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Multicriteria Optimization Method of LNG Distribution

E. Chłopińska & M. Gucma
Maritime University of Szczecin, Szczecin, Poland

ABSTRACT: Liquefied Natural Gas (LNG) is considered as a realistic substation of marine fuel in 21 century. Solution of building new engines or converting diesels into gas fueled propulsion meets the stringent international emission regulations. For HFO (heavy fuel oil) or MDO (marine diesel oil) propelled vessels, operation of bunkering is relatively wide known and simple. Its due to the fact that fuel itself doesn't require high standards of handling. Where for LNG as a fuel its very demanding process – it evaporates and requires either consuming by bunker vessel or reliquefication. Distribution of such bunker is becoming multidimensional problem with time and space constrains. The objective of the article is to review the methods of optimization using genetic algorithms for a model of LNG distribution. In particular, there will be considered methods of solving problems with many boundry criteria whose objective functions are contradictory. Methods used for solving the majority of problems are can prevent the simultaneous optimization of the examined objectives, e.g. the minimisation of costs or distance covered, or the maximisation of profits or efficiency etc. Here the standard genetic algorithms are suitable for solving multi-criteria problems by using functions producing a diversity of results depending on the adopted approach.

1 INTRODUCTION

The dynamic development of global technology in all industries, including automation is associated with the use of high quality environment-friendly technical goods. Nowadays, manufacturing processes undergo continuous development, and this also applies to the wide use of liquefied natural gas (LNG), the most common energy carrier.

LNG is created from gaseous state through the process of liquefaction. The process brings many advantages, namely reduction of fuel volume by 600 times makes transport of LNG over long distances viable and cost-effective. One quarter of global LNG trade refers to its liquefied state [5].

LNG in fact is pure methane (CH_4) with small additives of heavier hydrocarbons which makes it nearly 100% clean fuel. The fuel, commonly called "blue fuel" is very clean, safe, and free of moisture and other undesired components.

Due to its ecological characteristics and a wide range of applications, LNG is present in the various stages of the logistics chain. In order to meet the requirements of the Directive 2012/33/EU of the European Parliament and of the Council, amending Directive 1999/32/EC concerning the sulfur content in marine fuels, and to improve the safety of human health and protect the environment, LNG has been used as an alternative to traditional marine fuels [20].

In Polish and foreign literature, the methods of bunkering ships in technical terms and legal regulations have been widely described. Marine units used for LNG transport, LNG bunker and LNG ports are described in detail. The low profitability of the creation of the LNG bunkering network and LNG distribution are rarely discussed.

Currently there have been no work on the possible use of the LNG terminal in Swinoujscie port as a bunker port. There were conducted tests to determine the real demand for LNG as bunker fuel in the Baltic Sea. The work proposed a universal LNG distribution model.

2 MODEL

The model of location of routes and warehouses will be an original optimization model based on the mechanism of natural evolution. The model will be built on a simple evolutionary algorithm, thanks to which it is possible to quickly and efficiently search for the best possible allocations.

Analyzed such input data as geographical coordinates of real ports, technical parameters of LNG bunkers, LNG distribution costs, types of LNG units, LNG demand will allow for the best distribution of LNG warehouses along the Polish Baltic Sea coastline and determine the distribution range of a given warehouse (Figure 1).

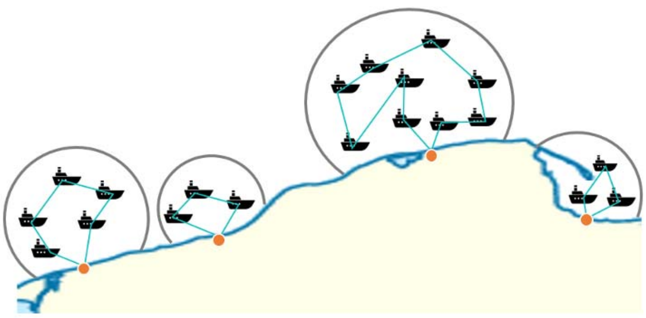

Figure 1. Model examples

The optimal route location method is designed to match LNG units to LNG bunker units that provide the total required LNG quantity and which are respectively assigned to optimally placed individual LNG warehouses.

Two approaches of multi-criteria optimization are distinguished:

1 Combining all objective functions into one complex function. In this case, the difficulty consists in an appropriate, precise and accurate choice of the weights or utility functions (even minor variations in the weights may yield various solutions). Therefore, a set of solutions is often used when multiple objectives are taken into account [18]. Defining one objective function is possible by using:
   - the theory of utility,
   - the method of weighted sum.

2 The determination of optimal Pareto sub-set or set. The optimal solution for a Pareto set is referred to as a set of non-dominated solutions. This is a solution x'∈ D where there is no solution x ∈ D, that enables the improvement of the value of at least one objective function, while the other defined objective functions do not get degraded. The methods used include:

– meta-criterion - a function defined on partial criteria that enables the decision-maker to utilize particular decisions:

$$u(x)=u[f_1(x), f_2(x),\dots, f_s(x)] \quad (1)$$

The simplest meta-criterion is a weighted sum:

$$u(x)=\sum_{k=1}^{s} w_k f_k(x) \quad (2)$$

The solution for a defined task is a decision, found in a set of acceptable decisions, that in the sense of meta-criterion u(x) is the best. It should be noted that the best decision in the sense of u(x) is a searched for tradeoff decision.

– The main criterion and secondary criteria - a function seeking the best solution for the main criterion f_1 while ensuring the indicated level of solutions for the secondary criteria p_k:

$$\begin{cases} f_1 \rightarrow max \\ f_k(x) \geq p_k \quad dla\, k=2,\dots,s \\ x \epsilon D \end{cases} \quad (3)$$

– The strict hierarchy of objectives - ordering the criteria starting from the most important. In this method, the determination of a tradeoff decision consists in solving the auxiliary tasks $L_k L_s$ (k=1, …, s) where the solution for the final task is a determinant of the multi-criteria task tradeoff decision.

– minimization of the distance from the ideal point - the acceptable solution is the point nearest to the ideal point. The point $\bar{z}=[\bar{z}_1,\dots,\bar{z}_s]$ point is the ideal point in the space of results, while $\bar{x}=[\bar{x}_1,\dots,\bar{x}_n]$ is the ideal point in the space of solutions if:

$$\bar{z}_k = f_k(\bar{x}) = \max\{f_k(x) : x \in D\} \text{ for k = 1, …, s,} \quad (4)$$

if:
$\bar{x} \epsilon$ D, then $\bar{x}$ is an optimal task;
$\bar{x} \notin$ D or it does not exist, then we seek point x′ ϵ D,
where
$z' = [z_1',\dots,z_s']$, which lies as close as possible to the ideal point $\bar{z}$,
where
$z_k' = f_k(x')$ for k = 1, …, s,
while:
$\bar{z}_k > 0$, then

$$\begin{cases} y \rightarrow max \\ f_k(x) - \bar{z}_k \geq 0 (k=1,\dots,s) \\ x \in D \end{cases} \quad (5)$$

where
y – minimum degree of the implementation of particular objectives, when:
$\bar{z}_k \le 0$, then

$$d_k(x) = \frac{\bar{z}_k - f_k(x)}{\bar{z}_k - m_k}, \quad (6)$$

where
m_k =min{ $f_k(x) : x \in D$}

$$\begin{cases} w \to min \\ d_k(x) \le w(k = 1,\dots,s), \\ x \in D \end{cases}$$

where
w - auxiliary variable determining the maximum relative deviation from the optimal value of the criterion.

For the problems being solved, an n-dimensional vector of the decision variable x = {x1, x2, … , n} in the set of solutions D. The task is to find the x′ vector that minimizes the objective function. Standard optimization tasks are formulated for a set of solutions with a series of constraints, where the considered objective functions conflict with each other. The optimization of the objective function for one solution les to unacceptable results. It is impossible to obtain multi-criteria solution of the task where particular objective functions are optimized. The solution for multicriteria problems is the examination of a set of solutions D that meets conditions at an assumed level.

3 MULTICRITERIA OPTMIZATION BY GENETIC ALGORITHMS

The concept of a genetic algorithm, a non-deterministic method for finding an optimal solution, is derived from the theory of evolution. The concept was developed by John Henry Holland in the 1960s and 70s [5]. The mechanism of genetic algorithms is inspired by the theory of evolution, according to which natural species that are not able to survive will be extinct. However, strong individuals will transmit their genes to future generations by reproduction. Over time, strong species that transmit a genetically correct combination begin to dominate in a population.

In a long process of natural evolution that takes place in nature, a random change in genes may occur. The changes that bring extra advantages in the struggle to survive lead to the evolution of the created individuals. Unsuccessful modification is eliminated by nature itself.

The greatest probability of evolution comprises solutions with the highest degree of fitness, defined by the value of the fitness function (objective function of the optimization task). The literature presents both hypothetical descriptions and practical examples of the genetic algorithm used for finding an optimal solution. The genetic algorithm is a convenient tool widely used for solving complex decision-making processes [3] [8] [10][11] [12].

Genetic algorithms based on natural evolution are used for solving optimization tasks with multiple objective functions. The essential characteristic of the algorithms is that the objective function can be easily modified to find secondary acceptable solutions in one population. The ability to search a few spaces simultaneously allows the solving of complex tasks with multiple objective functions. A number of algorithms shows no use of scaling or weighing.

Various authors propose the following classifications of genetic algorithms:
– Vector Evaluated Genetic Algorithms, VEGA [16] [13];
– Multi-objective Genetic Algorithm, MOGA [2];
– Niched Pareto Genetic Algorithm [6];
– Random Weighted Genetic Algorithm, RWGA [14];
– Nondominated Sorting Genetic Algorithm [17];
– Strength Pareto Evolutionary Algorithm, SPEA [19];
– Pareto-Archived Evolution Strategy, PAES [7];
– Fast Non-dominated Sorting Genetic Algorithm, NSGA-II [1];
– Multi-objective Evolutionary Algorithm, MEA [15];
– Rank-Density Based Genetic Algorithm, RDGA [9].

Special attention should be paid to numerous / a number of varieties of multi-criteria genetic algorithms that are widely known and used in various fields.

4 EVOLUTIONARY METHODS OF MULTICRITERIA OPTIMIZATION FOR A MODEL OF LNG DISTRIBUTION

The solution of the problem, using multi-criteria optimization for the LNG distribution model, involves the attribution of weights w_i to each defined objective function $f_i^{'}(x)$. To obtain one solution, the following method of weighted criteria is proposed:

$$min\, f = w_1 f_1^{'}(x) + w_2 f_2^{'}(x) + \ldots + w_k f_k^{'}(x) \quad (7)$$

where:
w ∈ [0, 1] and $\sum w_i = 1$

Using this transformation, we can optimize a single objective function using methods used for the solving of single-criterion tasks.

An example solution of the task is the determination of a cycle with least length, if:
– each LNG-powered vessel from a specified region must be visited only once by the LNG bunker vessel;
– starting point is also the final point (LNG terminal) - closed cycle.

The objective function *f(c)* assumes the following form:

$$f_c(d) = \sum_{j \in J} d_j \to \min \tag{8}$$

where
d_j – a distance travelled by *j-th* LNG bunker vessel between LNG-powered vessels, j = 1…. J.

To present an example [4], four points were selected and presented as a list with their geographical coordinates. The points represent the positions of the LNG distribution facility (bunker) and LNG-powered vessels.

1 φ_A = 53.93°N λ_A = 14.31°E
2 φ_B = 54.20°N λ_B = 14.73°E
3 φ_C = 54.25°N λ_C = 14.92°E
4 φ_D = 54.19°N λ_D = 15.13°E

Four points give six combinations of the acceptable solution:

1 A – B – C – D – A
2 A – C – D – B – A
3 A – D – C – B – A
4 A – C – B – D – A
5 A – D – B – C – A
6 A – B – D – C – A

First the distances, in nautical miles, between the points were calculated (Table 1, Figure 2):

Table 1. Examples of distances between the points

[Nm]	A	B	C	D
A	0	24	6.7	27.7
B	24	0	20.5	41.6
C	6.7	20.5	0	14.5
D	27.7	41.6	14.5	0

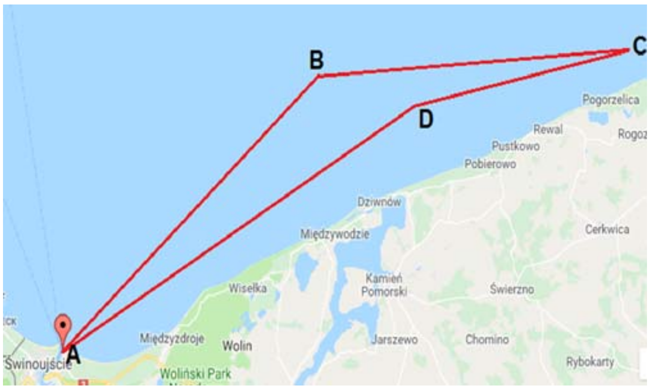

Figure 2. Examples of distances between the points

Genetic algorithms were used to generate a list with the best sequence of the visited points corresponding to the length of the cycle. According to the principle of elitism, one of the best equipped chromosomes is copied to the new population. To ensure that each subsequent population adapts better, it is assumed that chromosomes from the previous population with the highest values of the fitness function have the greatest impact on a new population.

In each evolutionary step, the chromosomes are analyzed according to the assumed criteria of fitness quality. Through selection, the worst individuals are eliminated from the population. Best-fit individuals are subject in this example to order crossover (OX) in which offsprings are created on the basis of 'subroutes' taken from the parents, where the 'subroute' of the first offspring is taken from the second parent while the 'subroute' of the second offspring is taken from the first parent. Subsequently, the created routes are completed so that no conflict of two identical points in the route arises. Then random changes are put into the genotype (mutation) that is aimed at introducing diversity in the population by adding new individuals to the population.

The evolutionary process resulting from the actions of crossover and mutation operator creates solutions from which a next generation population is built. The condition for termination of the selection of the best-fit chromosome of the evolution process is either reaching the defined number of generations or a satisfactory fitness level.

In the case considered herein the evaluation of each individual is the criterion of the route length they represent. Acceptable solutions were generated based on the values of the evaluation function, (Table 2).

Table 2. Evaluation of the individuals and selection

The value of the evaluation function					Sum [Nm]
A – B – C – D – A	A-B -> 24.0	B-C -> 20.5	C-D -> 14.5	D-A -> 27.7	86.7
A – B – D – C – A	A-B -> 24.0	B-D -> 41.6	D-C -> 14.5	C-A -> 6.7	86.8
A – D – B – C – A	A-D -> 27.7	D-B -> 41.6	B-C -> 20.5	C-A -> 6.7	96.5
A – C – D – B – A	A-C -> 6.7	C-D -> 14.5	D-B -> 41.6	B-A -> 24.0	86.8
A – D – C – B – A	A-D -> 27.7	D-C -> 14.5	C-B -> 20.5	B-A -> 24.0	86.7
A – C – B – D – A	A-C -> 6.7	C-B -> 20.5	B-D -> 41.6	D-A -> 27.7	96.5

Two routes were correctly distinguished, characterized by the least length of 86.7 Nm. Thus the solution of the analyzed problem: find a cycle of the least length is represented by two routes:
1 A – B – C – D – A
2 A – D – C – B – A

5 CONCLUSIONS

The main problem concerning LNG vessels is unavailability of LNG bunker station or any other infrastructure along the whole coastline. The models of the fuel distribution are built taking into account two co-dependent quantities, such as the route length of system units and the location of distribution facilities. In this case, the distribution problem is a combination of a classic problem of the route location and the availability of the distribution facility.

The problems of planning routes for vehicles are known in the literature as the multiple traveling salesmen problem. The problem of LNG distribution system is closely related to the problem of route planning. These problems are characterized by a simple definition of the task, unlike the solution. The problems concerning LNG distribution methods are the rules that assume NP-complete problems that can be easily formulated, but the optimal solution for the given problem is very difficult. The presented methods efficiently analyze the area of solutions for the problem considered. Above all, their purpose is the solution of optimization tasks. Their particular usefulness is demonstrated in the solution of problems of combinatorial nature. Finding the optimal outcome for a great number of points is a hard and work-consuming task. Genetic algorithms are an alternative for the methods commonly used so far.

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