

Decision-making model for propulsion system selection

Modelo de toma de decisiones para la selección del sistema de propulsión

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Abstract

History it has become evident that the military industry and its thriving action has generated change and development in different areas, and it is to be expected that a project as ambitious as the Strategic Surface Platform - PES focuses on the impact that internal combustion systems can generate in the design, therefore an evaluation model is developed for the selection of the propulsion system of the platform, which was based on the life cycle cost and performance of the main mechanical equipment, providing an additional tool for decision making. The cost side was estimated by breaking down the ROM (Rough Order of Magnitude) acquisition costs, maintenance costs and fuel and lubricant consumption costs, which leaves the performance side evaluated under the technical characteristics, considering the criteria of performance, reliability, delivered power and installation footprint; without leaving aside the mandatory requirements such as IMO TIER III gas emissions, reduction of the acoustic signature and the use of redundancy.

Key words: Maritime pollution; Greenhouse gases; Cost Effectiveness; Energy Saving; Propulsion System.

Resumen

A través de la historia se ha hecho evidente cómo la industria militar y su pujante accionar ha generado cambio y desarrollo en las diferentes áreas, y es de esperar que un proyecto tan ambicioso como lo es la Plataforma Estratégica de Superficie – PES se enfoque en el impacto que los sistemas de combustión interna pueden generar en el diseño, por lo anterior se desarrolla un modelo de evaluación para la selección del sistema de propulsión de la plataforma, el cual fue basado en el costo del ciclo de vida y el desempeño de los equipos mecánicos principales, brindando una herramienta adicional para la toma de decisiones. La arista del costo se estimó desglosando los costos de adquisición del tipo ROM (Rough Order of Magnitude), costos de mantenimiento y costos de consumo de combustible y lubricante, lo que deja la arista de desempeño evaluada bajo las características técnicas, considerando los criterios de rendimiento, confiabilidad, potencia entregada y huella de instalación; sin dejar a un lado los requisitos de obligatorio cumplimiento como lo son las emisiones de gases IMO TIER III, la reducción de la firma acústica y el empleo de la redundancia.

Palabras claves: Contaminación marítima; Gases de efecto invernadero; Rentabilidad; Ahorro de energía; Sistema de propulsión.

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Introduction

The maritime industry has received a growing demand in the variation of propulsion system configurations, which are not only limited to seeking significant fuel savings, but also focus their efforts on the optimization of environmental and performance variables, which directly and indirectly affect the development of the logistics chain to produce vessels. The military industry is no stranger to these processes, and, through the navies of the different nations, it is also taking part in these requirements, generating greater demands on each of the companies involved.

In this way, the increase in standards and regulations, force to establish strict acceptance criteria on the different configurations of propulsion systems traditionally used in the maritime industry, criteria such as reduction in emission percentages, variation in speed ranges, multi-mission units, reduction in crews, technical requirements, among others.

On the other hand, facing the challenges caused by the scarcity of fossil fuels and the problematic of its effects on global warming, as mentioned by Zhu (2018), for the design in the process of propulsion system optimization, international regulations have been promulgated, such as the energy efficiency design index (EEDI) and the ship energy efficiency management plan (SEEMP), aimed at reducing the growth rate of fuel consumption and greenhouse gas (GHG) emissions in the shipbuilding sector (Zhu *et al.*, 2018). Thus, different authors have shown the need to develop energy efficient ships, working in accordance with environmental regulations and giving rise to proposals for hybrid propulsion and generation designs and configurations (Geertsma, Negenborn, *et al.*, 2017; Geertsma, Vollbrandt, *et al.*, 2017).

Therefore, and in summary, the objectives achieved in the development of this work include:

- Development of a viable and robust methodology for the evaluation of a life cycle model (both in costs and environmental impacts) and performance model for different

propulsion system arrangements.

- To structure the evaluation model of the propulsion configurations CODAD (Combined Diesel and Diesel), CODOE (Combined Diesel or Electric), CODAG (Combined Diesel and Gas) and CODOG (Combined Diesel or Gas) with growing tendency in the market, which allows the Colombian Navy to technically identify the optimal propulsion configuration for the fulfillment of its mission.
- Through the appropriate parameters perform a comparative analysis of the propulsion configurations CODAD, CODOE, CODAG and CODOG offered by the market, using the propulsion evaluation model proposed by (Morales E. *et al.*, 2016b, 2016a). The results of this analysis will provide the Colombian Navy with sufficient arguments for decision making in the selection of the propulsion system configuration.

The structure of the article begins with a description of the decision-making model and the approaches available in the literature (research background), followed by a description of the life cycle cost and performance model, based on the analysis of four different propulsion system arrangements currently available in the market. Finally, based on the results obtained, conclusions are proposed showing the arrangement selected for the PES project, which best fits the established design parameters.

Theoretical Framework.

It is clear that there is a progressive trend towards partial or full electric propulsion, examples of which have been the British Navy's Type 23 ASW frigate, the German Navy's F125, the Spanish Navy's F110, the Italian and French Navy's FREMM, the Republic of Korea Navy's FFX-II frigate, and the Finnish Navy's SQ2020 frigate programs (Ohmayer, 2012; Royal Navy U.K., *n.d.*; Silatan *et al.*, 2014).

Despite this trend towards hybrid systems, making the decision to turn to their implementation becomes a long and tedious process that includes many angles (from the design phase to the

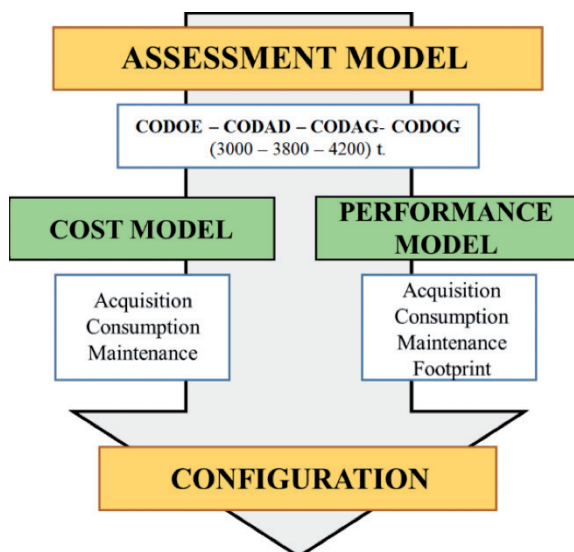
retirement phase), even more so, knowing that the decisions made during the early design phases will generate a significant impact throughout the entire life cycle. This is why this approach has become a design tool for strategic decision making throughout the entire life cycle (Zhu et al., 2018).

Table 1. PES design parameters.

General data	Value
Life time (years)	30
Hours of operation per year	2500
Displacement (ton)	3000-3800-4200
Crew (und)	100 trip +30
Maximum range	4000nm@14.5knots

In this sense, the evaluation model for the selection of the ESP propulsion system, shown in Fig. 1, was based on the parameters established in Table 1, considering the cost in the projected 30-year life cycle, associating the costs of acquisition, maintenance and operation of the equipment, also considering the cost of fuel and lubricant, as well as the performance of each configuration, evaluating the performance, reliability, power and footprint.

Fig. 1. Model selection propulsion system.



Power Analysis.

The development of a decision making model for the selection of the propulsion system became an essential part of the development process of the Strategic Surface Platform; managing to meet the requirements of speed and power of the ship, where undoubtedly, the Colombian Navy has considered each of the variables commonly evaluated in the maritime industry, such as rising costs or scarcity of fossil fuels, which lead to rethink the traditional systems or arrangements installed on warships, making these decisions are oriented towards more efficient solutions. However, the challenges for this process increase considering the additional demands, such as the speed-power profiles at which ships usually work, variability in electrical power ranges, and even the lack of resources for asset maintenance during the life cycle, which make the optimization process even more complex under this scenario.

Based on this, an evaluation was made of the propulsion system configurations existing in the market used in modern platforms, such as CODOE, CODAD, CODAG and CODOG, including the recommended operating variables for each gear at different platform speeds, analyzing acquisition costs, maintenance costs, dimensions, weights, technical specifications, and fuel consumption.

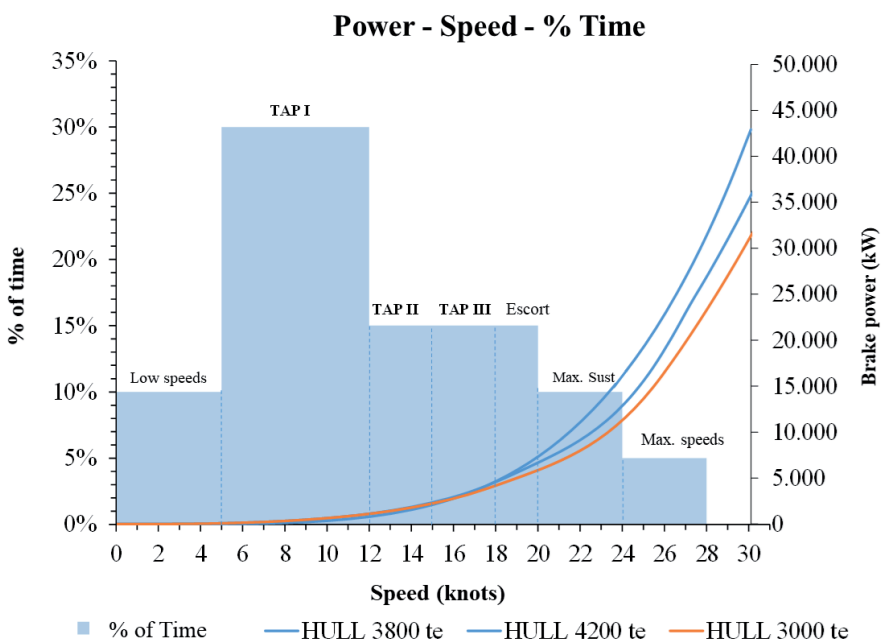
For the purposes of this analysis, propulsion configurations were selected for three types of vessels with expected displacements of 3000, 3800 and 4200 tons, considering high power diesel engines to supply each of these requirements, evaluating seven (07) possible speed ranges for each of the selected displacements as shown in Table 2.

Likewise, using the MaxSurf tool™ in its Resistance module, the statistical methodology for displacement vessels established by Fung and Holtrop (Caputo, 2010; Holtrop & Mennen, 1977) was applied. (Caputo, 2010; Holtrop & Mennen, 1977). The statistical methodology for displacement vessels established by Fung and Holtrop (Caputo, 2010; Holtrop & Mennen, 1977) was applied to obtain the predictions of drag and

Table 2. Power required for each array.

Operation	Speed (knots)	PB (kW)	PB (kW)	PB (kW)
Low Speed	5	104	103	19
TAP I	12	1203	1215	819
TAP II	15	2217	2315	2148
TAP III	18	4554	5025	4721
Escort	20	6040	6893	7444
Max. Sustained	24	12590	14353	16364
Max. Speed	28	23622	27260	31853

Fig. 2. Brake power curve and % operating time as a function of speed profile.



effective power, as well as the power to the brake using a total efficiency margin of 50%.

Configuration Analysis.

CODOE configuration

In this configuration, four engines satisfy the different speeds of the operational profile, requiring four diesel engines (MD) for maximum speed and two engines (diesel or electric) (G) for transit and patrol speeds, analyzing five different engine arrangements and brands.

CODAD configuration

For this configuration, four diesel engines satisfy the different speeds of the operational profile, requiring all four for maximum speed and two engines for transit and patrol speeds, also analyzing five different engine arrangements and makes.

CODAG configuration

In this case, the gas turbine (TG) provides the power required to replace the engines, however, the gearbox (ER) becomes a critical element, since failure would leave the vessel without propulsion.

Fig. 3. CODOE Configuration Representation.

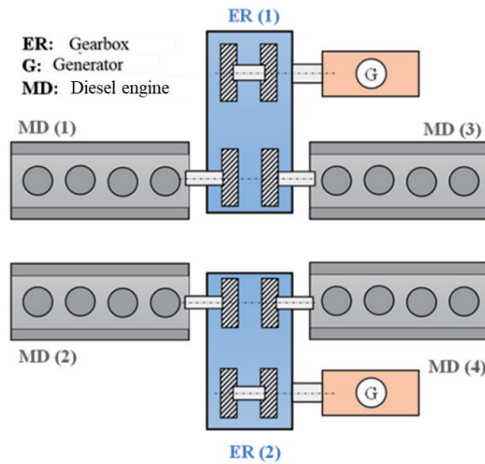


Fig. 4. Representation of CODAD configuration.

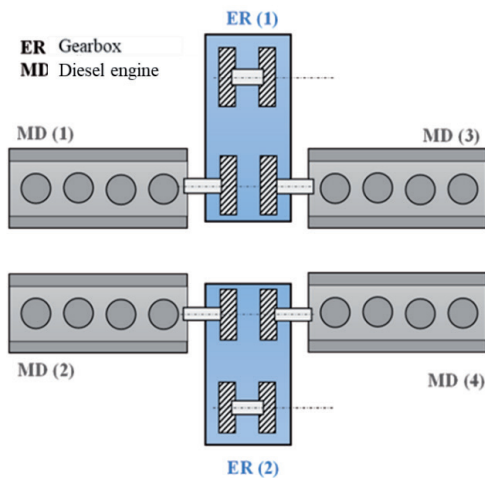
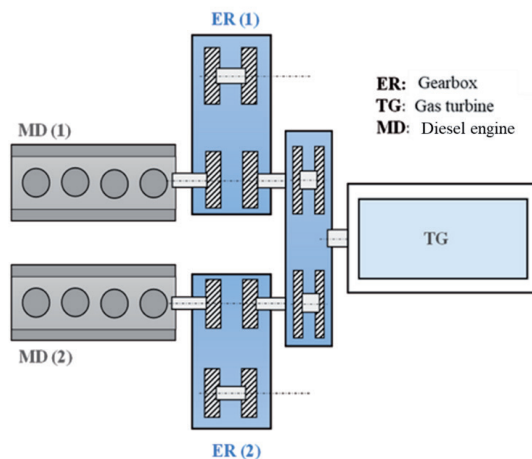


Fig. 5. Representation of CODAG and CODOG configuration



CODOG configuration

The distribution of equipment for this arrangement is the same as in CODAG, the difference lies in the requirements of the turbine to reach maximum speed without the use of diesel engines, additionally the box will have the mechanism to clutch or not the diesel engines. Eleven different engine arrangements and brands were also analyzed.

In this sense, a total of 30 different arrangements were evaluated for each of the proposed vessels of 3000, 3800 and 4200 tons, as shown in Table 3.

Cost Model.

The model estimated the relative costs of acquisition and operation in each proposed configuration, through the analysis of the cost of acquisition of type (ROM), maintenance and consumption of fuel and lubricant, determined for each of the stipulated configurations (to facilitate the compression of the process, the results obtained for the displacement of 3000 t. are presented (see Fig. 6), as follows:

- Acquisition cost: includes the cost of propulsion engines, i.e., each configuration includes the cost of diesel engines, electric motors and/or gas turbines.
- Consumption: the calculation of fuel consumption in the life cycle is considered for 30 years. This consumption was calculated according to the specific fuel consumption information in gr/kWh of the equipment of each configuration, using the established operational profile.
- Maintenance: maintenance was considered for a period of 30 years, including consumables for the recommended cyclic or general preventive maintenance, and considering the design parameter of 2,500 operating hours for this projection.

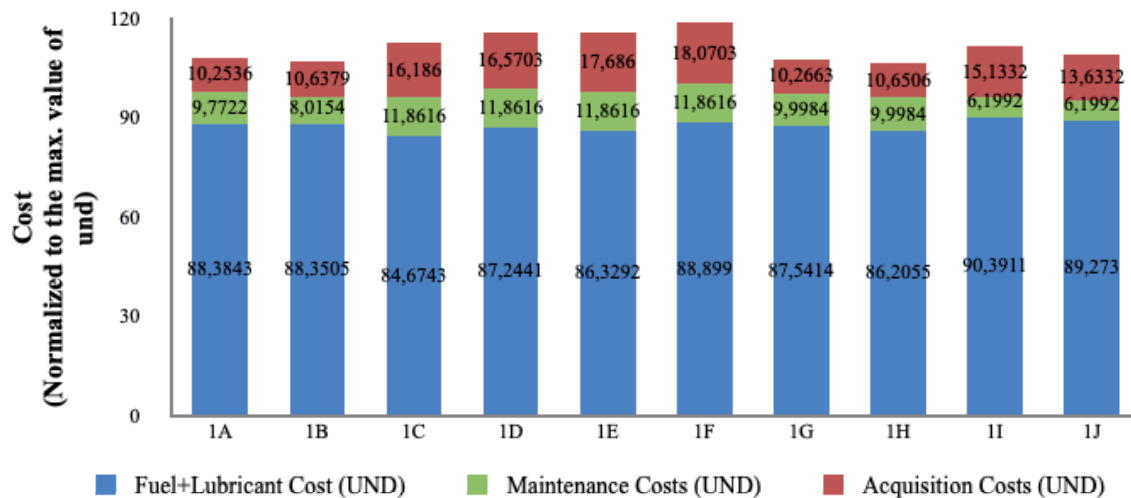
Performance Model.

To evaluate the technical characteristics of the propulsion configurations and quantitatively compare the different proposals, the performance model was developed using the analytical

Table 3. Configurations analyzed by displacement.

3000 t.		3800 t.		4200 t.	
Code	Configuration	Code	Configuration	Code	Configuration
1A	CODAD 3	2A	CODOE 3	3A	CODAD 2
1B	CODOE 3	2B	CODOG 3	3B	CODAG 2
1C	CODAG2	2C	CODOG+PTI 3	3C	CODOG 2
1D	CODAG + PTI 2	2D	CODAG 2	3D	CODAD 1
1E	CODOG 2	2E	CODOG 2	3E	CODOE 1
1F	CODOG + PTI 2	2F	CODAG 2	3F	CODOG 1
1G	CODAD 1	2G	CODOG 2	3G	CODAG 1
1H	CODOE 1	2H	CODAG+PTI 2		
1I	CODOG 1	2I	CODOG+PTI 2		
1J	CODAG 1	2J	CODAD 1		
		2K	CODOE 1		
		2L	CODOG 1		
		2M	CODAG 1		

Fig. 6. Life Cycle Cost Reference Image - 3000 t displacement.



hierarchical process (AHP) (see Fig. 7), which allowed establishing levels according to each configuration, with weightings in the criteria and subcriteria established at each level, to give greater specificity to the determination of performance in the situation analyzed.

For the performance model is analyzed (see Fig. 8):
 I. The (geometric) footprint generated by the propulsion system where the weight/power ratio and the area required inside the engine rooms are immersed.
 II. Power behavior at unit-relevant speeds

Fig. 7. Tree structure - evaluation criteria.

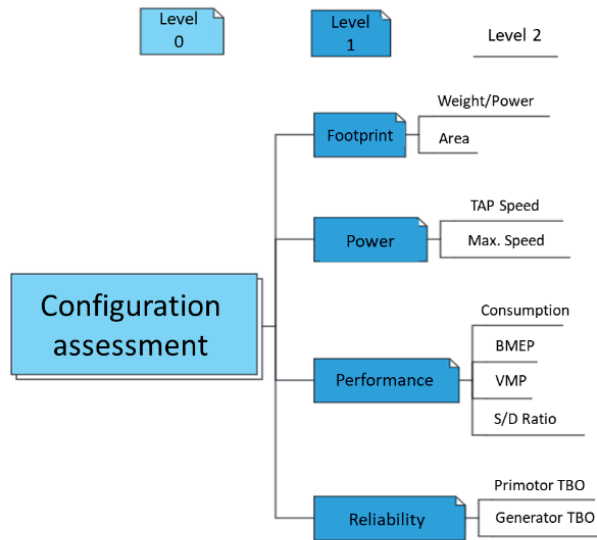
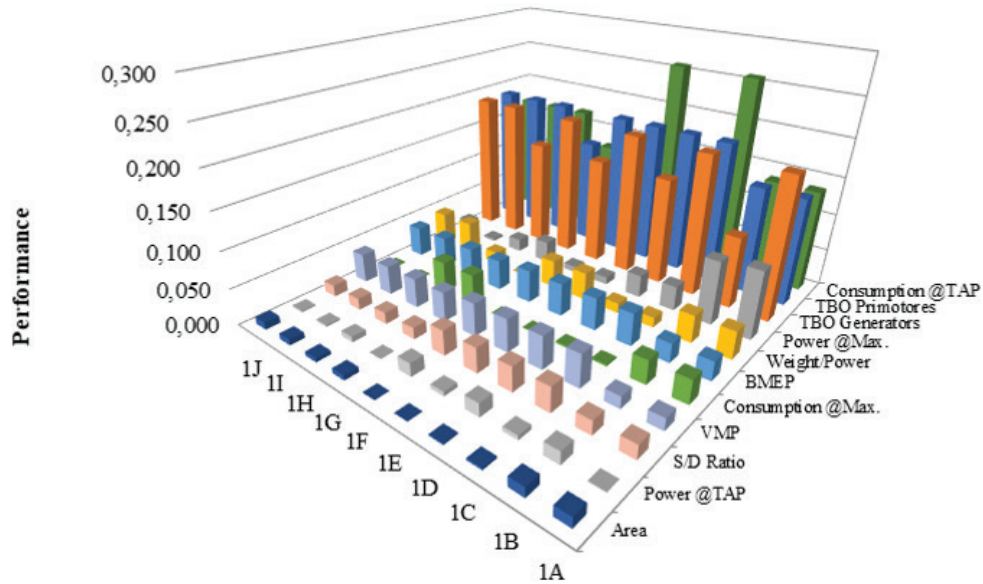


Fig. 8. Reference image of the Performance Result - 3000 t displacement.



(TAP and maximum).

III. Performance is evaluated from four aspects such as fuel consumption, brake mean effective power (BMEP), piston mean velocity (VMP) and piston stroke to diameter ratio (S/D).

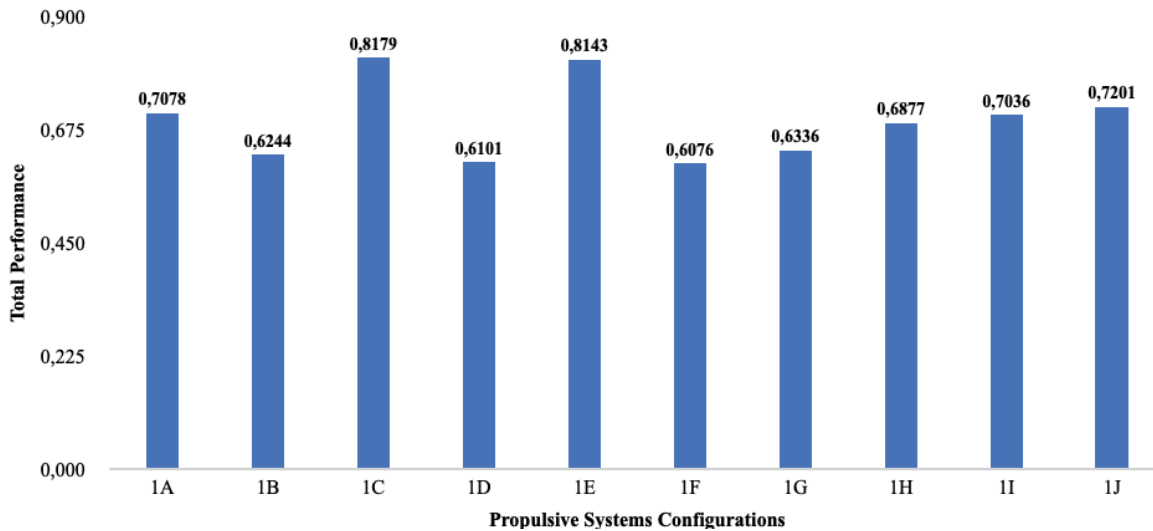
IV. Reliability presented as the time between overhauls (TBO) for prime movers (diesel engines and turbines) and for generators.

Likewise, using the matrix of pairwise comparisons (AHP methodology) of technical characteristics of each configuration evaluated by the Corporación de Ciencia y Tecnología para el Desarrollo de la Industria Naval Marítima y Fluvial - COTECMAR and the panel of experts of the Colombian Navy - ARC, the weights of each criterion were determined, to subsequently evaluate the

Table 4. Curves by criteria and levels.

Criteria	2do Level	3er Level	Curve
Performance	Consumption	Transit and Patrol	Exponential Dec
		Maximum Speed	Exponential Dec
	BMEP		Logarithmic
	VMP		Logarithmic Dec
	S/D ratio		Linear
Reliability	TBO Primotores		Linear Dec
	TBO Generators		Linear Dec
Power	Transit and Patrol		Exponential Dec
	Maximum Speed		Exponential Dec
Footprint	Weight/Power Area		Logarithmic Dec
			Linear Dec

Fig. 9. Reference image of Comparison of Alternatives - 3000 t displacement.



alternatives according to the available information, the latter using the ExpertChoice software™. In this way, each level, criterion and subcriterion was weighted through curves (linear, linear decreasing, logarithmic, logarithmic decreasing, exponential, exponential decreasing, sigmoidal and sigmoidal decreasing), according to the choice of the panel of experts, based on the real needs of the Colombian Navy and that which best fits the requirements of Table 4.

From this analysis and the respective weightings for each level, the total performance shown in Fig. 9 is obtained.

Result Analysis.

The results of the cost and performance models were analyzed and determined for each arrangement and for each displacement, as follows:

- Displacement of 3000 t., Fig. 10: the most economical configurations for this situation are 1H and 1B (CODOE); and 1G and 1A (CODAD), the most expensive being 1F (CODOG) and the best performing were 1C (CODAG) and 1E (CODOG).
- Displacement of 3800 t., Fig. 11: the most economical configurations for this situation are 2K (CODOE); and 2J (CODAD), with the most expensive being 2C (CODOG+PTI) and the highest performance being 2H (CODAG+PTI) and 2I (CODOG+PTI).
- Displacement of 4200 t., Fig. 12: the most economical configurations for this situation are 3E (CODOE); and 3A (CODAD), with

3B (CODAG) being the most expensive and 3A (CODAD) and 3B (CODAG) being the highest performing.

Regarding costs, in general the CODAG and CODOG configurations represent a low maintenance cost related to the low frequency required for the execution of major repairs (Overhaul) during their useful life, however, the overall cost of the gas configuration is high, emphasizing the initial acquisition cost compared to the CODAD and CODOE configurations. On the other hand, when analyzing fuel and lubricant consumption, there is no marked trend that depends on the type of arrangement; however, its

Fig. 10. Results with 3000 t displacement.

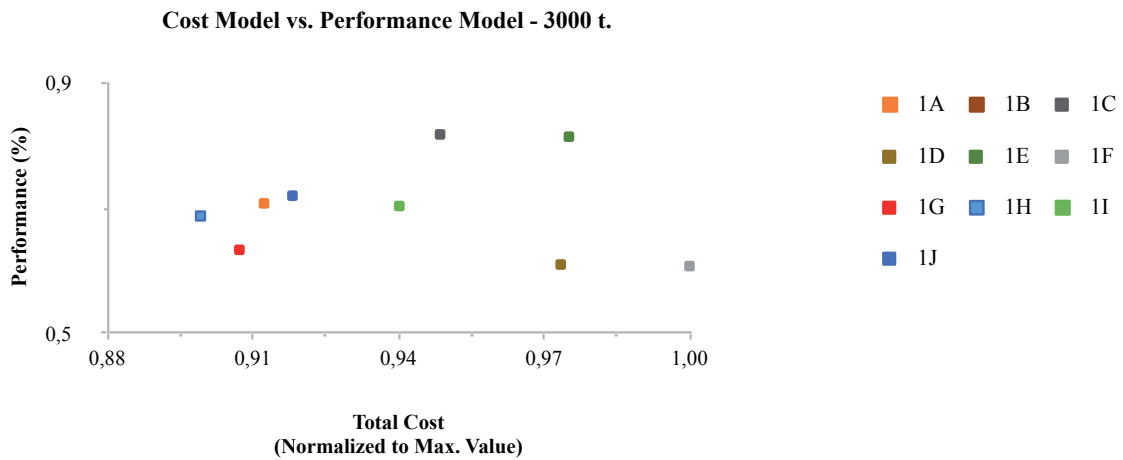


Fig. 11. Results with 3800 t displacement.

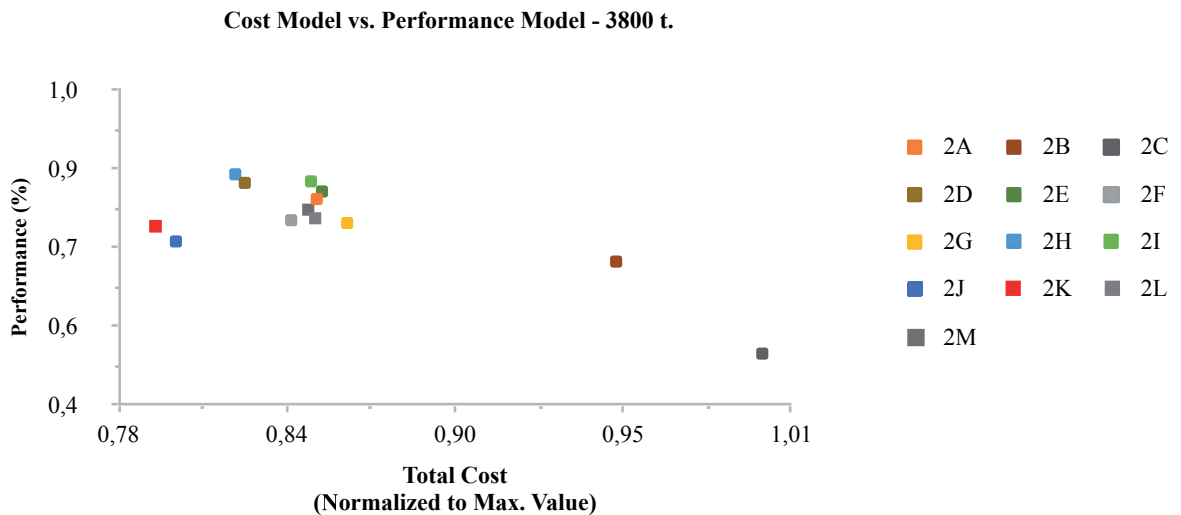
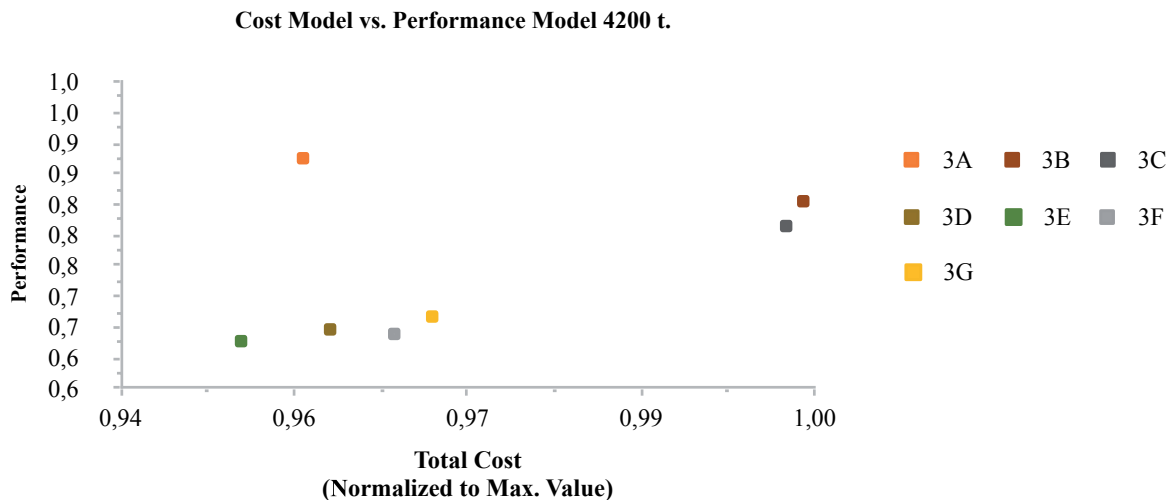


Fig. 12. Results with 4200 t displacement.



impact is directly related to the use profile, engine brand, among others.

Other analysis factors.

Emission control: is considered as a vital variable within this analysis, which is aligned with the compliance of the International Convention for the Prevention of Pollution from Ships (MARPOL) - Annex IV in the TIER III level required for ships built after 2016, in this sense, based on the results presented, aligned with what has been exposed by (Aakko-Saksa et al., 2023; Lindstad & Sandaas, 2016) the percentage of carbons, carbon dioxide, nitrous oxides (NOx), sulfur oxides (SOx), among others, rise mainly at low speeds and operating powers.

The above leads us to the operation profile analyzed (see Fig. 2) which will maintain low speeds 10% and speeds below 18 knots 70% of the time, this urges us to evaluate efficient alternatives that allow us to mitigate or reduce emissions levels, this is how the implementation of a hybrid system, in alternative combinations CODOE - CODAD, in this case one of diesel-electric and diesel engines (CODELAD), shows significant advantages that provide solutions to some problems raised by optimizing the operation of the machinery in each of the profiles according to the operational need and thus ensuring the

proper operation in controlled environmental areas, without impacting their performance and seeking the best cost-benefit ratio (Ammar & Seddiek). (Ammar & Seddiek, 2021).

On the other hand, (Silatan et al., 2014) mentions that the high efficiency of hybrid systems (due to the variation of the configuration adapted to the speed profile) leads to low fuel consumption and causes a reduction of environmental pollution, achieving lower emissions of 4.3 gr/kwh of NOx and less than 1% of Sox, required to operate in the Emission Control Zone, contributing to regulatory compliance for the units where it is implemented.

Signatures: are not considered as a design parameter in the present work, even so, it is sought to maintain directives in Grade A equipment assemblies that classify propulsion equipment as necessary equipment for the safety and combat capability of the ship, in this way a CODELAD configuration presents significant advantages, such as the reduction of acoustic, infrared and electromagnetic signature, up to TAP II speeds (see Table 2), where Diesel-Electric propulsion is used (Barlas & Azmi Ozsoysal, 2001). (Barlas & Azmi Ozsoysal, 2001).

Redundancy: has been considered in the design of the vessels as one of the parameters that has been handled as a restriction, where it is necessary

the ability to maintain the vessel's operations even after losing an engine room. This study considers the distribution of the electrical load in four (04) generators and that they comply with the N-1 restriction, i.e. that due to redundancy and separation, two (02) generators are located in two (02) engine rooms separated by at least one watertight bulkhead and that when losing one of these rooms, the remaining generators in operation are capable of satisfying the vital loads of the entire vessel.

Conclusions

The analysis presented in this paper is an extract of the activities developed by the ARC and COTECMAR work team, who have generated several tools, among them, the decision-making model for the selection of the propulsion system of the Strategic Surface Platform, which represents one of the steps that the program has fulfilled for the selection and validation of the platform systems, and through which it can be concluded:

- The model highlights that the CODAD (1B and 1H for 3000 t.; 2J for 3800 t.; 3A for 4200 t.) and CODOE (1B and 1H for 3000 t.; 2K for 3800 t.; 3E for 4200 t.) configurations prove to be the most economical solutions, mainly due to the low acquisition cost and low consumption presented by the configurations, in addition to their adaptability to the operating profile of the platform.
- Considering the above, the beneficial cost/performance ratio found in each of the CODAD and CODOE configurations and their hybrid CODELAD implementation, contributes to the mitigation of emissions generation as reported by different authors and thus facilitates compliance with the International Convention for the Prevention of Pollution from Ships (MARPOL) - Annex IV at TIER III level.
- Finally, for the PES project it is imperative to have a solution with a low life cycle cost, which allows its acquisition and maintenance throughout its life cycle. Therefore, and despite having a higher weight compared to

other alternatives that use equipment such as turbines, the CODAD and CODOE solutions became the most appropriate for the selection, in addition to the hybrid configuration CODELAD, for its significant improvements in aspects of fuel consumption and reduction of signatures, factors of great importance for the Strategic Surface Platform.

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