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System simulation as decision support tool in ship design

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Abstract

Due to new regulations about emissions, ship design needs to face in these years the challenge of implementing new technologies on-board vessels. All these technologies cut in different ways SO_x, NO_x and CO_2 emission and affect different ship's systems. Pollution reduction can be archived by implementing emission reduction systems, like scrubbers, or switching from traditional residual bulk fuels to different ones. To evaluate impact of each solution on-board, a system engineering approach must be applied since early-stage design. In this paper a simulation tool able to support ship design is presented. Thanks to a system simulation, different possible solutions for power generation are evaluated in three different cases, distinguishing specific weight factors for each evaluation criterion. Then, a rank of the different solutions is done in order to reflect the weight of the attributes in defining alternative layouts for the generation power plant.

Keywords: System simulation; Generation power plant; Decision support system; Ship design

1. Introduction

Ships have been used for thousands of years and are one of the oldest means of transport. Today the vast majority of world fleet is used to carry goods in various ways, mostly in bulk, liquid form or containerized. There are also a lot of different applications, like offshore vessels, pleasure yachts, cruise ships and fishing vessels that make it difficult to find general trends is marine sector.

The shipping industry is facing many changes in these years. National and international organizations are trying to cut emissions from ships with mandatory regulations that limit quantities of Green House Gases (GHG), SOx, NOx and other pollutants that a vessel can produce, especially near coastal areas and in ports. International Maritime

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Organization (IMO) is one of the institutions that can issue rules and regulations that must be implemented on new or existing ships. From 1973, for example, IMO is committed to cut emissions from shipping and issued regulations to limit GHG, SOx, NOx and other pollutants produced by vessels. Limits progressively increasing on SOx and NOx have been imposed with International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI. For example, from 1st January 2020 global sulphur limit was decreased from 3.5% mass on mass content to 0.5% in fuel oil used on-board. Also, IMO has delineated an initial strategy to reduce CO2 emission per transport work by at least 40% by 2030 and GHG emissions from ships by at least 50% by 2050 compared to 2008 [1]. For these reasons ship owners are asking designers to find technical solutions to comply with emission's requirements with minimum impact on CAPital EXpenditure (CAPEX), OPerating Expenditure (OPEX) and payload. There are two main ways to reduce emissions. Today the main fuel used in shipping sector is Heavy Fuel Oil (HFO), which is a residual product of distillation process of crude oil. First option to reduce emissions is switching from HFO to more refined fuels, like Low Sulphur Fuel Oil (LSFO), Marine Gas Oil (MGO) or others not obtained from crude oil. Among these alternatives, Natural Gas (NG), hydrogen and methanol are gaining interest because they all reduce emissions and have specific benefits for ship utilization. Switching fuels also allows ship implementing different power generators, like Dual Fuel Internal Combustion Engines (DF-ICE) or even Fuel Cells (FC), that can be beneficial to further cut emissions and improve efficiency [2]. The second option to cut pollutant coming from ships is to eliminate part of them with emission reduction systems, as SCR and scrubbers. During past years, ship's performances were improved by new production technologies, software and simulation instruments, like robotic welding systems, Finite Element Method (FEM) analysis and Computational Fluid Dynamics (CFD). Today and in the near future these tools will not be enough. A new approach to ship design is needed in order to address the challenge of implementing innovative technologies on-board [3]. These actions have a big influence on ship design, construction, operation and maintenance and so they need to be considered carefully and from early-stage design. System engineering should be used in this context because it allows a multi-disciplinary approach to design. This philosophy aims to satisfy all stakeholder's needs considering how a solution performs through its whole life-cycle [4]. Especially in early-stage design, very important decisions must be taken without having detailed information about each system that will be inside the ship. Evaluating overall impact that a new system has to others that are already present in ships is essentially a multi-criteria decision process. In order to support decision making, simulation of different alternatives since early-stage design is beneficial as allows conflict resolutions [5] [6] [7] [8].

In this paper a simulation tool to assess the overall impact of different energy generation systems is used to support decision making in ship design. In order to preliminarily address this process, a trade-off analysis is carried out for eight different layouts of power generation systems with respect to sixteen different attributes. The present study will highlight the main challenges to be considered when a new generation system is set up. Pros and cons of each solutions will be analyzed.

2. System engineering and ship design

System engineering is an interdisciplinary method that permits to comprehend a problem in his wholeness. It is based on systems thinking, that is a perspective on reality that can increase someone's consciousness about wholes and how parts within them interrelate. With this philosophy a person can understand how a system behaves in a larger context and how it can be managed. System engineering also leads to discover real requirements of a system and helps to deal with complexity, allowing anticipating unpredictable behaviors and minimizing undesirable consequences [9]. Ship designers are closely related to systems engineers. Both of them must have an interdisciplinary approach, because ship designers must deal with technical aspects, as mechanics, fluid dynamics (dealing with water, air and the interaction between them), physics, electrical engineering, but also with economics, logistics and other disciplines. Ships are composed by various systems interacting with each other. Basically ships are composed by four main systems [10]. The hull is the whole structure that needs to withstand internal and external loads, while having a shape and a volume distribution both inside and outside water suited to minimize power required to move the vessel and to guarantee maximum stability and payload weight. Platform systems are the ones that allow to sail the vessel and control it, not only rudders, propellers and their auxiliaries, but also navigation systems. Mission systems are systems required for ship's specific purpose as required by ship-owner specifications. Outfit and furnishing are deck equipment and internal furniture. Each system above listed is composed by other subsystems that can vary in number depending how complicated is the ship under investigation. System and subsystems interact with each other in multiple ways and they all contribute to general aspects like CAPEX, OPEX, payload capacity and safety. Finding best possible compromise is an activity that should be carried along ship early-design phases. During these phases, named concept and preliminary design, requirements from ship-owner must be translated in a possible vessel's configuration, specifying shape, dimensions, layout and main characteristics [3]. In this phase, among various aspects considered, ship's electric energy generation and distribution system should be outlined specifying main machinery types, data and functioning philosophy [11]. Dealing with multi-objective design problem requires adoption of decision-making techniques suitable for each design stage. In this paper the decision matrix method is applied to assess the impact of different possible solutions for power generation on-board since early-stage design. This tool has been used for many years to help high level decision making in complex projects and is still one of the most applied methods [12]. Decision matrix allows evaluating different project alternatives with respect to different attributes, often associated with weights that define relative importance of each one of them. A tool for system simulation developed by authors has been applied to evaluate how each alternative performs, in order to determine the scores that fill the matrix. After that phase, combining scores and weights, closeness to ideal solution has been determined using TOPSIS (Technique for Order Preference by Similarity to the Ideal Solution) method. Final rankings for different weights are then determined on the basis of closeness previously calculated.

3. Emerging technologies in marine sector

Regulatory framework is one of the main driving forces involved in ship's whole life cycle, because it can affect not only the design of future ships, but also vessels already operating. There is no clear unique solution for emissions reduction as required by IMO, because a lot of distinct alternatives are characterized by various positive and negative aspects. In the following sections different technologic solutions for energy generation are briefly described.

3.1. HFO

First alternative is the classical configuration of an all-electric cruise ship power plant, where Diesel Internal Combustion Engines (ICE) coupled with generators produce electric power. These engines burn HFO and emit great quantities of GHG, SO_x, NO_x and PM emissions. Fuel must be properly treated before being burned inside ICE because it's a residual product with high viscosity. First of all its heavier part is separated by a coalescing filter, and then it is heated to reach an acceptable viscosity (less than 20 cSt). This alternative is taken as reference to evaluate the others in the decision matrix.

3.2. HFO Scrubber

Second alternative allows complying with current emission regulations by means of an exhaust gas treatment system. Configuration of generative power plant is the same than the first alternative and fuel is the same too, but in exhaust gas ducts scrubbers are installed. Basically these equipment use water to absorb sulphur oxides in towers where reaction takes place and exhaust gases are washed. In January 2020, an estimate number of over 4000 scrubbers have been installed, covering almost 11% of global fleet by tonnage and 4.5% by number of ships. By the end of 2020 it is expected that these percentages will be increased up to 15% of global fleet by tonnage and to 6% by vessel count [13]. Scrubbers allow reduction of SO_x emissions and compliance with most recent IMO regulations, but let GHG, NO_x and PM emissions almost unchanged. By the way, this alternative allows complying with current regulations from IMO because it can assure a reduction of SO_x emission up to 98% while exploiting ICE and fuels that ship-owners have already installed. CAPEX and OPEX of scrubbers can change depending on ship size and type, but among all the alternatives scrubbers are characterized by a relatively short payback period.

3.3. LSFO – MGO

Another option is replacing HFO with liquid-phase fuel characterized by lower sulphur content. Two main types of marine bunker fuels are available: heavy fuel oils and distillates. First one comprehends HFO, LSFO (with 1%

mass on mass maximum sulphur content) and Ultra LSFO (ULSFO, with 0.1% mass on mass maximum sulphur content). LSFO are produced desulfurizing HFO or Intermediate Fuel Oil (IFO), while ULSFO could theoretically be produced in the same way, but it would be too expensive. So with term ULSFO usually are indicated fuels obtained by blending a small portion of heavy fuel oil and a bigger part of distillates, like Marine Diesel Oil (MDO). If heavy fuel oil is the prevalent part of the blending, marine fuel is called IFO followed by three digits indicating its viscosity in mm^2/s. A higher viscosity indicates a higher percentage of HFO and so a higher sulphur content. Marine fuel consisting only in distillates is known as Marine Gas Oil (MGO). Price of fuel increases with distillate percentage of overall fuel composition. An overview of marine fuel prices is given in Table 1 [14].

Table 1. Overview of marine fuel prices in \$/ton and in \$/kWh (between brackets) on 27th April 2020

Region	IFO380	IFO180	ULSFO	MGO
Americas Average Price	338.00 (31.20)	429.00 (38.60)	318.50 (27.90)	461.00 (38.80)
Europe, Middle East and Africa Average Price	217.50 (20.10)	380.10 (34.20)	293.50 (25.70)	361.00 (30.40)
Asia Pacific Average Price	226.00 (20.90)	403.00 (36.30)	322.00 (28.20)	454.50 (38.22)
Global Average Price	266.50 (24.60)	399.50 (36.00)	309.50 (27.10)	429.50 (36.10)

3.4. Methanol DF-ICE

Besides bunker fuels, other hydrocarbons are considered a viable options for marine application. One of these is methanol, an alcohol used mainly as precursor to common chemicals produced worldwide. It's liquid at ambient temperature, it does not produce SO_x emissions and also allows reducing both NO_x and PM. Its use in ICE properly modified is currently in a demonstration phase and some engines capable of burning methanol are currently installed and in operation on-board ships. In this alternative, a generative power plant composed by only methanol fueled ICE is considered. Methanol in the future could represent a net zero carbon emission fuel because it can be produced from renewable feed-stock or as an electro-fuel. Right now, methanol is produced almost entirely by natural gas. Its energy density is low, about 50%, than bunker fuel, so to store the same amount of energy bigger volumes are required.

3.5. LNG DF-ICE

When considering different fuels, a proven option as marine fuel is natural gas. Dual Fuel Internal Combustion Engines (DF-ICE) burning natural gas and MGO as pilot fuel are installed on-board ships from at least ten years, especially on LNG carriers, roll-on roll-off vessels and cruise ships. To comply with emissions limits, Diesel ICE can be replaced by DF-ICE burning natural gas and MGO as pilot fuel. Natural gas must be stored on-board as Liquefied Natural Gas (LNG) at about -163°C in cryogenic insulated tanks. This technology provides elimination of sulphur emission and a significant decrease in NO_x and PM emission, while cutting by almost 30% the amount of CO_2 produced by the engine. LNG has higher energy density then methanol, but still lower than bunker fuels. Also the fact that there is need to store it in cryogenic tanks makes fuel storage and handling more complex. For LNG installation principles IMO has provided an international standard named International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code). This standard provides precise guidelines for ships where natural gas is used as fuel, and prescribe for other low-flashpoint fuels an alternative design approach. Also draft interim guidelines for methanol are in development.

3.6. LNG + SOFC

The usage of gas as on-board fuel allows also the integration of different generative solutions that can furtherly cut emissions, and improve energy efficiency, like fuel cells. Fuel cells are electrochemical devices that combine batteries and engine benefits, because they do not have mechanical moving parts, so they do not generate vibrations, and can generate continuously electrical power when fuel is supplied. Fuel cells can be classified according to operating temperature and electrolyte used inside them. Among all technologies, PEMFC and SOFC are considered the most suited for marine installation for their good efficiency and their proved operating life [15] [16]. Each technology can work with different fuels. SOFC are characterized by high operating temperature (from 650°C to 1000°C) and can operate with both hydrogen and natural gas. When natural gas is used as fuel, CO_2 is present in exhaust gases, but emissions are lower compared to DF-ICE also thanks to a higher efficiency (up to 80%) obtained also via heat recovery. SOFC need a less expansive catalyst when compared to PEMFC thanks to higher operating temperature. Also the fact that can be fed by natural gas is an advantage in terms of design and safety, because it is a fuel already present on-board. In this configuration, DF-ICE is used to generate propulsive power, while SOFC is used for non-propulsive loads.

3.7. HFO + PEMFC

PEMFC can only operate with high purity hydrogen: this fuel allows generating electrical power without having emissions, but only water as by-product. These benefits are balanced by some disadvantages, mainly due to low energy density of hydrogen and platinum electrolyte, which is both expansive and sensitive to carbon monoxide poisoning. In order to have an acceptable amount of hydrogen available on-board, it must be liquefied and stored in cryogenic tanks at about -253°C (at 1 bar), but even in this extreme condition its energy density is lower than methanol and LNG. PEMFC are also characterized by low operating temperature (between 60°C and 80°C): this is good for safety but does not allow heat recovery. Fuel cells generally have some issues related to on-board installation. First, they generate direct current, while ships normally have an alternate current distribution network. In order to implement these technologies, DC/AC converters and other electrical devices need to be installed. Also, they do not have capability to sustain quick step load variations that can occur during normal ship operations, and so fuel cells should always be supported by a storage device, such as batteries or supercapacitors. For this reason both SOFC and PEMFC could be well suited to power cruise ship’s payload. In this alternative, PEMFC are dedicated to non-propulsive load while classic Diesel ICE burning HFO equipped with scrubbers provide propulsive power. Hotel loads are powered without having emissions of any kind both in navigation and in port, resulting in a high emission reduction and an advantage in case of possible further future emission restrictions.

3.8. HFO + Batteries

Batteries are a general category under which a lot of different energy storage systems are comprehended. Batteries are already present on-board ships as Uninterruptible Power Supply (UPS), so their scope is to guarantee power supply during transitional moments of emergency. Their adoption on vessels can only be considered if they are used as peak shaving source, to increase main engine efficiency, reduce fuel consumption and emissions. In any case, batteries cannot be used to continuously feed power loads. All of them suffer from recharging issue and from a general low energy density. In this alternative, batteries are implemented to improve Diesel ICE performances and reduce emissions by making them work only around their peak efficiency power. In this way, batteries would provide power peaks for limited period of times without having to run another ICE. Batteries can also store energy surplus generated for a limited period of time when an important load is disconnected from the electrical grid.

4. Tradeoff analysis about new generative solutions

The need to implement new generative technologies on-board is causing an increase in number of aspects that ship designers need to face since early-stage design. During the first design phase, named concept design, ship-owner’s qualitative requirements are considered for generating a set of feasible design alternatives. Among owner’s requests there is at present and probably even more in the future the need to have a less pollutant and more efficient ship in order to comply with national and international regulations. Ship-owner dream is to buy a better vessel, greener and obviously cheaper to acquire and to operate. Installation of different technical solutions for energy generation on-board is probably going to contrast with current systems and some ship-owner requests, so a trade-off analysis should be performed. In Figure 1, the flowchart of the trade-off analysis performed in this work is represented. The first data to be input in the model is ship’s operating profile and main characteristics (block ①). For this reason, a cruise ship with main data shown in Table 2 is taken as reference for further considerations. The vessel has an approximate installed power of 60 MW and a gross tonnage of about 150000 GRT (Gross Register Tonnage).

Table 2. Main characteristics of reference vessel

Length	[m]	~ 300
Beam	[m]	~ 40
Draught	[m]	~ 9
Tonnage	[GT]	~ 150000
Total installed power	[MW]	~ 60

Total installed power is mainly related to two big users: propulsion systems and non-propulsive loads. Approximately for a cruise ship like one with main data as shown in Table 2, non-propulsive users require about 15 MW, while propulsion at contractual speed needs about 30 MW. Cruise ship's daily operating profile can be simply modeled as 12 hours moored in port and 12 hours in navigation at the contractual speed. This is an approximation but can be useful to preliminary address how much each generative system is loaded during the day and is used as an input for the system simulation tool to calculate for example the size of generators and fuel tanks. In order to set this analysis, sixteen attributes have been identified in order to perform a preliminary evaluation of the performances of different alternative solution for energy generation on-board (block ②). Nine attributes are related to designers and how new ship generation systems can influence vessels characteristics in relation to general arrangement or other systems installed on-board. These are volume occupied by respective generative solution, weight of respective generative solution, hull structure modifications due to technologies implemented, ship stability changes due to weight and position of new machineries, ventilation system changes due to particular requirements for each alternative, fire safety, both active and passive systems, heat recovery system changes, fuel management system changes and electrical distribution system changes.

Three attributes describe how each alternative affects ship emissions, namely SO_x, NO_x, and CO_2 caused by new generative plant. Four attributes are related to ship-owner expectations and requests, like CAPEX, OPEX, perceived safety for crew and passengers, and payload capacity.

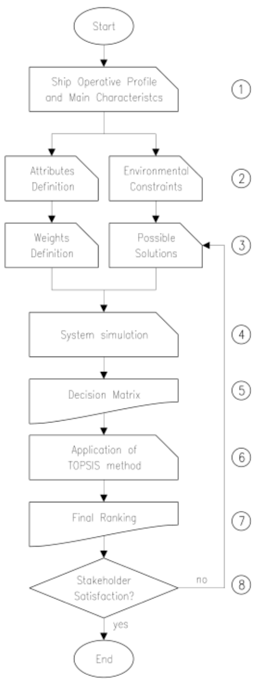

Figure 1. Flowchart of the trade-off analysis model

Weight factors have been assigned to all attributes, distinguishing three cases (block ③):

A. Equal importance to owner requirements and emissions, smaller weight factors to design implications. This scenario can describe a probable future in which owners will require ships compliant with emission regulations;
B. Highest weight factors to emissions, secondary importance to owner requirements and lowest weight factors to design implications. This scenario describes a future in which emissions will have highest importance. For example this is the case in which emissions will be not only regulated, but also punished with fees directly proportional to them;
C. Highest importance to design implications and lowest weight factors to emissions and owner's requirements. This scenario is included to represent how functional design phase is affected by different solutions and which one is the most desirable to ship designers.

According to inputs related to the specific ship under analysis, the simulation tool determines for each alternative energy generation system how it performs about each attribute (block ④). Knowing ship operative profile and the total power installed, system simulation tool calculates the size of generators, fuel tanks and total emissions. Knowing these data, impact on auxiliaries, like ventilation, fire safety, heat recovery, fuel management and electrical distribution system can be determined. Also CAPEX, OPEX and payload capacity are calculated at this stage. After this phase, the tool is able to evaluate hull structure modification, ship stability changes and safety perceived by passengers. Then, the decision matrix has been filled with scores using a 10 levels scale where a higher value means a better performance for the associated attribute (block ⑤). Output of system simulation tool has been translated into a score because results it can be considered as an initial estimation of the real attribute's value, since simulation is performed during concept and preliminary design phases. In the decision matrix rows represent attributes while columns stand for present and future generative solution described before. First column is taken as reference to evaluate how other solutions perform regarding each attributes. If a generative solution has a greater score in an attribute than another, it means that regarding that topic it performs better. Decision matrix is represented in Table 3.

Table 3. Decision matrix

	HFO	HFO Scrubber	LSFO - MGO	Methanol DF-ICE	LNG DF-ICE	LNG + SOFC	HFO + PEMFC	HFO + Batteries
Volume occupied	5	4	4	4	3	3	3	2
Weight	5	5	5	5	4	3	3	2
Hull Structure	5	5	5	5	4	4	4	4
Ship Stability	5	5	5	5	6	6	6	6
Ventilation	5	5	5	5	4	4	3	3
Fire Safety	5	5	5	4	4	4	4	4
Heat recovery	5	5	5	5	5	6	4	4
Fuel management	5	5	6	4	4	4	3	5
Electrical Distribution	5	5	5	5	5	6	6	4
SO_x emissions	5	8	9	8	9	9	8	8
NO_x emissions	5	5	5	7	8	8	7	6
GHG emissions	5	5	5	6	6	7	7	6
CAPEX	5	4	5	4	4	3	3	3
OPEX	5	5	4	4	6	6	4	5
Safety	5	5	5	4	4	4	3	4
Payload	5	4	5	4	4	3	3	2

For example, considering NO_x emissions, each solution has a score equal or higher than HFO solution (so each one emits the same or less nitrous oxides), but best ones in this attribute are solutions where LNG is used as primary fuel

(Gianni, Pietra and Taccani 2020). Another good example is electrical distribution. Solutions that include fuel cells installation (both PEMFC and SOFC) can benefit of a low voltage distribution via continuous current and so they reach a higher score for this attribute. "HFO + Batteries" on the other side would just add other equipment, like converters and transformers, to an already established electrical grid. Batteries are not capable to provide multi Megawatt power for multiple hours or even days, as requested onboard cruise ships. These energy storage systems should otherwise be used to improve efficiency of ICE storing or releasing power while letting Diesel generators run on their best efficiency rating..

A comparison of volumes occupied for storage of fuels of each possible solution is shown in Figure 2. "HFO Scrubber" scores 4 in attribute "Volume occupied" because, confronted with "HFO" solution, the system for emission abatement is bulky and so this solution occupies more volume. Liquid bunker fuels have high energy density when also storage system is included in calculations. They do not require specific storing devices, such as LNG or hydrogen that need insulated cryogenic tanks. For this reason liquid bunker fuels occupy smallest volume among alternatives. Also they have a small influence in total volume required by most bulky solutions, namely "HFO + PEMFC" and "HFO + Batteries". It must be noted that battery solution does not require another machinery to generate power, because batteries are not only capable of storing energy, but also of its generation. Other volumes are referred only to means of energy storage and not to conversion systems, like engines or fuel cells.

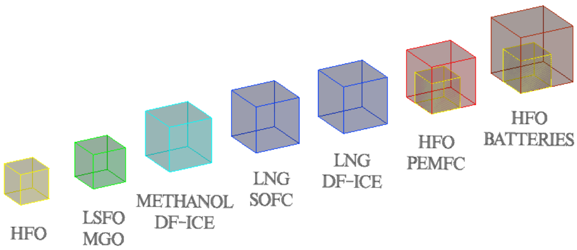

Figure 2. Volumes occupied by fuel necessary for 1 day of operation

After decision matrix have been filled, TOPSIS method has been used to determine a ranking for the alternatives under evaluation (block ⑥). Each element of the matrix have been normalized using equation (1), where y_{ij} is the score of the jth alternative about ith attribute, $\bar{y}_{ij}$ is the normalized score and n stands for number of alternatives.

$$\bar{y}_{ij} = \frac{y_{ij}}{\sqrt{\sum_{j=1}^{n} y_{ij}^2}} \qquad (1)$$

After having normalized decision matrix and having established three different weight sets, each element have been multiplied by its associated weight (2). With this operation three different weighted normalized decision matrices have been determined. In equation (2), , w_i for the ith weight and $\bar{v}_{ij}$ for the normalized weighted score.

$$\bar{v}_{ij} = w_i \cdot \bar{y}_{ij} \qquad (2)$$

At this point ideal (A^+) and anti-ideal (A^-) solutions must be determined as the collection of the best and worst values of the attributes as shown in equations (3) and (4), where m stands for the number of attributes.

$$A^+ = \left\{max\, \bar{v}_{ij}\, , i = 1,2, \dots, n\right\} = \{v_1^+, \dots, v_m^+\} \qquad (3)$$

$$A^- = \left\{min\, \bar{v}_{ij}\, , i = 1,2, \dots, n\right\} = \{v_1^-, \dots, v_m^-\} \qquad (4)$$

Than the separation distance from ideal and anti-ideal solution has been calculated for each alternative design solution by the 2-dimensional Euclidean distance with equations (5) and (6).

$$S_i^+ = \sqrt{\sum_{i=1}^{m} \left(\bar{v}_{ij} - v_i^+\right)^2} \quad (5)$$

$$S_i^- = \sqrt{\sum_{i=1}^{m} \left(\bar{v}_{ij} - v_i^-\right)^2} \quad (6)$$

The last step of the TOPSIS method is the calculation of the closeness of each alternative with respect to the ideal solution determined with the equation (7).

$$C_i = \frac{S_i^-}{S_i^- + S_i^+} \quad (7)$$

Closeness can range from 0 to 1 and a higher value corresponds to a better alternative. Results for each case are shown in Table 4, where for each solution are listed closeness and ranking (block ⑦).

Table 4. Distances from ideal solution and ranks

	A		B		C	
	C	Rk.	C	Rk.	C	Rk.
HFO	0.59	3	0.28	8	0.69	2
HFO Scrubber	0.56	5	0.42	7	0.65	3
LSFO - MGO	0.63	2	0.50	5	0.69	1
Methanol DF-ICE	0.56	4	0.64	3	0.61	4
LNG DF-ICE	0.66	1	0.76	2	0.52	5
LNG + SOFC	0.54	6	0.78	1	0.48	6
HFO + PEMFC	0.39	8	0.64	4	0.34	7
HFO + Batteries	0.33	7	0.49	6	0.28	8

When analyzing case A, three preferred alternatives are “LNG DF-ICE”, “LSFO-MGO” and “HFO”. The reasons behind these standings are related to the relative low or neutral impact that these alternatives on owner requirement and the beneficial impact on emissions that “LNG DF-ICE” and “LSFO-MGO” have, especially on SO_x ones.

When maximum importance is assigned to emission reduction, as shown in columns B, “LNG DF-ICE”, “LNG DF-ICE + SOFC” and “Methanol DF-ICE” are the preferred options. Natural gas is a proved good option as fuel for ships, because has been already installed, doesn’t affect heavily payload capacity and has a competitive price, both in terms of CAPEX and OPEX. Also, without needing an exhaust gas treatment system, LNG provides a good decrease of noxious emissions PEMFC and batteries, on the orher hand, do not produce any emission while generating electrical power. These benefits are influenced by bad performances regarding volumes occupied, weight added and reduction of payload onboard, so design alternatives “HFO PEMFC” and “HFO + Batteries” are not among top three highest degree of closeness.

When functional design impact is considered most important aspect, as represented in columns C, traditional and well-known solutions for power generation on-board ships have highest rankings, leaving especially “HFO + PEMFC” and “HFO + batteries” as less desirable solutions. These technologies occupy big volumes and have a significant weight when they need to generate a lot of energy. Also ventilation system is heavily affected for safety reasons. For PEMFC fuel management is also a possible problematic feature, while for batteries electrical auxiliaries must be considered as additional complexity added to the system. These considerations must be shared with all stakeholders involved in ship’s whole life cycle in order to define if everyone is satisfied of results obtained (block ⑧). If someone is not happy with the outcome, new solutions must be generated and evaluated with the same method described.

Best solution for the future must take into consideration ship’s type and operating profile, because these boundary conditions can influence the choice of preferred solution among the one cited in this paper. Also, if new limitations or taxations on emissions will be issued from national or international organizations some technologies will became more attractive.

5. Conclusions

In these years, ships are undergoing a lot of changes, in particular new requests of ship-owners are influencing the generative power plant, and inevitably the entire ship design. To address these new requests, also due to international rules and regulations, a system thinking approach must be adopted. To know how different solution designed to reduce emissions caused by vessels can influence whole ship's behavior, these changes must be considered since early-stage design. A decision matrix has been set up to evaluate how different alternative power generative solutions perform regarding different aspects related to ship design, emissions and owner's requirements. System simulation has been performed in order to fill out with scores the decision matrix, assessing all attributes considered in this work Since decision matrix is sensitive to weight factor, three different sets of importance have been assigned to attributes in order to compere results. To rank the alternatives, TOPSIS method has been applied. Solutions implementing LNG resulted most desirable because they had the highest closeness to ideal solution both when emissions have maximum importance and when pollution and owner's requests have biggest weights.

When functional design impact is given maximum importance, low sulphur marine bunker fuels and scrubbers reached highest standings. Attractiveness of each solution now and in the future depends on ship operating profile, vessel's type, possible new emission's limitations and taxes proportional to pollution.

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