from the present node i as a link (i, j). Distance values of these nodes need updates;
c) For each node $j \in J$, the distance d_j of node j is updated as follows:
$$new\ d_j = \{\min d_j, d_i + c_{ij}\}$$
wherec_{ij} is the link cost (i, j), as presented in the network;
d) Find a node j which has the minimum distance value d_j, among all nodes $j \in J$.
Determine $j*$such that -
$$\min \sum_{j \in J} d_j = d_j * \quad (5)$$
e) Alter the node label $j*$ to constant and mark this node as the present node.

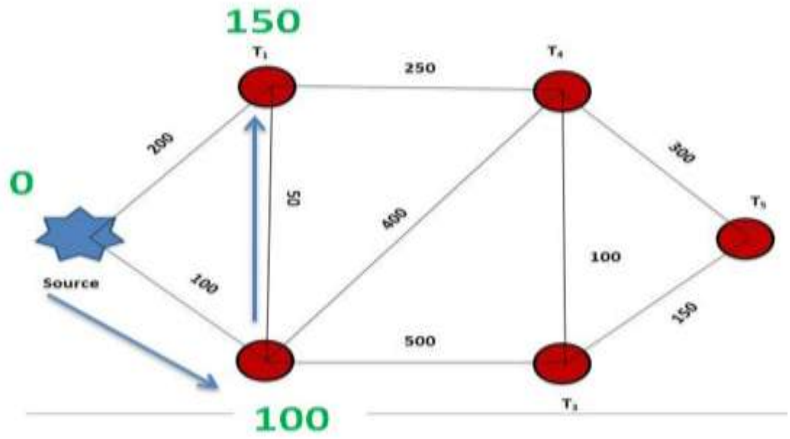

Fig. 4: Dijkstra's algorithm - II

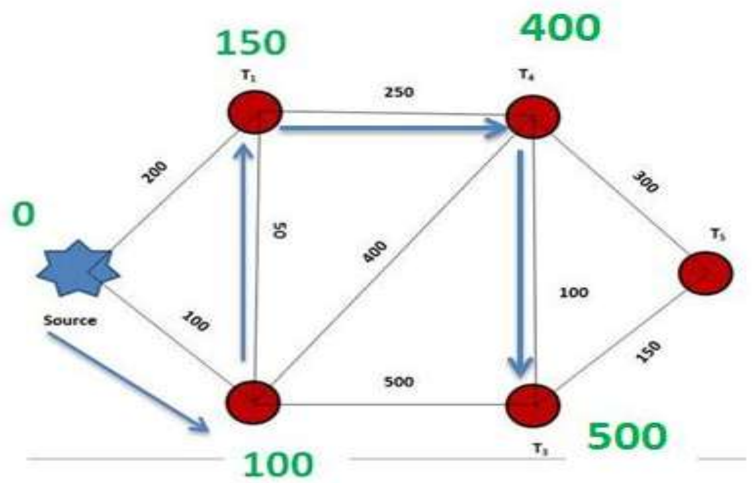

Fig. 5: Dijkstra's algorithm - III

Step III – Termination and Criterion

a) If every node which can be accessed from node *s* have been constantly labeled, then stop – the problem has been solved.
b) If it's not possible to reach any temporary node from the present node, then all the temporary marks become constant - we are done.

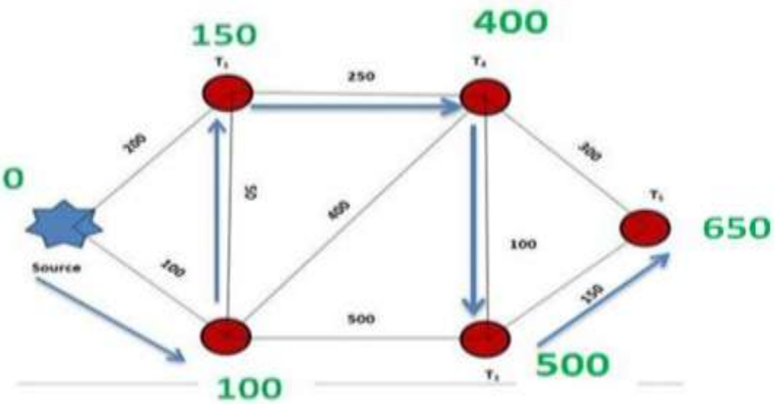

Fig. 6: Dijkstra's algorithm - IV

Now, as we can see that Dijkstra's Algorithm has terminated, we have developed a new route for transportation. Let's calculate the total distance in miles and the time, t, needed to complete one cycle.
The new sailing route looks as follows (Fig.7) -

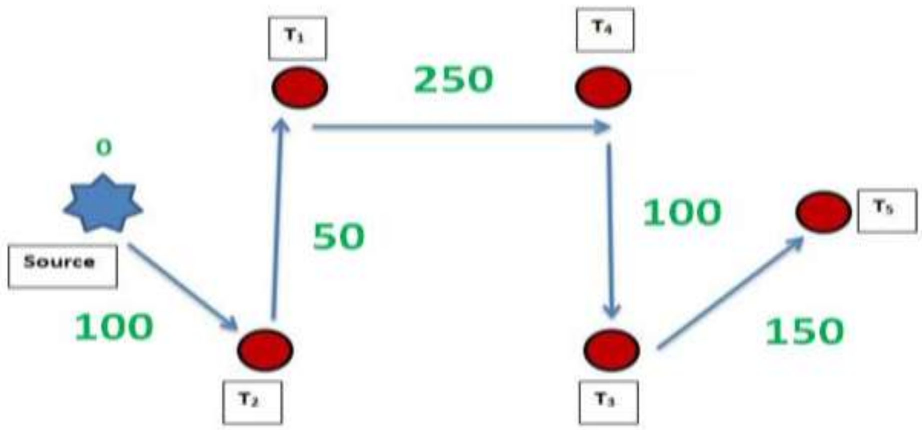

Fig. 7: Dijkstra's algorithm - V

So, the distance between the customers after applying Dijkstra's Algorithm becomes as follows:

1) From Production source to T_2 is 100 nm;
2) From T_2 to T_1 is 50 nm;
3) From T_1 to T_4 is 250 nm;
4) From T_4 to T_3 is 100 nm;
5) From T_3 to T_5 is 150 nm;

Usually, the total distance which a ship has to cover to transport gas from source site to its last customer is 100+50+250+100+150 = 650 nm. The same distance will be covered when travelling back from last customer to source site. Therefore, by applying Dijkstra's Algorithm total distance to complete one cycle becomes 1300 nm. Hence, there's a difference of 200 nm between the initial calculations and the ones received after Dijkstra's Algorithm.

The total connecting and disconnecting time at each recipient is 1.5 hours respectively. In this way, the total connection and disconnection time during one cycle is 18 hours (1080 minutes). The ship is sailing with the speed of 18 knots, to find out the total time taken by the ship we use the following formula-

$$60 . \mathrm{D} = \mathrm{S}.\mathrm{T} \quad (6)$$

Where,
D – Distance (nm);
S – Speed (knots); and
T- time (minutes).
60 is used to ensure that time is calculated in minutes.

$$60 .\ 1300 = 18.\mathrm{T}$$
$$\mathrm{T} = 4333.33$$
$$\text{Total Time} = 4333.33 + 1080 = 5413.33 \text{ minutes}$$

Therefore, the total time needed to transport gas from production source to all recipients is 5413.33 minutes or 3 days and 18 hours.
Hence, it has been proved that by applying Dijkstra's Algorithm, there's a significant reduction of sailing distance as well as sailing time, which in its own turn gives a handsome reduction of transportational costs as well.
The difference in calculation of ordinary method and the calculations after using Dijkstra's Algorithm is given below:

Results of 5 study-cases

Study Cases	Method used	Production sources	Recipients	Total Distance	Time	
					Minutes	Days
1	Ordinary Method	1	5	1500 nm	6080	4 days & 17 hours
	Dijkstra's Algorithm			1300 nm	5413.33	3 days & 18 hours
2	Ordinary Method	1	6	1800 nm	6000	4 days & 16 hours
	Dijkstra's Algorithm			1590 nm	5300	3 days & 16 hours
3	Ordinary Method	1	7	1729 nm	5763,33	4 days & 2 hours
	Dijkstra's Algorithm			1515 nm	5050	3 days & 10.5 hours
4	Ordinary Method	1	8	2134 nm	7113,33	5 days & 1 hour
	Dijkstra's Algorithm			1868 nm	6226,67	4 days & 21 hours
5	Ordinary Method	1	9	2290 nm	7633,33	5 days & 10 hours
	Dijkstra's Algorithm			1930 nm	6434,22	4 days & 23,5 hours

Table 1: Results comparison

The results above prove the efficiency of Dijkstra's method as it minimizes the distance. Hence, less time is needed for the ship to complete its one cycle, which in turn minimizes the transportational expenses by 20-35%.

Solving Dijkstra's Algorithm Using C++ Language

To determine the shortest path among customers, a flow chart for Dijkstra's algorithm was designed. After designing algorithms, we developed C++ tool for solving the problem in LP. The C++ language was used to facilitate getting the result and the complex problems which take long time using LP solution. In the study cases (CNG Transportation), we use the C++ programs to determine the shortest distance among customers, when the single production site is responsible to supply gas to all consumers. Since Dijkstra's Algorithm involves complex calculations, we have designed the following tool to make calculations quicker and easier. The main idea to design C++ program for Dijkstra's Algorithm was to save time, money, and effort.
The minimum distance calculated by running Dijkstra's Algorithm using C++ language is 1300 nautical miles among 5 customers. The distance from source i to recipients j is as follows:
source [1] to customer [1] = 200
source [1] to customer [2] = 100
customer [1] to customer [2] = 50
customer [1] to customer [4] = 250
customer [2] to customer [3] =500
customer [2] to customer [4] = 400
customer [3] to customer [4] = 100
customer [3] to customer [5] =150
customer [4] to customer [5] =300
Press any key to continue

Notes:

1. Thecodecomputestheshortestdistance, butdoesn'trepresentthepathinfo;
2. Thecodedeterminestheshortestdistancesamongsinglesourceandallrecipients;
3. TheDijkstra's algorithmdoesn'tfunctionsforgraphswith-iveweightedges.

This tool was developed by using MIT/X11 (9.02 version).
The complete script for transportation tool is given below-

```
Code:
/*****************************************************************************
*/
/*          Title:  Dijkstra's Algorithm
/*          Author: Engr. Muhammad Akram Khan (Ph.D.)
/*         University: WarsawUniversityofTechnology
/*          Mail-ID: akram_khan@is.pw.edu.pl
*/
******************************************************************************
*/
(intintsrc)graph[V][V],
{
    Theoutputarray.  intdist[V];     // dist[i] willholdtheshortestdistancefrom sto i;
     // startalldistanceswith INFINITE andfalsestpSet[] as
        sptSet[i] = false;
boolsptSet[V]; // ifvertex i isincludedsptSet[i] willbetrue;
     // Distancefromsourcevertexitselfis 0; dist[s] = 0;
dist[i] = INT_MAX, for(inti = 0; i < V; i++); // Findshortestpathforallvertices
          forcount< V-1 (intcount = 0;; count++)
     {
     if                    u              isalwaysequalto             s            infirstiteration //
selecttheshortestvertexfromverticesnotyetprocessed//
      intu = (dist, sptSet)minDistance;
// Markthepickedvertexasprocessed
sptSet[u] = true;
          for(intv = 0; v < V; v
// Updatedistvalueofadjacentverticesofpickvertex.
      ++)
Input:
         0    0    0    0     0      0
         0    1    0    0     200   0
         0    1    0    2     100   0
         0    1    0    2      50   0
         0    1    0    4      250   0
         0    2    0    3      500   0
         0    2    0    4      400   0
         0    3    0    4      100   0
         0    3    0    5      150   0
         0    4    0    5      300   0
Enter
        onlyifisnotinsptSet, // Updatedist[v] thereisanedgefrom
// smallerthancurrentvalueofdist[v]
      // andtotalweightofpathfromsrcto v through u is // u to v,
  if(!sptSet[v] &&graph[u][v] &&dist[u] != INT_MAX
  &&dist[u]+graph[u][v] <dist[v])
                                   dist[v] = dist[u] + graph[u][v];
          Output:
          0    0    0    0    0      0
          0    0    0    1   100    0
          0    1    0    2    50    0
          0    2    0    3   250   0
          0    3    0    4   100   0
          0    4    0    5   150   0
     }
[Total=650]
 printSolution(dist, V);
     // printtheconstructeddistancearray.
```

Therefore, by applying the Dijkstra's algorithm, we determine the shortest path between the consumers while the schedule of gas supply must be such that each destination point T_1 ...T_N is visited by the ship on due time, offloads the gas (some quantity of gas is passed to the market for consumption), and has a lot of gas, in storage facility until the next ship visits the site.

This means that n similar ships visit each of the N consecutive recipient places to supply gas, almost half of which is stored in storage facility, it should continue until the resonance circuit starts to supply further. Assuming that the loading = $Q_{load} = Q_{offloading}$ max > Qu, and using the notation the graphical explanation of how ship completes its one cycle is illustrated below:

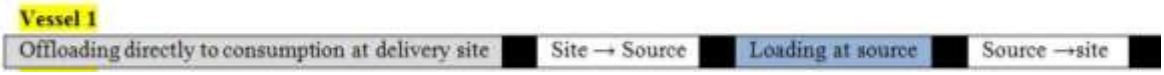

Fig. 8: deliverycycleof a vesselduring MR-Pattern

Since, the single ship delivers the natural gas to multiple receiving stations, the storage facility is mandatory in this type of distribution pattern. Therefore, to calculate the capacities and volumes of vessels used during the transportation of CNG using Milk-Run pattern, we use the following formulas.

Determine the Capacity of ship – (Q) (for M-R Pattern)

The ships used for this distribution scheme must have the volume such that the quantity of gas is sufficient enough to offer the continuous gas supply for consumption until the ship completes its cycle and returns back for reloading. The following equation help us to appropriate calculate the capacity of ship.

$$Q_{min} = \frac{T.k.q}{1-2\frac{q}{q_{off}}} \leftrightarrow \frac{Q_{min}}{T.k.q_{off}} = \frac{n}{1-2\frac{n}{k}} \qquad (7)$$

where,
Q_{min} – minimum storage capacity of vessel;
T – total sailing time;
K – number of cycles completed by the ship;
q – consumption rate;
q_{off} – CNG offloading rate from ship;
n – number of vessels used.

Conclusions

The following conclusions can be made from above discussion: -

- The Milk-Run pattern of CNG Distribution will be used when the demand of gas at the receiving stations is very small;
- The single source will supply gas to multiple receiving stations during M-R scheme;
- The single ship will visit certain destinations and delivers gas to these recipients according to their demand;
- The storage facilities are mandatory in this type of CNG distribution pattern;
- The Dijkstra's Algorithm efficiently minimizes the sailing distance among CNG markets;
- The application of Dijkstra's Algorithm minimizes the transportational expenses up to 30%, by reducing the distance among recipients;
- The C++ Tool makes the complex and longer calculations much easier and quicker;
- Dijkstra's Algorithm doesn't work for graphs with negative weight edges;
- The Milk-Run pattern of CNG distribution is only designated for smaller markets. If the demand at the destination is greater, The Hub-and-Spoke pattern must be used for distribution.

Acknowledgement

This research has been carried out with the support of **Sea-NG Corporation**. The input data has been consulted with Sea-NG Corporation.
Sea NG is a worldwide leader in marine CNG (compressed natural gas) transportation. Sea NG designed and developed the Coselle System, which consists of the innovative Coselle and the purpose-built CNG vessels that integrate the technology to safely, efficiently and economically transport gas. Sea NG's success is the result of over a decade of design, engineering and testing with the goal of a project-ready marine CNG transportation value chain.

REFERENCES

[1]. Energy Information Administration, 2008. Country Analysis Briefs – Caribbean. Available from: http://www.eia.doe.gov/emeu/cabs/caribbean/pdf.pdf.
[2]. Nikolaou, M., Economides, M.J., Wang, X., Marongiu-Porcu, M., "Distributed Compressed Gas Sea Transport",Proceedings of the 2009 Offshore Technology Conference, Houston, OTC 19738, 2009, pp. 1-14.
[3]. C. A. Luongo, B. J. Gilmour, and D.W. Schroeder, "Optimization in natural gas transmission networks, a tool to improve operational efficiency". Technical report, Stoner Associates, Inc., Houston, April 1989.
[4]. A. K. Muhammad, A. Osiadacz, "The Economics of Marine CNG Transportation from Stranded Fields",Modern Scientific Researches and Innovations, ISSN-2223-4888, UDK-55-321, Moscow, 2016.