Fuzzy Multi-objective Ranking of Scenarios/Technologies aiming at Reduction of SO_x Emissions by Ships

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Abstract: - This work deals with multiobjective ranking of scenarios/technologies aiming at reduction of SO_x (Sulphur Oxides) emissions by ships. Initially, It is proved that there is a continuum between alternative scenarios/technologies rather than candidate distinct solutions, recognized as such on an *a priori* basis. Subsequently, a methodological framework under the form of an algorithmic procedure is presented, where a multicriteria tool is embedded by using six criteria, namely economic cost, environmental cost, reliability in performance, flexibility/adaptability, technology maturity, and technology perspective. The available scenarios/technologies have been categorized to form the following seven quasi-distinct alternatives within an ***a*(i,j)** 6×7 preference matrix: mixed hybrid fuel, A1; marine gas oil, A2; liquefied natural gas, A3; modified fuel cell, A4; dry scrubber technology, A5; hybrid wet scrubber based on NaOH, A6; hybrid wet scrubber based on MgO, A7. Fuzzy values were assigned to the matrix elements in fuzzy triangular form by means of a modified Delphi method to count for uncertainty. The matrix solution gives the ranking A3 > A1 > A2 > A7 > A6 > A5 > A4, where the symbol '>' stands for 'better than'. Sensitivity/robustness analysis is performed, the results obtained and the assumptions made are discussed, remarks for specialization of multi-criteria analysis are presented, and directions for further research are suggested.

Key-Words: - Multi-objective ranking, Air pollution, SO_x emissions, Marine Industry, SECA zones

1 Introductory Analysis

According to Ma *et al.* [1], two distinct scenarios, with various potential alternatives, may be related to the marine industry's compliance to the IMO's SO_x emissions regulations:

(I) The marine industrial sector adopts exhaust gas treatment systems by continuing to use high Sulphur (S) fuels, namely Heavy Fuel Oils (HFOs); i.e., the ship-companies comply with regulations by installing on-board equipment for SO_x abatement.

(II) This industry adopts stricter refining processes as regards desulphurization, producing HFO with S-content < 0.5%, named Marine Distillate Oil (MDO), through investment in new higher capacity and/or technology of ultra-low Sulphur distillates.

This distinction is oversimplified since there is actually a continuum between these two scenario-solutions, created by economic/operational/ technological reasons. We can prove it by considering a generalized example concerning a ship that may successfully adopt usage of either HFO combined with proper installation of on-board equipment or low S-content fuel. Let now examine the cost (C) variation dependence on spatiotemporal capacitance exploitation *E*, which is the annual percent usage of ship's capacity. The solution (I) is represented by the line I, which starts from $C = C_0$ at $E = 0$ because of quasi-constant expenditure expenses, mainly due to depreciation and maintenance expenses (see Fig. 1). The solution (II) is represented by the line II, exhibiting higher slope, because of fuel's higher price. The intersection of

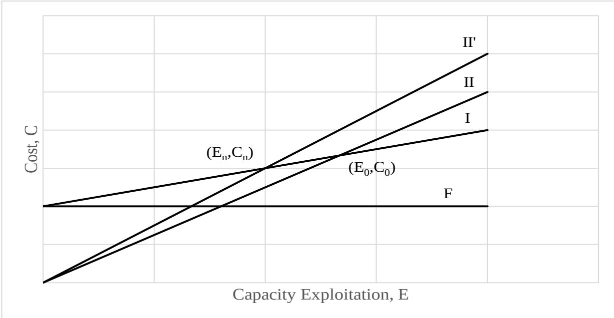

Fig. 1. Determination of the critical point (E_c, C_c), beyond which the solution (I), with fixed cost F, dominates; the shifting to the new critical point (E_n, C_n) is the result of fuel price increase.

these two lines at (E_c, C_c) gives the critical point, after which the solution (I) dominates. Evidently, an increase in fuel price (e.g., because of imposing green tax to the refinery or directly to the consumption) will move line II to its new position II'; as a result the critical point is shifting to (E_n, C_n), making the solution (I) further more attractive. Since green taxes vary in time and space (geographical area and country) while the independent variable *E* depends heavily on demand in the world market, it is well understood that a continuum is established even at the ship design stage, since market fluctuations and green taxes imposition cannot be forecasted with reliability over the ship's lifetime, not even for the depreciation period, if revenues are also taken into account in the relevant break-even-point analysis (see the Discussion section).

The continuum mentioned above is more expressed when the various SO_x abatement/ reduction technologies are taken into consideration, since each one of them implies a different critical point (E_c, C_c), while the corresponding variations give a set of such points. Bearing also in mind that the objectives/criteria are not limited to economic ones, we can determine the difficulties in decision making on the adoption of proper scenario/ technology in relation with ship category and capacity, either for a new or an old one (but suitable for renovation/retrofitting in the last case). The suitability of a special technology for retrofitting is a criterion that should be taken into account by on-board equipment constructor/providers (supply side analysis).

2 Methodology

For the purpose of effectively dealing with the difficulties quoted in the last paragraph, we have developed a methodological framework under the form of an algorithmic procedure, including 23 activity stages and 5 decision nodes (for their interconnection, see Fig.2). The stages are properly formulated to serve solving air pollution problems other than SO_x emission by ships, the specialization starting only at stage 12.

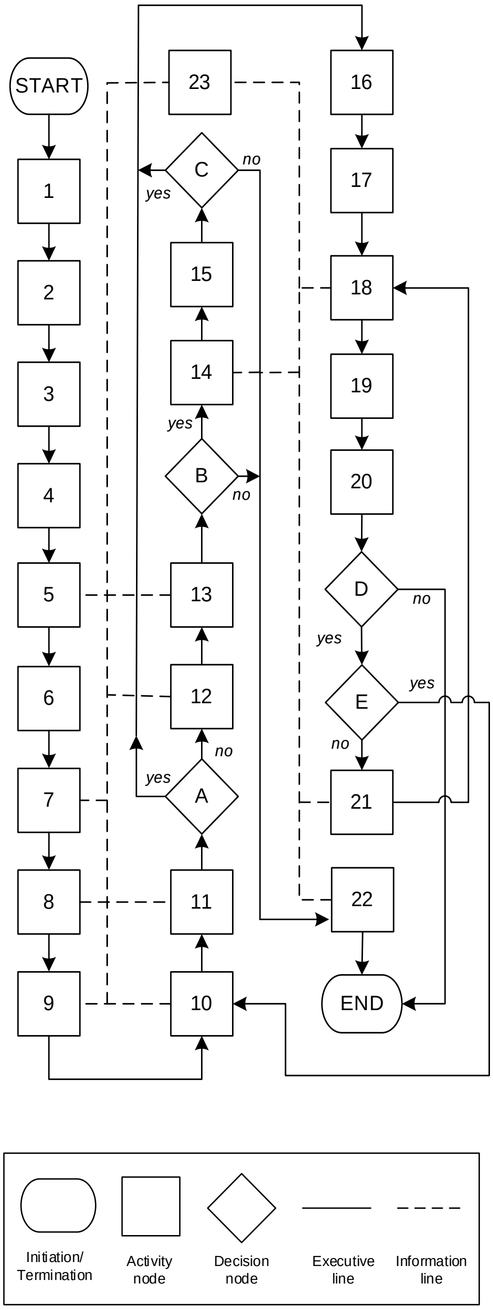

Fig. 2. Flowchart depicting the algorithmic procedure presented in the Methodology section herein.

1. Description of the local/wide area under surveillance for potential air pollution as a system including both, sources and sinks of polluting species.
2. Localization of these sources/sinks as points, linear segments, sub-areas (e.g. chimneys of the industrial units or ships' funnels/stacks, rivers or artificial lands, ponds/lakes/wetlands or harbors, respectively).
3. Qualitative/quantitative determination of the corresponding primary pollutants.
4. Registration of system's pollutant input-output together with the relevant meteorological data.
5. Registration of environmental policy measures and estimated secondary pollutants.
6. Time series analysis per each compartment of the system under consideration.
7. Local area implications in economic terms.
8. Wide area implications in economic terms
9. Correlation between local and wide area implications in physical/economic terms at macro-level and determination of the respective influence on the design of environmental policy measures, according to 'think globally, act locally'.
10. Specification of these measures at micro-level, concerning system modules, implying environment standards, legislative rules/obligations and clauses in signed agreements (deductive approach).
11. Registration of the results obtained by following the preceding stages 9, 10, in order to formulate a feed-back loop through the KB-IA (Knowledge Base, Intelligent Agent, respectively) mechanism quoted in stage 23 (inductive approach leading to 'think locally, act globally', e.g., by offering information for negotiating at summit level or simply at higher administrative level when the partners/stakeholders belong to different scientific domains or districts or countries/unions.
12. Consideration of relevant R&D projects, aiming at reduction of SO_x emissions by ships, as the main paradigm.
13. Feasibility study of them, putting emphasis on the economic part.
14. Formulation of scenarios/technologies as alternatives.
15. Running of scenarios/technologies by simulations.
16. Synthesis of the criteria vector for ranking the alternatives.
17. Selection/hiring of experts.
18. Assignment of (i) grades on the elements of the preference matrix and (ii) weights in the criteria vector, in fuzzy version to count for uncertainty.
19. Fuzzy multi-objective/multicriteria ranking of alternatives, after defuzzification (consensus in input).
20. Sensitivity /robustness analysis of the ranked first alternative.
21. Incorporation of additional information /knowledge obtained so far into the consultation domain of the KB quoted in stage 23.
22. Preparation of report documenting the causes of failure and considering the possibility of further economic support under the form of subsidies to deal with the relevant difficulties.
23. Design/development/enrichment of the internal KB with the respective Inference Engine (IE) and the corresponding IA, according to [2].

A. Are there available technologies to prevent pollution at micro-level?
B. Are they feasible?
C. Are there favourable results?
D. Is it sensitive within the preset interval of specifications?
E. May we broaden the interval of specifications?

The vector synthesized in stage 16, quantified in stage 18, and implemented in stage 19 includes the following criteria: economic cost, f_1; environmental cost, f_2; reliability in performance, f_3; flexibility/adaptability, f_4; technology maturity, f_5; technology perspective, f_6.

3 Implementation

The alternative technologies used are: mixed hybrid fuel (MHF), A1; marine gas oil (MGO), A2; liquefied natural gas (LNG), A3; modified fuel cell (MFC), A4; dry scrubber technology (DST), A5; hybrid wet scrubber based on NaOH (WSN), A6; hybrid wet scrubber based on MgO (WSM), A7. Their main characteristics and comparative advantages/disadvantages are described below.

Hybrid fuels are new generation marine fuels of ultra-low Sulphur percentage (0.1%). They incorporate great similarities and some differences compared to ECA (Emission Control Area) compliant MGO. Though in early entry in the marine bunkering, hybrid fuels seem to be promising to acquire a significant market share. They have relatively high pour point, higher flash point and viscosity in comparison with ultra-low Sulphur MGO. Thus, combustion characteristics are considered to be improved comparable to ultra-low Sulphur MGO. Operational feedback of hybrid fuels is currently almost non-existent. Therefore, there has been a lot of skepticism on potential upcoming incompatibility issues in 'change over method' on-board, (i.e. switch from one fuel to another), a common sea operational practice, to meet the Sulphur emission caps in ECA zones [3].

Ultra-low Sulphur MGO is much easier to supply, which render MGO a very competitive marine fuel alternative, yet with less well-defined specifications. Hybrid fuel prices cannot be predicted with certainty. Additionally, hybrid fuels market spots globally are considerably limited in certain zones. A significant proportion of the fleet, mainly of higher age, will still rely on distillate fuel for ECA compliance [4]. 'Change over method', is an easy application for the ships with segregated tank design, generally considered to be a low budget solution and rather easy to operate though susceptible to the uncharted ultra-low Sulphur market prices. Implementation prerequisite is the extra space on-board needed for the different fuel type storage. [5]. $DeSO_x$ scrubbing technologies in comparison to the hybrid and ultra-low Sulphur MGO fuels are of (i) highly cost investments, (ii) space consuming with installation and (iii) operating limitations when retrofitting, with the additional problem of acidic sludge production.

LNG fuel, a mixture, mainly methane with small quantities of ethane, is a highly compressed and worldwide used fuel in heavy industry & power-plants. LNG and gas/dual marine engines are having an operational edge (cost effectiveness), mainly for ships that spend great deal of time in ECA zones. LNG engines are quite mature in every technological aspect (durability, efficiency, eco-friendliness). LNG marine engine emissions (i.e. SO_x, NO_x, PMs, CO_2) are significantly lower compared to antagonistic operational solutions such as Hybrid Fuels/MGO/HFO with scrubbers all types fired engines. Only fuel cells surpass LNG in terms of environmental friendliness. Additionally, LNG fuelled engines have lower operational cost and prolong marine engines lifespan [6].

Fuel cells are quite flexible when installed in retrofitting, replacing auxiliary engines. They have great compatibility with various type vessels' interface when integrated in ship's machinery during the installation. Still, greater space on-board demands incur installation limitations. Thus, turns out to be less attractive in terms of installation flexibility when compared to hybrid/MGO fuels. In every aspect is considered to be less reliable when in comparison to other already mentioned desulphurization technologies (wet/dry scrubbing); it is questionable whether fuel cells might cover the ship's energy demand over 250 kW in great vessels. The expected operation life of fuel cells propulsion systems are far lower than other antagonistic propulsion technologies. That fact is zooming up the mid-term operational cost. Furthermore, the highest initial investment cost is a hindrance to future penetration into the ship building market [7].

Examining this alternative technology at a deeper phenomenological level, we conclude that fuel cell power derivation is based on modular installation philosophy, therefore is less vulnerable to single failures when commissioning and operating. There are certain types of fuel cells. The most promising consuming material for fuel cells is methanol derived from organic based wastes. In that case, the environmental cost might be minimized. On the other hand, methanol based cells enclose high safety risks onboard, and thus numerous precautions have to be taken along with extensive training programs that should be carried out by the crew. Environmental advantages are much more tangible when Molten Carbonate Fuel Cells (MCFC) are fuelled with biogas, landfill gas or green fuel from renewable sources (e.g. hydrogen from water electrolysis powered by wind electricity) rather than natural gas. (MCFC) are operating at 650^oC and the overall thermal efficiency approaches 90%, of which up to 48-49% is electric power. [8], [9]. There are more than 50 fuel cells installations worldwide producing over 300 MW of clean electric power. Nevertheless, the sensitivity to fuel contaminants and high initial investment costs are inhibiting full market penetration [7].

Dry scrubbing technology is the counterpart of hybrid (open/closed loop) wet scrubbing. Dry scrubbing is a reliable, mature technology, since it has been used widely in solid fossil fuel fired power-plants several decades before and can achieve desulphurization efficiency somewhat lower compared to wet scrubbing. Dry scrubbing is a more advantageous technique in terms of final by-products to be disposed. It operates independently of the seawater quality, which is an advantage against open loop wet scrubbing. Dry technology delivers no significant fluid by-products to the sea, since gypsum is the solid by-product. In dry operation, exhaust gases do not pass through water, do not cool and therefore dry scrubbers can be placed before an Exhaust Gas Economizer (EGE) or used in conjunction with Selective Catalytic Reduction (SCR) installation for higher $deSO_x$ abatement [10].

Wet scrubbing (WSN) technology has a long history and is more extensively tested on ships. Compared to dry scrubbing, installation is less robust and space consuming, with considerably lower installation cost. Thus dry technology is surpassed by the antagonistic wet scrubbing in terms of market competitiveness [10], [11]. Nevertheless, it is questionable whether the worldwide refining capacity is sufficient to incur Sulphur content reduction from 3.5% (S) to 0.5% (S) in a short period. Price difference between low-Sulphur MGO & HFO regulates the profitability of the use of a scrubbing system [4].

An alternative reactant of the wet scrubbing process (WSN) is the magnesium oxide (MgO) based deSO$_x$ **installations (WSM)**, which can be easily reengineered / rescaled in order to meet the SO$_x$ abatement needs. Some up-coming concerns regarding the solid MgO handling and storage can be easily overcome with certain compromises [12].

Revisiting certain technologies analyzed above to identify their comparative Strengths, Weaknesses, as well as Opportunities and Threats, expected to play a significant role in the near future (SWOT Analysis), we may put emphasis on the following (also helpful as an informative background for the subsequent multi-objective).

Only speculations can be drawn especially for hybrid fuel blendings in marine fuel market share. Blending fuels onboard to achieve Sulphur caps in Sulphur Emission Controlled Areas (SECAs), was a sufficient measure to meet SO$_x$ emission limits of 1.5% S up to now [5]. Nevertheless, it is questionable whether the same practice shall cover areas of SO$_x$ caps of 0.5% after 2020. Ultra-low Sulphur fuel prices are expected to affect significantly only transatlantic, very long distance sea routes and will reduce the profit margin of exporters rendering them uncompetitive in foreign markets. Higher fuel prices of ultra-low Sulphur are expected during the first years of IMO emission's strict rules implementation. Nonetheless, in long term, distilleries' management policies are expected to meet the global needs of maritime transportation, taking under consideration the future penetration of biogenous LNG production, and shall bring about a significant price reduction in maritime fuel markets of all kinds of ultra-low S marine fuels [5],[13].

LNG is well entrenched as the single propulsion fuel in LNG carriers the last decade. Up to now LNG propulsion engines are mounted on small cargo ships, small oil product tankers, Ro-Ro ships, coast line vessels, i.e. coast ferries, etc. All afore-mentioned vessel types operate in sea-routes where emission restrictions are applied; i.e., Finnish gulf, Nord Sea, Norwegian cost-line, Danish straits and Canadian estuaries. Yet, the installation of gas propulsion engines in great vessels encounters problems and limitations summarized as follows: LNG storage vessels mounted on ships at the expense of cargo loading, crucial safety matters, high installation cost, scarcity of LNG bunkering stations worldwide, small methane slip, etc. Due to the given reasons, LNG is not expected to penetrate open seagoing merchant fleet market the next decade. Nonetheless, LNG fired marine engines are expected to increase their share, to be installed on coastal vessels and small cargo ships which are constantly operating in SECA zones. Since LNG is in liquid form only at low temperatures, it requires proper infrastructure in the form of terminals, bunker structuring, sufficient storage capacity, adequate distribution network and on-board new engines installation when retrofitting is the case. Use of gaseous fuels results in lower emissions of particles during their life cycle and therefore enable us to reduce the negative aspects on human health from shipping traffic [14].

Main restriction in the use of fuel cells is the operational time limitations and the high energy needs of the ships to be installed. It is questionable whether fuel cells might cover the ship's energy demand over 250 kW. Fuel cells have high factory cost, and low production up-to-now. Numerous pilot hybrid propulsion systems using fuel cells are already installed. Fuel cell onboard mounted projects are active covering close shipping routes in Californian waters, in New York ferries in Canadian water, as well as in Baltic and North Sea. LNG-fueled engines are expected to be the intermediate step for the wide adoption of LNG-fueled fuel cells as propulsion medium in the near future [7].

The multi-criteria/multi-objective preference matrix was structured according to stages 13-16 and the grades on its elements were assigned by three experts, according to stages 17, 18, in a fuzzy version to count for uncertainty. These grades are shown as mean values after deffuzification (consensus in input, see [15-17]) in Table 1. Crisp numbers were assigned to the elements W_i (i=1, …, 6) of the weights vector, based on empirical knowledge acquired by the authors and presented in the first numerical column of Table 2. In the same Table, mono-parametric sensitivity/robustness

	MHF	MGO	LNG	MFC	DST	WSN	WSM
f_i	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**
f_1	6.57	6.13	7.23	3.20	3.90	4.27	4.60
f_2	5.03	5.03	6.17	5.63	6.60	6.83	7.07
f_3	7.37	8.00	7.73	6.53	4.03	6.77	6.83
f_4	5.03	6.97	4.53	2.53	5.80	6.60	6.27
f_5	7.40	7.67	7.73	3.07	7.40	7.30	7.23
f_6	7.43	5.57	6.73	7.80	2.57	6.63	5.57
$\mathbf{S_j}$	6,47	6,44	6,96	4,59	4,99	5,98	6,04

Table 1. The preference matrix **a**i,j after defuzzification (consensus in input) according to the centroid method. The last row includes the output of fuzzy multicriteria analysis, indicating the ranking A3 > A1 > A2 > A7 > A6 > A5 > A4, where the symbol '>' stands for 'better than'. $\mathbf{S_j}$ = $\mathbf{SWG_j}$ denotes Sum of Weighted Grades for each technology Aj (j=1,…, 7).

f_i	W_i	X_n	X_o	I%
f_1	0.34	8.001	6.567	21.842
f_2	0.21	7.356	5.033	46.137
f_3	0.17	10.235	7.367	38.941
f_4	0.06	13.161	5.033	161.48
f_5	0.14	10.883	7.400	47.072
f_6	0.08	13.529	7.433	82.007

Table 2. Estimation of each new grade X_n that should be assigned to the respective element of the 'second best' vector A1, by replacing the corresponding initial grade X_o, so that $S_1 = S_3$ (sensitivity/robustness analysis).

analysis is presented by estimating each new grade X_n that should be assigned to the respective element of the 'second best' vector A1, replacing the corresponding initial grade X_o, so that $S_1 = S_3$. The X_n values are also shown in Figs. 3-5, as the ***a*(i,j)** values (intersections with the horizontal axis) for which SWG_3-SWG_1 = 0; there is always a unique solution, since all functions are linear. In the last column of Table 2, the percentage increase I% = $100(X_n-X_o)/X_o$ required for the initial grade X_o to reach the new grade X_n of the equilibrium vector is shown. Evidently, from the robustness point of view, the criteria contributing to robustness are f_4 >

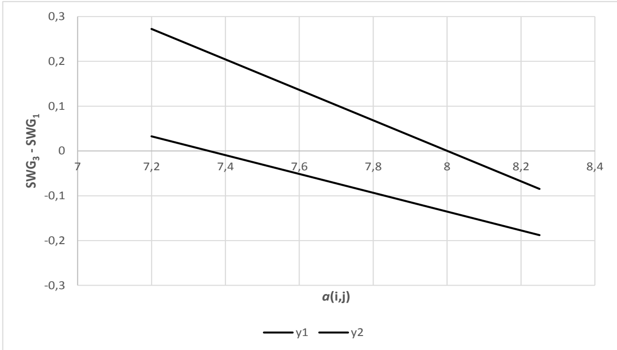

Fig. 3. Sensitivity analysis of the ranked first alternative A3 (LNG), indicating relative robustness of the preference matrix solution, when the value of the ***a*(1,1)** and ***a*(2,1)** elements are changing, as shown by the upper and lower lines (with intersection critical values 8.001 and 7.356, respectively).

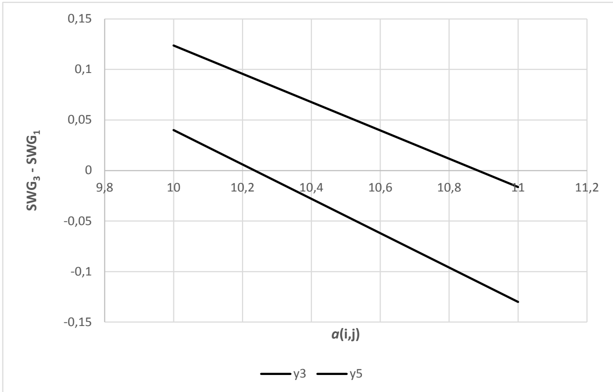

Fig. 4. Sensitivity analysis of the ranked first alternative A3 (LNG), indicating absolute robustness of the preference matrix solution, when the value of the ***a*(5,1)** and ***a*(3,1)** elements are changing, as shown by the upper and lower lines (with intersection critical values 10.883 and 10.235, respectively, out of the grading range).

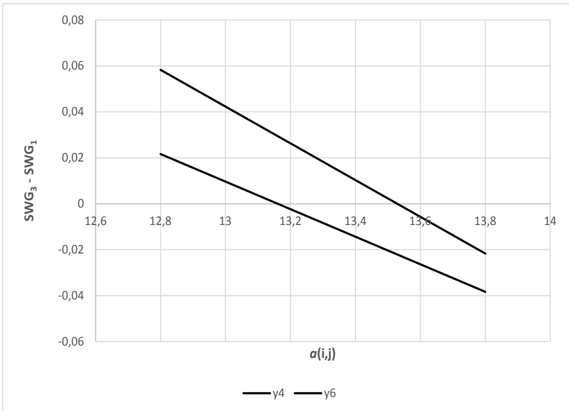

Fig. 5. Sensitivity analysis of the ranked first alternative A3 (LNG), indicating absolute robustness of the preference matrix solution, when the value of the ***a*(6,1)** and ***a*(4,1)** elements are changing, as shown by the upper and lower lines (with intersection critical values 13.529 and 13.161, respectively, out of the grading range).

$f_6 > f_5 > f_2 > f_3 > f_1$, where the symbol '>' means 'contributing to robustness more than' or 'contributing to sensitivity less than', under the *ceteris paribus* clause.

4 Discussion

The ranked first alternative of using LNG is based on the following assumptions that seem to be currently (or at least in the near future) realistic:

(i) Progressive extension of SECAs is on the track, under the pressure exerted by the developed countries in order to mitigate/eliminate undesired competition realized through introducing low-price fuels with high S-content; the supply of such fuels may follow unofficial ways in order to avoid taxes, not mentioning the possibility of contraband; combating against this taxes avoidance or even illegal situation, may lead to LNG production increase resulting to price decrease, shifting the critical E_n-value to the right (as shown in Fig. 6), thus making the LNG solution more favorable.

(ii) Safety requirements are fulfilled in accordance with IGF (International Gas Fueled ships) code of safety when gas or other low flash-point fuels are used.

(iii) The technology of constructing LNG tanks is already matured while some further improvement is shortly expected, as regards the insulated materials and the SCADA systems.

(iv) The supply chain providing LNG to ships will continue expanding not only through the existing infrastructure in medium/small port facilities but independently as well.

(v) Subsidization of the infrastructure mentioned above not only for environmental protection of ports and conventional energy sources substitution, but also for regional development in the case of medium/small ports and independent remote facilities; as a result of LNG availability increase, the fixed cost *F* is decreasing to *F'* and, consequently, E_n is shifting to the right (due to indirect subsidization of the LNG supply), making the LNG solution more attractive, as shown in Fig.7.

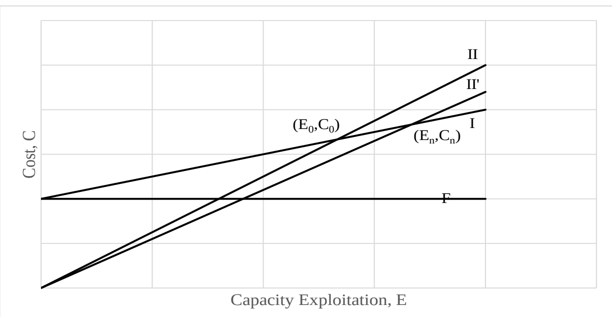

Fig. 6. Depiction of the situation described in (i), making the LNG solution more favorable.

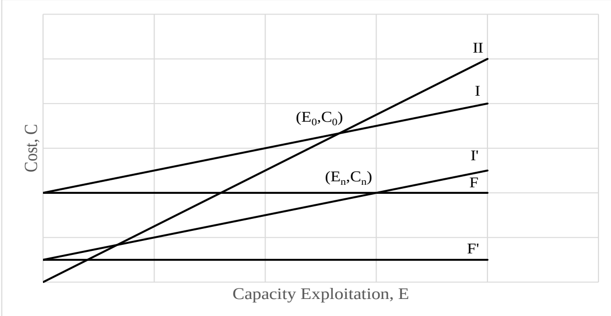

Fig. 7. The effect of indirect subsidization of LNG supply inventories/channels resulting to fixed cost decrease (from *F* to *F'*) and, consequently, to LNG price decrease causing shift of the critical value E_n to the right.

(vi) Ship retrofitting might be proved feasible for converting older vessels to LNG, since there are satisfactory examples, although this possibility is not considered in the present work, which is based on building new ships; nevertheless, we might not ignore that expansion of LNG market will create scale economies and relevant technological innovations, further pressing LNG prices downwards, provided the supply side will respond accordingly.

5 Conclusions

The multi-criteria ranking of SO_x reduction scenarios/technologies A_j (j=1,…,7) has been implemented successfully in the case of the marine industry. The alternatives considered herein are: mixed hybrid fuel, A1; marine gas oil, A2; liquefied natural gas, A3; modified fuel cell, A4; dry scrubber technology, A5; hybrid wet scrubber based on NaOH, A6; hybrid wet scrubber based on MgO, A7. Fuzzy values were assigned to the matrix elements in fuzzy triangular form by means of a modified Delphi method to count for uncertainty. The matrix solution gives the ranking A3 > A1 > A2 > A7 > A6 > A5 > A4, where the symbol '>' stands for 'better than'. The numerical results indicate the formation of three pairs (A1,A2; A7,A6; A5,A4), which may be extended to clusters, if the various versions corresponding to each technology (forming respective sub-scenarios) are taken under consideration. Consequently, the ranked first alternative A3, suggesting usage of LNG as a fuel, is insensitive/robust while the internal/partial ranking in each pair is easily interchangeable. By comparing fuel based with on-board equipment based technologies, we found that, in general, the critical capacity exploitation, beyond which the second technology prevails is (i) lower, if the fuel price is expected to be higher in the energy market, (ii) higher, if long terms supply contracts may guarantee low prices with lower volatility (as it is the case of LNG), (iii) lower, after the depreciation period of the installed equipment investment, and (iv) higher, by decreasing capital/fixed cost through subsidizing the investment, since it is fulfilling certain EU imposed criteria for successful/substantial contribution to conventional energy sources substitution and environmental protection (as it is the case of LNG).

Acknowledgement: The publication of this paper has been partly supported by the University of Piraeus Research Center.

References:

[1] Ma H., Steernberg K., Riera-Palou X., Tait N.. “Well-to-wake energy and greenhouse gas analysis of SO_x abatement options for the marine industry”, *Transportation Research Part D*, Vol. 17, 2012, pp. 301-308.

[2] Batzias F.A., Marcoulaki E.C., Restructuring the keywords interface to enhance CAPE knowledge via an intelligent agent, *Computer Aided Chemical Engineering*, Vol. 10, 2002, pp. 829–834.

[3] Notice for Low Sulphur “hybrid” fuel operation, Technical update No3, (March 2015), DNV-GL.

[4] Maarten H., Den Boer E., “Scrubbers - An economic and ecological assessment”, NABU, Delft, March 2015, available on the website https://www.nabu.de/downloads/150312-Scrubbers.pdf.

[5] Yang Z. L., et al., “Selection of techniques for reducing shipping NO_x and SO_x emissions”, *Transportation Research Part D*, Vol.17, 2012, pp. 478-486.

[6] Livanos A., G., Theotokatos G., Pagonis D. N., “Techno-economic investigation of alternative propulsion plants for Ferries and RoRo ships”, *Energy Conversion and Management*, Vol. 79, 2014, pp.640-651.

[7] Ryan, M., “Fuel Cells for greener shipping”, Analyst view, *Fuel Cell Today*, 2012.

[8] Mehmeti A., “Life cycle assessment of molten carbonate fuel cells: State of the art and strategies for the future”, *Journal of Power Sources*, Vol. 308, 2016, pp.97-108.

[9] Alkaner S., Zhou P., “A comparative study on life cycle analysis of molten carbon fuel cells and diesel engines for marine application”, *Journal of Power Sources*, Vol. 158, 2006, pp. 188–199.

[10] ABS, "Exhaust Gas Scrubber Systems Advisory, Status & Guidance".

[11] Jiang L., Kronbak J., Christensen P., L., “The costs and benefits of sulphur reduction measures: Sulphur scrubbers versus marine gas oil”, *Transportation Research Part D: Transport and Environment*, Vol. 28, 2014, pp.19–27.

[12] Tang X.J., et al., “Prediction model for desulphurization efficiency of onboard magnesium-base Seawater scrubber”, *Ocean Engineering*, Vol. 76, 2014, pp. 98-104.

[13] Article title “Low-sulphur fuel costs charging in”, October, 30th 2014, Green4Sea official website, http://www.green4sea.com/low-sulphur-fuel-costs-charging-in/

[14] Bengtsson S., Fridell E., Andersson K., “Environmental assessment of two pathways towards the use of biofuels in shipping”, *Energy Policy*, Vol. 44, 2012, pp. 451–463.

[15] Batzias F., Markoudakis Y., “Development of a local/wide area network (LAN-WAN) hybrid system for monitoring air pollution caused by oxides, particles, and secondary products”, *Proc. 12th WSEAS Intern. Conf. on Energy, Environment, Ecosystems and Sustainable Development*, A. Bulucea (Ed.), Venice, Italy, Jan. 2016, pp.111-121.

[16] Batzias F., Sidiras D., Siontorou C., Bountri A., Politi D., “Fuzzy multicriteria ranking of waste materials to be used as adsorbents within an industrial ecology framework”, *Proc. 10th WSEAS on Environment, Ecosystems and Development*, S. Oprisan et al. (Eds.), Montreaux, Switzerland, Dec. 2012, pp. 236-241.

[17] Batzias A., Batzias F., “Fuzzy Multicriteria Choice of instrumental methods for measuring physical quantities – application in the case of dielectric aluminium anodic oxide films”, *Proc. of IEEE Instrumentation and Measurement Technology*, Vol. 3, May 2004, IMTC 04, pp. 2217-2222.