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Mathematical Algorithms Application for Improvement of Ships' Energy Efficiency

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Key Words: *Ships' energy efficiency; mathematical theory of games.*

Abstract. *The International Maritime Organization (IMO), through its Maritime Environmental Protection Committee (MEPC), has been carrying out substantial work to provide the fundamental conditions for the reduction of greenhouse gas emissions from international shipping since 1997, following the adoption of the Kyoto Protocol and the 1997 MARPOL Conference. Many documents, issued in this respect, are dedicated to different types of vessels. More of the requirements and regulations for establishing of efficiency criteria are based on commercial activities of the vessels and respective fuel consumption. There is the big difference between offshore vessels and all other vessels. Offshore shipping industry has other criteria for effective fuel consumption. As longest, as the job is with very high risk Safety is with high priority. The offshore industry tries to find another way and means for implementation of MARPOL Annex VI requirements. The article summarizes Classification Societies requirements regarding offshore vessels. The requirements are compared with IMO Resolutions in this field and conclusions are made. The author has made proposals to education system, which are related to STCW Convention Code, Part B.*

1. Introduction

Maritime transport retains its strategic importance as a major sector of world trade in goods and of passenger transport, despite the dynamics of the economic processes. The financial crisis at the end of the first decade of the 21st century delayed to a certain extend the development of shipping, changed a number of operational criteria such as ship scrapping age, ship green passport, energy efficiency operational indicator, etc.

The United Nations data, published in the annual report of the Conference on Trade and Development titled „Review of maritime transport 2018", shows that World seaborne trade forecast for the period of 2018-2023 is projected to grow to 3.8% [1]. Along with the development of maritime trade, the UN reports also sustainability in the environmental protection. A number of International Maritime Organization (IMO) 8 initiatives aim at encouraging further investment in installations, which use ecological fuels, improving the structural and operational indicator of ships in service, etc [2]. Against the background of these activities one is puzzled by the general wording of the requirements of international institutions, the generalized formulae for calculating the ships' energy indicators, the lack of specific coefficients or multipliers which take into account the nature of the ship activities. An example in this respect are the offshore ships whose operational process is very different from that of traditional merchant and passenger ships.

A series of publications of scientists and specialists go deeper into the IMO guidelines contained in Maritime Environment Protection Committee (MEPC) circular letters and point at the versatility of the multipliers in the formula for calculating the operational energy efficiency indicator [3].

$$(1) \quad EEOI = \frac{FC_i . C_F}{m.D}$$

where:

EEOI – Energy Efficiency Operational Indicator;

FC_i – mass of fuel consumed by main and auxiliary engines during a single task performance[t],

C_F – conversion rate expressed as a relation of CO_2 mass generated during used fuel combustion process [t CO_2/t fuel];

m – mass of freight onboard [t];

D – distance expressed in nautical miles that the vessel travelled during the performance of a specific task [Nm – nautical mile].

The Gaspar/Eriksted and Glowacki/Benkendt studies provide a good basis for presenting the specific activities of offshore ships and the differences from merchant ships in this respect [4,5].

Although Gaspar and Eriksted investigate the activities of offshore ships such as Offshore Supply Vessel (OSV) and Anchor Handling Tug Supply (AHTS) in the EEOI context, they ask important questions which refer to the operational activities in this sector of the maritime industry:

- How to calculate the work done by the aforementioned types of ship.
- How is the performance of the specific mission related to fuel consumption and to the emissions discharged into the atmosphere, from the point of view of the necessary power used.
- How can activities which are not part of the routine operational process such as fire extinguishing, rescue operations, oil spill clearance, etc., leading to non-production costs, be included in the calculations [4].

Therefore, it is not possible to calculate the energy efficiency of these ships using formula (1), and other specific ships due to the specificity of their use and the tasks they perform.

The methodology proposed here is a possible approach to tackling the problem and, hopefully, it will not only help to find a practical solution that will increase the energy efficiency of vessels not covered by the formula proposed by the IMO but will also lead to environment protection decisions.

In this vein, other question could also be formulated. For the purpose of the present study, the author of the present article rely on his personal experience and accumulated statistics from the work as a Designated Person Ashore (DPA) at the offshore company Bon Marine International AD and the above-cited publications.

2. Application of the Mathematical Theory of Games for Assessing the Ship's Energy Efficiency

Theory of games is the theory of formal or mathematical models for making optimal solutions in situations of conflict and uncertainty.

All the phenomena and processes in which the participants have dissimilar interests and have ways to achieve their goals are to be considered conflicts.

Conflict is any phenomenon in which the following is known [6]:

- Who is involved.
- How does he/she participate.
- What outcomes may this situation have.
- Who is interested in these outcomes.
- What does this interest include.

The concept of "optimality" is one of the fundamental concepts. That is why optimality is a formal model in the theory of games and it includes within itself:

- Rationality.
- Profitability.
- Expedience.
- Feasibility.
- Sustainability.
- Fairness.

When solving applied tasks, an optimum is chosen in the model which meets a pre-selected criterion and corresponds to the real perception of the optimality of the participants in the conflict [7].

A game is a system of the interacting parties, the behavior of each of the parties, the possible outcomes of the conflict, the interested parties, the latter are called a coalition of the interests and the preferences of each party over the set of situations. Therefore, the mathematical model should reflect the following factors:

- Parties to the conflict are actors capable of making a decision.
- It is necessary to specify precisely what types of decisions each party may make.
- There are parties in the conflict who assert incompatible interests.
- It is necessary to describe the individual interests and objectives of the interested parties.
- Define the set of possible outcomes and evaluate their usefulness for the parties concerned [7].

The final issue is that it is not necessary for the objectives of the participants in the conflict to be incompatible (antagonistic). Significantly more frequent are the encountered situations where the interests of the parties coincide partially or almost completely. A conflict may arise rather because of non-matching positions and the multiplicity of interests, and not due to incompatible interests.

All this should convinces that this theory could play a significant role in determining the optimal strategy for offshore ship operation and in assessing their ships' effectiveness. In addition, in order not to dwell any longer on the theory of games, we would just like to emphasize that the theory of statistical games is of fundamental importance in the decision-making theory.

3. Applying the Theory of Games in Determining Ships' Energy Efficiency

To limit the number of possible strategies and to simplify the task, we will proceed from John Nash's theorem:

„There is at least one equilibrium situation (in mixed strategies) in each non-cooperative game G = <B, A, L>" [8].

The company's pre-strategy can be selected by analyzing the situation using the theory of non-cooperative games [7] to assess the general strategy. It can be illustrated with an example.

Should be analyze a game where each player has two strategies: strategy A – aggressive and strategy P – peaceful. We assume that it is better for the two parties to be peaceful, i.e. seek non-antagonistic decisions and actions rather than being aggressive – ready for „war" and not afraid of conflicts. If one player is aggressive and the other is peaceful that is good for the aggressor, and his profits are maximum and we estimate it at 3 points whereas the other party gets 0 points. If two aggressive strategies meet, both parties win something but lose more and the profits are appreciated as 1 point for each party. In the event that two non-aggressive strategies meet, losses (concessions) are also realized, but the profits are higher than those in the situation with two aggressors. Here the profits are estimated at 2 points for each party. The structure of winnings is presented by the matrices in *the table 1*.

The strategy of player 1 is expressed in the matrices of payment lines H1 and H2, and of player 2 – the matrix columns, respectively. The dominant strategies for each player are as follows – for the first player A1 – P2 (profit – 3p.) and for the second player – 21 – P1 (profit – 3p.). This condition, however, is a state of „war", which leads to mutual aggression and a condition profit of 1point and loss of 2 points. The only equilibrium situation is (P1, P2) – „peace" produces a better result for both players – 2 points. Therefore, the non-cooperation behavior is detrimental to the common interest, and collective interests suggest the

Matrices of payment and profit values in choosing the optimal strategy of a non-cooperative game

		P2	A2				P2	A2
H1 =	P1	2	0	and	H2 =	P1	2	3
	A1	3	1			A1	0	1

choice of peaceful strategies. At the same time, if players cannot exchange information, the most likely outcome is war. This game is known in the economic circles as „The Dilemma of the Prisoner" and gives us a basis for choosing a general strategy and from there we can limit the set of acceptable strategies and simplify the solution to the task.

A. Wald, the founder of statistical games, notes that all statistical models have the same structure, similar to a two-player strategic game: man (subject of governance) and nature (environment), using additional statistical information about environment strategies or the state of the economic environment [9]. Here we analyze a situation where we have an antagonistic game between two „players" – that is the environment and the offshore company. This game is slightly different from a standard antagonistic one for the following reasons:

- The environment cannot choose its optimal strategies because it is an unreasonable opponent and is not interested in winning the game, so the company plays against an imaginary opponent.
- A reasonable partner (IMO) is involved on the side of the environment, who in turn also has its own strategy.
- The environment has a random selection mechanism, which, with a certain probability, implements its various strategies. Since this mechanism has NOT changed for centuries, statistics can give us information about the probability distribution of its conditions [9].

The following parameters with the following designations are introduced:

- B – set of the of the state of the environment.
- b – a separate state of the environment.
- A – a set of the company's decisions (strategies).
- a – a separate decision of the company.

We assume that the set of states of the environment B and the set of company decisions A must be determined by the statistics presuming that they are measurable. Each distribution ξ of set B of the environment states assumed by the statistics before the experiment (the beginning of the game) is called the distribution of environment.

Assuming that the individual states of nature b are random variables with distribution ξ, provided that the function has already been fixed, then the risk R = R (b, δ) becomes a random variable. Here, with δ, we designate the mixed strategy of the subject in their statistical game with the environment. The risk is called Bayes' risk of decision-making, taking into account (by statistical data) the distribution of the variable state of the environment.

We denote L (b, a) the function of the losses, and the game G = <B, A, L> is called a starting strategy game of the statistical decision-making task. Taking into account that in the game only the company deliberately strives for profit, then the solution is to seek an optimal strategy for the company, which is to achieve the optimal solution, complying with the limitations set by the partner of the environment – i.e. IMO. In case that we assume the state of the environment to be a random variable b with distribution ξ, which also depends on the company's decisions, we can also calculate the mathematical expectation of the risk in a distribution which risk is also a variable. For example, in the case of uncontrolled air pollution with nitrogen oxides and CO_2 and the sea with petroleum products [6].

Taking into account that in the statistical game G = <B, A, L> only the subject (the company) deliberately strives for profit, then the decision of the statistical game is limited to the search for an optimal strategy for the subject, i.e. to the best functions of decision. It would be such a function δ for which the risk R = R (b, δ) is minimal, in an arbitrary state of the environment (*figure 1*).

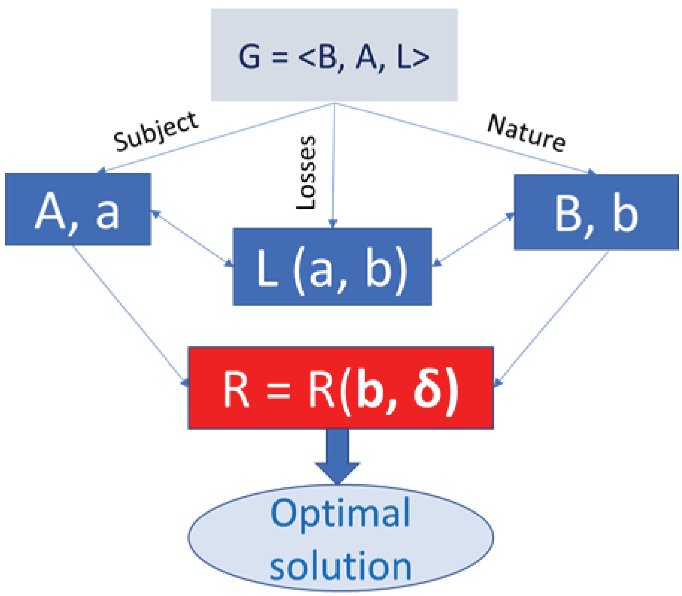

Figure 1. Presentation of non-cooperative game

Typically, such a best function is rare to be found, since each state of the environment is characterized by a „best function" of its own.

The lack of the best decision function of a solution to all states of the environment requires the subject to use methods that provide optimal solution functions in the narrowest sense, i.e. when selecting certain criteria for optimality. The theory offers two approaches for determining optimal solutions that depend on the selected optimality criterion:

- Application of methods that relate the set of solutions to a subset of „good“ functions.
- Application of methods that order the functions of the decision in accordance with the risk function, and the choice of the „best“ functions is made using selected criteria for an ordering.

It should be noted that, having an evaluation criterion, we can choose the best solution, but there is no criterion for selecting the „best“ criterion. Criterion selection depends on the goals, interests and experience of the subject (the company) [6].

4. The Operation of Offshore Ships Presented as a System of Operations

If the EEDI was incorporated during the building of a ship and its change during the service life of the vessel is a difficult process, then the EEOI allows enough freedom of choice of operational measures aimed at reducing fuel consumption and hence the emissions of green house gases. The authors cited in [4,5] make a profound analysis of the IMO guidelines in this respect. An ICCT study published on the Council's website also analyzes the abilities of the constructive index to enhance the energy efficiency of non-commercial vessels [10,11]. The authors of the present article, however, believe that additional possibilities should be sought in improving the operational indicator, despite the numerous constructive improvements on offshore industry ships. Their operational profile requires an in-depth and critical processing of statistic data in order to highlight the specific stages of each mission and to point out the possibilities for reducing energy costs. To make such an analysis, it is necessary to present the voyage or the mission as a system of operations. Gaspar & Eriksted and Glowacki & Benkendt chose a similar approach in their publications. The understanding of the activity of offshore ships as a „mission“ fully corresponds to their operation and formulates the distinction from merchant ships. This summarized characteristic also covers the non-productive activities defined in the third question above. A shortcoming of the cited analyzes is the lack of correlation of the missions with the meteorological situation, the training of the crews and the elements of the passage plan.

The specifics of the passage plan are well described by a number of authors. They adhere to the operation of merchant ships, which provides a summary of their conclusions on the nature of a voyage [12,13]. Fun-Sang and Caprace, who use a non-parametric model to describe the operation of ships during a routine voyage, represent another interesting and useful approach. The author offer a data analysis method and multi-criteria decision analysis to describe ship operation [14]. Similar reasoning is presented by Behrandt, who analyzes the specifics of the operation of fishing vessels and the possibilities for reducing energy costs in their routine operation [15].

Analysts and researchers of the Energy Efficiency Operational Indicator draw their conclusions on the IMO formulae enclosed to the MEPC circular letters. This approach limits the possibilities to search for reserves in offshore ship operation due to the limited number of their mathematical multipliers. In the next part of the article we propose another approach to assessing the working environment.

5. Use of Rectangular Games for Assessing the Energy Efficiency of Offshore Vessels

The rules of DNV Classification Society of July 2011 lay down the requirements for the construction, equipment and stability of all ships, which are designed to perform offshore activities [16]. The summarized performance characteristics of these ships are:

- The working environment – usually they operate in adverse weather conditions, heavy hydrodynamic loads on the ship's hull, machinery and auxiliary mechanisms.
- Experience of the crew to cope quickly with private and common tasks for each mission.
- Experience of ship masters to take quick decisions in non-standard situations.
- Flexibility of the ship's management by the mission leaders.

Ships in the offshore industry perform specific tasks, which can be described as permanent strategies. The practical approach requires systematic collection of information such as:

- The type of the mission.
- Meteorological conditions in the area of the ship's mission.
- Time required to perform the mission.
- Ability of the crew to perform the mission and necessity to attract additional members and specialists.

Based on the general description of the offshore mission, it can be stated that mission performance means solving a conflict situation. Typical for conflict situations is that each country in the conflict tries to gain maximum benefit regardless of the other party's counter action or of chance. The performance of an offshore ship mission can be presented as a conflict situation for which the Theory of Games is applicable.

The conflict situation for each mission can be described as a counter action of the ship in pursuit of her specific tasks and against the nature, in compliance with IMO's requirements for safety at sea. Assuming that nature has only two strategies, unfavorable and favorable weather conditions, then each strategy of the ship depends on her mission. In this way, a graphical method is used to solve a rectangular game U with a matrix of $2xn$, where 2 are the above-mentioned states of nature, and n is the number of the ship's strategies:

$$(2)\quad U = \begin{Bmatrix} a_{1,1}, a_{1,2}, a_{1,3}, \ldots, a_{1,n} \\ a_{2,1}, a_{2,2}, a_{2,3}, \ldots, a_{2,n} \end{Bmatrix}.$$

Let's assume that the mixed strategy of the ship is $X = (x, 1\text{-}x)$. For this example, mixed strategy is the strategy in which a ship has options x for reaction with different probability when the nature has only two options. Then for the pure nature strategy q_1 the following inequality will be fulfilled:

$$(3)\quad a_{1,1} \cdot x + a_{2,1} \cdot (1 - x) \leq V$$

where V is the profit of the game.

If the ship uses the second, third, etc. strategies, the inequalities will form a system of the kind:

$$(4)\quad \begin{cases} a_{1,1} \cdot x + a_{2,1} \cdot (1 - x) \leq V_1 \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ a_{1,n} \cdot x + a_{2,n} \cdot (1 - x) \leq V_n \end{cases}$$

For the inequality (3), (4) and the limitations $x > 0$ and $x < 1$ the theory of linear programming is applied by which the solution of the inequation system can be represented graphically by *figure 2*. The straight lines drawn, m in number, determine the strategies of the ship in the present state of the meteorological conditions. Empirically, the fuel consumption can be determined for each strategy 1, 2 or 3 and then the optimal one corresponding to the lowest operational indicator can be selected. Area L on the interval (0,1) is the profit area, from which the winning strategy can be chosen. The profit of the game is $V = MN$.

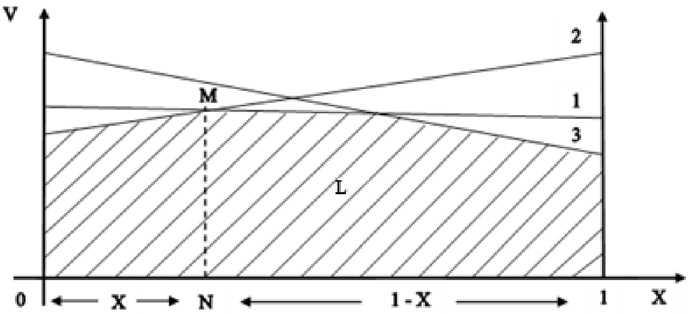

Figure 2. Representation of solution for system (4)

The presented study responds in part to the questions put in the introduction of the article on the application of formula (1) to the operation of special purpose vessels. The exploration of offshore operations suggests some solutions that can be applied universally. With the example shown in Figure 2, there is a graphical approach to solving the task of choosing a winning strategy to provide maximum V gain on the ship. The application of the overall algorithm in practice requires prior expert evaluation of the ship's various strategies to solve conflicting situations with the Nature. This article launches a comprehensive study on the application of game theory, information theory and fuzzy sets that can use virtual and real environments to improve ship energy efficiency.

6. Conclusion

The proposed method for assessing energy efficiency requires preliminary preparation by the Company which manages according to the ISM Code. In order to introduce a rating system, a procedure must first be developed to form part of the company's SMS. This procedure would assist offshore ship crews in implementing the energy efficiency management plan and the choice of an optimal strategy even when performing an advanced mission.

Solving the problems of improving a ship's energy efficiency requires systematic training of ship crews. Here the training has very similar features to the risk assessment training adopted in 2010 when the ISM Code was amended. The international maritime community has become aware of the need for crew training and the results of various projects funded by European Commission programs illustrate it. The authors of the present article are participants in such a project titled "Diversification of the employability paths of seafarers through collaborative certification of the competences". Under this project the author has developed a program and materials for a training course "Ship Energy Efficiency". Raising an awareness of the need to enhance the energy efficiency of ships has to be also part of the competences that the STCW Convention regulates. Thus the process will be completed and applied to all levels of responsibility of ship crews.

The present article is the initial stage and the basis for experimental work on the implementation of different types of operational strategies in offshore ship operation. It can also serve for carrying out an empirical analysis of the SEEMP performance results of merchant ships.

References

1. UNCTAD. Review of Maritime Transport. New York and Geneva, 2018, ISBN 978-92-1-112922-9.

2. Baltic and International Maritime Council *Macroeconomics:* Economic Indicators Have Been Pointing up in Recent Months. 20 April 2017. [Electronic version], Access through URL: https://www.bimco.org/news/market_analysis/2017/20170420_marcosmoo_2017-02 (Date of using::6 September 2018).

3. IMO MEPC 1/Circ. 684. Guidelines for Voluntary Use of the Ship Energy Efficiency Operational Indicator (EEOI). 17.08.2009. [Electronic version], Access through URL: https://www.classnk.or.jp/hp/ pdf/activities/statutory/eedi/mepc_1-circ_684.pdf (Date of using: 06.12.2018).

4. Gaspar, H., S. Erikstad. Extending the Energy Efficiency Design Index to Handle Non-Transport Vessels, 23.01.2017, [Electronic version], Access through URL: https://www.academia.edu/3217290/Extending_the_Energy_Efficiency_Design_Index_to_Handle_NonTransport_Vessels, (Date of using: 16.03.2017).

5. Glowacki, B., C. Bechrendt. Energy Efficiency of Offshore Support Vessel. The 58th International Conference of Machine Design Departments ICMD 2017, 6th-8th September 2017, Prague, Czech Republic, 88-93.

6. Vorobyov, N. Theory of Games – Lectures for Economists (Russian). Leningrad, Leningrad University, 1974.

7. Dochev, D., Y. Valkova. Applied Theory of Games (Bulgarian).

Science and Economics Publishing house, University of Economics, Varna, 2009.

8. Nash, J. Non-Cooperative Games. Annalise of Math, Econometric 54, 1951, 286-295.

9. Wald, A. Statistical Decision Function. New York, J. Wiley, 1950.

10. The Energy Efciency Design Index (EEDI) for New Ships. The International Council on Clean Transportation. 03.02.2017. [Electronic version], Access through URL: https://www.theicct.org/sites/default/files/publications/ICCTpolicyupdate15_EEDI_final.pdf (Date of using: 16.03.2017).

11. Anink, D., M. Krikke. Analysis of the Effect of the New EEDI Requirements on Dutch Build and Flagged Ships. Commisioned by the Ministry of Infrastructure and the Environment, Projectnumber 3134, Centre for Maritime Technology and Innovation, July 2011.

12. Belev, B. Ship Energy Efficiency Management (Bulgarian). Monography, Largo City, Dobrich, Bulgaria, 2017, 213.

13. Hasan, R. Impact of EEDI on Ship Design and Hydrodynamics. Master of Science Thesis, Chalmers University of Technology, Gothenburg, Sweden, 2011.

14. Fun-sang, M., J. Caprace. Improving Ship Fleet Performance Using a Non-Parametric Model. 18.02.2018, [Electronic version], Access through URL: http://labsen.oceanica.ufrj.br/ arq_publicacoes/improving-ship-fleet-performance-using-a-non-parametric-model.pdf (Date of using: 26.02.2018).

15. Behrendt, C. Energy Saving Technologies for Fishing Vessels. *Scientific Journals*, Maritime University of Szczecin, 39, 2014, 111, 11-15.

16. Offshore Service Vessels. Tugs and Special Ships, Rules for Classification of Ships, Part 5, Chapter 7, DNV-GL, July 2011, 111.

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