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"The Non-Linear Programming Model (NLPM) for Minimizing the Operating Costs of Marine CNG Transportation"

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Abstract: *The marine compressed natural gas (CNG) was initially envisioned to target small volumes of gas located in relatively closed proximity to markets. However, the recent breakthroughs in this technology have suggested, and in some cases validated, marine CNG's potential to cost effectively ship much larger volumes of gas over much greater distances. The creative solutions have been proposed by many companies for the choice of materials and configuration of gas containers, as well as for container loading and offloading techniques because this part of a marine CNG project consumes almost 70-80% of the investment. But for commercial success of transportation projects it is important to reduce the operating costs as well. The ship's expenses account for 65-70% of operating costs. Therefore, the charges for fuel used by the ship contribute to a higher extent in overall operating costs of a project. In this paper, a Non-Linear Programming Model (NLPM) has been proposed which focuses upon the optimization of fuel consumption of CNG ships during transportation. The objective function, taking into account the total fuel consumed by the ship engines, is proposed. The optimization problem stated consists in evaluating the number of simultaneously operating ship engines and determining such a distribution of the capacity that total unit fuel consumed by each engine is minimized subject to the constraints imposed. NLPM presents an algorithm of automatic search for the optimal values of the operating parameters of engines. The proposed algorithm can be implemented on a digital computer.*

Keywords: *operating costs, transportation problem, non-linear programming, fuel consumptions, engine load, optimization.*

I. Introduction

Marine compressed natural gas (CNG) has been considered as a means of transporting natural gas in the past, but proved to be non-efficient for a number of reasons, including long distance or large volume of gas compared to liquefied natural gas (LNG), however, Marine CNG still appears economically attractive for shorter distances (up to ~ 4000 km) and relatively smaller volumes of gas. Years of engineering and development in containment systems have provided the marine CNG as a major stimulator of new and previously stranded hydrocarbons by becoming an important tool to optimize the operation of the petroleum wells.

The demand of natural gas in regional markets has been driven by several factors, including the crucial shift of the power sector to natural gas fired stations, a huge demand of gas in the city gates, and industrial consumers to switch to natural gas from other fossil fuels. This remarkable growth in gas demand over the past decade has led to the development and installation of a large number of gas transmission projects. These base-load projects have focused on the basic operation of a relatively large gas reserves, typically as 5 Tcf +. *[2]*. However, the gas markets are now seeing the structural changes with the advent of the mid markets i.e. regional markets, which tend to be relatively are combination of small gas and LNG trading. Marine CNG has arisen as an alternative to LNG, to fulfill the gas demand of these average markets. A typical marine CNG project consumes almost 70-80% budget in its transportation vessels, while the remaining 20% is consumed in operational expenses. The selection of possible shortest path and optimization of fuel consumption can save a significant amount. These problems related to optimization of operational expenses of ships have not attained much attention in the literature, in contrast to other similar issues, such as the vehicle scheduling and routing issues. The reason for this insufficient attention is dependent upon many factors; visit the discussions of Christiansen et al. in 2004. During the last decade, massive demand of other documents about optimization and papers on routing problems has been observed. The three scientific surveys about maritime optimization and scheduling problemsare more dominant in Literature: Ronen focuses on these issues in early years; i.e. 1983, Ronen again reviews the following decade in 1993, and Christiansen et al. considered these problems in the succeeding decade in 2004. A detailed overview of models about maritime optimization of ship's operational expenses and comprehensive schemes of shortest path selection have been adopted by Christiansen et al in 2007. The marine CNG supply chain has been investigated by MikhaelNikolau in detail in 2010. *[2]*.He presented a solution on how to select an optimal design of a CNG ship and also proposed the two popular methods of CNG distribution i.e. Hub-and-Spoke pattern and Milk-Run pattern. Yet, there's a big scarcity of literature about the optimization of operational expenses. Furthermore, Tanizawa and Tsujimoto 2006, Fagerholt, Norstad&Laporte 2010, Yiyo 2011 presented certain models for reducing the fuel consumption of ships. In 2014, Tomasz Cepowski presented a concept of modeling the ship’s operating parameters in order to optimize the operational expenses of a ship.

II. Objective Function Of Ship Engine’s Fuel Optimization

The operating costs of a ship mainly depend upon the following factors.

1. Daily fuel consumption of main engine for ship’s speed
2. Daily fuel consumption of the auxiliary engines
3. The owner’s daily costs
4. Routine maintenance costs

While some consider loading/offloading costs also as ship operating costs According to ***Stopford, M. 2009***, the fuel consumption accounts for 76% of voyage costs, while, other shipping companies consider that fuel cost is 60% of overall operating expenses of a ship. Hence, minimizing the fuel consumption reduces a considerable amount of OPEX in a marine CNG project. The experiments proved that reducing the ship speed and decrease in ship engine load can minimize the fuel consumption to a larger extent.

The total cost (*J*) of fuel consumption can be divided into two costs as follows:

$$J = J1 + J2 \qquad (1)$$

Where, J1 is the total fuel consumed by the main engines and J2 indicates the other expenses such as crew costs, maintenance costs and for running ship’s electricity plants etc. The component J1 is minimized by an algorithm for finding the optimal working parameters of main engines. The main goal is to minimize the fuel consumed by the main engines used for propulsion while the costs of auxiliary engines are neglected in our case as they are very minute (relatively 4% of the costs mentioned above). The objective function that considers only the consumption of main engines is determined as follows:

$$J_1 = \sum_{m=1}^{M} A_m + \sum_{r=1}^{R} B_r + \sum_{k=1}^{K} \int_0^T f_k(p_1, p_2, Q_{vT}^*)\, dt \qquad (2)$$

Where,

M is the total number of engines installed on the ships, [0, t], *R* is the number of engines working in specific time interval, [0, t]. *A* – the cost of start operation and *B*- the cost of stop operation. *Qvt* is the capacity of the engine. The problem under consideration is limited to the optimization of parameters of work of ship’s main engines during a certain voyage. This leads to the expression:

$$\sum_{k=1}^{K} \int_0^T f_k(p_1, p_2, Q_{vT}^*) dt \qquad (3)$$

In this situations, where ratio p_2/p_1 is constant and the given engine will be fed with fuel of net calorific value Wu=constant. This value can be minimized by improving the efficiency ηor in other words, by minimizing the g_e, because,

$$\eta = \frac{632}{g_e W_u} \qquad (4)$$

The final form for the objective function needed to be optimized over each interval looks as follows:

$$J1 = \sum_{k=1}^{K} g_{ek} \qquad (5)$$

III. Problem Formulation

The optimization of fuel consumption of ship’s engines involves finding a value of vector x.

$$x = \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_k \end{bmatrix}$$

For a given value of vector y

$$y = \begin{bmatrix} Q_{vT}^* \\ p_1 \\ p_2 \end{bmatrix}$$

Which, along with an assumed value of vector z becomes,

$$z = \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_k \end{bmatrix}$$

where,

$B_k = \frac{Q_{vK}^*}{n_k}$, *Minimizes the value of* J_1 *in a certain interval.*

There are the following constraints:

$C_i = constant;\ \ i = 1,2,3;$ K ≤ L. *(6)*
Where, L represents the number of engines installed on a ship.
As x∈Rk, and the components of vector z take only defined values determined by the feasible values of the factor C, the values of x over the feasible points expressed by,
$Q = \{x: g_i(x^T e_k) \leq 0\ \ for\ i = 1,2,3; k = 1,2,3 \ldots\ldots K, h(x) = 0\}$ *(7)*
are sought for the given values of z. In this problem, the function constraints are Linear and this leads to the convex sets Q of feasible points.

IV. Problem Solution

A control algorithm for automatic searching of the optimal parameters of engines, in situations where the values of vector y are stipulated, was elaborated. This algorithm is suitable for computation by means of a digital computer and provides a means of performing the following computations to solve the problem:

1. Determine the number of engines required for transportation of certain amount of gas. An example of a flow chart can be observed below:

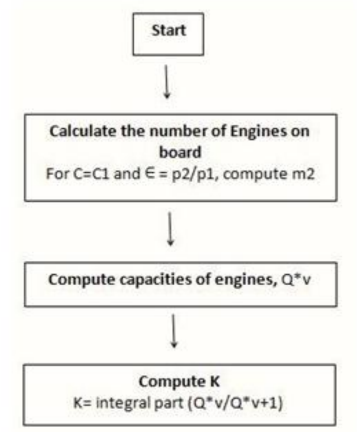

Fig. 1: : Theflowchartfordeterminingthe K ofenginesrequiredforoptimaltransportation

2. Predict a matrix W=[wi,k]I,K of a feasible combination values C for K engines required onboard ship.
3. Determine the co-ordinates of start points xi on the basis of the initial distribution of the capacity between the individual engines, when their value is stipulated as:

$$x^i = \begin{bmatrix} Q^*_{V1} \\ Q^*_{v2} \\ \vdots \\ Q^*_{vK} \end{bmatrix}$$

Determine the optimal speed over the set of feasible points that minimize the values of f(x), with selected convex programming methods with constraints being employed, from which the minimum value is selected. Those values which fulfill the requirements,
$min_i \sum_{k=1}^{K} g_{ei,k}$ are the solution of optimization problem. *(8)*

6.1 Technical Characteristics Of Ship's Engines

To minimize the overall fuel consumption during the voyage, it is necessary to install certainhigh-power different engines on the CNG vessel. For instance, we will consider the following three engines and then apply non-linear programming to optimize their fuel consumption:

1- Four-stroke engine 20V35/44G
2- Man B&W 7G70ME-C9.2-GI
3- Man B&W 5G70ME-C9.5-GI

Engine Type	**No. of cyl.**	**Mean piston speed, (m/s)**	**Lube oil consumption (kg/h)**	**Heat rate**	**Electrical Eff. (%)**	**Dry mass engine (t)**	**Dry mass generator efficiency (t)**
20V35/44G	20	11	3.7	7,618	47.3	113.5	30.5
7G70ME-C9.2-GI	25	14	4.4	8,612	49.3	119.7	34.5
5G70ME-C9.5-GI	27	16	4.8	8,912	49.7	121.7	37.3

Table 1: Technical characteristics of ship's engine

The following methods can be used to determine optimal values of n_k.

i) Rosenbrock’s Method:

When two kinds of constraints (inequalities and equalities) are involved, we apply the objective function, $P(x) = P(x^1) + P(x^2)$; where we will use the two penalty functions $f(x^1)$ and $F(x^2)$ in the following way:

$P(x^1) = f(x^1) + F(x^1);\ P(x^2) = f(x^2) + F(x^2).$ *(9)*

ii) Davidon’s Gradient Method:

For this method, let’s assume that objective function is:

$$P(x, r_1^m, r_2^m) = f(x) + r_1^m F_1(x) + r_2^m F_2(x) \quad (10)$$

Here, the penalty functions can be as follows:

$$F_1(x) = \{\max[0, |h(x)|]\}^2$$

$$F_2(x) = \sum_{i=1}^{2} \sum_{k=1}^{k} \{0, g_i(x^T, e_k)]\}^2 \quad (11)$$

Values of multiplier will be determined from following equations

$$r_1^m = a_1 . b_1^m; \quad (12)$$

$$r_2^m = a_2 . b_2^m \quad (13)$$

where,*m* is the number of iterations.

The influence of speed upon fuel consumption and relationship between Ship’s Engine Load and speed is explained below:

V. Influence Of Ship Speed On Fuel Consumption

The mainly affecting parameter of fuel consumption is the vessel speed. The Admiralty coefficient, which is commonly used in shipbuilding, illustrates the relationship of fuel consumption and vessel speed. The formula was initially used to determine the relationship between the force and displacement speed vessel. But it may also be used to compare values inter related with the power, for example, resistance to the hull or fuel consumption. Therefore, the formula described in the literature as the coefficient of fuel can be written:

$$2EFc = \frac{\Delta^{2/3} . V}{2EF} \quad (14)$$

Where,

EF_C – fuel coefficient;

Δ – Ship displacement;

V – Ship speed;

EF – main engine fuel consumption.

As described above, speed of the vessel appeared to the third power, is a dominant factor. This finding is consistent with the experience gained from the analysis as a test ship models and measurement of fuel consumption during operation of ships. Hence, the binomial power model must be applied in order to describe the daily fuel consumption and speed of the vessel:

$$EFc(V) = x . V^y . e \quad (15)$$

where:

EFc – daily fuel consumption of the main engine for speed V [t];

V – speed of the vessel for which EFc is determined [kts];

x, y – parameters of the model;

e – the error of term power regression function.

For the previously reported theoretical considerations, the parameter “b” should be set to three. Due to mechanical losses and propeller sliding screw increases the speed of the vessel more slowly than the screw revolutions. Practical dependent binding of daily consumption of ship's speed will be of the order of a few more than three. Again, value of “b” of power regression functions should be in the range from 3 to 4. The regression parameters “A” and “B” can be determined by known methods by using commonly available software for statistical analysis.*[4]*.The analytical graph describing consME depending on *V* for modeled ship at full loading condition is shown on figure below.

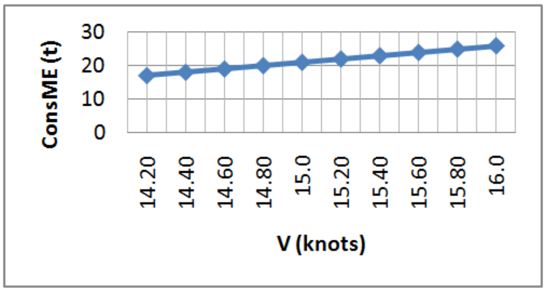

Fig. 2: Function consME (V) of fully loaded vessel.

VI. Influence of Ship Engine Load on Fuel Consumption

The two important parameters of a diesel engine are (i) Continuous rating service - CSR and (ii) Maximum continuous rating - MCR. The ratings, which are usually concerned, are the maximum power at which the engine will run continuously to maintain the desired vehicle service speed when fully loaded. There's a maximum power limit, beyond which the engine must not be operated continuously. Usually, the economy rating is an option available to reduce the fuel consumption of diesel engines.

Results

Studycases	**Weight,** tones	**coefficient, k**	**numberofengines, K**	**Speedofengines**				$\sum HP$
				n_1	n_2	n_3	n_4	
1	3900	11	3	138	138	118		133000
2	5500	12	3	170	158	162		267300
3	5900	12	3	144	148	153		272434
4	6200	13,5	3	174	163	155		276321
5	6400	17	4	154	185	135	151	279453
6	6800	15	4	197	183	179	164	282458
7	7300	16	3	217	193	181		285762
8	7800	13	4	155	179	168	134	288654
9	8500	19	3	177	159	183		292479
10	9200	16,5	3	203	218	199		296503

8.2 Fuel Consumption Estimation

As explained in Lloyd's Register, 2008 – to measure the volumetric flow of fuel consumption in accordance with mass flow of fuel, the following formula is used

$$Fc = \frac{VFc.Pf}{T} \qquad (16)$$

where:

Fc - the mass flow of fuel [kg/s],

VFc- the volume of fuel consumed during the measurements [m^3],

Pf – the gravity of fuel under measurement condition [kg/m^3],

T – Measurements time [s].

To estimate the mass flow of the fuel system of the engine fuel oil, the certain standard tools are used i.e. the main engine fuel oil flow meter equipped with temperature sensor. The receipt of fuel oil analysis will be used as a source of fuel oil input data for further measurements. The correction factor of fuel oil gravity temperature will be taken accordingly. The specific fuel oil consumption of the main engine is calculated with the formula:

$$Fc = \frac{MFc}{Pc} \qquad (17)$$

where:

Fc –fuel consumption [kg/kW·h],MFc–mass flow of fuel [kg/hr],P_c– engine's effective power [kW].

VII. Case Study 2:

If a 300,000 DWT VLCC loaded in the Eastern Med. takes about 30 days to sail to the Japan at 16.7 knots (engine speed). Its fuel consumption is on average 99 ton/day. The sailing distance between the source and consumers is 10,000 nm. The correlation between speed reduction and decrease in ship engine load can be used to calculate the reduction in fuel consumption rate. By using the formula mentioned above, the decrease in fuel consumption is significant with the decrease in engine load and ship speed.

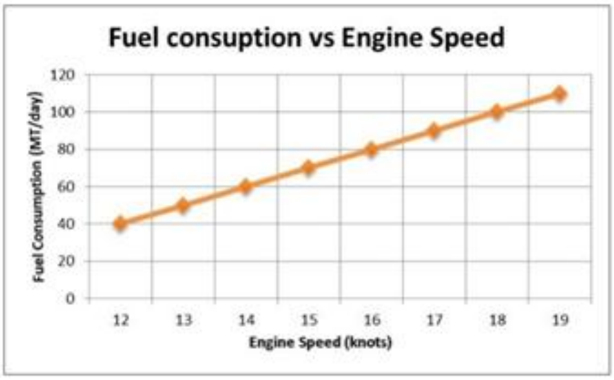

Fig. 3: Fuel consumption versus Engine Speed (actual voyage data)

From the graph above, a 50% reduction in fuel consumption is obvious just by decreasing the ship speed only for 3 knots. Fuel consumption is usually also stated as fuel consumed per day. So, for a 13,000 TEU Ultra Large container ship with a main engine powered at 70,000 kW with 100 rpm at maximum continuous rating can be determined with the formula, mentioned below. The engine loads corresponding to different ship's speeds vary according to the cubic law: kW varies as V^3 where V is ship's speed in knots. The combination of different engine loads and ship speeds are calculated with this formula and given below in table 2.
So,
FC (tons/day) = $24 \times 10^6 \times \text{kW} \times \text{SFC}$ *(18)*

No.	**Engine Load** (%)	**Fuel consumption** (t/d)	**Ship speed** (nm)
1	100	302	20.0
2	75	214	18.0
3	50	144	15.8
4	25	75	13.7

Table 2: Relationship among engine load, fuel consumption and ship speed

The above formula can also be used to determine the number of days to sail 10,000 nautical miles at different engine loads and the associated theoretically different overall fuel consumptions with associated fuel saving. The following table expresses the number of days to voyage 10,000 nm under different engine loads and vessel speed.

No.	**Engine load** (%)	**Days**	**Fuel consumption** (t/d)	**Savings** (%)
1	100	16.6	5030	
2	75	18.4	3930	22
3	50	21	3030	40
4	25	26.5	1990	60

Table 3: The percentage of fuel savings shown in relation to engine load

These analyses demonstrate the usual generalization that a 1% reduction in vessel speed can result in approximately 2% saving in fuel costs.

VIII. Conclusion

The successful implementation of marine CNG project lies in its low cost technology. Companies have been experimenting and after the decades of engineering, they have developed sea- vessels which are light weight and cost efficient. The ship building covers 70-80% funds of overall project, that's why; many companies have introduced their efficient containment systems, such as Coselle system by Sea NG, EnerSea VOTRANS, and TransCanada's GTL etc.

The Nonlinear Programming Transportation Model discussed above efficiently reduces the operating costs. The model is only affective when 3-4 heavy power engines are installed on transportation vessels. By selecting the optimal working parameters of the engines and distributing the load among them, a significant reduction in fuel consumption has been observed. Once the number and optimal parameters of engines and load distribution has been determined, the possible low sailing speed will reduce the overall fuel consumption.

The study case above proved that, by reducing the vessel speed up to 3 knots reduces the fuel consumption almost up to 40%.

The application of this algorithm seems to be the only possible solution having the full economic benefits under these conditions. These benefits will increase as the size of the problem increases.

This model seems to be ineffective when only one engine is installed onboard CNG transportation vessels. In this case, instead of applying this algorithm, it's economically preferable to operate ship's engine on economic mode according to the engine's passport provided by the manufacturer.

Abbreviations

L- Distance
J- Set of terminals
V- Speed of the vessel
I*j* – Set of possible cargoes to be loaded / unloaded at terminal *j*
J*v* – Terminals that ship *v* can depart to after visiting terminal *j*
VFc- the volume of fuel consumed during the measurements [m^3]
CNG – compressed natural gas
LNG – liquefied natural gas
LPG - liquefied petroleum gas
TCF – trillion cubic feet

MMscm – million standard cubic meters
CAPEX – capital expenditures
OPEX – operational expenditures
SFC – standard fuel consumption
VLCC – very large crude carrier
ULCS – ultra large container ship

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