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SCIENCE & TECHNOLOGY
CIENCIA & TECNOLOGÍA DE BUQUES

COTECMAR
COLOMBIA

Vol. 15 - N.° 29
(1 - 98) July 2021

ISSN 1909-8642 (Impreso)
ISSN 2619-645X (Online)

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SCIENCE & TECHNOLOGY

CIENCIA & TECNOLOGÍA DE BUQUES

Volume 15, Number 29 - July 2021 ISSN 1909-8642 (Impreso) - ISSN 2619-645X (Online)

Ship Science & Technology is a specialized journal in topics related to naval architecture, ship design, hydrodynamics, dynamics of ships, structures and materials, vibrations and noise, technology of ship construction, ocean and marine engineering, standards and regulations, oceanography, maritime and river transport, and port infrastructure. Every six months, the journal publishes scientific papers that constitute an original contribution in the development of the mentioned areas, resulting from research projects of the Science and Technology Corporation for the Naval, Maritime and Riverine Industries, and other institutions and researchers. It is distributed nationally and internationally on paper and online.

A publication of

Corporación de Ciencia y Tecnología para el Desarrollo de la Industria Naval, Marítima y Fluvial - COTECMAR
Electronic version: www.shipjournal.co

COTECMAR
COLOMBIA

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Printed by C&D Publicidad & Marketing. Bogotá, D.C.

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Editorial Note

Cartagena de Indias, July 30, 2021.

Greetings to all our readers, once again we come to you through our Ship Science and Technology Journal, to publish the results of the main research in the naval, maritime and river fields, developed by researchers whose academic work drives the growth and the generation of new knowledge in these topics.

In this new edition of the journal, we present topics of academic interest related to Shipbuilding 3D CAD Tool as an Integrated Solution from Concept to Production, Atmospheric and Economic Impact of LNG fueled Dredging. The Argentine Case, Creating a rule framework for the green revolution, the Study of maneuverability and behavior at sea of the Light Cabotage and Logistics Support Vessel (BALC-L), the improvement of shipbuilding with the Internet of Ships concept, the multi- physics Analysis of a pressurized water reactor for military ships, and the design and validation by the Finite Element method of the structure of a low draft boat for river reconnaissance.

We hope that these topics of academic and professional interest meet your expectations and we reiterate our permanent and cordial invitation to continue building science and knowledge together with our Journal.

Cordially,

Captain (ret.) CARLOS EDUARDO GIL DE LOS RÍOS
Ship Science and Technology Journal Editor

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Nota Editorial

Cartagena de Indias, 30 de julio de 2021.

Cordial saludo a todos nuestros lectores, nuevamente llegamos a ustedes a través de nuestra revista Ciencia y Tecnología de Buques, para dar a conocer los resultados de las principales investigaciones en el ámbito naval, marítimo y fluvial, desarrolladas por investigadores cuyo trabajo académico impulsa el crecimiento y la generación de nuevo conocimiento en estas áreas de actuación.

En esta nueva edición de la revista, presentamos temas de interés profesional relativos a la Herramienta CAD 3D para construcción naval como solución integrada desde el concepto hasta la producción, al caso argentino sobre el Impacto atmosférico y económico del dragado alimentado con GNL, a la creación de un marco normativo para la revolución verde, el Estudio de maniobrabilidad y comportamiento en la mar del Buque de Apoyo Logístico y Cabotaje Liviano (BALC-L), a la mejora de la construcción naval con el concepto Internet of Ships, al análisis multi-físico de un reactor de agua presurizada para buques militares y finalmente el diseño y validación por el método de Elementos Finitos de la estructura de un bote de bajo calado para reconocimiento fluvial.

Esperamos que estos temas de interés académico y profesional llenen sus expectativas y les reiteramos la permanente y cordial invitación a continuar construyendo ciencia y conocimiento de forma conjunta con nuestra Revista.

Cordialmente,

Capitán de Navío (RA) CARLOS EDUARDO GIL DE LOS RÍOS
Editor revista Ciencia y Tecnología de Buques

Multiphysics analysis of a pressurized water reactor for military ships

Análisis multi-físico de un reactor de agua presurizada para buques militares

DOI: https://doi.org/10.25043/19098642.217

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Abstract

The naval industry has integrated the generation of energy through nuclear processes, due to the large amount of energy that is produced in these processes, for example, the ship NS OTTO HAHN, which used a propulsion plant with energy generated by a reactor of pressurized water (PWR), which operated under a nuclear fission process. Also, other examples are military ships and icebreakers. In order to know the energy contribution of this type of nuclear propulsion plants, this work carries out a multiphysics analysis of a PWR reactor, considering a turbulent behavior for the fluid that comes into contact with the uranium rods. Finally, the results of the fluid velocity fields along the fuel elements and the outlet nozzles are presented, as well as the temperature fields inside the reactor.

Key words: NS OTTO HAHN, nuclear fission, nuclear propulsion, multiphysics, PWR reactor.

Resumen

La industria naval ha integrado la generación de energía mediante procesos nucleares, debido a la gran cantidad de energía que se produce en dichos procesos, por ejemplo, el buque NS OTTO HAHN, el cual utilizó una planta de propulsión con energía generada por un reactor de agua presurizada (PWR), que operó bajo un proceso de fisión nuclear. Además, otros ejemplos son los buques militares y los buques rompehielos. Con la finalidad de conocer el aporte energético de este tipo de plantas de propulsión nuclear, este trabajo realiza un análisis multifísico de un reactor PWR, considerando un comportamiento turbulento para el fluido que tiene contacto con las varillas de uranio. Finalmente, son presentados los resultados de los campos de velocidad del fluido a lo largo de los elementos de combustible y de las toberas de salida, así como los campos de temperatura en el interior del reactor.

Palabras claves: fisión nuclear, multifísico, NS OTTO HAHN, propulsión nuclear, reactor PWR.

Date Received: April 15th, 2021 - *Fecha de recepción: 15 de abril del 2021*
Date Accepted: July 21st, 2021 - *Fecha de aceptación: 21 de julio del 2021*

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Introduction

Nuclear propulsion systems have been investigated due to the large amount of energy they generate, despite this, there are certain factors by which the energy generated cannot be used efficiently. Among them, the most widely used is the PWR reactor (Pressurized Water Reactor). These types of reactors are very stable due to their tendency to reduce their power in the face of increases in temperature, this helps to reduce the possibility of losing control of the chain reaction [1].

Its operation is based on fission reactions, which occur in the fuel rods, located inside, which behave as a heat sink. In addition, they use water as a coolant that is highly pressurized to keep the water in the liquid phase [1] at the operating temperatures of the reactor. This places demanding requirements on the pipes and the pressure vessel of the reactor and therefore increases construction costs and the risk of an accident with loss of coolant from the primary system [2]. That is why PWR reactors are the subject of research, which have been studied from the fuel rods to the structure of the reactor in general.

In the present work, a local and global study has been carried out. The local study consists of the simulation of the fuel rods that have been studied and computationally modeled in detail, applying knowledge of heat transfer, in the work called "Modeling of heat transfer in the fuel rods of the PWR nuclear reactor". The results obtained in this work have been qualitatively validated with generally accepted operating curves [3]. The results obtained in the local study are validated with those obtained in the previously mentioned work. In addition, the results of the local study are the basis for developing the global study on fuel elements and the PWR, to carry out an energy analysis.

Study Model

The present research work takes the PWR reactor as its object of study (Fig.1) to which local and global studies have been carried out.

Table 1 shows the geometric characteristics of the fuel rod, which is made up of a metal tube, which acts as a coating to retain the radiation produced inside by the cylindrical Uranium dioxide pellets. Between the outer surface of the pellets and the coating, there is the gas gap [3].

Fig. 1. Isometric view of the PWR reactor.

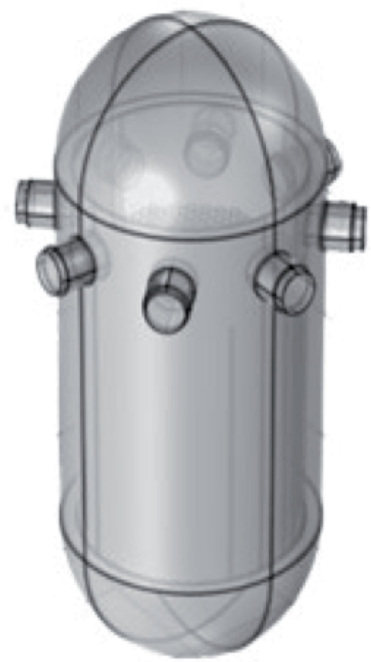


Fig. 2. 2D view of fuel rod.

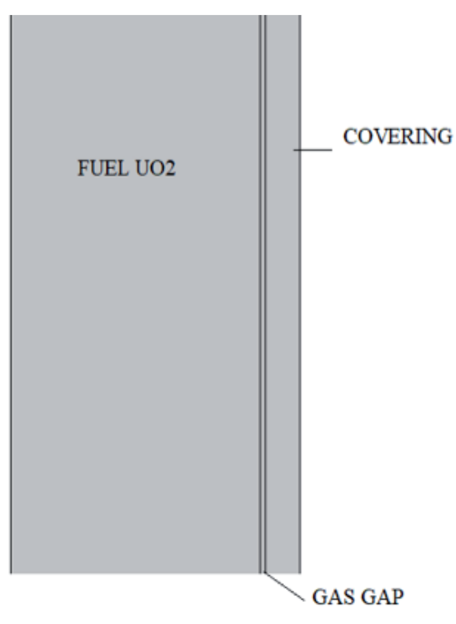


Table 2 shows the geometric characteristics of the models used for the global study, made up of the thermodynamic study of the fuel element and the multiphysical study of the reactor, as shown in Fig.3 and Fig.4, respectively.

Table 1. Geometric characteristics of the fuel rod [1].

Medium	Width (m)	High (m)
Fuel UO2	4.09575e-3	4.2672
Gas gap	8.255e-5	4.2672
Covering	5.715e-4	4.2672

Table 2. Geometric characteristics of the global study [4].

Element	Radio	Side	Height
Refrigerant	2185 mm	-	6900 mm
Nozzle 1,2,3,4	375 mm	-	500 mm
Fuel element	-	22 cm	4800 mm

Fig. 3. 2D view of fuel element geometry.

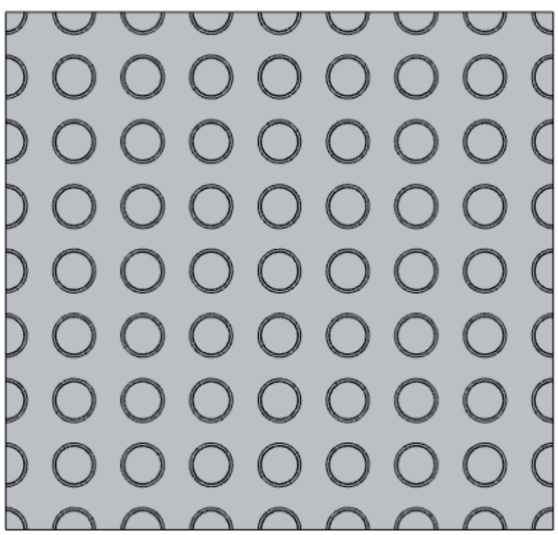


Fig. 4. 3D view of the geometry of the second global study.

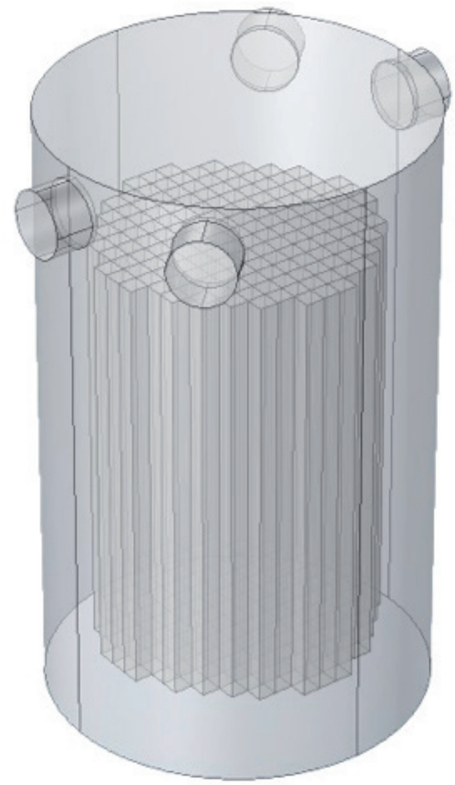


Table 3. Characteristics of UO_2 [3].

Properties	Value
Density	18.95[g/(cm^3)]
Thermal Conductivity	(1/(0.07426+0.0001743*T[1/K] +3.648e-008*(T[1/K]) ^2) +2024*exp(-16340/T[1/K])/(T[1/K]) ^2.5) [W/(m*K)]
Alpha	(1.083e-005-3.354e-9*T[1/K]+2.909e-12*T^2[1/K^2]+7.39e17*T^3[1/K^3]) [1/K]
h1	0.0001[W/(m^2*K)]
q_l	(39430.44*cos (0.7011*z[1/m])) [W/m]

Table 4. Characteristics of gas [3].

Properties	Value
Thermal Conductivity	(0.002517*(T[1/K]) ^0.72) [W/(m*K)]

Numerical Model

Materials

The fuel rod model is composed of 3 materials, which are characterized by equations dependent on temperature (T) and vertical position z, as shown in Table 3, Table 4 and Table 5. The fuel element is made up of UO2; the gap, covered with gas and the coating of Zircaloy-4.

Table 5. Characteristics of Zircaloy-4 [3].

Properties	Value
Density	18.95[g/(cm^3)]
Thermal Conductivity	(12.767-0.00054348*T[1/K] +8.9818e-006*(T[1/K]) ^2) [W/(m*K)]
Alpha	7.092e-006[1/K]
h3	0.0001[W/(m^2*K)]

Table 6. Characteristics of refrigerant [3].

Properties	Value
Thermal Conductivity	(7.566e-1) *(2.71828^(8.156e-6*T[1/K])) -(8.904e4*(2.71828^(0.009427*T[1 /K]))) [W/((m)*K)]
Density	(-6.778e-8) *(2.71828^(0.03407*T[1/K])) +(2.082e3*(2.71828^(-0.001788*T[1/K]))) [kg/m^3]
Heat capacity at constant pressure	(1.922e3) *(2.71828^(0.001726*T[1/K])) +(2.571e12*(2.71828^(0.05622*T[1 /K]))) [J/(kg*K)]

Table 7. Coating contour features [3].

Properties	Value
Tm	611[K]*exp (-(((z[1/m]-2.198)/ (9.911)) ^2)) +128.5[K]*
h	(1.136e-011*exp (0.05563*Tm[1/K]) +16610*exp(0.001083* Tm[1/K])) [W/(m^2*K)]
Tw1	q_l/(2*pi*0.0047498[m]*h) +Tm
Tw2	618.01[K]+22.65*exp(-15.5132/8.7) *(q_l*1e-6[(K*m)^2/W]/ (2*pi*0.0047498[m]))^0.5

Table 8. Boundary Conditions in the model [3].

Domain	Condition	High (m)
Fuel UO2	Heat Source	(q_l/(pi*(0.00409575[m]) ^2))
Gas gap	Surface Radiosity	J= 5800[W/(m^2)]
Covering	Temperature	min (Tw1, Tw2)

Inside the reactor, there is a light coolant, which serves as a support to maintain the temperature of the reactor, and generates water vapor, which is used to produce energy.

Boundary Conditions for Local Study

The local study was carried out with a multiphysical study of the fuel rod that was developed in an axisymmetric model, where the fuel acts as a source of heat, which will propagate in the form of radiation towards the coating of the rod.

In the contour of the coating that is in contact with the refrigerant, the characteristics have been designated, shown in Table 7.

To carry out the study, thermodynamic concepts have been used (Equation 1) that describe the heat transfer in the solid and fluid parts, which are found inside the fuel rod [5].

$$\rho C_p u.\nabla T + \nabla.q = Q + Q_{ted} \tag{1}$$

Where:

ρ: Density[kg/m^3]
C_p: Specific heat capacity at constant pressure [J/kg. K]
u: Fluid velocity vector [m/s]
∇_T: Temperature gradient[K/m]
Q: Heat Source[W/m^3]
Q_{ted}: Thermoelastic damping [W/m^3]

In the part of the gap of the rod, the heat is transferred in the form of radiation through the gas from the surface of the fuel to the surface of the coating, considered as opaque bodies, and the gas, as a transparent body. These designations are important to determine the radiosity on the surfaces.

$$J = \varepsilon e_b (T) + \rho_d G \tag{2}$$

$$G = G_m (J) + G_{amb} + G_{ext} \tag{3}$$

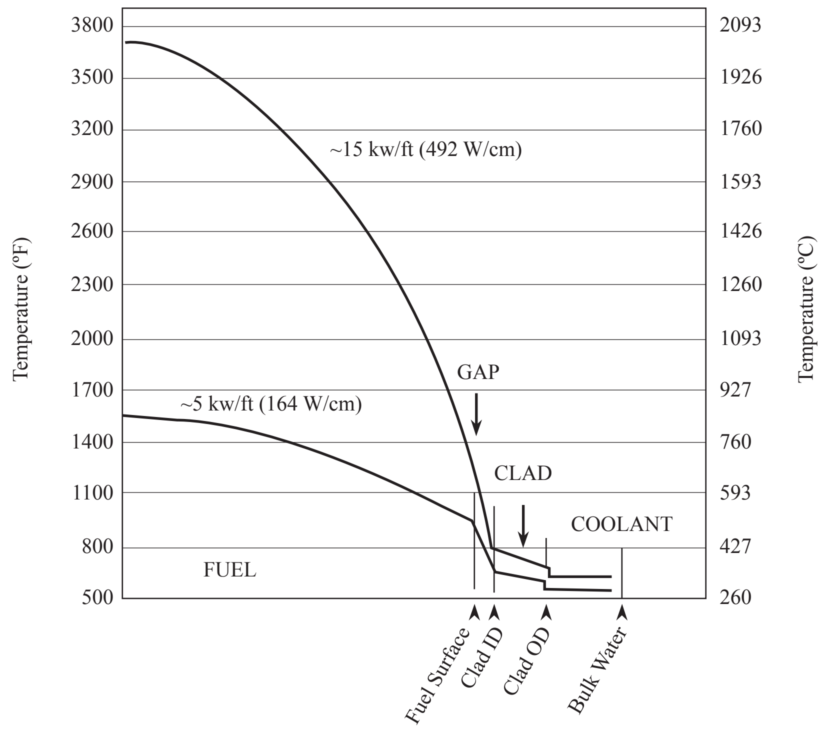
$$G_{amb} = F_{amb}\, e_b(T_{amb}) \tag{4}$$

$$e_b = n^2 \sigma T^4 \tag{5}$$

Where:

J: Surface radiosity [W/m^2]

Fig. 5. Typical radial temperature profile in PWR for two linear rates of heat generation [3].



G: Surface irradiation [W/m^2]
C_{mb}: Ambient irradiation [W/m^2]
G_{ext}: External irradiation [W/m^2]
ε: emissivity
e_b: Total hemispheric emissive power [W/m^2]
T: Temperature[K]
T_{amb}: Ambient Temperature [K]
F_{amb}: Ambient view factor
σ: Stefan-Boltzmann constant [W/m^{2}K^4]
ρ_d: Density, damaged tissue[kg/m^3]
n: transparent media refractive index

The radial profile of the temperature of the fuel rod in a PWR reactor that you must obtain in the computational results, must follow the same trend as shown in Fig.5, since these are the curves of the typical radial temperature profile [3].

Boundary Conditions for Global Study

The global study was divided into 2. In the first stage, a time-dependent global analysis of the fuel elements was carried out, which are made up of a 17x17 arrangement of fuel rods. The same boundary conditions as in the local study were placed on this arrangement of rods, with the difference that in this study symmetry conditions were applied on all faces and it was considered that the refrigerant with a temperature of 553 K that moves between they, in the form of turbulent flow k-ε [4].

Turbulent flow is governed by the following equations [6]:

$$\rho \frac{\partial u}{\partial t} + \rho(u.\nabla)\,u = \nabla.\,[-pl + K] + F \tag{6}$$

$$\rho\nabla.\,u = 0 \tag{7}$$

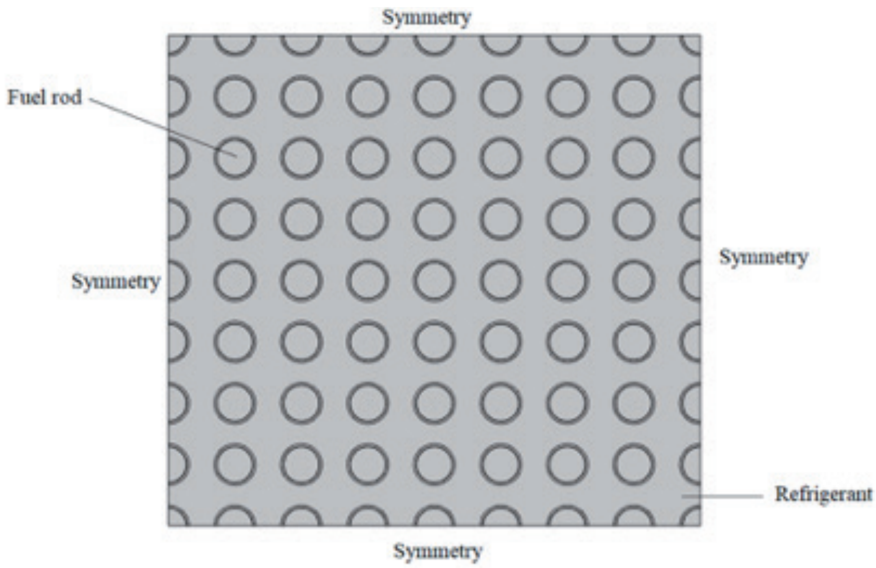
Where:

$$K = (\mu + \mu_T)\,(\nabla u + (\nabla u)^T) \tag{8}$$

The transport equation for ε reads:

$$\rho \frac{\partial \varepsilon}{\partial t} + \rho(u.\nabla)\,\varepsilon = \nabla.\left[(u + \frac{u_T}{\sigma_\varepsilon})\nabla\varepsilon\right] + c_{\varepsilon 1}\frac{\varepsilon}{k}P_k - c_{\varepsilon 2}\frac{\varepsilon^2}{k}\rho \tag{9}$$

Fig. 6. Boundary conditions of the fuel element.



Where:

ε=*ep*: Turbulent dissipation rate
μ: Dynamic viscosity [Pa.s]
μ_T: Turbulent dynamic viscosity
P_k: Production term
k: Turbulent kinetic energy [J/kg]
u: Velocity field [m/s]
ρ: Density[kg/m^3]
p: Pression [Pa]
F: Volume Force [N/m^3]
$c_{\varepsilon 2}, c_{\varepsilon 1}, \sigma_{\varepsilon}$: Model constants

Additionally, a meshing was carried out considering the characteristics of the domains. In Table 9, you can see the minimum and maximum sizes of the elements and in Fig.7, you can see the meshing of the fuel element.

Table 9. Size of Elements of mesh of the fuel element.

Domain	Max. element size	Min. element size
Refrigerant	0.00316	4.52E-5
Gas	0.00316	4.52E-5
UO_2, covering	0.00647	3.66E-5

The second stage of the global study consists of a more comprehensive development of the reactor, made up of 157 fuel elements, an inlet and 4 coolant outlets with a k-ε turbulent flow characteristic. Each fuel element is a source of heat, at an average temperature of all the rods found inside, obtained from the first part of the global study.

Fig. 7. Mesh of the fuel element.

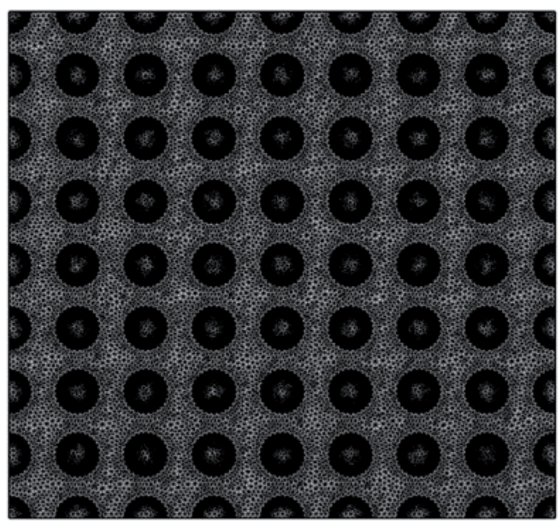


Table 10. Features in the second global model [4].

Features	Value
Temperature of fuel element	707.33 K
Heat Source	7.66862e8
Velocity (intlet)	19.5 m/s
Velocity (outlet)	5.5 m/s

Fig. 8. Features of second global model.

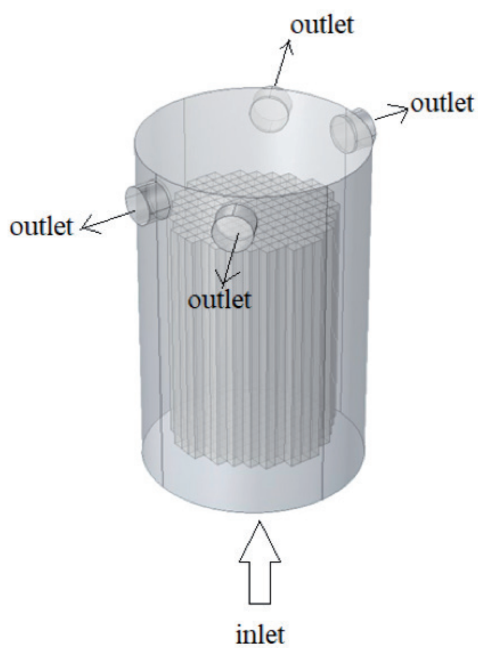
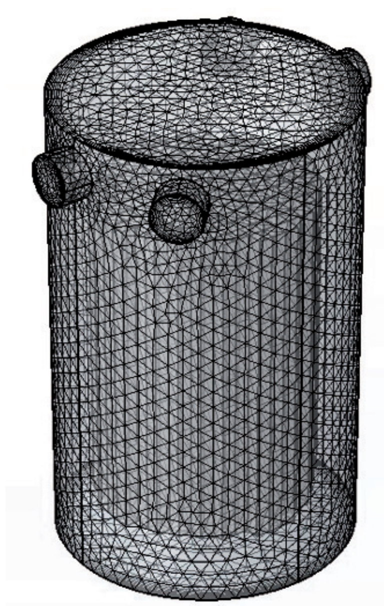


Table 11. Size of Elements of mesh of the second global model.

Domain	Max. element size	Min. element size
Refrigerant	0.253	0.0477
Fuel element	0.69	0.124

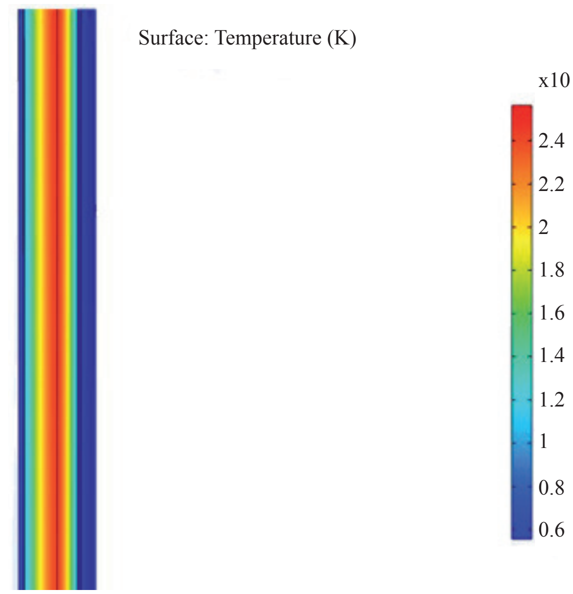
Fig. 9. Mesh of second global model.



Results and Discussion

Local Study

Fig. 10. Temperature in the fuel rod.



The temperature obtained as a result has a maximum value in the center of the fuel of approximately 2588 K and follows the trend of the typical temperature graph in the radial direction (Fig. 5), as can be seen in Fig.11, obtaining a high value in the fuel, which is decreasing in the direction of the coating. These values depend on the heat source and the radiation that is effected through the gas gap.

First Global Study

The results obtained in the first global study, the highest temperature is in the center of the fuel elements; however, these temperatures vary according to the location of the rod and time, for example, in Fig.14, the radial temperature profile is shown in 2 rods that are in different locations in a time of 60 seconds. In addition, an average temperature value of the system of 707.33 K was obtained, which is used for the second global evaluation, and the internal energy of the system shown in Fig.13, shows that heat is being transmitted from the heating rods. fuel to the coolant.

Fig. 11. Radial temperature profile on the fuel rod.

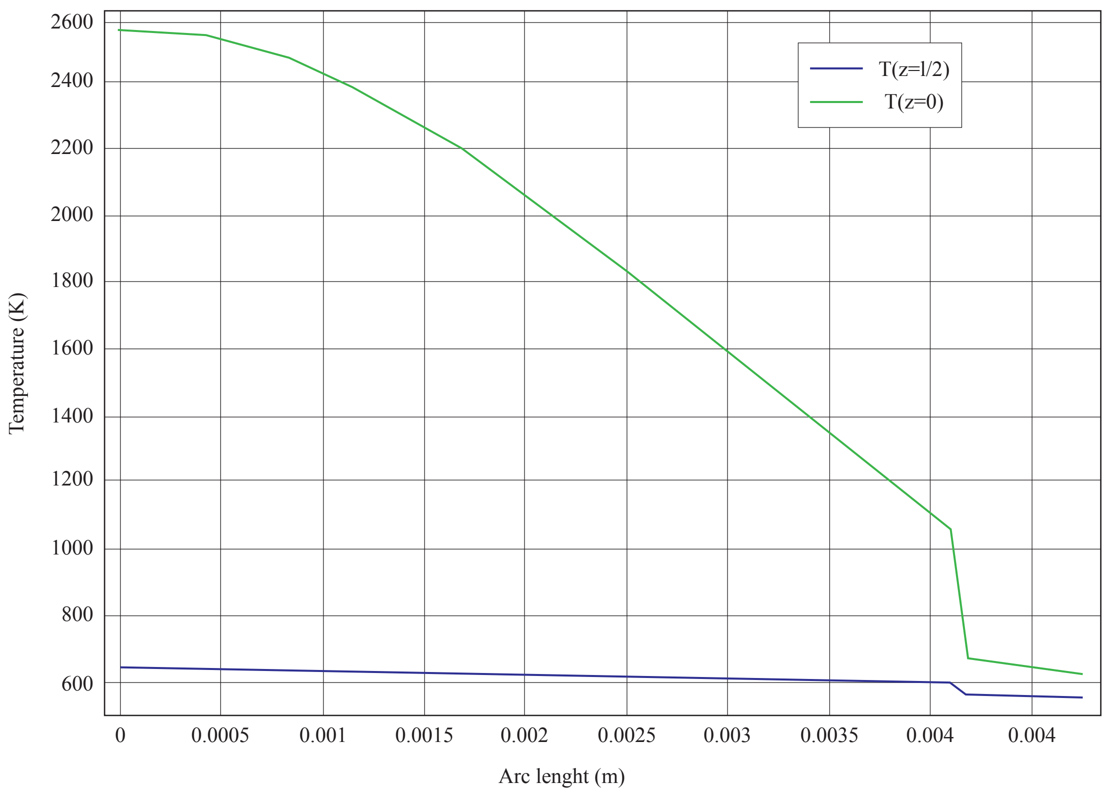


Fig. 12. Temperature in the fuel elemenet (t=60 s).

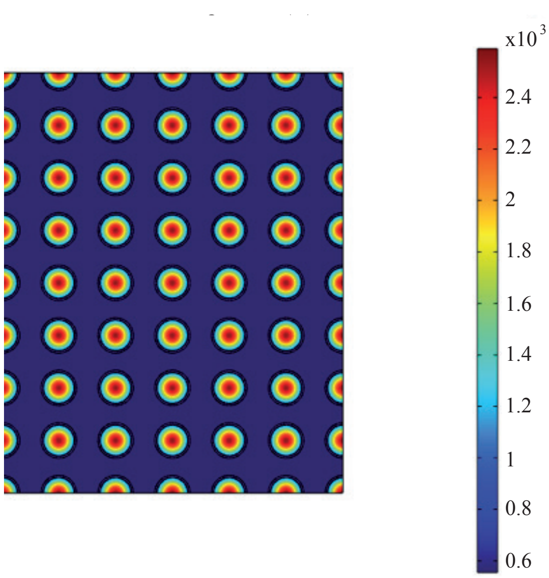
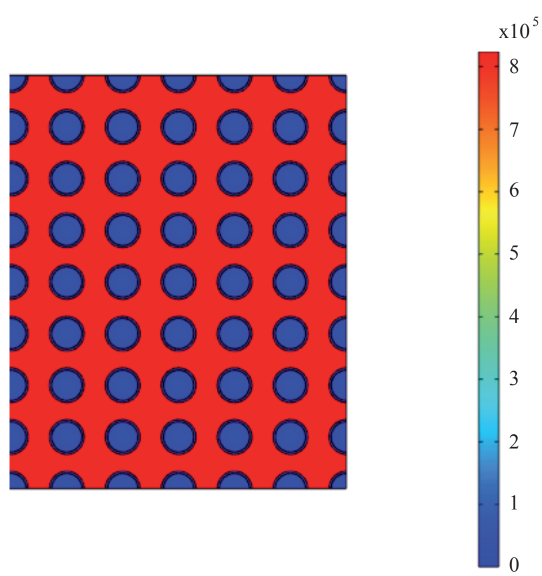


Fig. 13. Internal energy in the fuel element (t=60 s).



Second Local Study

For the second global study, the results in an initial time show that the temperatures are below the temperature in a fission reactor for industrial heat that is 1000°C [7]; however, as time passes, extremely high temperatures of the degree of 10e4 are obtained, this is because in the simulation there is no fluid circulation, so the refrigerant is absorbing heat and will continue to increase its temperature. The internal energy of the system is in the order of MJ / s, as shown in Fig.16, which integrates the kinetic energy and the potential energy of the refrigerant, since gravity has been considered in the study. The velocity profiles in the nozzles show that the coolant outlet velocity does not present a homogeneous behavior, as can be seen in Fig.19, which may be part of the beginning of the problems of low efficiency in PWR reactors.

Fig. 14. Radial temperature profile at the rods of the fuel element (t = 60 s).

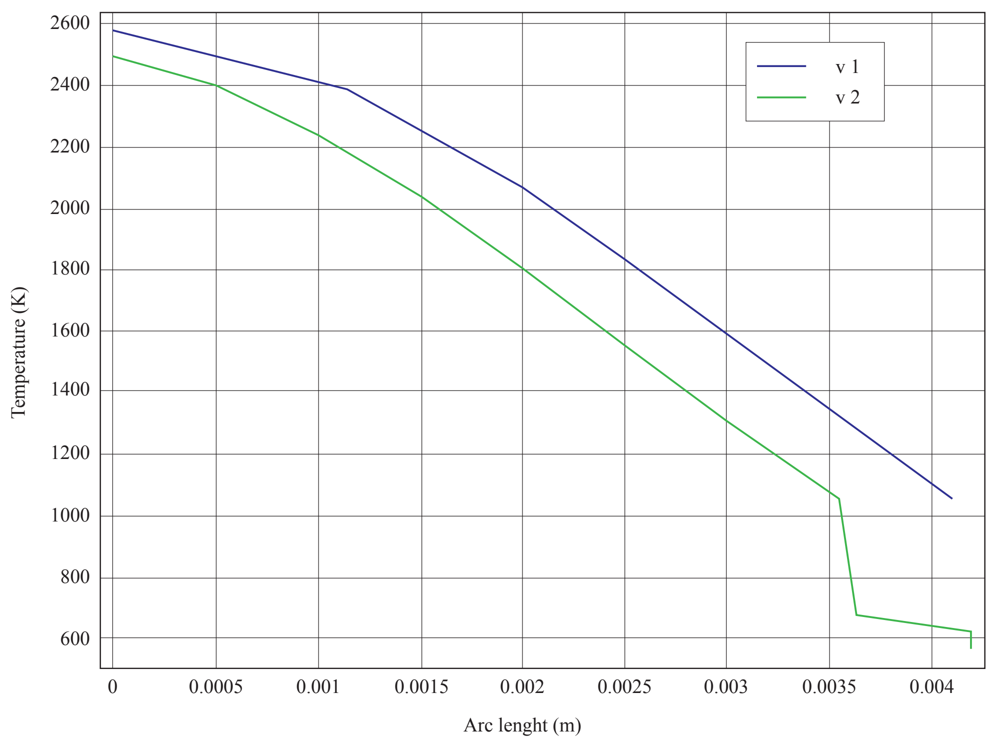


Fig. 15. Temperature in the second global study.

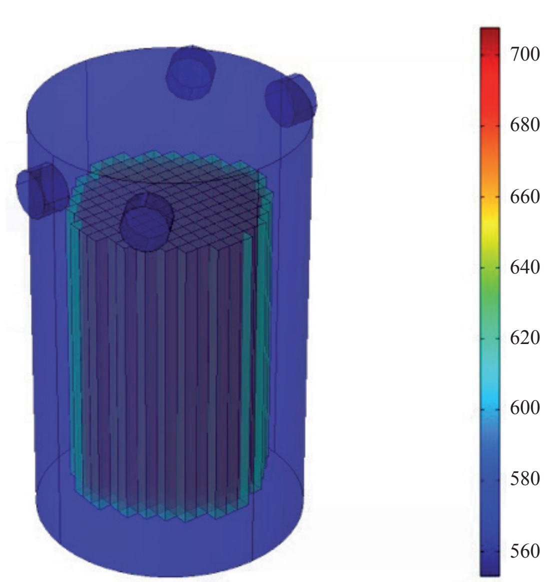


Fig. 16. Internal energy in the second global study.

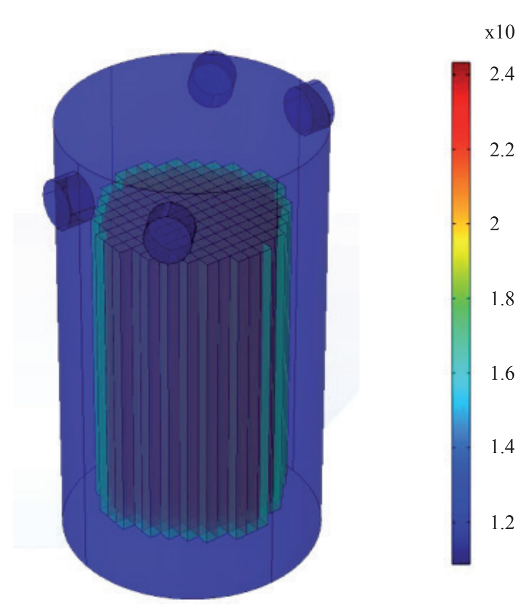


Fig. 17. Pressure fields in the reactor PWR.

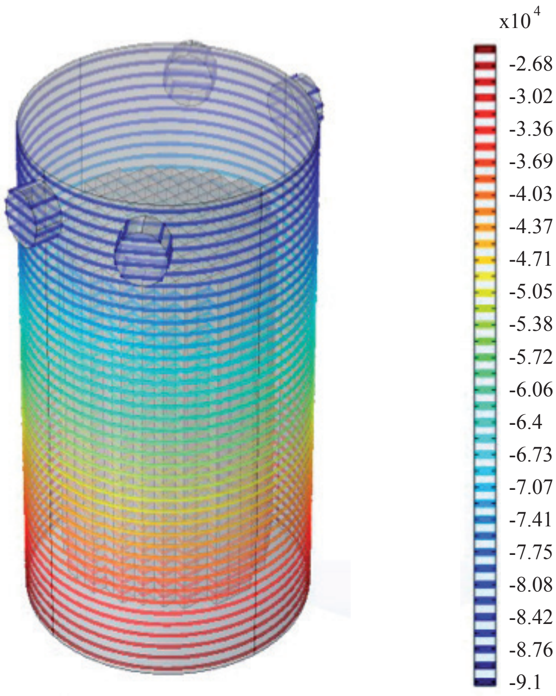


Fig. 18. Wall resolution in viscous units.

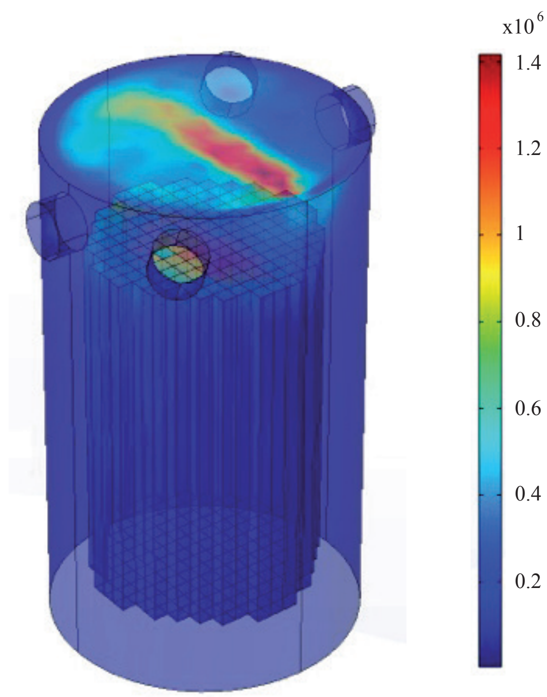
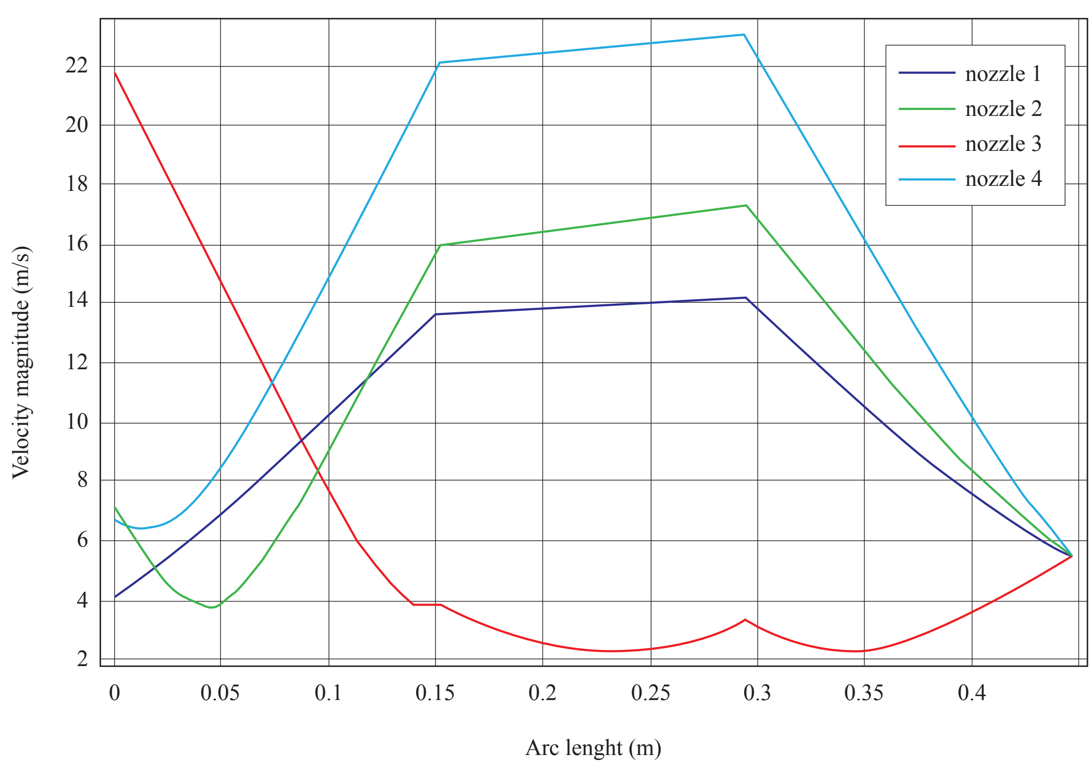


Fig. 19. Radial temperature profile at the rods of the fuel element (t = 60 s).



Conclusions

- The results of the radial temperature profile obtained in the local study vary throughout the length of the rod, this is since the heat source presents a dependence on the vertical positions. In addition, they are related to typical radial profiles, which is why it is concluded that the local study developed in the present work can be considered valid to carry out the global study.

- The first global study, carried out on the fuel element, shows that the rods tend to transfer heat through convection, affecting their temperature, which is why different radial temperature profiles are obtained at different positions in the system.

- The internal energy, observed in the first global study, shows that a high energy is generated that is transferred in the coolant, which is beneficial for the functionality of the reactor.

- The temperature in the second global study shows a high value, this can become harmful, since, if the temperature continues to rise, it can not only cause the refrigerant to evaporate, and not to produce the energy required for the functionality of the ship, but it can affect the structure of the reactor, and the set of pipes, causing a possible collapse of the propulsion system.

In the velocity profiles found in the nozzles, a variation is observed in the values reached, this can be caused by the production of a counter flow at the outlet of these, that is, by the turbulent nature of the fluid or by the impact of the flow on the walls of the nozzles, change their direction, opposing the exit velocity, which would imply, that a loss of kinetic energy occurs, and as a consequence it would reduce the efficiency of the reactor, since of the nozzles flow is directed to steam generators. It is here where the loss of energy begins, which will subsequently increase, as it travels, until it reaches the propellers in the form of electrical energy.

Acknowledgements

To thank the National University of Engineering, for providing excellent teaching to its students, to apply their knowledge in the development and innovation of naval technology. In addition, to the DSc. Nain Ramos Alvaréz, for the motivation and high-quality contribution, to achieve the advancement of both the naval engineering career, and the National University of Engineering.

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Design and validation by the finite element method of the structural arrangement of a riverine low draft combat boat

Diseño y validación por el método de elementos finitos del arreglo estructural de un bote de combate fluvial de bajo calado

DOI: https://doi.org/10.25043/19098642.218

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Abstract

Inland navigation in shallow waters with partially submerged objects and riparian vegetation might represent severe restrictions to patrolling operations of the Colombian Navy. Consequently, there is a need for a riverine combat and reconnaissance boat with the ability to operate in 0.4 m depth shallow waters and which structural arrangement is to be designed according to maritime classification societies and operational requirements of the navy.

The aim of this work is to explain and to validate the 20 knots, 3.8 tons of displacement, 8.6 m length, 2.6 m beam and 0.35 m draft boat scantling by guidelines of the classification societies and hence, improving and validating by direct analysis the hull structural arrangement.

Key words: Scantling, direct analysis, aluminum hulls, riverine combat boats.

Resumen

En la navegación fluvial, las bajas profundidades, objetos parcialmente sumergidos y la presencia de vegetación representan restricciones para las labores de patrullaje y reconocimiento de la Armada Nacional. Por tal motivo, surge la necesidad de contar con una embarcación con capacidad de operar con un calado mínimo de 0.4 metros y que su arreglo estructural esté diseñado acorde con las recomendaciones de las sociedades clasificadoras y las necesidades operacionales de la Armada nacional.

En el presente trabajo se detalla el escantillonado de un casco en aluminio con 8.6 metros de eslora total, 2.6 metros de manga y 0.35 metros de calado cuyo diseño permite una velocidad de 20 nudos, y un desplazamiento de 3.8 toneladas. Se siguió las recomendaciones establecidas por las sociedades clasificadoras y se realizó una posterior validación y mejoramiento del arreglo estructural por el Método de Elementos Finitos.

Palabras claves: Escantillonado, análisis directo, cascos en aluminio, botes de combate de río.

Date Received: April 15th, 2021 - *Fecha de recepción: 15 de abril del 2021*
Date Accepted: July 25th, 2021 - *Fecha de aceptación: 25 de julio del 2021*

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Introduction

In military river operations are important the availability of high-speed crafts capable of performing patrolling, tactical offensive and defensive maneuvers and additional tasks related to homeland security and defense in shallow, secluded and hard-to-reach harsh inland waters [1].

The riverine low draft combat boat designed with naval- grade aluminum and 10 m^2 polymeric ballistic protection panels on deck, can develop riverine patrolling and reconnaissance operations in shallow depth waters. The technical feature of this boat includes a 15 knots maximum speed, an operative range of 300 km, and the capability to provide tactical fire support.

To carry out the previously explained operations, the design and manufacturing of a low-draft inland waters combat boat is required [2]. Thus, the structural arrangement of the designed boat is intended to maintain a low weight while the security of the crew, the structural integrity of the hull and the boat performance remain preserved.

To ensure the structural integrity of the hull, the scantling was performed according to recommendations and requirements of the classification societies ABS in "Rules for Building and Classing, High- Speed Craft; Hull Construction and Equipment" [3] and ISO 12215 "Small craft – Hull construction and scantlings – Part 5: Design pressures for monohulls, design stresses, scantlings determination" [4]. Given the structural arrangement obtained, its structural integrity was evaluated and improved by direct analysis in a global model according to "Class Guideline- Finite Element Analysis" by DNV-GL [5].

The hull scantling refers to the assessment of selected plates and stiffeners' geometrical dimensions according to their mechanical properties, global position, and section modulus. The strength of the hull to environmental and duty external loads depends largely on the structural arrangement and its capability to withstand bending and shear stresses [6]. Scantling leads to an iterative process in which calculations are based on semi-empirical relations, Euler-Bernoulli beam theory, and principles of linear-elastic mechanics. First, the hull girder strength was assessed according to cross-section inertial properties followed by local calculation of plates thickness and cross-section of primary and secondary stiffeners. Structures which effect on the structural arrangement are considered local were calculated according to rules calculations [7] [8]. The structure Von Mises stress levels were compared with limit values allowed by the classification societies.

High strength aluminum alloys, in recent decades, have been increasingly applied for the design and construction of high-speed vessels as the size of these vessels has grown and their operation moved to harsher conditions [9]. Aluminum alloys, compared to steel, show advantages such as a better strength/weight ratio and a higher corrosion resistance [8].

In comparison to high-speed crafts manufactured with Glass Fiber Reinforced Plastic (GFRP), aluminum alloys manufactured hulls have a lower weight and a higher toughness against bottom impacts; the bottom plates are prone to dissipate energy as deformation instead of crack propagation [10]. Nevertheless, aluminum alloys show disadvantages such the yield and tensile strength are deeply affected by high-temperature gradients as a consequence of welding procedures [8] [11]. As a result of these procedures, high temperature zones are spotted which consequent expansion and contraction gradients resulted in high residual stresses [12].

It is estimated in scantling calculations a mechanical properties reduction between 50% and 70% depending on the used aluminum alloy [3] [11], on the other hand, some researchers such as Paik et al. [13] and y Collete [14] stated that these mechanical properties reductions might be conservative. Collete [14] in his research has shown that series 5000 aluminum alloys presented, in heat-affected zones, tensile strengths values close to those of not welded aluminum alloy conditions whereas 6000 aluminum alloys series showed a noticeable decrease. The 6000 series alloys are not as corrosion resistant as the 5000 series, but are easier to extrude, making them attractive for producing structural shapes [14]. Additionally, it must be considered that imperfections resulting from welding processes such as the permanent deflection of plates, might imply an 18% decrease in tensile properties and an increase in buckling failures probabilities [7] [15].

Aluminum plates and stiffeners must have a stiffness equivalent to steel counterparts as a design criterion [16]. In this way, the plates of the structure and the respective primary and secondary structural reinforcements are to be designed in such a way their mechanical strength is high enough to prevent crack initiation due to wave pressures on the hull [17]. The vessel, during its lifespan, will be subjected to loads as a function of contact time such as collisions, slamming and grounding. Due to light materials used in their construction, high-speed crafts subjected to slamming phenomenon are prone to present high elastic deformations in the bow by impacts with the water surface [18].

For small crafts, under riverine conditions, classification societies' rules dictate a design wave height of 0.5 m and a design speed of 20 knots speed to calculate vertical accelerations in the hull. Next, from plate pressures, spacing between stiffeners and selected materials properties, it can be selected the hull´s plates thickness. The hull girder amidship section modulus can be determined with cross-section properties of longitudinal plates and stiffeners which length is superior to 60% of scantling length. The resulting structural arrangement will be detailed in the methodology section and scantling calculations can be revised in [3] [4].

The structural arrangement assessment from rules and guidelines of the classification societies, which calculations are generally of semi-empirical nature and also are calibrated to secure the lifespan expected, allow a simplified approach of complex structural problems [7]. However, classification societies' rules might imply suppositions that can only be used with certain limits, then, those calculations might not fit well to the studied arrangement and the obtained structural arrangement could have a more effective and lighter alternative. Therefore, in recent decades, direct analysis by the finite element method has increased its importance in the shipbuilding industry [19].

Hence, the main aim of this work is to evaluate, by classification societies semi-empirical rules calculations and direct analysis by finite element method, the strength of the obtained structural arrangement of this combat boat. Additionally, a modal analysis was performed to estimate the resonance frequencies of structural elements and a linear buckling analysis was also carried out to dismiss the possibility of the hull failure by compressive loads.

Methodology

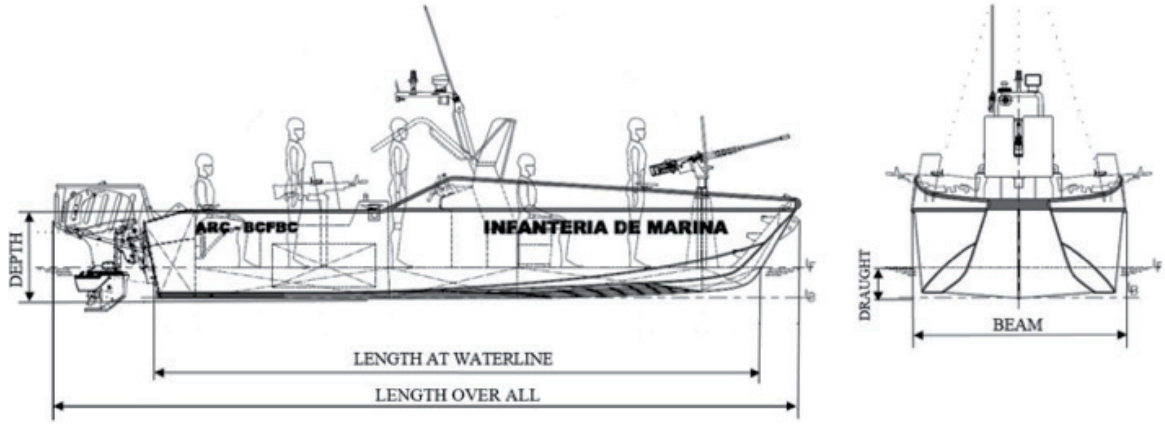
With the present methodology it was detailed the obtained structural arrangement, the rules and guidelines applied and the followed procedure to prepare the computational modeling.

Structural Arrangement

The principal characteristics of the designed combat boat are summarized in the next table [see table 1]. The bottom structure of the vessel consists of a 12 mm of thickness AW 5083 H321 keel, four AW 6082 –T6 longitudinal bulb stiffeners, and two 4 mm thickness side girders. These elements are spacing 250 mm whereas frames have a 750 mm spacing, except for frames in the bow, and a 6 mm thickness AW 5083 H321 bottom plate [see Fig 1].

The sides' structure consists of AW 6082-T6 flat-bar longitudinals; whose purpose is to provide the required stiffness to 4 mm thickness AW 5083 H321 side plates. These plates are to be vertically supported by 4mm thickness AW 5083 H321 frames [see Fig. 2]. Four of these frames are 4mm thickness watertight bulkheads. The deck is composed of a 4 mm thickness AW 5083 H321 plate and five type flat-bar longitudinal stiffeners. This deck is transversally supported by 'L' profiles deck beams and bulkheads and longitudinally supported by two side girders. The transom is composed of 10 mm thickness plates between the

Fig. 1. Riverine combat boat principal dimensions.



two side girders and 6 mm thickness AW 5083 H321 plates in the rest of the hull given the force reactions of the assembled outboard motors.

Table 1. Riverine combat boat principal characteristics.

Characteristics	Value
Length over all	8.60 m
Length at waterline	7.05 m
Beam (molded)	2.42 m
Depth amidship (molded)	1.03 m
Draught	0.35 m
Installed power	120 hp (89 kW)
Fully loaded displacement	3650 kg

Scantling rules applied

The followed scantling rules [3] [4] are based on hull girder strength and local strength requirements. Then, from principal dimensions of the boat, the proposed structural arrangement and design pressures, scantling of plates and stiffeners are calculated [see Fig. 3].

Direct analysis

Global modeling of the boat and the subsequent finite element method analysis are explained in detail in this section. This analysis implies local refinements of relevant structural details. Furthermore, the analysis is subjected to plain stress and linear-elastic mechanics simplifications.

Fig. 2. Typical frame.

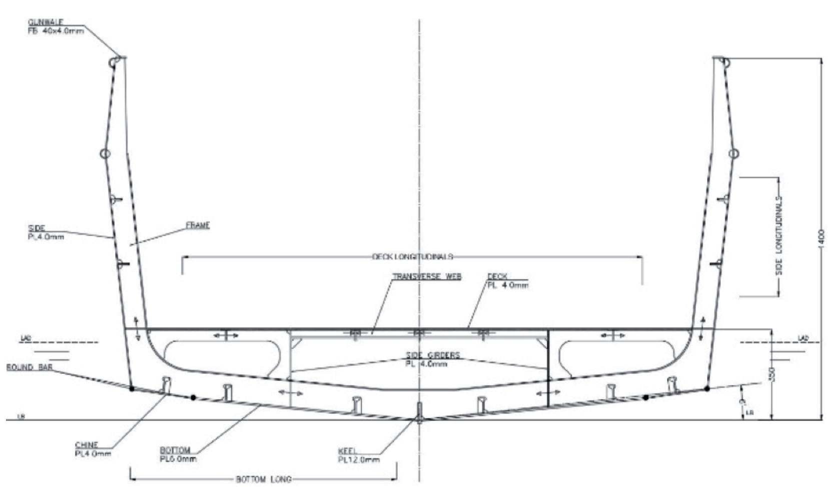
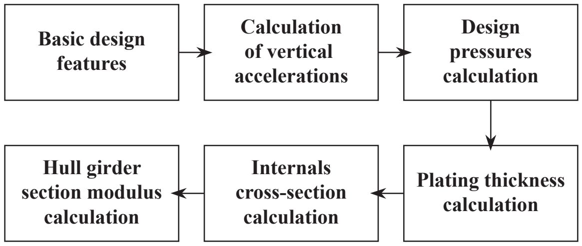


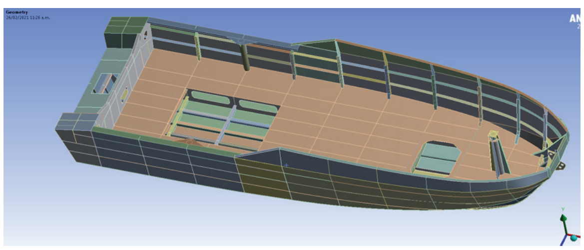
Fig. 3. Scantling methodology.



Geometry

The whole structural arrangement was modeled including examples of critical connection details. Shell modeling was carried out by using ANSYS SpaceClaim 2019 software [see Fig. 4]. *Bonded* contacts were used among structural elements given their welded connections.

Fig. 4. Global modelling using Ansys SpaceClaim.



Meshing

SHELL181 elements were used for meshing. This four-node element with six degrees of freedom at each node is suitable for analyzing thin to moderately thick shell structures [see Fig. 5]. After a convergence test, a 20 mm meshing element size was used. For structural details element size, up to 4 mm were set. The shell geometry is represented by *4 Node Linear Quadrilateral* elements; the degenerate 4 Node Linear Triangular option was only used as filler in mesh generation [20].

Boundary conditions

The boundary conditions for the global structural model should reflect simple supports that will avoid built-in stresses so the reaction forces in the boundaries are to be minimized [5]. ANSYS Inertia relief option allows to balance the force differences on the supports creating a state of static equilibrium. Two of these fixation points were applied at transom intersecting the main deck at port and starboard, and the last one, in the bow centerline intersecting waterline.

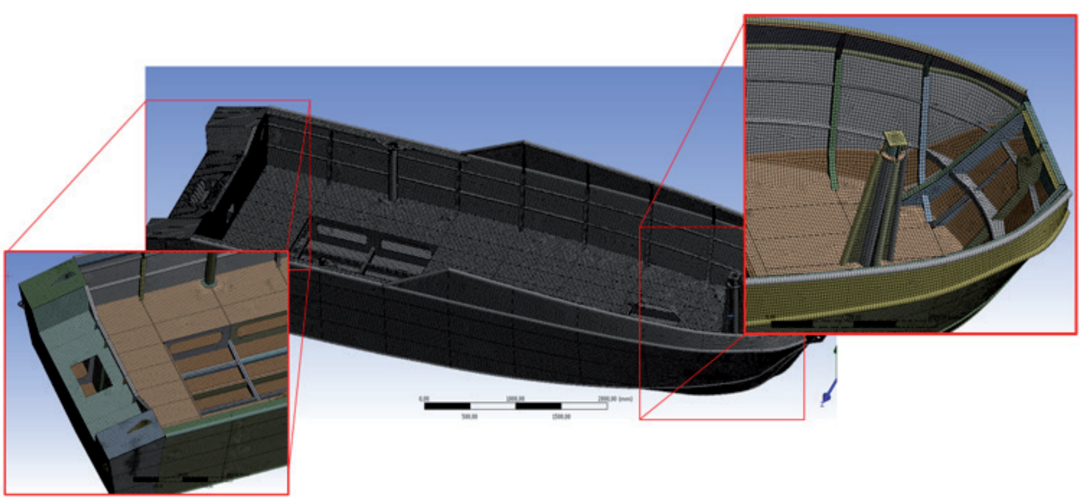
Materials

5083- H116/ H321 aluminum alloy mechanical properties were assigned to plates whereas aluminum alloy 6082 T6 properties were set to stiffeners [see Fig. 6]. The mechanical properties of both aluminum alloys are detailed in the next table [see table 2].

Allowable stress

This analysis is completed using the Maximum-Distortion- Energy Criterion in order to assess the structure against failure. This criterion takes both

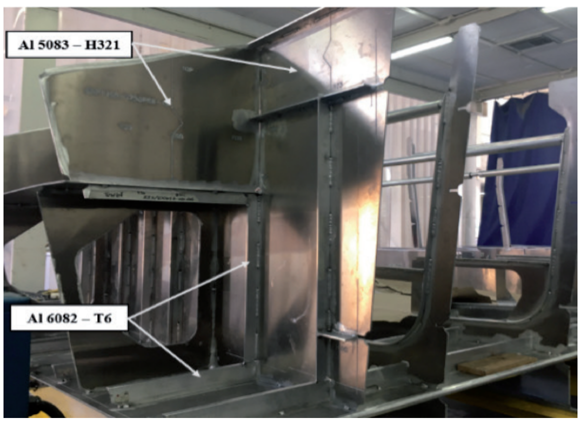
Fig. 5. Meshed model.



shear and normal stresses into account to develop a combined equivalent stress, σ_e.

According to this criterion, the structural arrangement will not fail as long as $\sigma_e<S_y$, where S_y is the tensile yield strength of the material. A class allowable stress factor (F_p=0,85) is added in such a way yield strength of the material is reduced [20]. The maximum allowable stress for plates is 123 MPa and 106 MPa for stiffeners specifically in heat-affected zones.

Fig. 6. Plates and stiffeners materials.



Load conditions

Design pressure calculations from class requirements of both classification societies [3] [4]

Table 2. Aluminum alloys mechanical properties defined for the model.

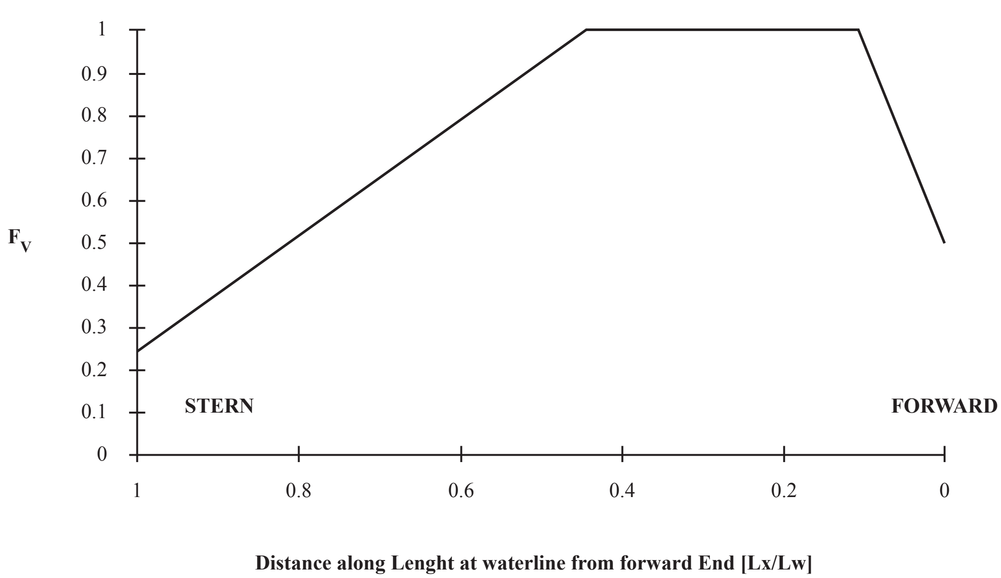
Properties	Al 5083-H116/ H321	Al 6082- T6
Density [g/ cm3]	2.66	2.7
Poisson's ratio	0.33	0.33
Young's Modulus [GPa]	70	70
Tensile yield strength [MPa]	220	260
Tensile yield strength (welded) [MPa]	145	125
Tensile ultimate strength [MPa]	305	310
Tensile ultimate strength (welded) [MPa]	290	190

are detailed in the next table [see table 3]. Due to design pressures calculations are slightly higher in HSC rules of ABS, these values are taken into account in the finite element model load inputs [see Fig. 7].

Table 3. Calculated design pressures.

Design pressures [wave height = 0.5 m]	HSC ABS [3] [kN/m²]	ISO 12215-5 [4] [kN/m²]
Bottom	79.9	72.7
Sides	18.4	17.0
Main deck	5.0	5.0
Watertight bulkheads	4.5	2.1

Fig. 7. Bottom slamming pressure distribution.



Modal Analysis

This analysis allows to determinate the inherent dynamic characteristics of a system in forms of natural frequencies. Then modal analysis is used to identify natural frequencies and vibration modes of the structural arrangement. A special emphasis was placed in transom due to the outboard motors effect on the structure; mass and inertial properties of these motors were taken into account. Structural displacement restrictions are maintained for this analysis.

Linear buckling Analysis

An eigenvalue buckling analysis was performed to ensure no structural elements failures by compressive loads. For this analysis, structural displacement restrictions are maintained but inertia relief option was disabled.

Results and Discussion

In this section, the results of scantling by HSC-ABS and ISO 12215 rules are detailed and compared. Then, the structural direct analysis, modal and linear buckling analysis are discussed.

Structural Analysis

***Scantling Result*s**

By relating the plate thickness obtained for both Classification Societies rules, it can be noted that bottom plate thickness requirements from HSC rules from ABS [3] are 4.6% higher than obtained by ISO 12215. Nevertheless, when bottom design pressures are compared, the difference between both rules increased to 8.9%, which means design pressure is a parameter of greater influence in ISO12215 rules [see table 4]. HSC rules by ABS were shown to have more conservative thickness requirements in all cases.

It was decided to select a bottom plate thickness 27% higher than obtained by HSC-ABS rules because both rules do not take into consideration possible hull- river bottom contacts and higher abrasives wear rates due to the riverine combat boats operative tasks.

Table 4. Plates thickness calculated.

	ISO 12215-5 [mm]	**HSC ABS [mm]**	Plate thickness [mm]
Bottom	4.5	4.7	6.0
Sides	2.7	3.5	4.0
Decks	1.4	3.5	4.0
Bulkheads	1.7	3.5	4.0

From slamming design pressures and plates thickness (t) previously calculated, it can be estimated the required moment of inertia and section modulus for stiffeners. These both cross-sectional properties were calculated considering the associated effective plating as 60*t [see table 5].

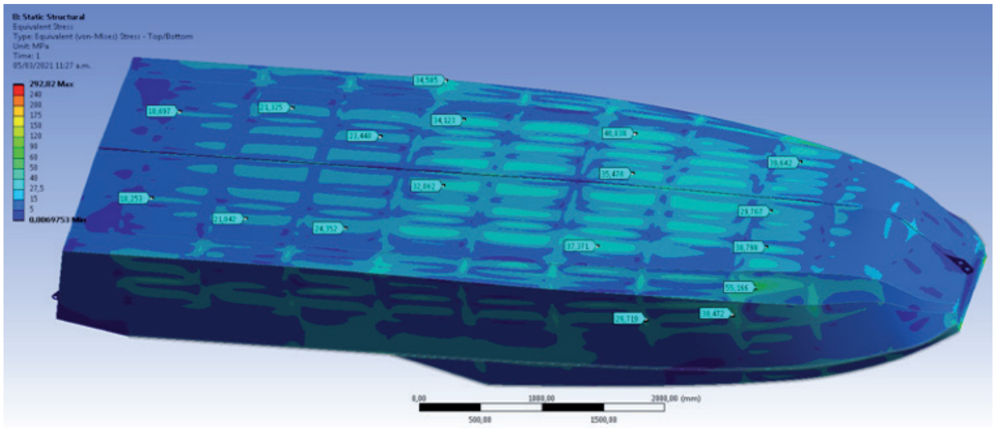
According to the presented results in table 5, it can be shown that all the selected profiles meet the section modulus rules requirements [22]. By relating the minimum section modulus requirements of both rules; profiles section modulus requested for HSC by ABS are slightly more conservatives in most cases.

Despite the fact slamming bottom pressures differences between both classification societies' rules are close to 8,9%, the section modulus requirements differ in 36%; design bottom pressures represent a higher influence factor in HSC rules.

Table 5. Section modulus of stiffeners.

	ISO 12215-5		**HSC ABS**	
Bottom longitudinal stiffeners	**SM req.**	**S.F**	**SM req.**	**S.F**
Sides longitudinal stiffeners	8.44	1.60	11.5	1.17
Deck longitudinal stiffeners	2.39	1.33	2.88	1.10
Deck transvers stiffeners	1.67	1.89	1.81	1.75
Floors	3.57	1.20	3.13	1.36
Frames	12.91	2.16	12.49	2.41
Bulkheads	6.41	2.87	6.48	3.30

Fig. 8. Slamming stress distribution in the bottom.

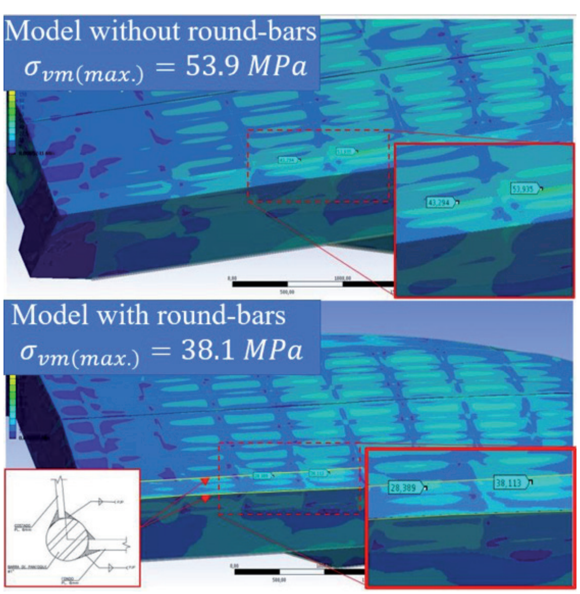


Direct Analysis

In this section, the direct analysis results are explained. First, the 6 mm thickness bottom hull presented low stress levels by slamming pressures close to the chine, then, it was decided to reduce the bottom thickness to 4 mm in this zone given that chine is also reinforced with round-bars and a bulb profile [see Fig. 8].

The highest stress level (close to 55.8 MPa) can be found in the bow between frames 9 and 10 [see Fig. 8]. These stress levels might be due to the hull's geometry, this zone, given its geometry, is not reinforced with bulb profiles. Nevertheless, a 2.2 safety factor is expected. When the obtained safety factor is compared to the 1.27 bottom thickness ABS scantling safety factor it is discernible how conservative the scantling approach might be.

Fig. 9. Round-bars effects in chine stress distribution.



During the first steps of design process, it was intended to remove the round-bars from side-chine and bottom- chine welded connection for weight reduction [see Fig.2]. However, the utility of these bars is to improve the available welding surface area and raising stiffness. Because the use of these round-bars is not explicit considered in scantling rules, their effect was evaluated by the finite analysis method. Regarding this issue, beam type elements with cross section properties equivalent to the round-bars were added, it was found that chine stress levels showed a 30% stress level reduction [see Fig. 9].

On the other hand, both longitudinal and transverse vessel reinforce panels showed safety factors of 67% and 41% higher respectively in comparison with scantling calculations and, hence, a more conservative approach from Classification Societies rules. In the next table, safety factor results of direct analysis and scantling are detailed [see table 6]. There is non-heat affected zones that despite presenting high stress levels, these present elevated yield strength properties, such as the case of hull's sides and deck [see Fig. 10].

Fig. 10. Stress distribution on the sides and the deck.

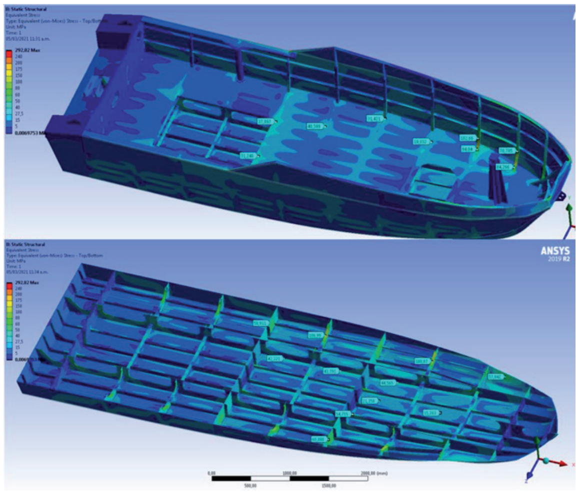


Table 6. Safety factors and stress levels of stiffeners.

	Equivalent stress [MPa]	Allowable stress [MPa]	Safety factor	Scantling safety factor
Bottom longitudinals	63.9 MPa	106 MPa	1.66	1.17
Side longitudinals	42.0 MPa	106 MPa	2.50	1.10
Side girders	62.8 MPa	123 MPa	1.96	1.40
Floors	55.8 MPa	123 MPa	2.20	2.41
Frames	89.1 MPa	123 MPa	1.38	3.30
Transverse web	82.0 MPa	106 MPa	1.29	1.20
Deck longitudinals	82.1 MPa	106 MPa	1.29	1.75

From table 6 results, in most cases, safety factors reported by direct analysis are higher than the calculated by classification societies scantling rules. However, spotted stress concentration safety factors in deck longitudinals, floors, and frames are shown to be higher by the scantling approach [see Table 6].

This could be explained given the limitations of the scantling rules related to geometry and stress concentrations in some connections as these rules only consider spacing, the length between supports, hull pressures and design stress. Even so, stress levels in these elements are below the design stress and the effect of stress concentration zones are deemed local [see Fig. 11].

Static structural analysis was performed on critical structural details and focalized regions with equivalent stresses over the allowable value. Localized areas of high stress arising from geometry are not a concern since localized plastic deformation will not compromise overall strength. Also, localized plastic deformation would imply strain hardening and a slight loss of ductility. The spotted high stresses, which maximum value is close to 140 MPa, are remarkably below than aluminum tensile ultimate strength at heat-affected zones [see Fig. 12].

Structural details are characterized by high stiffness at their end connections and sharp corners. That ends might produce singularities; which means, there are points in the model where stress values tend towards non-real infinite values. If mesh convergence cannot be reached in certain high-stress points even with mesh refinement, these points are deemed to be singularities.

Fig. 11. Stress levels in a typical frame.

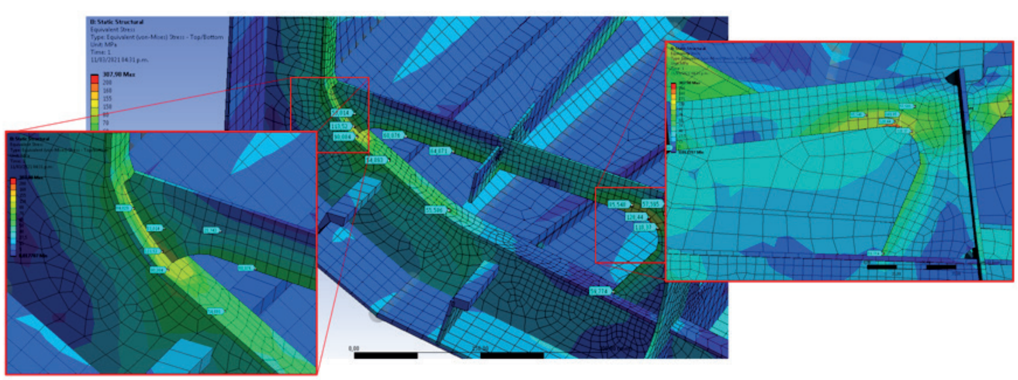
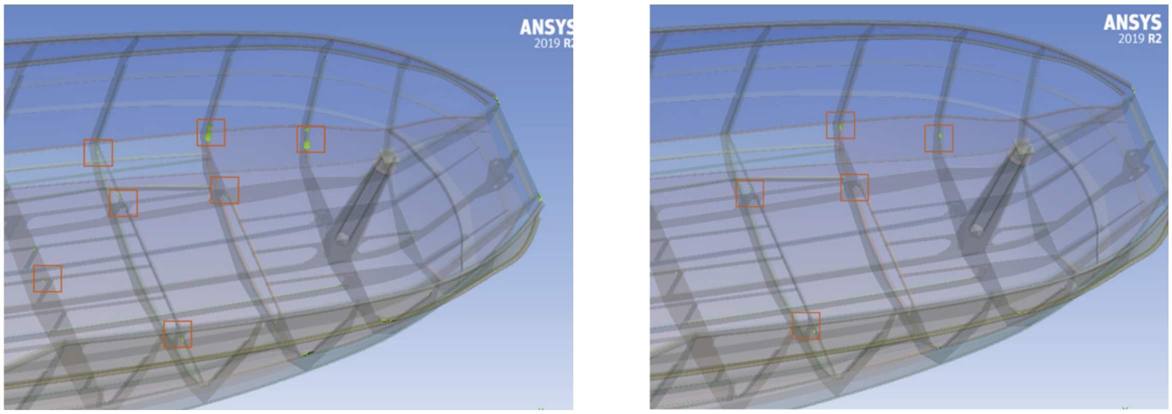


Fig. 12. Equivalent stress over 100 and 120 MPa.



A high gradient stress zone was spotted at the port gunwale, after mesh convergence was not reached; the reported high stress values are deemed as a singularity [23] [see Fig. 13].

The following assessed structural details, after their mesh convergence was found, showed relatively high stresses in their end connections. First, transverse webs - side girders bracket connections stress levels were analyzed. In general, the stress is moderate and typically below 70 MPa but the upper bracket toe presents localized 125 MPa stress values due to stress concentration [see Fig. 14-left]. Given a design yield strength of 123 MPa at welded conditions, these stress values would not compromise the overall bracket strength, considering fillet welds might reduce the effects of the bracket toe's sharp edge.

Fig. 13. Gunwale singularity.

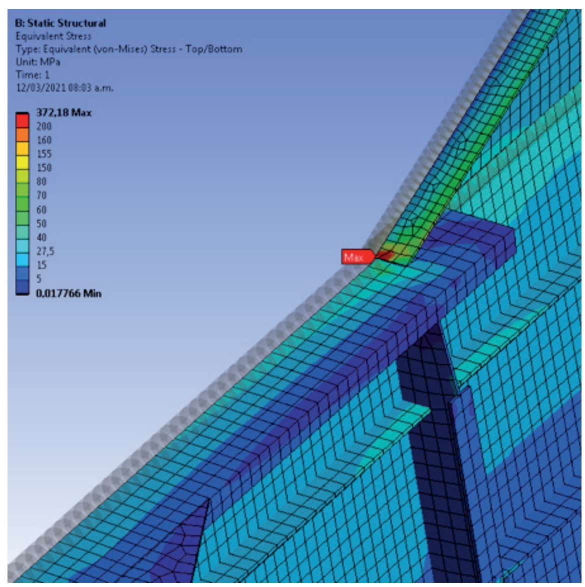
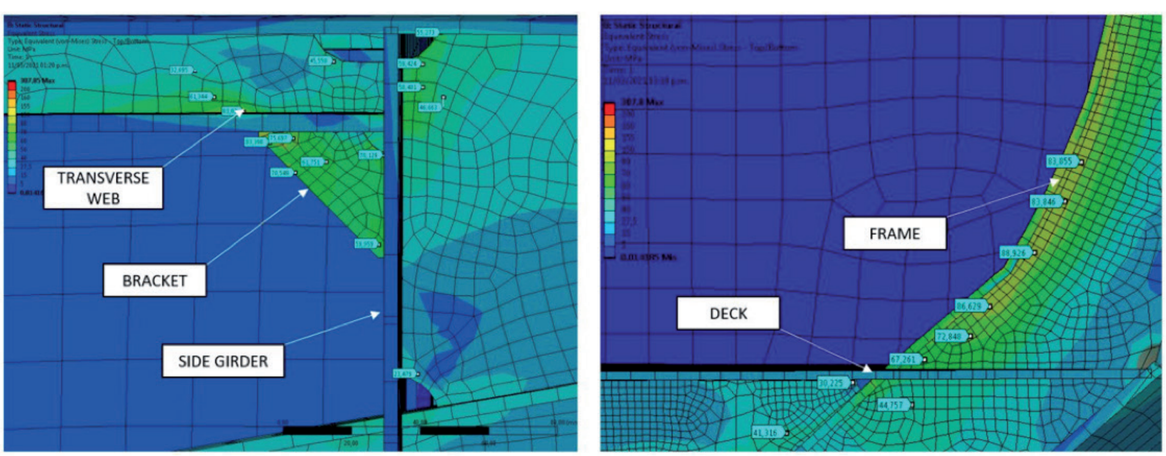


Fig. 14. Transverse web- side girder connection (left) frame-to-deck connection (right).



Regarding the frame-deck intersection, typically below 90 MPa stresses were reported in frames due to their curvature near the deck [see Fig.14- right].

The connection between deck longitudinals and bulkhead stiffeners was also revised [see Fig. 15-left]. Near bulkheads, deck longitudinals present stress levels close to 86 MPa, specifically in connections with bulkhead stiffeners. These stress levels are not a concern given they are below the allowable design stress.

A maximum 63 MPa stress value was found near the deck and the side girder – bulkhead connection between frame 7 and 8 [see Fig. 15 – right]. The high stress influence is limited among the upper radius of the girder's lightening hole, the bulkhead and deck.

The Transom structural arrangement was designed to withstand two outboard motors' continuous operation of up to 7000 N thrusts each and an individual 210 kg weight. In the early stages of this design process, the transom was thought of as a 12 mm thickness Al-5083 plate. Nonetheless, by direct analysis, it was possible to support the thickness reduction of the transom plate.

The structural arrangement of the transom is composed of a 10 mm thickness plate between side girders and 6 mm outside of them. Internally, the outboard motors are supported by the side girders and the rest of the transom is stiffened with flat-bar profiles and a single transverse bulb profile.

The applied loads and the obtained stress distribution on the 10 mm plate are shown next.

Fig. 15. Deck longitudinals and bulkhead connection (left) side girder and bulkhead connection (right).

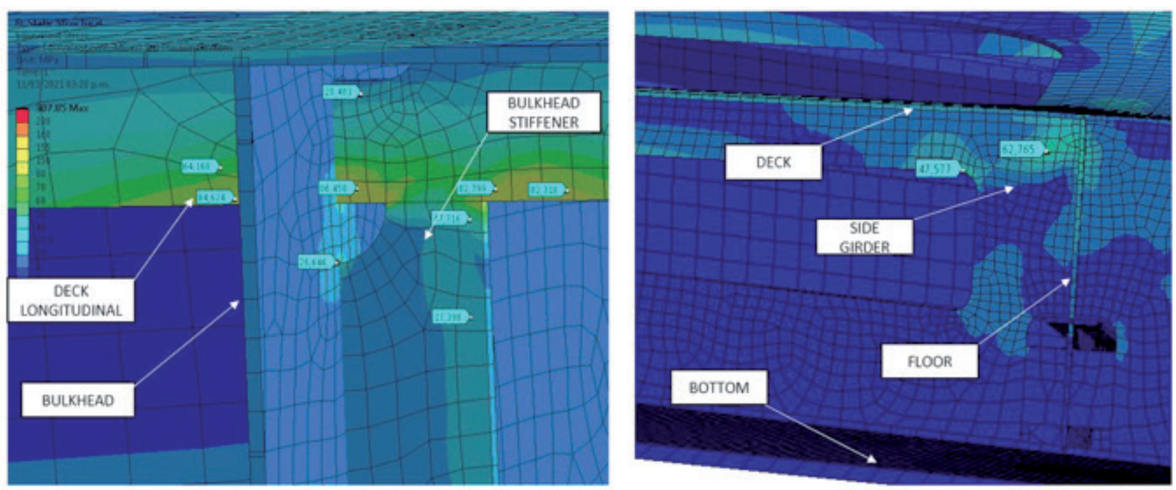
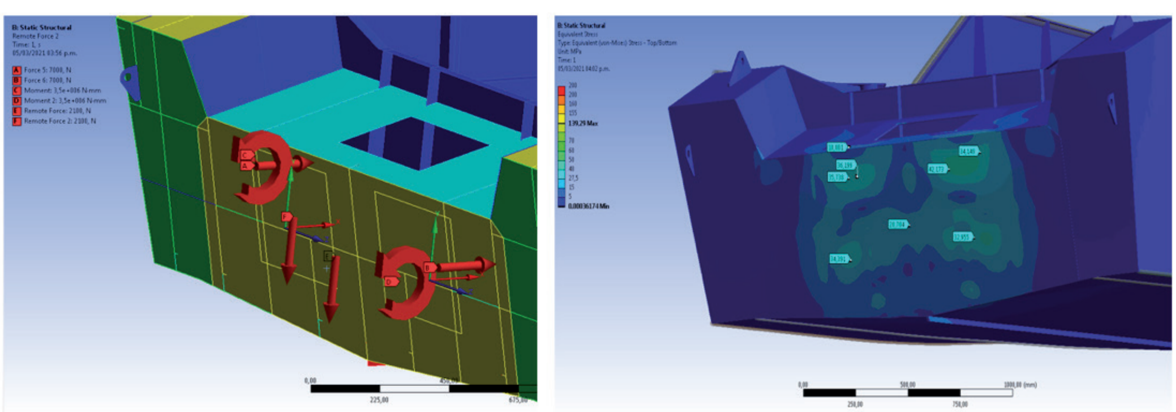


Fig. 16. Applied loads on the transom and stress values obtained.



A 45 MPa maximum stress value was reported on transom plate and, therefore, a safety factor of 4.4. It was decided to allow this safety margin taken into consideration aft collision loads, vertical shear forces; as result of outboard motors impacts with objects in the riverbed and future motor updates.

Transom plate reinforcements present equivalent stress values below 50 MPa except for reinforcements at 250 mm from the centerline. These Al- 6082 -T6 profiles present local stress levels close to 140 MPa. This magnitude is only reported in non-heat affected zones, so the allowable design stress takes a value relative to 190 MPa and a 1.35 safety factor [see Fig. 17].

Modal Analysis

A modal analysis was performed principally to estimate the effects of operating outboard motors frequencies on the structural arrangement natural frequencies. 10 vibration modes were evaluated; 5 of which imply transom vibrations while the rest of vibration modes refer to negligible amplitudes in the structural arrangement and can be neglected [see Fig. 18].

According to datasheets provided by the manufacturer, the highest operative motor frequency is 155 Hz and the idle frequency of 22 Hz. The idle frequency is 25% higher than the second vibration mode with a consequent amplitude of 0.81 mm. In the same way, idle frequency is 15% lower than the fourth vibration mode with and associated amplitude of 1.5 mm. In both cases, resonance amplitude is below the maximum allowable deflection which depends on the spacing between stiffeners and plate thickness [24].

Linear buckling analysis

Eigenvalue buckling test was performed to ensure an adequate behavior of the structure under compressive loads. The analyzed modes found a load multiplier factor equal to 4.66; given a load multiplier factor higher than 1.0 this structure will not present failure by buckling [see Fig. 20].

Conclusions

The designed structural arrangement for a riverine low-draft combat boat meets all requirements

Fig. 17. Equivalent stress on transom structure.

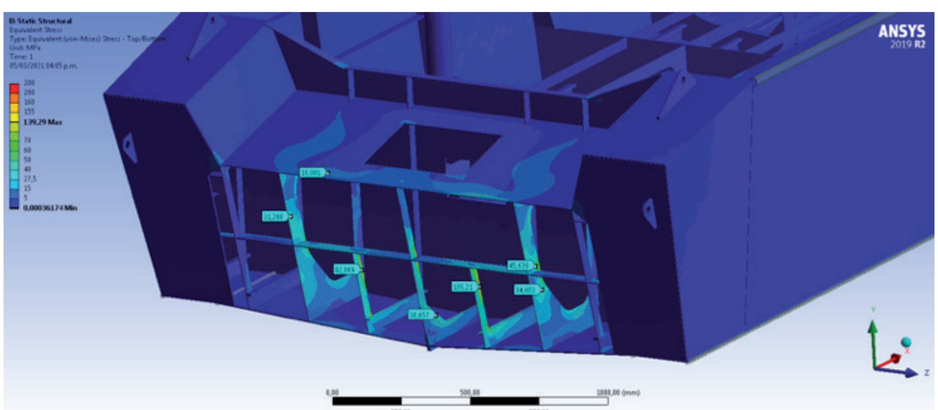


Fig. 18. Vibration modes of the structural arrangement.

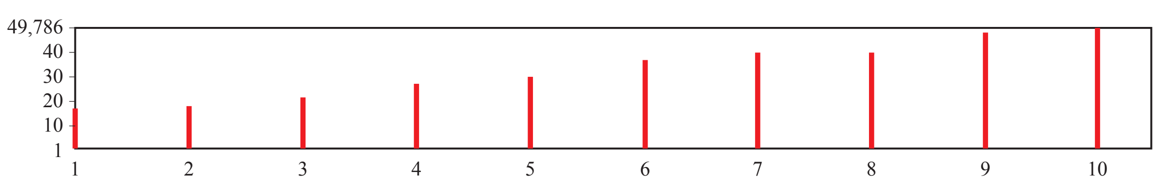


Fig. 19. Vibration modes related to the transom.

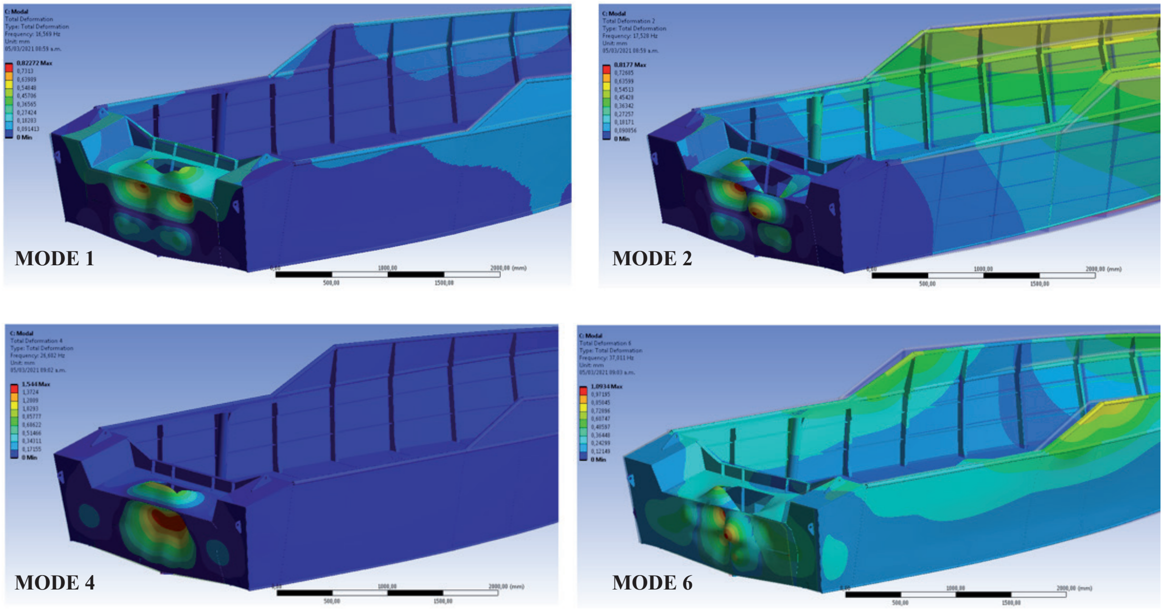
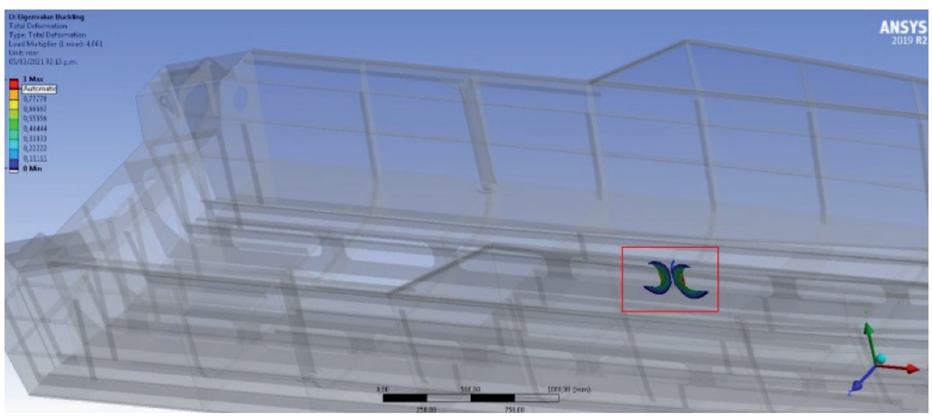


Fig. 20. Buckling load multiplier factor affected zone.



stipulated in both HSC- ABS and ISO 12215 scantling rules.

In most of cases, scantling requirements are more conservatives in HSC-ABS rules [3] than stipulated in ISO 12215 [4].

The performed direct analysis reported safety factors, in most cases, higher than obtained by scantling rules and, therefore, the direct analysis approach is prone to be less conservative. Nevertheless, there are cases where direct analysis presents lower safety factors. This might be because of scantling rules limitations related to structure geometries and stress concentrations. The structural arrangement natural frequencies are out of range from operative outboard motors frequencies. The idle frequency is 15% lower than one of the transom vibration modes, but, due to deformation amplitude is below the maximum allowed, safety operations of the vessel are not deemed affected.

From linear buckling analysis it can be shown that no structural elements will be failing by compressive loading instabilities.

Acknowledgements

The authors are very grateful for the constant support of The Science and Technology Corporation for Naval, Maritime and Riverine Industry Development (COTECMAR) and the Colombian Navy.

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Study of maneuverability and behavior in the sea of the Light Cabotage and Logistics Support Vessel (BALC-L)

Estudio de maniobrabilidad y comportamiento en la mar del Buque de Apoyo Logístico y Cabotaje Liviano (BALC-L)

DOI: https://doi.org/10.25043/19098642.219

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Abstract

Colombia's hydrographic wealth is of great importance for the development of the economic sectors throughout the country, and together with neighboring countries such as Peru and Brazil, different needs arising from the difficult access to their more remote populations are shared. This is why, humanitarian missions are carried out through the ships of the Colombian Navy (ARC), which are at the service of the most remote civilian populations, providing, for example, response to disaster situations or covering logistics support. However, in the framework of these operations, problems have arisen due to the absence of having adequate vessels for navigation in shallow waters. To combat the problem, the ARC and the Administrative Department of Science, Technology and Innovation (MINCIENCIAS) have designated resources for Science and Technology Corporation for Naval, Maritime and Riverine Industry Development (COTECMAR) and Colombian Naval Academy (ENAP) to carry out research for the design of a new prototype vessel called BALC-L (Light Boat Logistic Support Vessel) that will meet the needs of logistics and disaster response. This paper focuses on studying and analyzing the behavior of the BALC-L ship in shallow waters, coastal areas and deep-water operations by means of numerical simulation, in order to know its movements and operational limitations under these conditions. This research presents a theoretical introduction, numerical simulation results and the validation of the data obtained from maneuverability and behavior at sea.

Key words: Maneuverability, seakeeping, numerical simulation, logistic support and coasting, river vessel.

Resumen

La riqueza hidrográfica de Colombia es de gran importancia para el desarrollo de los sectores económicos de todo el país, y junto a países vecinos como Perú y Brasil, se comparten diferentes necesidades derivadas del difícil acceso a sus poblaciones más alejadas. Por eso, las misiones humanitarias se realizan a través de los buques de la Armada de Colombia (ARC), los cuales están al servicio de las poblaciones civiles más remotas, brindando, por ejemplo, respuesta ante situaciones de desastre o cubriendo el apoyo logístico. Sin embargo, en el marco de estas operaciones han surgido problemas por no contar con embarcaciones adecuadas para la navegación en aguas poco profundas. Para combatir el problema, la ARC y el Departamento Administrativo de Ciencia, Tecnología e Innovación (MINCIENCIAS) han designado recursos para que la Corporación de Ciencia y Tecnología para el Desarrollo de la Industria Naval, Marítima y Fluvial (COTECMAR) y la Academia Naval de Colombia (ENAP) realicen investigaciones para el diseño de una nueva embarcación prototipo denominada BALC-L (Light Boat Logistic Support Vessel) que satisfará las necesidades de logística y respuesta ante desastres. Este trabajo se centra en estudiar y analizar el comportamiento del buque BALC-L en aguas someras, zonas costeras y operaciones en aguas profundas mediante simulación numérica, con el fin de conocer sus movimientos y limitaciones operativas en estas condiciones. Esta investigación presenta una introducción teórica, resultados de simulación numérica y la validación de los datos obtenidos de maniobrabilidad y comportamiento en el mar.

Palabras claves: Maniobrabilidad, Navegación, simulación numérica, apoyo logístico y cabotaje, embarcación fluvial.

Date Received: April 15th, 2021 - *Fecha de recepción: 15 de abril del 2021*
Date Accepted: July 18th, 2021 - *Fecha de aceptación: 18 de julio del 2021*

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Introduction

This research was developed with the purpose of carrying out a series of simulations of the maneuverability and behavior of the ship BALC-L within an R&D from the Francisco José de Caldas, project bank which is being carried out between ENAP and COTECMAR. It is of vital importance for the Colombian Navy to be able to simulate in advance how the ship will behave before its construction takes place, in order to be able to propose improvements and avoid later transformations in its design which will result in costs and elongating the development phase of this project. Consequently, and given the vessel's operational purpose, communities in need located in the Colombian Pacific region will benefit from having a means of humanitarian aid when necessary.

The BALC-L class vessel is a ship that is in the design phase at the COTECMAR shipyard, which can be said to be a derivative version of the conventional BALC, but designed to have a shallower draft and access to places of difficult access through the rivers and therefore inner and remote parts of the country. In addition, it is designed to provide fast, flexible, modular and mobile logistical support and disaster relief, all this focused on the civilian population.

Thanks to studies carried out *(Carreño, 2011)* with vessels that operate using pump-jet propulsion system in shallow waters, mathematical models have been developed that take into account the NS or "Non-Squat" effect, which translates into an increase of the turning capacity in shallow areas *(Clarke, 1998) (Eloot, 2013)* for vessels with BALC-L characteristics. Traditionally, this effect has been studied in conventional vessels, being called "Squat effect" *(Sierra et al, 2000)*, which depending on the Froude number *(Escalante, 2010)* of the vessel can generate the opposite effect to the one mentioned above, evidencing that by increasing the draft when the vessel reaches shallow waters, there is a considerable decrease in the maneuverability capabilities of these vessels *(Herreros, 2000)*.

Seakeeping

The seakeeping behavior of a ship (Riola et al, 2017) is described by the balance equation, expressing the sum of the restoring moments that the ship will have, where it must be equal to the external force exerted on it *(Medina, 2016)*.

$$\sum_{k=1}^{6}[(M_{jk}+A_{jk})]$$

$$\sum_{k=1}^{6}[(M_{jk}+A_{jk})].\eta_k(B_{jk}.\eta_k)+(C_{jk}.\eta_k)] = F_j . e^{-i.w.t} \quad (1)$$

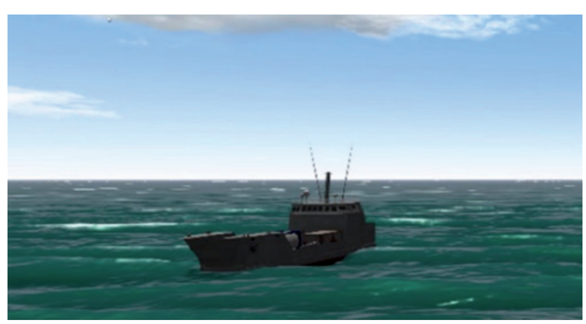
The behavior of vessels at sea *(Vidal, 2008)* is represented by the Amplitude Response Operators (RAO) *(CEHIPAR, 2020)*, which give the vessel's responses to motion in regular waves and represent the transfer function of input (waves) and output (motion) being of total importance in determining the necessary parameters for the design of a vessel.

$$RAO_{pitch} = \left(\frac{\theta_0}{\xi_0}\right)^2 \qquad RAO_{roll} = \left(\frac{\phi_0}{\xi_0}\right) \quad (2)$$

Where the spectral crossover *(Sz (w))* is one of the most important aspects for these responses in irregular waves in space, and time where the sea spectrum *(S(w))* is represented by the RAO or transfer function *(France et al, 2001)*.

$$S_z(w) = [RAO]^2 . S(w) \quad (3)$$

Fig. 1. BALC-L sailing.



Source: CICEN Transas Simulator, 2020.

The aim of this project is to study the behavior at sea of the BALC-L through a series of simulations with Maxsurf Motions Advanced of a 3D prototype provided by the shipyard. The shape plan and the hydrodynamic coefficients *(Holtrop et al, 1978)* of the ship were obtained in order to transfer them to the Maxsurf Motions Advanced program, in which the simulations were carried out by varying the speed with increments from knot to knot and course changes every 15°.

To later analyze the validation of the results obtained and full fill a greater characterization of the ship with the Transas full vision simulator of the Center for Research, Development and Innovations for Marine Activities (CIDIAM) of ENAP, a similar simulation was made in the Maxsurf program, varying the speed from 0 to 8 knots and the course every 15°, with the same conditions, however this simulator does not use only the shape plans but, takes advantage to complete the characteristics of the ship with the values extrapolated from those it has in its database of other ships. The idea is to determine the characteristics of interest of the ship and to propose its possible improvement for this purpose it was studied in 2 maritime conditions according to Douglas scale *(Cazatormentas, 2019)*, as shown in Fig, 1.

The limit criteria defined by STANAG 4154 *(NATO, 2000)* for a patrol and transit vessel in its wheelhouse of 4° RMS for rolling and 1.5° RMS for pitching are used to study the ship's movements and accelerations.

Table 1. Seakeeping criteria of TAP.

TAP mission parameter	Limit value
Roll angle	4,0° RMS
Pitch angle	1,5° RMS

The values obtained contribute to know if the vessel will be a risk for the safety of the ship, the habitability and comfort of the personnel, and the relevant operation of the equipment, systems and weapons, and thus contribute these results to this design that COTECMAR is carrying out in order to optimize the vessel to the maximum.

Maneuverability

Mathematical models *(Carreño, 2011) (Riola et al, 2017)* come, among other factors, from the need to economize the evaluation of vessels. They usually work in an inertial reference system whose center with coordinates is located at the point where the maneuver starts *(Cipriano, 2009)*. And they generally require obtaining hydrodynamic derivatives by means of tests whose validation is subsequently performed with full-scale tests *(Aláez, 1996)*. For three degrees of freedom, the following equations are considered *(Cipriano, 2009)*:

$$m\ (\dot{u} - vr) = X \tag{4}$$

$$m\ (\dot{u} + ur) = Y \tag{5}$$

$$I_z\,(\dot{r}) = N \tag{6}$$

These three differential equations express the respective forces and moments as seen from the inertial reference frame on the right side of each equation, while the left side presents the accelerations as seen from the body-centered, non-inertial reference frame *(Inoue et al, 1981)*. To achieve this, the two reference systems are related by means of a transformation matrix *(Carreño, 2011)*.

The forces and moments must be decomposed into the different factors that affect the maneuvers to be studied, in which the vessel must be subjected to the regulations reflected in resolution MSC.137 (76) *(IMO, 2002)*. It is important to mention that one of the critical aspects to take into account in the preliminary design stage of a vessel that navigates in rivers with strong currents, is the level of control that can be expected of it, in the horizontal plane, when navigating, which is known as its behavior or maneuverability. This can also be defined as the percentage of efficiency in achieving a certain position of the bow of a boat with respect to a defined space *(Sagarra, 1998)*.

For the Society of Naval Architects and Marine Engineers (SNAME) not only maneuverability should be studied, but also controllability, taking into account that in order to define maneuverability the human factor should be taken into account.

Fig. 2. Warship undergoing maneuverability tests.

Source: Defense one website, (2016).

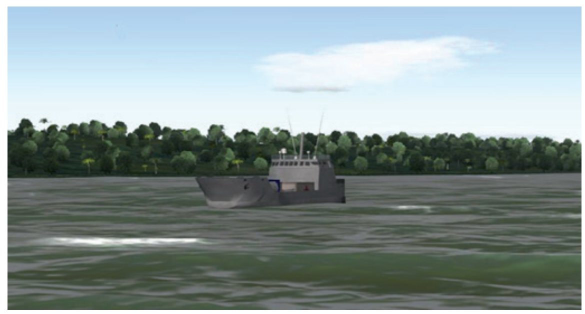
Since many of the critical maneuvers of warships are operated manually, which makes it difficult to determine. In the present research, the term maneuverability is used from a safety point of view *(Sukas et al, 2019) (Aoki et al, 2006)*, taking into account the importance of the vessel's own shapes, which is especially critical in our case, given the shallow draft required for the vessel to be able to go up rivers as high as possible.

Due to this situation, maneuverability has gained importance in recent years, to such an extent that different international organizations

interested in maximizing efficiency maritime transport, trying to avoid material losses and mainly to protect the lives of crew members and passengers, have made great efforts to standardize regulations to assess the maneuverability of most vessels in most cases. These include the International Maritime Organization *(IMO, 2002)*, the European Parliament, the Council of the European Union and the Russian River Registry *(Carreño, 2011)*.

In our study and in order to carry out the maneuverability tests to the BALC-L in shallow waters, the mouth of the San Juan river has been simulated, for which it was necessary to compile the bathymetry of the river provided by the Center for Oceanographic and Hydrographic Research (CIOH), the ship design data and the hydrodynamic theories related to the evaluation of the maneuverability of a warship. In order to carry out this maneuverability study, the Maneuvering Simulation Laboratory (MANSIM) simulation program was used. The results were later validated with the Full Vision navigation simulator of Transas, owned by CICEN (ENAP's research center). Fig. 4 shows the virtual model of the BALC-L vessel navigating in the mouth of the San Juan river. This location was chosen because of its difficult maneuvering characteristics due to the strong currents and tides in the area.

Fig. 3. Virtual model of the BALC-L navigating in the mouth of the San Juan river.



Source: CICEN full vision simulator.

Results

According to the proposed methodology, a model of the BALC-L was designed with the help of the Virtual Shipyard software to perform a validation of the results in ambient conditions in Simulator Transas. Thus, after performing the pertinent maneuverability validations in said program in deep waters, and the necessary adaptations to the propulsion with pump-jets, the model was taken to the virtual scenario of the river at the mouth of the San Juan River, in which two types of maneuvers were performed: evolutionary circles and zig-zag maneuvers.

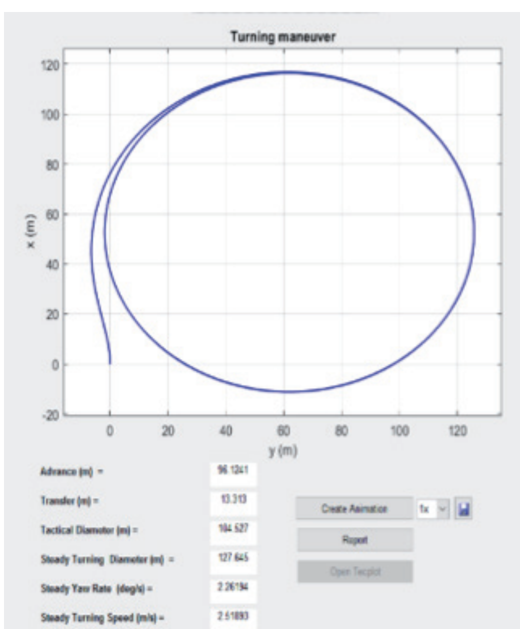
The Fig. 5 shows the trajectory of the BALC-L, at the moment of executing an evolutionary circle maneuver at 35° to starboard and a Zig-Zag maneuver at 20°, this was developed by the MANSIM maneuverability software, which was executed in this case in deep water conditions and with a propeller and rudder maneuvering system.

Table 2. Specifies the use of each of the software and the conditions under which different maneuvers.

Maneuverability Software	Conditions	Maneuvers executed
MANSIM	Maneuvering with a propeller and rudder system.	-Evolutive circle 35° to starboard -Zig-Zag 10° to starboard -Zig-Zag 20°. Maneuvering in deep water conditions
Virtual Shipyard	Maneuvers with a pump-Jet propulsion system.	Maneuvering in deep water conditions: -Evolutionary circle 35° to starboard. Maneuvering in shallow water conditions: -Evolutionary circle 35° to starboard.
Full Vision	The maneuvers in this simulator were performed with a Jet propulsion system.	Maneuvering according to conditions in the area of the mouth of the San Juan River: -Evolutionary circle 35° starboard side -Zig-Zag 10° to starboard -Zig-Zag 20°.

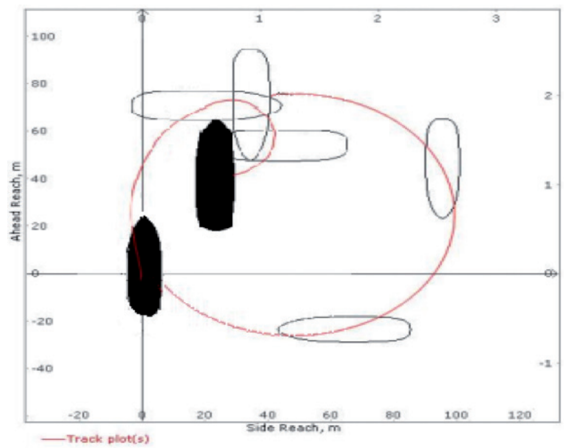
Source: Authors.

Fig. 4. Maneuvering trajectory of evolving circle 35 degrees to starboard and Zig-Zag 20 degrees, vessel with rudder and propeller propulsion, deep water condition.



Source: Simulator MANSIM, 2019.

Fig. 5. Comparison between the 35-degree starboard evolving circle maneuver trajectory in shallow water and deep-water conditions.



Source: Virtual Shipyard Software, 2020.

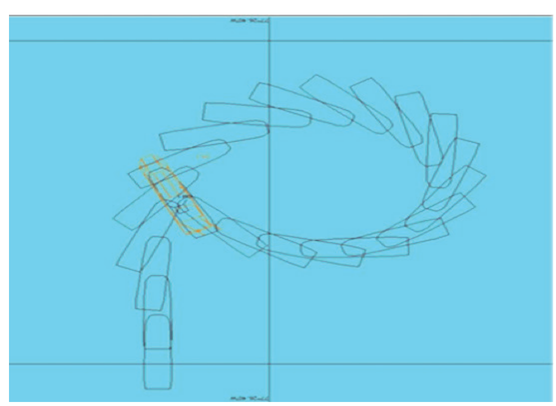
Table 3. Maneuverability result.

VARIABLES	Deep waters	Shallow water
Tactical Diameter	90 m (2,54 L)	30,75 m (0,82L)
Advance	72,15 m (1,92 L)	64,25 m (1,71L)
Transfer	29,44 m(0,78 L)	18,4 m (0,49L)

Source: Authors.

The following graph shows the trajectory of the BALC-L, at the time of executing an evolutionary circle maneuver at 35 degrees to starboard,

Fig. 6. Evolutive circle maneuver 35º to starboard at the mouth of the San Juan River.



Source: Simulator Full Visión, 2020.

this was developed by the Virtual Shipyard maneuverability software, which executed it in deep and shallow water conditions, with a pump-jet maneuvering system.

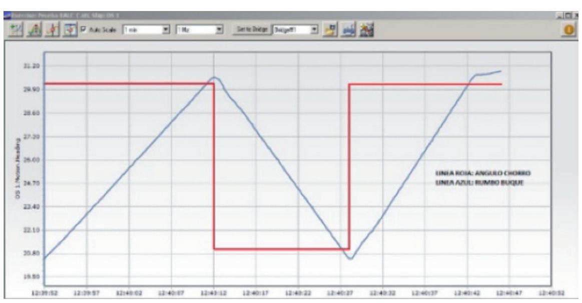
Table 4. Maneuverability results.

VARIABLES	DATA
Tactical Diameter	111 m (2.70 L)
Advance	104 m (2.6 L)
Transfer	70.4 m(1.67 L)

Source: Authors.

The following graph shows the trajectory of the BALC-L, at the time of executing an evolutionary circle maneuver at 35 degrees to starboard, this was developed by ENAP's Full Vision simulator, which was executed at the mouth of the San Juan river and with a pump-jet maneuvering system.

Fig. 7. Plot of course and rudder angle vs. time for Zigzag maneuver 10 and 20 degrees, pump jet propulsion vessel.



Source: Authors.

Table 5 below shows the relationship of course vs. rudder angle of the vessel when executing a zig-zag maneuver 10° and 20°, this was developed in the Full Vision simulator, which executed it at the mouth of the San Juan river and with a pump-jet maneuvering system.

According to these results, a verification was made with the IMO international maneuverability standards according to resolution MSC.137(76) (IMO, 2002) and NATO, in the publication "Guidance for naval surface ships mission oriented maneuvering requirements (ANEP-70)", in order to determine if the vessel complies with the requirements to be considered maneuverable. 2 shows the maneuvering criteria established.

Table 5. Overshoot angles in zig-zag maneuvers.

Overshoot Angle	**Zig-Zag 10º**	**Zig-Zag 20º**
Overshoot First Angle	0.50	1.1
Overshoot Second Angle	0.70	2.1

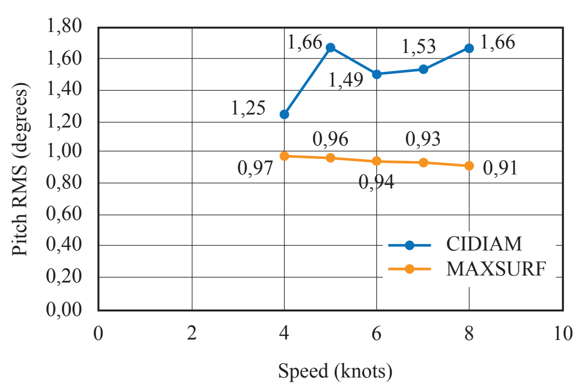
Source: Authors.

Table 6. Maneuvering Criteria.

Maneuver	**Units**	**Criteria proposed**		**IMO Requirements**
		Transit speed	Low speed	
Course stability	Degrees	4	4	-
Evolution circle	Lengths	3	2	5 Lengths
Crash Stop	Lengths	10	10	15 Lengths
Zig-Zag	Seconds	7	10	Overshoot Angle

Note: The table shows the comparison between NATO criteria and IMO requirements (NATO, 2001).

Fig. 8. "Comparison simulation of pitch 060° RMS SS3 Maxsurf vs CIDIAM"..



Source: Authors.

In Fig. 8, data comparisons were made between the results of the Maxsurf Motions Advanced simulator and the CIDIAM full-vision simulator. At the 060° heading the highest RMS values were given in the 2 simulators therefore, to compare the data it was evaluated for this heading when the wave has crashes on the port or starboard side of the vessel, meaning this will be at its maximum wave resonance and hence simulate as accurately as possible real sea conditions, where significant waves reach heights of 1.2 m with periods of 10 s. This is the equivalent of this of this wave height found in the data that was supplied by the CIOH, taken at a speed between 4 to 8 knots that are the values at which warships tend to sail.

Conclusions

- Despite its shallow draft, the BALC-L Vessel developed by COTECMAR, both in propeller and rudder propulsion and in pump jet propulsion, meets the maneuverability criteria contemplated by IMO and STANAG

- It is confirmed and validated that the turning diameter of the maneuver is reduced when the rudder angle is increased, and when the depth is lowered, improving considerably in shallow waters, such as those found in the San Juan River at the Colombian Pacific.

- When comparing the results obtained with the software used by CICEN, the MANSIM and virtual shipyard simulators (Zubaly, 1996) , a difference can be appreciated, however, the data of these mentioned sims are taken as an approximation and those of CICEN as the real validation. The results for both programs allow us to conclude that the BALC-L complies with the international standards mentioned above.

- Despite the good results obtained, the operational performance of the BALC-L cannot yet be assured, since the approach has been entirely theoretical and no use was made of scale models to perform tests with free or captive models in order to calculate its maneuvers with the degree of accuracy required by a ship of the Colombian Navy.

- By having a draft of 1.45m and its hull forms almost flat, the vessel will not have a good performance at sea according to STANAG limits, as extracted from the results of the Maxsurf program as in the CIDIAM program, for neither of the 2 cases, however the vessel is in optimal conditions to be able to navigate in shallow waters.

- The vessel should navigate in open waters with swell less than SS3 for transit between river areas.

- With a sea state SS3 her minimum RMS pitch value were 1.49° respectively allowing her to sail at a heading 060° with a speed between 6 knots. This is the limit sea state in which the vessel will be able to sail but trying to avoid taking the waves other than by the bow or stern.

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Shipbuilding 3D CAD Tools as an Integrated Solution from Concept to Product

La herramienta CAD 3D para la construcción naval como solución integrada desde el concepto hasta la producción

DOI: https://doi.org/10.25043/19098642.220

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Abstract

In the naval design process, there is still no consensus on the use of 3D CAD (Computer Aided Design) systems in the early stages of design. However, the integration capability of different modules is currently making their incorporation in the initial stages more appealing. The objective of this paper is to study the early stages of design as part of the whole process and to demonstrate the convenience of using a single 3D tool during the whole project. Therefore, its impact on the whole design process will be analysed by considering the basic and early design capabilities of current CAD systems, reviewing how the main naval architecture and marine engineering demands match the features and what is the solution provided by the CAD for each case. The methodology presented offers advantages from a technical, economic and time point of view.

Key words: Ship design, CAD, NURBS, topological model, integration, hydrostatics, structures.

Resumen

En el proceso de diseño naval no existe aún consenso referente al empleo de los sistemas CAD (Computer Aided Design) en 3D en las primeras etapas del diseño. No obstante, la capacidad de integración de diferentes módulos en la actualidad está haciendo más atractiva su incorporación en las fases iniciales. El presente trabajo tiene como objetivo estudiar las primeras etapas del diseño como parte de todo el proceso y demostrar la conveniencia de utilizar una sola herramienta 3D durante la totalidad del proyecto. Por lo tanto, se analizará su impacto en todo el proceso de diseño considerando las capacidades de diseño básicas y tempranas de los sistemas CAD actuales, revisando cómo coinciden las principales demandas de los ingenieros navales con las características aportadas por el CAD y cuál es la solución proporcionada para cada caso. La metodología presentada ofrece ventajas desde un punto de vista técnico, económico y de tiempo.

Palabras claves: Diseño naval, CAD, NURBS, modelo topológico, integración, hidrostática, estructuras

Date Received: April 17th, 2021 - *Fecha de recepción: 17 de abril del 2021*
Date Accepted: July 15th, 2021 - *Fecha de aceptación: 15 de julio del 2021*

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Introduction

There are several fields in which CAD (Computer Aided Design) systems could be further developed in the near future. However, the focus of this paper is on the functionalities that are currently being improved. E.g. in the fairing of hull shapes or the global modelling of shapes, they could transform complex surfaces with excellent results, reduced interaction, high precision and complete control. These techniques drastically shorten the design time from days to minutes with excellent results *(Pérez & Alonso, 2014)*.

Another area of improvement concerns one of the most time-consuming tasks in equipment design, the routing of pipes, HVAC (Heat Ventilation Air Conditioning) ducts and cable trays. Automatic routing options minimise this time, but without reducing the robustness of the design there are automatic routing algorithms which provide simple solutions with material optimisation. But the issue is not only to consider existing elements for future routing, but also to prioritise and eventually perform automatic modifications of existing elements as a consequence of future additions. The complexity of the problem explains why there are still no completely satisfactory solutions for automatic routing. However, the current solutions provided by CAD systems solve partial problems and already offer significant support.

Ship design is commonly split into different stages, in most of the cases developed by different agents. As a consequence, tools used for these stages are traditionally different and provide solution only to their particular problems.

At the same time, hard competitiveness in shipbuilding, and subsequent shortening of delivery times and optimization of designs, produce the overlapping of the different design stages, even forcing to follow an iterative and integrated design process. This implies therefore the convenience of using a single tool instead of several ones.

In recent years, improvements have focus the attention in combining basic and detail designs, creating a single 3D model able to obtain classification and production drawings in the most automatic possible way *(Alonso et al., 2013)*. But further improvements are still ahead: to extend the use of this 3D model to the earliest stages of the design, (hull forms definition, naval architectural calculations, definition of compartments, arrangement of main equipment...) thus allowing basic and detail design to take advantage of it.

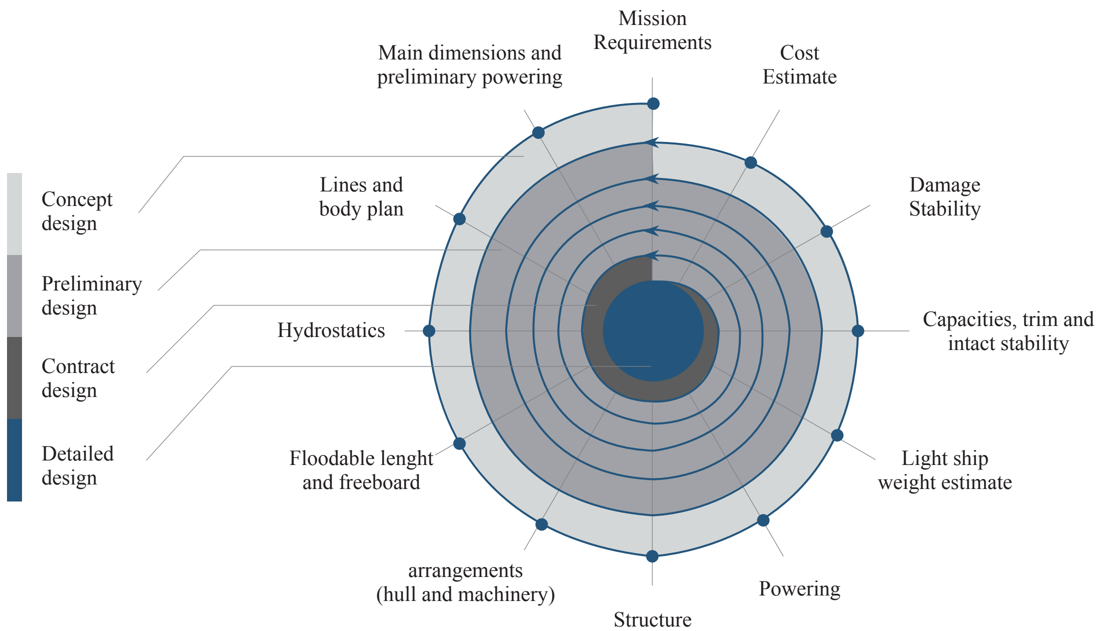
The Design Process

Changes in shipbuilding industry, consequence of the objective of reducing costs and delivery time but maintaining and even improving quality, have produced changes in all aspects: construction process, project management process and design process. Although changes in any of these processes affect the rest, as all of them are interrelated in the common objective of building the ship better, faster and cheaper, it actually happens that the design process is the one mostly affected by the others. For instance, the needs for building optimization had as a consequence the creation of the building strategy concept and the necessity to provide with interim product drawings. Also, the convenience of lowering costs by subcontracting tasks are pushing towards the normalization of collaborative design and the remote engineering in every stage.

Traditionally, the design process has been conceived as a set of stages, each with its own objectives and scope of supply, performed in a sequential way but represented in a spiral format: concept (preliminary) design, basic (class) design, and detail design. These stages were performed sequentially, starting each once the previous one was finished and approved (Fig. 1).

However, changes above mentioned have obliged to abandon the sequential performance of the design stages, overlapping them, requiring to start with one before the previous one has been finished or approved. Even more, in many cases three stages are simultaneously being performed. With this, the spiral chart is converted into a set of concentric circles in which there is not clear the termination of one stage and the start of the next one. This design process, that we can call "integrated design

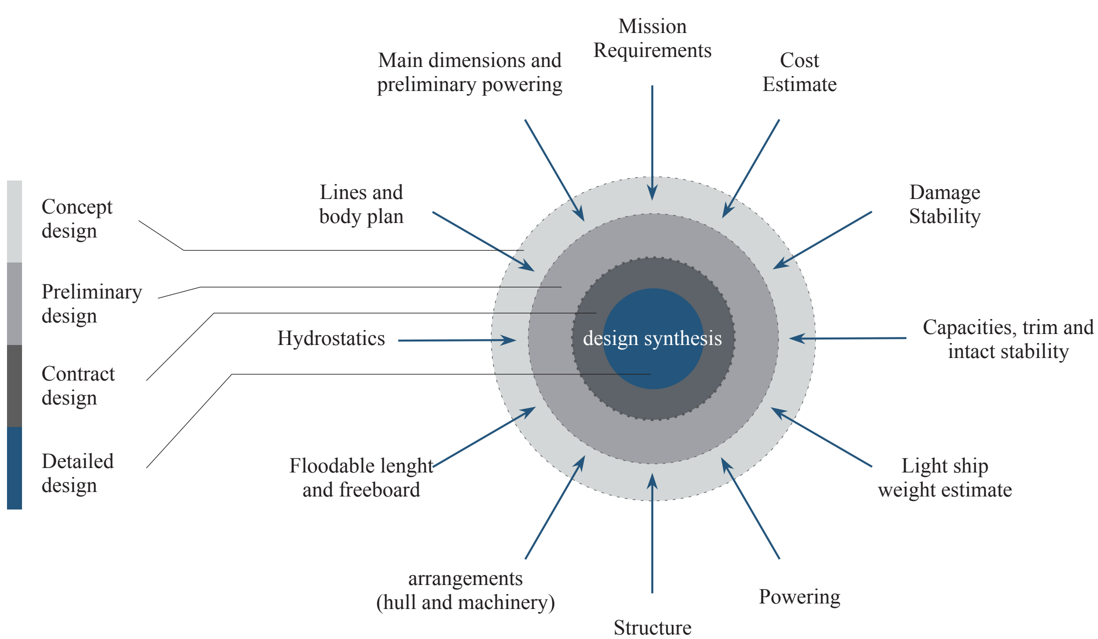
Fig. 1. Traditional spiral ship design process chart.



process", is the one assumed by ship designers as the standard one (Fig. 2).

Despite the fact that there is not a clear sequential performance of the different design stages, the impact that each of them has in the overall cost of the project, considering not only the design itself, but also the constructions and even the operational lifecycle of the ship, is different. In such a way, the consequences of decisions taken in earlier stages have much more consequences than decisions taken in later stages. This aspect, together with the fact that in many cases the success or the failure of a decision taken in one design stage is only visible

Fig. 2. Integrated ship design process chart.



after its completion. Therefore, suggesting the use of the same design tools for all design stages of the process.

The Design Tools

Traditionally, 3D CAD systems have been used in the later design stages of the project, manly in detail design. Nowadays, major ship design agents have realised the importance of using a 3D solution for the basic (class) design, allowing to review previous decisions and facilitating the re-work tasks. However, still there is no consensus on the use of 3D CAD systems in earlier stages of the design.

In fact, on top of hull forms, outputs generated during early stages of the design do not require any 3D model, and that is the reason suppliers of software conceived for these stages have not provided enough attention to this. And as a consequence, interaction between early design software and 3D CAD systems has been limited to the interchange of hull forms lines and decks. However, there are concepts defined during early stages of the design that could be fully reused in further stages, with the subsequent savings, and moreover, elements generated during later stages that could feed back early stages and facilitate the revision of previous works and decisions already taken. For this reason, it is very important that the early design solutions (mainly devoted to hull forms definitions and naval architecture calculations) should be the same as the 3D CAD system used in later stages. At least, they should have the possibility of sharing data in an efficient way.

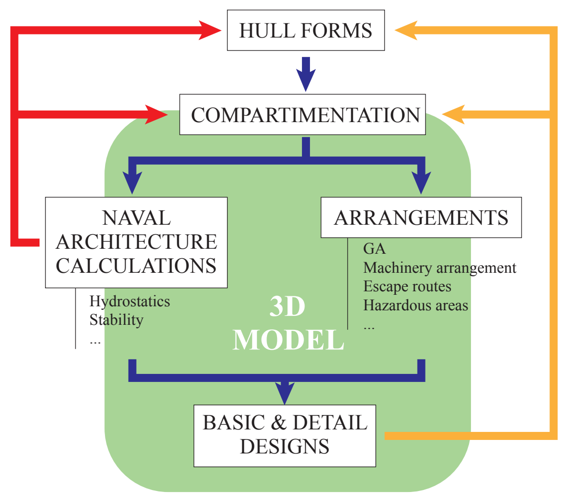
Integrated Early Ship Design

Outputs coming from early design can be grouped in four different concepts:

- Hull forms;
- Compartmentation (definition of spaces, tanks,…);
- Naval architecture calculations (including powering calculation and weight estimation); and
- Arrangements (mainly GA and also including hazardous areas, escape routes,…)
-

The key point is to combine these four concepts in the best form to allow that modifications are easily managed and outputs automatically reissued according to them. Moreover, as many of the parameters considered in this stage of the design correspond to estimations, it would be of extreme importance to have the possibility to feed these parameters with actual data coming from a later stage of the design (Fig. 3).

Fig. 3. Early ship design flow.



This approach for integrated early ship design has been adopted by some CAD providers and it will be described in the following paragraphs.

The CAD Approach

The key aspects of a CAD system to allow the use of this approach are the following:

- Database: The system is built on top of a relational database which ensures a single true of data during the whole design process
- Topology: The possibility of introducing quick changes that can be propagated through the model with a single click requires a topological approach. This is specifically relevant at early design stages, when important changes are introduced into the project, and where

important decisions need to be made having as much real information as possible

- Integration: All disciplines are required to be totally integrated in a single environment. So, the early 3D model of structure needs to be generated with the same tool as the one used for the detail approach. The reuse of information is absolutely critical. Thanks to this, the amount of effort during the detail design stage is substantially reduced.

At the end of the process, the results in terms on quality and time are greatly improved.

The proposed solution is based on a 3D ship product model, see an example on figure 5, in which the geometry and the attributes of the elements of the ship are stored. The model is built as an essential part of the engineering work. It can be used to visualize the progress at all stages and can be exploited to obtain information for material procurement and production. The main characteristics of the ship product model are discussed in the following paragraphs.

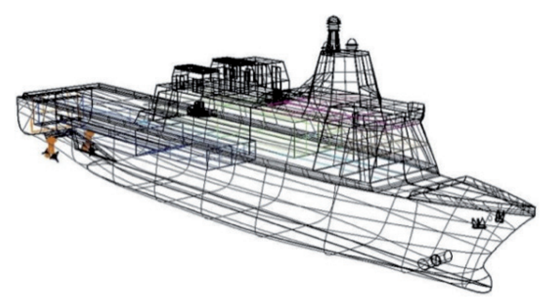
Building an early 3D model allows to improve the design process of the ship and to study different design alternatives in shorter periods of time, which reduces both delivery schedule and cost.

As a result, it is possible to reach a better performance when developing the design and, at the same time, to obtain a product of high quality in a very competitive way. An optimal CAD solution should be based on the integration of all the design stages and disciplines by means of a single database. Thus, allowing for the implementation of collaborative engineering and ensuring information integrity.

The use of a topological model instead of a geometrical model, facilitates its definition, and allows for a quick study of different design alternatives. Furthermore, it simplifies the implementation of modifications, which are very common in the early design stages. The main advantage of the topological definition, where geometrical data are not stored but calculated on-line, is that changes in the main hull surfaces are automatically incorporated in the modified elements, just by reprocessing them. In addition, the topological definition allows the existence of powerful copy commands making thus the definition far more efficient than working only with geometry. Another benefit of the topological model is the size of the information stored in the database, which is significantly lower than for geometrical models.

The key aspect of the design process is the definition of a single ship 3D model, accessible for several designers working concurrently, to be used in all stages of the design. While the project is progressing, the level of detail is increasing and the different parts of the model are subdivided by means of a progressive top-down definition. The solution implemented should include tools to facilitate the direct transition from basic to detailed design *(Lee et al., 2013)*, by means of simple operations that include block splitting, the assignment of parts to blocks and the completion of the model with attributes for the manufacturing phase *(Pérez & Lee, 2014)*.

Fig. 4. LPD Surface definition using NURBS.

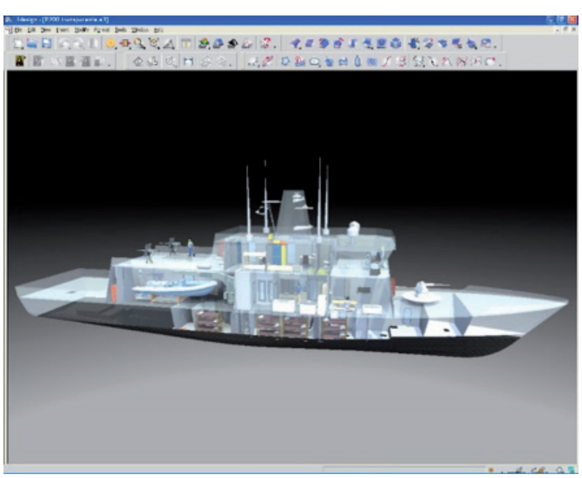


Some CAD systems are developed with the capabilities to define a surface model based on NURBS (Non-uniform rational B-spline) formulation. The surface model is one of the most important components of the ship model, especially for basic design and detail design. NURBS is considered the most generic formulation to represent a surface in Computer Aided Geometric Design and in nearly all cases is very suitable for the definition of hull forms. An unlimited number of NURBS patches can be defined, and this collection of patches can then be used to define the hull forms file. Patches can be edited, and a complete set of geometric transformations is provided *(Pérez & Toman, 2014a)*.

In order to complete a production quality model definition, they may include sophisticated tools such as sewing patches to patches and to curves, fitting curves and patches and management of patches tangent condition among others. Also they may include the construction frame system as well as the deck and bulkhead surfaces of the Ship, which in turn benefits the hull forms information. The next step after the hull forms, the decks and the bulkheads are defined, is the definition and management of the compartments of the ship in a fast and flexible way. Based on a hierarchical tree structure, theoretical surfaces, compartments and versions of them need to be defined and easily managed to offer different alternatives to the compartment arrangement of the project. In a 3D environment and using as initial information the main surfaces of the ship, any ship compartment is easily defined by means of subspaces, that are the geometrical representation of the compartments. These sub-spaces are created using different geometric operations. Combination of different subspaces may define complex geometry. Negative spaces and appendages can be defined, such as bow-thrusters or rudders (Fig. 5).

The topological definition of all these elements ensures that any modification to their limits is automatically applied to the compartment geometry.

Fig. 5. Compartmentation of a vessel using the CAD/ CAM/CAE system FORAN.



Once the geometry has been determined, the Hydrostatics can be evaluated, which consist of the calculation of:

- Hydrostatic characteristics.
- Bonjean curves.
- Deadweight scale.
- Cross curves of stability.
- Freeboard.
- Floodable lengths.
- Curves of section areas and half-breadths.
- Trim diagram.

The hydrostatic values can be obtained for different drafts, for different trim angles and for different densities of seawater. Furthermore, some systems give the option to obtain the numerical output in sagging or hogging situations.

The cross curves of stability can be obtained for different trim angles, heel angles and displacements introduced as data by the user or for standard values. Calculations are carried out with the ship in still water or in a trochoidal or sinusoidal wave. Hull openings are considered in the calculations.

The calculation of the regulatory freeboard is to be carried out according to the Load Lines Convention of 1966 and its latest updates.

Main aspects included under the Intact Stability are:

- Lightship weight distribution and inclining test.
- Loading conditions and equilibrium waterplane calculation.
- Stability calculation taking into account the corresponding stability criteria.
- Longitudinal strength calculation.

Distribution of lightship weight is preliminary calculated by estimate or definition. It is important to remark that the aim of this job is not the calculation of lightship weight, which must always be an input data, but the lightship weight distribution. The more detailed the 3D model of the ship is being built, the more accurate should be the calculation, as many of the weights could be directly considered instead of being estimated.

Following types of calculations can be performed, with numerical and graphical outputs:

- Equilibrium waterplane for the ship in still water, in a trochoidal wave or in a sinu-soidal wave. Asymmetrical loading conditions and calculation of the necessary cargo density value to obtain a required mean draft are available.
- Static and dynamic stability for heeling angles defined by the user or requested by Regulatory Bodies. Maximum KG complying with stability criteria can be obtained, as well as maximum allowable grain heeling moments for ships engaged in grain carriage.

International and national stability regulations, as well as specific criteria for special vessels according to different CCSS and any other specific criteria defined by the user are normally checked.

Longitudinal strength calculations are carried out with the ship in still water or in a trochoidal or sinusoidal wave. Shearing forces and bending moment curves, as well as the weights and buoyancy curves, distributed by construction frames, are obtained. Shearing and bending deflections are part of the calculations completed.

Different types of cargoes are handled:

- Cargoes in defined spaces;
- Modular cargoes (special facilities for defining containers and pallets);
- Other cargoes (giving weight, distribution and position of the centre of gravity).

After the process of a load condition, weight, coordinates of centre of gravity (total and itemized), equilibrium waterplane and even keel flotation, static and dynamic stability tables, checking of the stability, shear forces, bending moments, deflections and other relevant data is obtained and verified.

The purpose of the Damage Stability is the calculation of flooding conditions (defined as combinations of initial situations and damage conditions) and damage stability according to the deterministic and probabilistic methods, depending on the type of ship.

For deterministic method, input data for the calculation is an initial condition given by: previously defined loading condition, fore and after drafts and height of centre of gravity, and a set of drafts (for maximum KG's calculation). The damage situation is given by the damaged compartment, including the corresponding permeability and, in case of liquids, filling percentage and density. Information such as the equilibrium waterplane, compliance with corresponding international and national stability criteria, centre of buoyancy position and location of the hull openings after flooding can be obtained, together with graphic representations of the flooded compartments. The equilibrium waterplane and the static and dynamic stability curves are also obtained for the intermediate stages of flooding. It is also possible to calculate maximum KG's, and water on deck considering the residual freeboard and damage stability.

For probabilistic method, the Attained Subdivision Index 'A' and the Required Index 'R' for cargo and passenger ships, according to latest regulations for cargo and passenger vessels are calculated. For the first steps of the project, using the hull forms and the main deck, it is possible to define a geometric subdivision and to obtain automatically a generation of the spaces of the ship. This option allows the definition of the final compartmentation of the ship according to regulations. In advanced steps of the design, when additionally spaces and loading conditions are provided, the module takes into account the intact stability conditions and associates the spaces to the geometric subdivision defined in the module. During the process, it is possible to define a subdivision by selecting a set of sections (transversal, longitudinal and horizontal) and intact stability conditions. The module calculates all the indexes (compartments and groups) and their contribution to the evaluation of the 'A' Index.

Several tasks are performed under Powering prediction: calculation of towing resistance by means of the most modern prediction methods, propeller selection, powering, rudder geometry and manoeuvrability characteristics, propeller geometry and schematic stern profile definition.

The calculation of the power-speed curves requires the main particulars of the ship as input data in the calculation process. The ship data is taken through the integration with the hull form definition information, although manual data input is also available.

After defining the range of speeds, the designer may select the power prediction method that best fits the ship type. Different power prediction methods can be used for a fast comparison of results and for different types of ships.

Different alternatives for the propeller selection may be provided: i.e. Wageningen B Series, Propellers in Nozzle, Gawn-Burril and Newton-Rader. With the required data listed below:

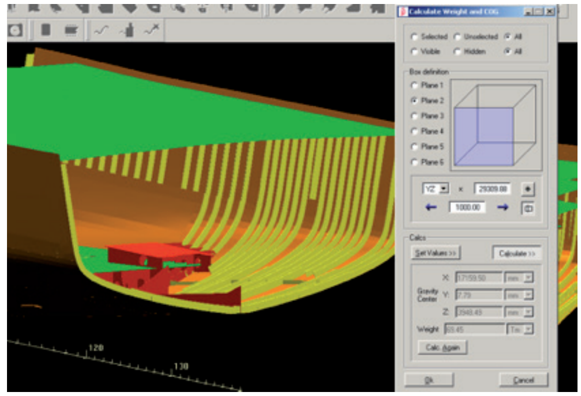
- Propeller diameter and ship speed.
- Propeller rate and ship speed.
- Power installed and propeller diameter.
- Power installed and propeller rate.

The output information includes the main features of the propeller, power-speed curves (at fractional draughts if required), prediction for service and trial condition (even for trawl condition in case of trawler ships) and open-water propeller diagrams.

Once the hull forms, decks, bulkheads and other surfaces are created, it is possible to commence with the definition of the hull structure of the ship: major openings in all surfaces, scantling of the main surfaces for plates and profiles, as well as the main structural elements (floors, web frames, girders, stringers, etc.). The definition is usually based in the frame and longitudinal systems which allows a full recalculation of the model in case of changes in the spacing between elements.

In early stages, plates and profiles are created as objects representing zones of a surface with common scantling properties. Therefore, the size of the objects is not consistent with the manufacturability, which will be considered in later stages of the design. Other properties like the continuity and watertightness attributes of surfaces or parts of them can be defined at any time. Designers would normally follow the same

Fig. 6. Definition of structural main elements.



rules as when working in 2D, which means to start with the definition of the continuous elements because this will allow the automatic splitting of the non-continuous elements. However, that sequence could be modified by creating both plates and profiles at different design stages.

The assembly break down to unit or block is optional at this stage, and the level of detail of the 3D model is the one required by the classification drawings, with respect to the type of parts included (brackets, face bars, clips, collars, etc.) as well as to other characteristics (profile end cuts, scallops, notches, etc).

Due to the topological definition of all elements, any changes in a previous stage does not require the repetition of the work already done: all elements, calculations and parts are automatically updated to the new condition, with the subsequent savings in time and man hours. This also supports the designer when prototyping new ships and the optimisation phases.

The 3D curved surfaces context allows the definition of plates, profiles and holes. Work division is made by using the surface and zone concepts, which allows the multi-user access to any surface. A general zone may be used to contain the entities common to several zones. The following type of profiles can be defined:

- Shell and deck longitudinal
- Frames and deck beams
- General profiles

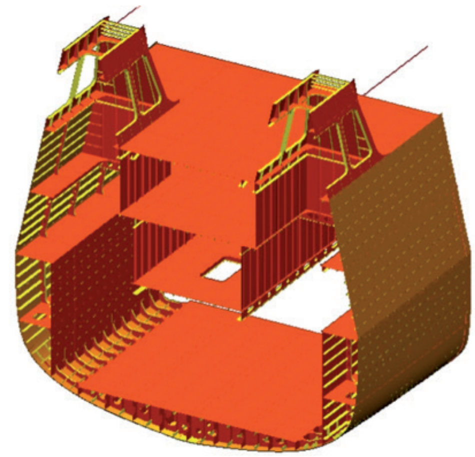
Profile definition is mainly based on topological references to already existing structural elements, as well as to auxiliary concepts used in the early stage of the design (longitudinal spacing, frame system, other profiles, etc). Then the user assigns different attributes such as material, scantling and web and thickness orientation. These basic attributes can be completed by adding constructive attributes (parametric web, flange end cuts, etc) at any time of the design process . The profiles can be split up in profile parts later, when the transition from basic to detail design is performed. When profiles cross other profiles the CAD systems generally generate the necessary cut-outs and scallops. Those profiles including flat, curved and twisted are represented as solids. Then web, flange and the corresponding end cuts are displayed depending on the configuration chosen.

Due to the intensive use of topology, the definition of the shell and deck plating can start in the early stages of the design, even with a preliminary definition of the hull and decks. In this regard, the basic concepts are:

- Butts: Lines lying on a surface used as aft and fore limits for the plates. Butts can have any shape or be located in transverse planes at any abscissa.
- Seams: Lines lying on a surface used as lower and upper limits for plates, with any geometric shape. Seams are usually defined by means of a set of points on the surface and some additional rules to define the layout.
- Plates: zones of the surface defined by aft and fore butts, and lower and upper seams, with attributes such as gross material, thickness and, optionally, bevelling/edge preparation, construction margins and shrinkage factors. Plates can also be the result of breaking down an existing plate in two smaller plates.

Flat and curved plates are represented as solids (including thickness) and the information for plate pre-development is automatically generated allowing thus an early material take-off list. The internal structure context is based on the same high performance topological and visualization environment of the curved surfaces, but applied to a section lying on a plane. This environment provides a set of advanced functions for the easy definition and modification of plates (flat, flanged and corrugated), straight and curved stiffeners, holes, face bars, standard plates, on and off plane brackets, collars and others (Fig. 7).

Fig. 7. Structure basic 3D model of a patrol vessel.



In order to facilitate the operations, it is possible to have several sections in memory, like copy or multiple editions of elements in different sections. The work division is made by using the section, structural element and zone concepts, which allows multi-user access to any section.

One of the most relevant aspects during the basic engineering of a ship is the structural analysis by means of the application of FEM. In practice, it is a laborious task that requires the preparation of a suitable model for calculation, meshing, the application of loads and constraints, processing, post-processing and analysis of the results.

Most of the finite element tools include standard formats for the direct import of 3D CAD models, but they fail when these models come from the shipbuilding industry due to the complexity of the ship models. The effort required in the manual simplification of the model is such that it is more efficient to repeat the model with a calculation-oriented approach, which slows down the analysis process dramatically.

The use of a ship model already created in a 3D CAD for FEM analysis would optimise the design performance in the early stages (Pérez & Toman, 2014b). A simplified ship model to be exported is preferable, and can be made possible leveraging its topological characteristics. Functional algorithms allow for the creation of an intelligent model, simplifying, filtering and deleting unnecessary data to guarantee the quality of the model transferred.

Among other functionalities, there are decisions to be made regarding the model being imported:

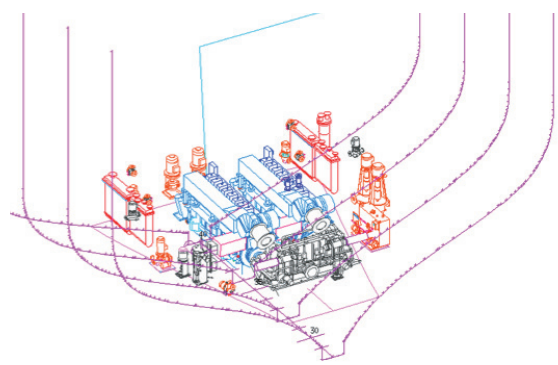
- Whether the plates are translated as surfaces by the neutral axis or the moulded line
- The automatic assignment of colours to every material and profile scantling
- Whether the profiles will be translated as surfaces or as curves
- The minimum area to discard the transfer of holes and brackets

With the information coming from the hull forms, decks, bulkheads and compartmentation, it is enough to start the basic design of machinery and outfitting, creating the outfitting 3D model. Although it is highly recommended to have the hull structure of the ship for reference purposes, this is not mandatory, and the designer can take enough decisions to consider this as a virtual one. When working in the 3D model, the user must check that there are not interferences even with virtual elements. In such a way the system will guarantee that the design is collision-free from the very beginning.

Equipment lay-out is an essential aspect, that compromises even the compartmentation of the ship as all rooms should be provided with enough space to guarantee the correct performance and handling of equipment inside. The sooner the equipment are positioned, the more advantages can be obtained from it. Normally the equipment in the actual models are unknown at this early stage of the design. However, it is possible to start with the positioning of rough models representing the equipment, and to gradually refine them as soon as more reliable information is received. The update of the model data in the corresponding library will automatically produce the update of the equipment already positioned. Equipment models are stored in libraries that can be created for a particular project or can be imported from other projects or from catalogues from suppliers. Models can incorporate, in separate layers, all information regarding necessary maintenance spaces in order to take into consideration from the very beginning of the design process all needs for dismantling, repair and any future update during the ship´s life cycle.

Equipment positioning is done with reference to existing structure (plates, profiles,..), but also it can be done with reference to theoretical lines and surfaces of the ship (hull forms, decks, bulkheads and frames). In such a way, equipment positioning can be started just upon having the hull forms data. Any modification in reference elements automatically updates the position of the equipment. Positioning can be done in a topological way, so any modification in referenced objects automatically produces the update of the position (Fig. 8).

Fig. 8. Equipment lay-out referenced to theoretical lines.



The objective of the P&I diagrams is to define ship system diagrams, including the associated logic of connecting equipment and fittings. Those diagrams include the following information:

- Automatic association of characteristics to pipes and fittings from the material specification as they are placed in the diagram. It is also controlled that no other materials than those declared in the material specification are incorporated to one system.
- Automatic control of the connection consistency between symbols, representing equipment or fittings, and the distributors.

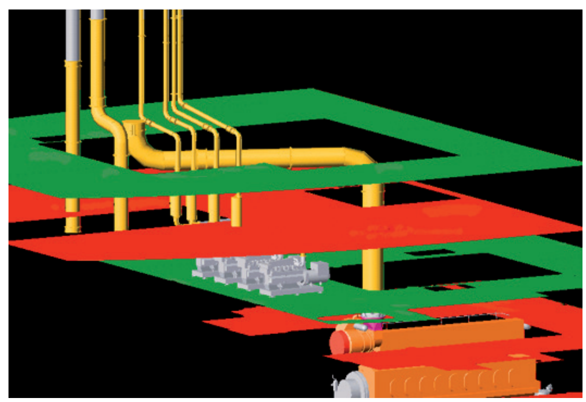
- Automatic orientation of fitting inserted symbols according to the flow sense.
- Automatic assignment of technological properties to distributors and fittings.
- Automatic association of graphic attributes (layers, colours, line pattern and thickness) depending on the fluid.
- Distributor flow direction checking and display.
- Symbols and distributors label structure customizable by the user.
- Automatic insertion of break points over intersecting distributors, texts and symbols.
- Possibility of modification of areas (zones) of the diagram (stretching, shrinking, copying, etc.) keeping all existing connections and creating new elements.
- Insertion of to/from sheet connectors and control of the consistency.
- Definition of complementary 2D geometry, texts, hatchings and standards, to complete the diagram.
- Automatic generation and display of "on-line material lists" for equipment and fittings.
- Automatic labelling of equipment, fittings and pipelines, with two different patterns.
- On-line edition of all characteristics of equipment, fitting or pipeline.
- Preliminary pressure drop and minimum bore calculations.
- Edition of fitting and pipeline logical data.
- Material reservations of pipes and fittings.
- Drawings from other modules.

The sooner the diagrams are created, the lesser technological information is available, so it is possible to start defining flow diagrams with almost only graphical information and to complete them gradually as soon as this information being available. Diagrams can be geographical or not, depending on the common practise for each ship system. In case of geographical diagrams, representations of the ship taken form the hull forms, 3D model or any drawing generated from them can be used for reference purposes.

Routing tools provide the functionalities to arrange the equipment, route the distributors (pipelines, ventilation ducts and cable trays as space reservation), generate the auxiliary structures (foundations, gratings, handrails,…), insert the supports (made with the auxiliary structures entities but linked to the distributors) and carry out the spooling of the pipes and ventilation ducts. Also, HVAC calculation can be done regarding to the 3D ventilation ducts existing in the model.

The aim is to create, at the basic design stage, a 3D model with the most complete information as regards distributor lines (supports are included if needed). This 3D product information is made available to other modules for clash detection, reference or generation of drawings and reports during the ship design process (Fig. 9).

Fig. 9. Routing of pipes referenced to theoretical surfaces (decks).



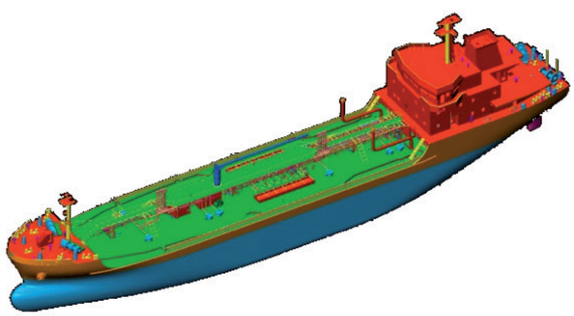
Common features available for this purpose are:

- Database access functions (access to the whole ship 3D product model).
- Clash detection tools (automatic and online).
- Availability of user-defined macros for representation, with editable parameters once positioned in the ship's 3D model.
- Pop-up contextual menus with the particular commands for each element.
- Undo-redo commands for the geometric transformations (move, rotate, connect and couple).
- Search and select command for all type of objects in the scene, applying filtering concepts at the same time, including also the user attributes.
- Model query functions.

- Use of local 3D grids to facilitate the design *(Pérez et al., 2013)*.
- Built-in walk-through application.

The key point to for any software solution aiming to provide a complete solution for ship design and manufacturing is the capability to offer a smooth transition between the stages of the design avoiding rework and delays. Thus, as a logical continuation of the basic design. For example, providing in the hull structure tools for subdividing and joining plates and profiles, including additional attributes for detail design such as bevelling, construction margins and shrinkage factors, and also for defining parts that are not relevant during the basic design stages. In outfitting, it should be possible to add technological properties and refine equipment, split pipes and ducts, and add fittings (Fig. 10).

Fig. 10. Basic 3D model of a tanker, ready for performing the detail design.



The methodology from the initial to the basic and the detailed design is also the approach from the conceptual and abstract to the concrete and manufacturable. Large conceptual parts useful to analyse, for instance weight and functional behaviour, must be converted into manufacturable parts reusing all the information provided in the conceptual stages and detailing when necessary.

Benefits

Among others, the benefits of this approach can be summarized as follows:

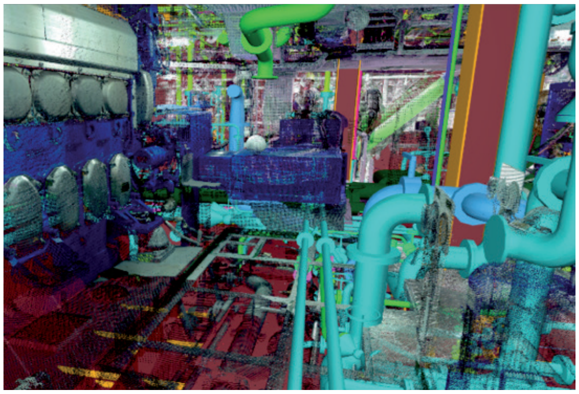
- Shorter evaluation of different design alternatives due to the high level of topology that allows an automatic recalculation in case of changes in previous stage.
- Decision making having actual information instead of estimations. Early and better estimation of materials and weights, including welding and painting.
- Less risk of inconsistencies. 3D CAD system combines the implicit intelligence associated to the 3D model by means of certain attributes (continuity, watertightness,...) with the checking performed by the user leading to a design with better quality.
- Easier link with analysis and calculation tools based in the existence of a single 3D model that, for the purpose of other calculations, is subject to an idealization process (i.e. FEM tools).
- Quick laying-out of relevant equipment, helping in setting the most important spaces of the ship and also for weights and CoG considerations.
- Seamless transition to further design stages, specially detail design, based in the reuse of data, reducing the overall design time and simplifying the overall process.
- More accurate design due to the use of a 3D tool building a visible and comprehensible 3D model.
- Easier co-ordination among disciplines as all of them are represented in the same underlying product model, guaranteeing a collision-free design from the very beginning considering even virtual elements as dismantling spaces, escape routes.
- Possibility to navigate through the 3D model at early design stages by means of Virtual Reality viewers. On top of being very useful from the design point of view, this is also an important advantage for marketing activities.

Conclusions

The CAD system approach discussed in this paper improves design quality, provides higher precision and reduces the risk of inconsistencies.

The rapid evaluation of several design alternatives and the early estimation of materials, weights,

Fig. 11. 3D model of a ship's engine room including outfitting.



welding and painting are additional advantages. Moreover, when efficiently used in conjunction with finite element analysis tools. Finally, it also facilitates the definition of the outfitting (general and critical compartments layouts) and improves the coordination between disciplines. In conclusion, the key points are the simple transition to detail design and the reuse of information.

This substantial change in the development of the basic design stage, which is now being required and implemented, is expected to become the routine way of working in the future, particularly when the continuation with the detail design is considered and/or outfitting design is part of the scope of work.

It is well known that most of the costs of a ship are compromised during the early design stages. The proposed solution delivers tangible benefits as it optimizes the process by reducing the time dedicated to design and consequently the cost, and at the same time improving the quality of the design, and therefore the quality of the ship.

Biography

Rodrigo Pérez Ph.D. is professor in several subjects at the Marine Engineering School of the Technical University of Madrid. He is also the Global Navy Sales Manager at SIEMENS Digital Industries Software.

Jaime Perez-Martinez MSc. holds the current position of Technical Manager at the Royal Institution of Naval Architects. He is currently pursuing his PhD at the Marine Engineering School of the Technical University of Madrid.

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Atmospheric and Economic Impact of LNG fueled Dredging. The Argentine Case

Impacto Atmosférico y Económico del uso de Dragas a GNL.
El Caso de Argentina

DOI: https://doi.org/10.25043/19098642.221

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Abstract

This paper takes a 2021 Argentine case to show the atmospheric and economic impacts of using LNG fueled dredgers in the second largest worldwide operation of its kind about to start in Rio de la Plata. From the emissions point of view, LNG (Liquified Natural Gas) would reduce 23%, mainly those (NOx, SOx and PM) affecting the coastal population health. The use of BioLNG would reduce 99% (60,000 Tons/yr), including as well the planetary impact of CO_2. The economic impact is estimated in savings of 14% of Dredging Cost: 665 Million Dollars (MMUsd), over the 15 years of operation. The origin of these savings is 48% Operational (reduced fuel cost) and 52% external cost mainly due to the reduced impact in Public Health Budget.

Key words: Dredging, Marine LNG, Atmospheric Impact, Economic impact.

Resumen

Este trabajo toma el caso de Argentina en 2021 para mostrar los impactos atmosféricos y económicos de usar GNL (Gas Natural Licuado) en la propulsión de dragas en la segunda mayor operación mundial de dragado a realizarse en el Rio de la Plata. Del punto de vista de las emisiones, el GNL las reduciría un 23%, actuando principalmente sobre las que afectan a la salud de las poblaciones costeras. El uso de BioGNL las reduce un 99% (60,000 Tons/a), incluyendo el efecto planetario del CO_2. El impacto económico se estima en un ahorro del 14% del costo total del dragado (665 Millones de dólares) a lo largo de los 15 años de concesión. El 48% de este ahorro se debe a una reducción de costo de combustible y el 52% son ahorros de costos externos por el menor gasto necesario en la Salud Pública.

Palabras claves: Dragado, GNL Naval, Impacto Atmosférico, Impacto Económico.

Date Received: April 20th, 2021 - *Fecha de recepción: 20 de abril del 2021*
Date Accepted: July 3rd, 2021 - *Fecha de aceptación: 3 de julio del 2021*

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Introduction

In November 2020, the Argentine government launched the bidding process for the new Dredging and Buoying Concession for the inland waterway on the Paraná and Rio de la Plata rivers up to where the latter empties into the Atlantic Ocean. This will make it possible to increase, and afterwards maintain, the width, depth and buoying of the waterways needed to allow some 6,000 ships to circulate with imports and exports from Argentina, Bolivia, Brazil, Paraguay and Uruguay. This is the second largest dredging operation of its kind at global level.

There is a worldwide trend to diminish the harmful effect of dredgers' atmospheric pollution, adopting LNG as fuel, for which reason this study analyzes the atmospheric and economic benefits of this energy transition solution.

Cost of the Investment in Dredgers

Given that the specific approaches covered in this study relate to the construction of new, environmentally-friendly Trailing Suction Hopper Dredgers (TSHD), here we analyze some cases that assist in estimating the cost of these new constructions.

A ship-owner's first reaction, when thinking about reducing pollution and economizing on the operation by using LNG-fueled dredgers, is to convert his existing dredgers. However, this isn't convenient in the cases of aging vessels since such a conversion demands a very large investment – of the order of 30% of the value of a new dredger – and poses serious space limitations.

A case in point is the transformation to LNG carried out by Damen in 2018 on the *Samuel de Champlain* dredger, built in 2002, owned by the French company Dragages-Ports Eig for operation at the Port of Nantes-Saint Nazaire *(GIE DRAGAGES-PORTS, 2017)*. The investment was of US$ 25MM, equivalent to 29% of the construction of a new conventional unit, and was subsidized by the *European Commission's Innovation Fund through its Connecting Europe Facility*.

In order to estimate the costs of new Trailing Suction Hopper Dredgers, a chart is shown (Fig. 1) *(Wowtschuk, B. M. 2016*) which indicates the evolution of prices since 1978 as a function of hopper volume. The following cases are indicated on the chart:

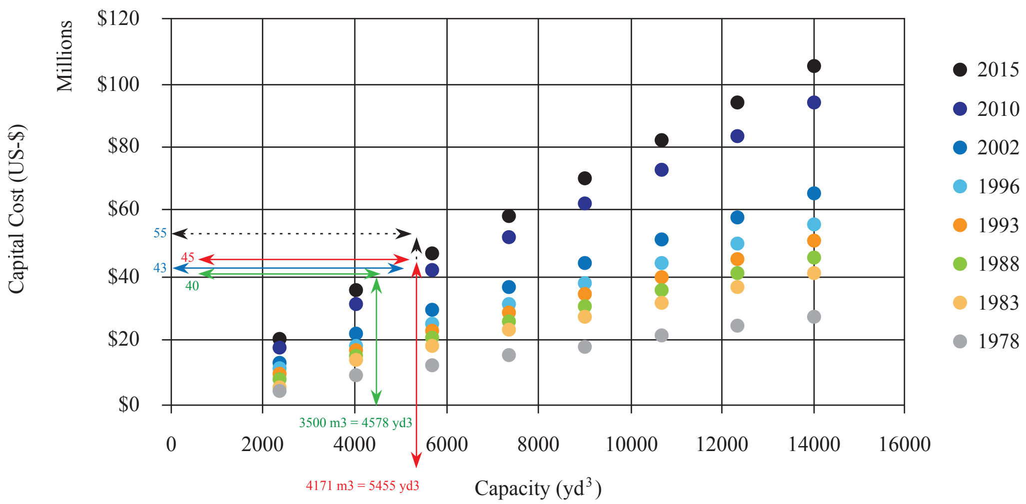
1. The building of the dredger *Afonso de Albuquerque*, owned by Jan de Nul, concluded in 2019 at the *Keppel Singmarine* shipyards in Nantong, China, at a cost of US$ 40MM. This value is 6% higher than that of a conventional dredger owing to the installation of a scrubber system to partially reduce exhaust gas emissions. This equipment has arrived for operation in Argentina (indicated in the color green in the chart).

2. Blue indicates the US$ 43MM cost bid by IHC to the Uruguayan National Ports Administration for the dredger *21 de Julio*, with a 4,200 m^3 hopper, built in Europe. That international tender was canceled and bids sought for the construction of the dredger in Uruguay – which was very successfully carried out in 2017. The new IHC value with partly Uruguayan construction is indicated with a dotted blue line at US$ 55MM.

3. Lastly, the red line indicates the "design dredger" of this study with a hopper volume of 4,171 m^3 which shows a value of US$ 45MM (US$ 10,800/m^3 of hopper).

In order to consider the extra cost of an LNG-powered dredger over a conventional one, the comparison is made with the case of the pushers *(Podetti R.E., 2021)* on the Paraguay-Paraná Waterway, for which an estimated extra cost of the order of 25% was arrived at. As the percentage cost of the motorization of a pusher is relatively higher than that of a dredger, the extra expense of LNG for the latter is considered to be 15%. In this way the designer LNG dredger in this paper is valued at US$ 51.7MM (US$ 12,400/m^3 of hopper).

Fig. 1. TSHD Cost Estimate.



Source: Bohdon Michael Wowtschuk, "Production and cost estimating for trailing suction hopper dredge," Texas A&M University, Ocean Engineering Dept., 2016. Chart modified by the author.

Dredging Concession in Argentina

The governmental information (ARGENTINA. HIDROVÍA FEDERAL) on the dredging operation under the current concession is analyzed in order to relate volumes dredged, hours worked, fuel consumption and type of equipment. To do this, the statistics available on the national government's official page were pored (Fig. 2) through, which initially led to the volumes dredged between 1995 and 2017, leading to an annual average of 28.6 million m3, representing 50% of

Fig. 2. Argentine Dredging Operation Data 2016-2017.

DREDGERS CAPACITY, VOLUME DREDGED AND DIESEL OIL CONSUMPTION 2016 / 2107

DREDGER		DREDGER VOLUME	TOTAL POWER	2016 (HIGH)			2017 (LOW)			2016+2017	
				HOURS /YR		DO CONS.	HOURS /YR		DO CONS.	DO CONS.	
Name	No.	M3	HP	Operat.	Std By	LiTERS/YR	Operat.	Std By	LiTERS/YR	LiTERS	
				63%	18%	<% AT 100%HP	63%	18%	<% AT 100%HP		
Niña	1	3.400	7.415	5.928	564	5.132.318	4.832	618	4.222.100	9.354.418	
Alvar N. C. De Vaca	2	3.400	5.494	4.913	515	3.160.201	2.412	424	1.582.463	4.742.664	
Americo Vespucci	3	3.500	6.968	5.451	527	4.436.771	2.763	343	2.266.329	6.703.100	
James Ensor	4	3.600	9.849	4.557	739	5.339.538	66	29	83.272	5.422.810	
Manzanillo	5	4.000	16.268	-	-	-	3.164	423	6.075.101	6.075.101	
Sanderus	6	5.300	9.085	1.652	147	1.749.376				1.749.376	
Capitán Nuñez	7	6.000	13.708	6.980	468	11.083.404	3.067	833	5.153.410	16.236.814	
Pedro A. Cabral	8	14.000	21.386	1.616	314	4.148.206				4.148.206	
Niccolo Machiavelli	9		31.517	1.465	1.041	6.327.403				6.327.403	
TOTAL HS /YR				32.562	4.315		16.304	2.670			
TOTAL LIT. D.O. /YR						41.377.219			19.382.674	60.759.893	1
TOTAL VOL DREDGED						53.122.000			29.445.000	82.567.000	2
DO /M3						0,78			0,66	**0,74**	3 = 1/2
AVERAGE DREDGER VOL.		**4.171**				**DREDGING AVAILABLE VOLUME(M3) :**				**67.100**	4
						ANNUAL DREDGING VOLUME (M3) / DREDGING AVILABLE VOLUME:				**1231**	5 = 2/4

Prepared by the author based on (WOWTSCHUK, B. M. 2016) and (ARGENTINA. HIDROVÍA FEDERAL) the volume projected *(LATINOCONSULT, 2020)* for the following period. The dredgers employed were almost exclusively of the TSHD type.

Next, an analysis is performed of the years 2016 and 2017 (with available complete information), which additionally represent two different situations: that for 2016 was of very high dredging activity, while that for 2017 was almost equal to the average for the previous 23 years.

Seven dredgers in operation were taken into consideration along with two additional ones that arrived for operating in one season in 2016. They are all trailing dredgers save one, the *Niccolò Machiavelli* (9), which is a "cutter."

D.O. Consumption was in each case calculated *(Wowtschuk, B. M. 2016)* multiplying by parameter 0.1818, the following factors:

- The dredger's total Power (HP)
- The dredgers' annual Hours of Operation.
- The percentage of Equivalent Hours/day, at 100% of Power, during Operation.
- The dredgers' annual Stand By Hours.
- The percentage of equivalent Hours/day, at 100% of Power, during Stand By.

The daily logs for each dredger (ARGENTINA. HIDROVÍA FEDERAL) yielded the Hours of Operation and Hours of Stand By, for each year analyzed.

In order to estimate the Equivalent Hours at 100% of power for each condition (Operation and Stand By), the values presented in Fig. 3 were employed.

Analyzing this information, the conclusion is that in this two-year period:

- Some 60.8 million liters of D.O. were consumed, and some 82.6 million m3 were dredged, leading to a specific consumption ratio of **0.74 Liters D.O./m³ dredged**.
- In order to achieve the 82.6MM m³ dredged, dredgers with a total hopper capacity of 67,100 m3 were on hand, making it possible to propose a ratio of **1,231 m³ dredged/m³ available hopper**.

These parameters are highly useful in carrying out the projections for costs, consumption and necessary investments for the new stage.

Fig. 3. Equivalent Hours at 100% Power.

EQUIVALENT HOURS AT 100% POWER

	OPERATION		STAND BY	
HP	HS/DAY	HS EQ 100%	HS/DAY	HS EQ 100%
100%	1	1,0	0	0,0
75%	18	13,5	3	2,3
10%	5	0,5	21	2,1
	24	15,0	24	4,4
		63%		**18%**

Projection for Volume and Total Cost of Dredging and Buoying

The basis adopted was a recent study *(LATINOCONSULT, 2020)*, financed by a series of organizations that represent the interests of sectors which the new concession impacts on.

The information is presented in Fig.4 and separately analyzed for two geographical sectors: SFC (Santa Fe-Confluencia), to the north, and SFO (Santa Fe-Ocean) to the south; and for two main activities: Dredging and Buoying. At the end the information is unified to obtain median parameters that are easier to handle.

Adding the two sectors together (SFC + SFO), the following overall results are obtained: the total volume of 896 million m³ to be dredged costs 4,153 million dollars (US$ 4.63/m³). Adding the cost of buoy laying for both stretches, some 460 million dollars, a final overall cost of US$ 4,612 million is reached, which corresponds to a final unit value of US$ 5.15/m³ of dredged material (buoying included).

The following table compares the volumes to be dredged in the projected fifteen years with 23 of the 25 years of the current concession for which reliable data were obtained.

Fig. 4. Dredging Cost.

TOTAL VOLUME AND COST OF DREDGING AND BOUYING

SFC

	DREDGING			BOUYING		
	MMm3	MMUSD	USD/m3	BOUYING	BATIM	CONTROL
CAPEX + OPEX	19	143	7,34	177	38	32
> Width	10	70	7,34			
	29	213	7,34	246		

TOTAL DREDGING AND BOUYING 459 MMusd

SFO

	MMm3	MMUSD	USD/m3	BOUYING
CAPEX	167	783	4,69	
OPEX	659	2778	4,22	
	826	3561	4,31	214

POTENTIAL EXTRACOSTOS OF DREDGING IN SFO (MMUSD)

MM m3	MMusd	USD/m3	
826	3561	4,31	1) BASIC ALTERNATIVE
826	3668	4,44	2) ACCELERATED OPERATION (14 DRG)
991	4271	4,31	3) COST GUARD REGULATION APLICATION
826	4261	5,16	4) SOIL TYOE UNKNOWNS
867	3.940	4,56	AVERAGE VALUES

TOTAL DREDGING AND BOUYING 4.154 MMusd

SFC + SFO

MM m3	MMusd	USD/m3	
896	4.153	4,63	460 MMusd

TOTAL DREDGING AND BOUYING 4.612 MMusd

UNIT VALUE 5,15 USD/m3

It is seen that the projected dredging effort is somewhat larger than twice what was carried out up to now in annual averages.

As a reference for the evolution of dredging costs over recent years, the following chart presents the U.S. case (in 2018 dollars). The rise is accounted for by increases in fuel, higher environmental demands and the concentration of supply among a few dredging companies, thus reducing real competition.

The following chart (Fig.5) shows the unit cost of dredging *(Fritelli, J. 2019)* at various U.S. ports and that which is projected for the River Plate. A good correlation with the dredged volume is observed.

Unit Cost of Dredging with LNG

Fig. 6 details the impact of the use of LNG on the combined result of the Cost of Dredging and Buoying, highlighting the values that are modified with regard to the use of Diesel Oil.

The unit cost is broken down into five factors: Ships, Fuel, Crew + Maintenance, General Expenditures and Others. The table analyzes them separately using the data obtained previously and with parameters from the references *(Wowtschuk, B. M. 2016; LATINOCONSULT, 2020 and CIRIA, 2016).*

A 7.5% reduction in the unit cost is seen, which translates into total savings of 321 million dollars. These would be the operational savings with LNG, which lead to greater competitiveness for Argentina's exports.

Toxic Emissions in Dredging Operations

There is overwhelming scientific evidence with regard to the impact that the toxic emissions of ships, including dredgers, have on health and the

Fig. 5. Dredging Unit Cost.

	MMm3	USD/m3
Los Angeles	0,99	17,37
New York	1,44	30,53
Detroit	2,28	12,37
San Francisco	4,10	31,97
Alaska	4,18	11,32
Philadelphia	4,56	26,18
Jacksonville	17,02	18,47
Portland	23,56	6,97
Savanah	28,20	8,42
Galveston	58,52	5,00
New Orleans	80,56	3,45
Río de la Plata	**59,74**	**4,63**

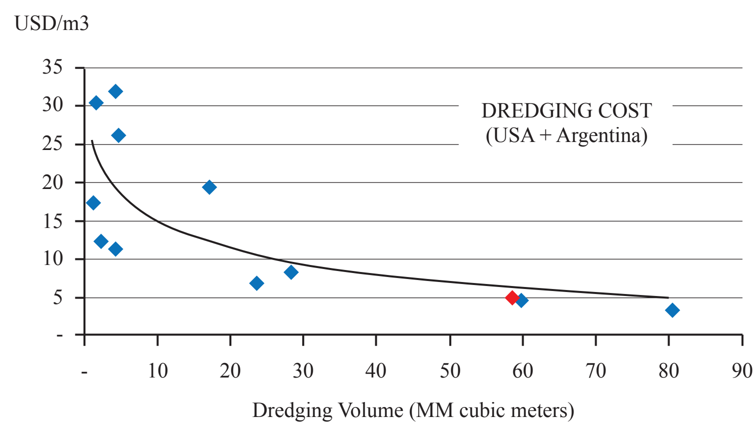


Fig. 6. Dredging Unit Cost Breakdown (LNG).

DREDGING AND BOUYING UNIT COST (w/LNG)

	USD/m3		ITEM	MMm3	MMusd	
				15 YEARS		
15,4%	**0,74**		**VESSELS**			
14,6%		0,70	DREDGERS			
0,8%		0,04	BOUY SETTERS	896	37	(7u x 15yearsx 0,35 MMusd/u-yr)
9,2%	**0,44**		**FUEL**			
7,7%		0,37	DREDGERS			
1,5%		0,07	BOUY SETTERS	896	63	(7u x 15years x 0,6 MMusd/u-yr)
37,3%	**1,79**		**CREW AND MAINTENANCE**			
34,8%		1,67	DREDGERS			
2,5%		0,12	BOUY SETTERS	896	105	(7u x 15years x 1MMusd/u-yr)
35,4%	**1,70**		**GENERALES**			OTHER OPERATING AND GENERAL COSTS AND BENEFIT)
33,3%		1,60	DREDGERS			0
2,1%		0,10	BOUY SETTERS	896	89	(7u x 15years x 0,85MMusd/u-yr)
2,7%	**0,13**		**OTHERS**			Buoys, Signals, Batimery, Control Administration
100%	**4,80**	USD/m3	**TOTAL**	**896**	**4291**	

-7,5%	Cost Reduction by the uso of LNG
-321	**MMUsd is the projected Saving with LNG**

90%	4,34	DREDGERS
6,9%	0,33	BOUY SETTERS
2,7%	0,13	OTHERS
	4,80	USD/m3

environment, particularly when traffic is intense and contiguous to areas near rivers where there is high population density.

It's interesting to note the corporate position which some global dredging firms are adopting with regard to the issue of pollution, even beyond the minimum regulatory obligations which some consider to be excessively permissive, given the extremely serious worldwide environmental situation. In order to reflect this, the following paragraph is quoted:

> *"With more than 1,100 dredging vessels worldwide, of which about half are trailing suction hopper dredgers, DEME believes that dredging companies can contribute to the call of the International Maritime Organization (IMO) for improvements in energy efficiency.*
>
> *The industry should not wait for policies and regulations to rethink the fuel efficiency performance of their dredging vessels, but should achieve sustainable growth by improving energy efficiency with regard to carbon emissions.*
>
> *Energy objectives at DEME are quantified through an increase in efficiency of 7% by 2022 compared to 2011." (J.B de Cuyper, 2014)*

At present, the replacement of Diesel Oil by Liquid Natural Gas (LNG) on trailing dredgers appears as the most convenient transitional option, for the following reasons:

- The current (and projected) cost of LNG is much lower than that of refined Diesel Oil and this difference is on the rise. *The Netherlands Expert Group for Sustainable Transport and Logistics* poses price differentials which on average are of 50% in favor of LNG.
- LNG very strongly reduces emissions that are harmful to health (NOx, SOx and PM).
- It permits being mixed with biogas to thus also reduce CO_2 emissions, up to total decarbonization.
- The technology is already tested and widely available on the maritime market with successful applications to new dredgers as well as to others converted from D.O. to LNG.

Nevertheless, to overcome dredgers' specific operational challenges, special designs became necessary that would make it possible to overcome the limitations of the dual (LNG/D.O.) engines applied to dredging *(W. Shi et al., 2015)*. The success of these designs is reflected in the rising percentage of new constructions of LNG-powered dredges.

In the majority of cases, it is necessary to build a new dredger since the large cost of conversion to LNG (of the order of 30% of a new one) isn't justified in the case of vessels nearing the end of their useful life – which will cause a large part of the fleet to be out of commission earlier than had initially been contemplated.

Unit Cost of Dredging with LNG

The harm to the environment and to health, caused by the toxic emissions of ships in general, is proportional to three factors: Nearness to population, Type of fuel used and Volume consumed.

- The Nearness of the contaminating ship to cities is critical, above all for the health of the most vulnerable populations (children and the aged).
- The Type of fuel consumed causes the specific levels of emissions to vary. Fuel Oil is much more contaminating than Diesel Oil, which in turn is much more contaminating than LNG, which in turn emits more CO_2 than biogas.
- The Volume of the harmful emissions generated by ships is proportional to the volume of fuel consumed.

In the case of dredgers and buoy layers, which we are concerned with here, we are in one of the worst situations, since the three factors pointed out combine negatively:

- They operate near the country's largest coastal population centers (metropolitan Buenos Aires-Santa Fe).
- Because of the age of the vessels used under the current concession, in certain cases, the type of fuel is highly contaminating, to which is added a low energy efficiency, this being another factor in the rise in emissions.
- By the high operating intensity of the dredgers and buoy layers, their fuel consumption levels, and therefore those of toxic emissions, are very high.

Volume of Consumption of Diesel Oil

In order to estimate the volume of fuel during the new concession, current consumption was taken and adjusted in proportion to the volume of dredging.

In Fig, 7 we see that this operation implies a consumption of the order of 52,300 m^3 of D.O. yearly by the 17-vessels fleet of the new concession. As a reference, it is pointed out that this is 77% of the volume currently consumed by river transport on the Paraguay-Paraná Waterway *(Podetti R.e., 2021)*.

Volume of Emissions

Fig. 8 presents the Emissions Factor associated with Diesel Oil and LNG for each of the four toxic

Fig. 7. Projected Annual Fuel Consumption of Dredging and Bouying.

PROJECTED ANNUAL DIESEL CONSUMPTION

	Qty of Vessels	LITERS OF DIESEL /YR		
		1 VESSEL	FLEET	
BOUY SETTERS	7	1.200.000	8.400.000	
DREDGERS	10	4.396.142	43.961.425	0,74 L/m3 x 59,7 MMm3/a
			52.361.425	
			=	
			52.361	Annual Consumption

Fig. 8. Projected Annual Emissions of Dredging and Bouying.

PROJECTED ANNUAL EMISSIONS OF DREDGING AND BOUYING

	EMISSION FACTOR Tons / Thous of Diesel (m3)		**EMISSIONS (Tosn/Yr)** for the projected DO Vol of: 52,36 Th m3 D.O/y		**EMISSIONS REDUCTION w/LNG** (Tons/year)		
Emission	D.0	LNG	D.0	LNG	**D.O - LNG**		Emission
CO2	1106	863	57922	45179	12743	22%	CO2
NOx	22,14	2,51	1159	131	1028	89%	NOx
SOx	0,74	0	39	0	39	100%	SOx
PM10	0,52	0,15	27	8	19	71%	PM10
			59147		13829		

emissions considered. Applying these factors to the annual 52,361 m^3 of consumption leads to the annual figure for toxic tons for each case.

Lastly, through the difference, the last column shows the improvement in tons and percentages, clearly demonstrating that the largest percentage improvements are obtained with regard to the emissions that are harmful to health (NOx, SOx and PM), and are much more moderate in relation to CO_2, which impacts on global warming. To eliminate these CO_2 emissions, LNG can be gradually replaced, over the coming years, by BioLNG, as the production of the latter increases in volume and it thus also becomes available for maritime use.

These reduction percentages are somewhat conservative when compared to other, similar studies on the industry *(Gabriel, J., 2016)* which indicate the following reductions: 25% for CO_2, 85% for NOx, 99% for SOx and 99% for PM.

Economic Assessment of the Damage caused by Toxic Emissions

In a just society, to every crime there corresponds a proportional penalty, which usually has an economic valuation commensurate with the cost of the damage generated. Something similar should occur with contamination, understood as environmental social harm. In Europe, where consciousness over this subject is high and rising, systems of economic penalization of pollution are already in existence. In Argentina (and in many other countries), environmental damages remain unpunished, and very often the problem generated – and therefore its economic impact – are denied.

The toxic emissions of dredgers and buoy tenders generate environmental damages with social costs that are not contemplated by the government and much less so by the concession holder, so that they are termed “external costs.” This name seeks to differentiate them from the “internal” costs (fuel, personnel, repairs, etc.) which a ship-owner knows and seeks to minimize since he must pay a price for them.

The environmental costs of ships’ emissions remain hidden, yet are very real. **They are generated costlessly by the ship-owner, but are paid by the contaminated population**, without charging them to the party causing them. This represents an unfair subsidy that fosters the continuation of costless contamination. In Europe, on the other hand, a fairer policy is already beginning to the applied, summarized in the phrase, he who does it, pays for it. This process seeks to “internalize” external costs; in other words, have the ship-owners shoulder the costs of the damage through higher taxes on contaminating fuels or, even better, by investing on more environmentally-friendly ships, etc.

External Costs of Dredging in Argentina

Below we analyze “Argentine external costs” – those that are caused by these vessels’ toxic emissions and that increase expenditure on public health because of illnesses and deaths. To which are added the economic losses through damage to infrastructure, harvests and biodiversity, as in the case of the acid rain generated by these harmful emissions.

Since no regional study on the valuation of these damages has been found, the results of European studies *(CE DELFT, 2011)* are extrapolated. This analysis was performed for the Waterway *(Podetti R.e., 2021)* and is applied to the case of dredging and buoying, being presented in the following table (Fig.9).

The first line shows the tons of toxic emissions and then the unit external cost for each toxic ton (extrapolating from the European case). It can be seen that particulate matter generates a relatively higher external cost per ton, mainly by being responsible for cardiorespiratory diseases, cancer and deaths among the coastal population.

The conclusion is that, if the current permission to pollute through the use of Diesel Oil in dredging and buoy laying is maintained, we Argentine would pay some US$ 391MM for the damages which the dredging concessionaire causes all of us as a society, at a pace of US$ 26MM/yr. If, instead,

Fig. 9. Projected Annual External Costs of Dredging and Bouying.

PROJECTED ANNUAL EXTERNAL COSTS

	PM	NOx	SOx	TOTAL	
EMISSIONS VOLUME W/DIESEL (Tons/Yr)	27	1.160	39		
UNIT EXTERNAL COST (Usd/Ton)	71.560	20.265	16.133		
TOTAL EXTERNAL COST (MM Usd/yr)	1,93	23,51	0,63	26	MMUsd/yr
			15 years	391	MMUsd
EMISSIONS VOLUME W/LNG (Tons/Yr)	8	131	-		
UNIT EXTERNAL COST (Usd/Ton)	71.560	20.265	16.133		
TOTAL EXTERNAL COST (MM Usd/yr)	0,57	2,65	-	3	MMUsd/yr
			ANNUAL SAVING:	23	MMUsd/yr
			15 years	343	MMUsd

the use of LNG were implemented, this cost would be appreciably diminished to only US$ 3MM/yr, i.e. to only 11%.

These results coincide by 95% with those obtained when employing the method proposed *(MERK, O. 2014)* in the OECD's International Transport Forum for ship emissions in port. To this end, the results are related as a function of per capita GDP and the size of the affected coastal populations.

In a way, allowing the use of Diesel Oil is a kind of US$ 391MM subsidy that the Argentine government awards the concession holder, which neither seems very convenient for the country nor is necessary for the company, which faces a large US$ 4.6 billion business. In addition, in this way the greatest incentive to cease polluting is lost.

External Costs of Dredging on the Planet

Another aspect which seems remote, but is equally important, is that of the assessment of the "planetary external cost," that is to say the cost related to the climate change that affects all of humanity (current and, above all, future) because of the global warming generated by greenhouse gases, the principal representative of which is CO_2.

Fig. 10 *(CE DELFT, 2011)* shows the projection for the external cost caused by CO_2 (euros/ton-CO_2). Located in the center, between the curves for the two most probable scenarios and for the concession period (2022-2037), is the median value of 80 euros/t-CO_2 (US$ 96/t-CO_2). The product of this parameter by the previously calculated volume of CO_2 emitted by D.O.-powered dredgers and buoy tenders (57,922 t-CO_2/yr) leads to an annual cost of US$ 5.6MM, which over the 15 years means **US$ 84MM**.

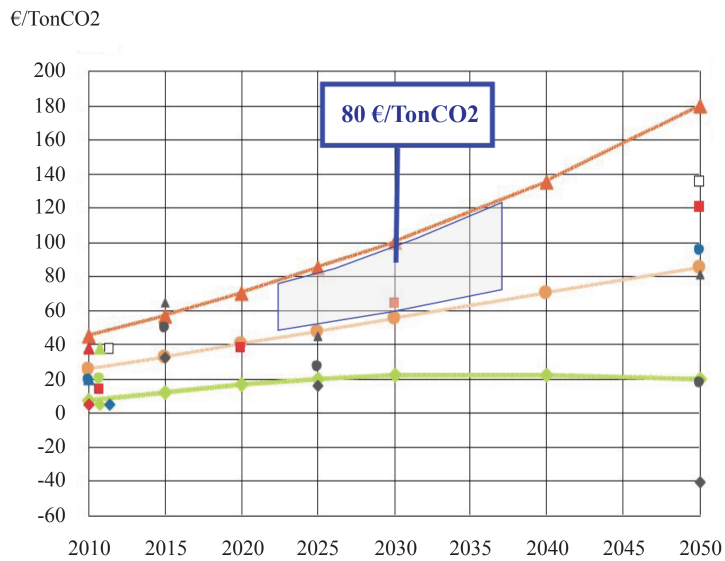
Another way to evaluate the economic cost of this planetary harm caused by CO_2 emissions is derived from the very recent "carbon market," which is an indicator of the price paid by those companies that emit CO_2 to those with activities that have a negative CO_2 balance.

This is a new type of market, which "compensates" those projects that make the biggest efforts in favor of the planet, through the sale and purchase of carbon bonds.

According to the study published by The Economist, the carbon market price (2007) applied to river navigation *(PIANC, 2010)* is the equivalent of an additional cost of US$ 0.15/L of Diesel Oil as a penalty for the emission of CO_2.

Applying this to the projected consumption by dredgers and buoy layers under the new concession (52.3 million L D.O./yr), detailed above, leads to a cost of US$ 8MM/yr., or **US$ 120MM** in total, which the company operating the concession ought to pay on the carbon market to compensate for the generated pollution.

Fig. 10. Projected Planetary External Costs.



Taking the average between the two monetary assessments, it can be estimated that, using D.O., the future dredging concessionaire on the River Plate will generate a planetary damage with effects on climate change with a value of the order of **US$ 102MM**, which could be initially reduced by 22% with the use of LNG, and by almost 100% with an increasing use of biogas in propelling the dredgers and buoy layers.

Total External Costs

The following table (Fig.11) summarizes the external costs detailed above:

In sum, the total external cost which the concession holder would generate if it were allowed to continue using Diesel would be of US$ 493MM, 79% of which (US$ 391MM) would be a hidden subsidy – which Argentines all pay together – issued to the dredging company, for it to continue polluting us for free.

If, instead, the concessionaire were to use LNG, this external cost (mainly social expenditure on health) to Argentina (hidden subsidy) would be reduced by 88%.

Lastly, the use of LNG under the concession allows savings in social expenditures of **US$ 344MM**

Fig. 11. Summary of External Costs of Dredging and Bouying.

SUMMARY OF EXTERNAL COST OF DREDGING

	DIESEL		REDUCTION W/	
	MMusd	MMUsd/y	**LNG**	**BIOGAS**
EXTERNAL LOCAL COST (PM10, Sox, Nox)>> HEALTH	391 79%	26	88%	99%
EXTERNAL PLANETARY COST (CO2) >> CLIMATE CHANGE	102 *21%*	7	22%	100%
TOTAL EXTERNAL COST	**493**	**33**	**74%**	**99%**

(88% of 391), and avoids many deaths, protecting our health and that of the planet.

Conclusions

The use of LNG (and even better bioLNG) to fuel the dredging operations in Argentina would impact in the health of local population and global climate change in a very positive way. But it would also save public funds and operational costs to the operators. Taking the above presented results, there would be large savings in operation and external costs. They are estimated in **US$ 665MM**, close to 14% of total Dredging Cost along the 15 years of concession.

For these reasons, the author has proposed the argentine government to include a simple but powerful clause in the international tender under preparation. This clause sets a limit to the maximum admissible volume of emissions, and on top of that, proposes a method to prize the bidders that guarantee lower emission levels. A heavy monetary penalty is proposed in case of contamination.

A similar clause is proposed to promote the construction of new dredgers in argentine shipyards.

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"Creating a rule framework for the green revolution in shipping industry"
Internal & territorial waters

Creando un marco normativo para una revolución verde en la industria naviera
Aguas internas y territoriales

DOI: https://doi.org/10.25043/19098642.222

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Abstract

Warning about global warming and the noxious effects of pollution, international institutions already settled drastic reductions in emissions that endanger the atmosphere. These challenges apply as much to the inland navigation industry and the coastal fleet as the ocean ships. Shipping companies are implementing new technologies to go toward the environmental goals. There is obviously a large panel of solutions. None of the solutions is a panacea and the stakeholders must make their choice depending on the type of vessel and the constraints of the area of operation, considering the related regulations to come, if not already in force. As a leading classification society, Bureau Veritas is committed to developing new rules and guidelines to keep shipping safe as it develops these innovative new green projects.

Key words: Alternative fuels, new technologies, carbon, risk, rules.

Resumen

Advirtiendo sobre el calentamiento global y los efectos nocivos de la contaminación, las instituciones internacionales ya establecieron reducciones drásticas en las emisiones que ponen en peligro la atmósfera. Estos desafíos se aplican tanto a la industria de la navegación interior y la flota costera así como a los barcos oceánicos. Las navieras están implementando nuevas tecnologías para avanzar hacia los objetivos ambientales. Obviamente, hay un gran panel de soluciones. Ninguna de las soluciones es una panacea y las partes interesadas deben hacer su elección en función del tipo de embarcación y las limitaciones del área de operación, considerando las regulaciones relacionadas por venir, si es que aún no están vigentes. Como sociedad de clasificación líder, Bureau Veritas se compromete a desarrollar nuevas reglas y pautas para mantener la seguridad del transporte marítimo a medida que desarrolla estos nuevos e innovadores proyectos ecológicos.

Palabras claves: Combustibles alternativos, nuevas tecnologías, carbono, riesgo, reglas.

Date Received: April 15th, 2021 - *Fecha de recepción: 15 de abril del 2021*
Date Accepted: July 22nd, 2021 - *Fecha de aceptación: 22 de julio del 2021*

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Introduction

As international institutions continue to warn about global warming and the noxious effects of pollution, the shipping industry is doing its part by developing new technologies that use green energy. Shipping faces several environmental challenges: the elimination of harmful substances in extinguishing and refrigerating media and anti-fouling paints; the correct disposal of garbage, liquid and ballast products together with appropriate onshore collection; and, of course, the development of a new generation of engines in order to reduce pollutant and greenhouse gas emissions. These challenges apply as much to the inland navigation industry as the deep-sea fleet.

Some countries are already imposing strict regulatory requirements in order to achieve their environmental goals, including reductions in emissions that endanger the atmosphere. At the same time, many shipping companies are implementing new technologies in anticipation of expected future regulation. However, each new energy source and its associated technologies presents new risks that must be managed and mitigated through suitable rules and regulations.

As a leading classification society, Bureau Veritas is committed to developing new rules and guidelines to keep shipping safe as it develops these innovative new green projects. These rules and guidelines must embrace new technology in all the life cycle phases of the ship, from design, to construction, equipment, maintenance and inspection, while always keeping in mind the special needs of the inland navigation fleet.

This paper proposes a review of the possible solutions, matters and technologies that may be implemented on board vessels operated on rivers, internal and domestic waters. The analysis highlights the main related risks to be mitigated as well as the main pros and cons. The study is based on Bureau Veritas Marine & Offshore's experience thanks to its R&D and Rules departments as well as approval process of numerous innovative projects.

Environmental challenges

Beside the political and economic influences, the citizens worldwide expect industries do their part to protect the environment and combat climate change. Transportation is one of the major pillars and shipping is watched closely.

Initial stages

It is logical that the first step is to avoid emission of pollutant substances in the environment. Additional BV's class notations "Cleanship" – for seagoing ship - or "Cleanvessel" – for inland navigation vessel - may be assigned when the Rules requirements for the prevention of pollution by oil, noxious liquid substances in bulk, harmful substances carried in packed form, sewage, garbage and gas emissions, are met. Those requirements cover waste management, oil wastes, wastewaters, garbage, hull antifouling systems, prevention of oil spillage and leakage, refrigerants, fire-extinguishing media and limitation of NOx and SOx from thermal engines. Supplementary class notations may be added when treatment plants are fitted on board.

Another step in protecting the environment is to identify all hazardous material that entered in the construction of a vessel and to keep the original inventory updated with modifications all along its lifetime. The class notation "Green Passport" (Bureau Veritas Rule book NR528[1]) includes the requirement of the 2009 Hong Kong convention (IMO), to ensure safe repairs over the ship's lifetime including the recycling process.

Moreover, the simplest way to avoid emission of exhaust gases in harbour areas is to connect the vessel to the shore installation for energy supply. Indeed, it implies that suitable facilities are available directly from the quay and there is appropriate equipment on board. The class notation "HVSC" covers design, safety, reliability and availability of shipboard electrical and control engineering arrangements to allow operation of services by connection to an external high voltage electrical power supply in port.

[1] https://marine-offshore.bureauveritas.com/nr528-green-passport

New Goals

IMO ambitions include[2] at least 40% reduction in CO_2 emissions per transport work by 2030 and further aims is reaching 70% reduction by 2050, and a global annual GHG emissions reduction of at least 50% by 2050, as compared to 2008. Inland navigation industry is expected to reach the same goals.

Three words pop up in articles and speeches about this topic: "sustainability", "decarbonization" and "resilience". Indeed, the so-called green energy must be sustainable, durable, that means consumed at insignificant rates compared to its supply, with manageable collateral effects and harnessed with little pollution. Decarbonization implies leaving fossil-based energy within the complete chain, well-to-wake, and not solely from ship's tank-to-wake. Indeed, zero-carbon fuel must be produced from sustainable processes. Resilience is based on the sustainability together with the ability to limit the magnitude of immediate production losses as well as to reconstruct and recover. Energy storage is among the key topics.

There is room for innovation in technology, to make the best of the renewable energy resources and to improve the energy efficiency. Wind power, solar power, hydro-energy, geothermal energy and bioenergy, all possible solutions are analysed at each level of the production chain that start from the raw materials until final consumption.

As each shipping segment is urged to contribute to the reduction of GHGs and to opt for green energy, there is need for the appropriate regulations to deal with the new risks generated by alternative fuels and the related new technology.

With the energy transition a priority, alternative fuels and battery power are increasingly on the agenda for shipowners and operators with the practical challenge of complying with the new regulations. Stakeholders need to evaluate fleet performance and identify sustainable solutions for existing ships, while deciding how to build future vessels which can deploy alternative fuels or battery systems. Shipowners need to identify how to build a vessel that can sail for the next 25 years or more, regardless of which legislation comes into effect.

While the shipping industry is navigating its way through this period of uncertainty and change, BV's specialists are working hard to prepare the appropriate classification Rules to deal with the new risks generated by alternative fuels and the related new technology.

Regulatory aspect

In order to support development of new solutions to go toward the environmental goals, appropriate technical regulations must be ready and applicable to ensure the same safety level as the other vessels and to allow the shipowners and managers to obtain the necessary licences to operate. Technologies are used to move forward faster than regulations and the technical challenges become regulatory challenges for most of the marine institutions. The national administrations are urged to provide the shipbuilders with appropriate requirements for design, manufacturing and equipment, notably for vessels operated in internal and domestic waters which are not strictly covered by the international conventions.

As an international classification society Bureau Veritas is committed to partner the shipping industry in development of new technologies and to publish comprehensive rules that embrace all the constructive aspects regarding safety and reliability of the installations. As well, those rules have to define the inspections to be performed once ships are in service in order that appropriate maintenance is carried out to maintain the original safety level.

The following pages aim at taking an objective look at the main alternative fuels and their related technologies, in a simple way, and to summarize the majors risks and obstacles together with the classification rules that may offer a suitable support to the stakeholders in designing, constructing and obtaining suitable licences to operate.

2 https://www.imo.org/en/MediaCentre/HotTopics/Pages/Cutting-GHG-emissions.aspx

Possible matters and fuel alternatives

To meet those environmental objectives, maritime companies are exploring a range of clean fuel alternatives. From increasingly common LNG solutions, via “start-up” fuels such as LPG, methanol and biofuels, to less developed options such as hydrogen and ammonia, everything is on the table.

On the pathways to decarbonization, each alternative fuel option has its own advantages and challenges. They are usually ranged as:

- Carbon fuels: LNG, LPG, Methanol/Ethanol
- Carbon neutral: biofuels/biomethane, synthetic methane SNG, green methanol
- Zero carbon: green hydrogen, green ammonia

Natural gas

Natural gas is a hydrocarbon mixture, mostly methane (CH_4) of variable composition, mainly methane for more than 95%. Natural gas is mainly from fossil origin, but it can be produced from biomass. Liquefied natural gas (LNG) is now a well-known alternative fuel within the shipping industry. Producing almost no sulphur oxide (SOx) or particulate matter emissions, it also boasts low nitrogen oxide (NOx) emissions and GHG (greenhouse gas) emissions between 7 and 22% depending on engine type. Despite these advantages, ships won’t achieve zero CO_2 emissions with LNG alone. LNG is still a fossil fuel, and it poses the challenge of methane slip.

LNG is stored at temperature of -162°C (1 bar) or -130°C (10 bars) where the volume reduction is about 1/600 compared to natural gas. Its flash point is -188°C.

If compressed at normal temperature (CNG), the pressure is 200 to 250 bars and reduction in volume is about 1/250 compared to natural gas. CNG needs two to three times the volume of LNG (its density is 0.16 at 200 bars).

LNG needs about twice the volume of gasoil for same energy (its density 0.45 at -162°C).

In the tank, LNG evaporates 0.15 to 0.4 % of its amount per day (boil-off). This gas must be used or released in order to maintain the pressure inside the tank.

The main hazards are:

- Jet fire: the leaked combustible material with high pressure can form a jet flow, if the gas is lit at the leakage split, then the jet fire happens.
- Rapid phase transition: phenomenon in incidents where LNG vaporizes violently upon coming in contact with water. There is no combustion, but a huge amount of energy transferred in the form of heat.
- Cryogenic temperature: conventional steel structure exposed at cryogenic temperature would risk brittle fracture where no apparent plastic deformation takes place before fracture.

Petroleum gas

Liquefied petroleum gas (LPG) is a flammable mixture of hydrocarbon gases used as fuel in heating appliances and vehicles. It is a mixture of propane (C_3H_8) and butane (C_4H_{10}).

LPG is prepared by refining petroleum or "wet" natural gas, and is almost entirely derived from fossil fuel sources, being manufactured during the refining of petroleum (crude oil) or extracted from petroleum or natural gas streams as they emerge from the ground.

LPG’s boiling temperature, vapour pressure and density are depending on composition. Anyway, the latter is greater than air.

Its energy density per volume unit of 26 MJ/L is lower than either that of petrol or fuel oil.

As its boiling point is low, LPG evaporates quickly at normal temperatures and pressures and it is usually supplied in pressure vessels. The ratio between the volumes of the vaporized gas and the liquefied gas is typically around 250:1. The lowest LPG flash point is -104°C. LPG is heavier than air, unlike natural gas, and thus will flow along floors and tend to settle in low spots. The main danger is a possible explosion if the mixture of LPG and air is within the explosive limits and exposed to an ignition source.

Commercially available LPG is currently derived mainly from fossil fuels. Although LPG is considered a clean, energy efficient and portable fuel with an affordable price tag, however burning LPG releases more CO_2 per unit of energy than natural gas.

In the meantime, as new technologies and techniques arise, LPG can be further produced from renewable sources.

Using LPG as a fuel can lower emission to air compared to conventional fuels; GHG, sulphur and NOx depending on the engine.

The infrastructure for distribution and bunkering is already largely available to serve potential marine market demand.

The main safety aspects associated with the use of LPG as fuel include:

- risk of fire and explosion after vaporization of liquid LPG into a gaseous state,
- risk of asphyxiation induced by high concentrations of LPG gas since it displaces the oxygen in the air.

Methanol

Methanol is an organic chemical compound of the alcohols group of substances with the chemical formula CH_3OH. Methanol is a clear, colourless liquid that is soluble in water and is biodegradable. It can be made from a variety of sources, including renewables and it is available around the world.

Methanol has a flashpoint of 12°C, it is flammable, and it burns with no visible flame. It has the potential to react violently with oxygen.

Using methanol as a fuel in spark-ignition engines can offer an increased thermal efficiency and increased power output due to its high octane ratio (114) and high heat of vaporization. However, its low energy content means that fuel consumption would be higher than hydrocarbon fuels.

Its combustion produces significantly reduced levels of CO_2 emissions, eliminates sulphur oxide (SOx) emissions and limits particulate matter. However, methanol is also toxic and flammable. Methanol-fuelled ships need to be designed and operated with special care, given the gases' toxic and flammable nature.

Bio-methanol, or green methanol, is methanol produced from biomass or the biodegradable element of waste. Bunkering facilities are still limited.

Biofuels

Biofuels are a sustainable form of energy derived from the harvesting and processing of different types of biomass, including waste, charcoal, wood, fishery and agricultural products. Burning biofuels can have a net-zero carbon impact on the environment, and reduce emissions of greenhouse gases (GHG) such as methane and ozone.

Liquid biofuels such as biodiesel and bioethanol are the most commonly used type of biofuels for ships. Biogas is naturally produced from the decomposition of biomass, which releases a blend of gases, including methane, which can fuel ships. Synthetic fuels, such as synthetic natural gas (SNG), which are created by reforming biomass feedstock can also be considered biofuels.

While the first-generation biofuels are organic materials grown for fuel production purposes, second-generation biofuels are either the by-products of other biomaterials (e.g. agricultural residue) or the products of non-arable land intended for use as biofuels, and the third-generation biofuels come from microorganisms such as algae.

Most of biofuels are already compatible with modern ship engines and are a convenient alternative fuel source, likely to benefit from a supply chain with fewer emissions.

Synthetic methane/substitute natural gas (SNG) and bio-methane are another set of attractive options, as they are compatible with current LNG propulsion technologies. However, making SNG carbon neutral depends on the availability of renewable energy, and production remains costly in the short term.

Hydrogen

Under normal temperature and pressure, hydrogen is gas with neither odour nor colour. It is the lightest element at the most plentiful in the universe, but which is scarcely in natural condition on Earth.

Hydrogen has the highest energy density, 120 MJ/kg that is 2.2 times more than natural gas.

Hydrogen gas does not have a flash point as it is already a gas at ambient conditions. It means that cryogenic hydrogen will flash at all temperatures above its boiling point (-252.8 °C at 1 atm).

It rises very fast up to the upper area and it does not stay in confined zone near the ground.

It is easily flammable due to its wide range of explosivity and its low energy of ignition. The flam is not visible, and it does not provide any heat.

Although hydrogen has a very high mass energy density, the fact that it is a very light gas makes its storage and transportation real challenges. The aim of hydrogen storage technologies is thus to reduce the volume that hydrogen naturally occupies in its thermodynamically stable state under ambient conditions.

Storage can be high pressure (700 bars or more) or liquefaction at -253°C, which generate additional risks. Also, the process uses energy that may consume up to one third of the gas energy. Another option would be solid storage, where hydrogen is absorbed by metal hydride or absorbed by porous material (solid with large surface like active charcoal, nanotubes of carbon, nanofibers etc.) but currently with limited capacity of storage.

Intrinsically carbon free, hydrogen produces zero CO2 emission when sourced renewably, and it is clean fuel solutions for internal combustion engines and fuel cells. While hydrogen has a favourable specific energy (about three times higher than that of fuel oil) its energy density is 4-8 times lower, depending on the hydrogen's state.

Production network is still to be intensified and costs (Capex/Opex) are still high.

Ammonia

Ammonia is a compound of nitrogen and hydrogen with the formula NH3. It is lighter than air (0.86 at boiling point) and it has a very narrow flammability range.

Ammonia has a much lower energy density than traditional fuel oils, weighs twice as much as fuel oil and requires three times the space to contain the same amount of energy (between hydrogen and LNG in terms of storage volume).

It ignites and burns poorly compared to other fuels and combustion could lead to higher NOx emissions.

Ammonia produces zero CO2 emissions, when sourced renewably, and it can be a clean fuel solution for both internal combustion engines and fuel cells.

There are safety issues associated with ammonia's toxicity and caustic properties, which create a need for careful storage and handling. Ammonia can either be pressurised (10 bars) or kept in cryogenic liquid form close to ambient pressure. It can be liquefied at -33°C and stored at atmospheric pressure for use as a marine fuel.

Toxicity is the main issue, but it is also flammable and corrosive.

Ammonia production levels reach nearly 200 million tons annually but price of green ammonia, produced from renewable energy, remains high.

Summary tables

Table 1. Alternative fuel properties – Storage characteristics.

	Mass energy density LHV (MJ/kg)	Volumetric energy density LHV (GJ/m³)	Storage pressure (bar)	Storage temperature (°C)	Relative tank volume (without insulation)
Marine Gasoil (reference)	42.8	36.6	1	20	1
LNG	50.0	23.4	1	-162	1.6
LPG	46.1	26	17	20	1.4
Methanol	19.9	15.8	1	20	2.4
Liquefied H_2	120	8.5	1	-253	4.3
Compressed H_2	120	7.5	700	20	4.9
Ammonia	18.6	12.7	1 10	-34 20	2.9

Table 2. Safety issues - Summary .

	Fire / explosion	Pressure	Toxicity	Corrosivity & Materials	Cryogeny
Marine Gasoil (reference)	X	X			X
LNG	X	X			
LPG	X				X
Methanol	X		X		
Liquefied H_2	X	X		X	
Compressed H_2	X			X	X
Ammonia	X		X	X	

Technologies

There are many options for reduction of air pollutants and GHG emissions. Although new fuels and sources of energy are shaping the future, however choosing optimization and energy savings can be a first step. It can start with improvement in energy management and operational conditions, with further optimization in hull forms, propellers and coating. However, many studies have been carried out, giving a panel of combinable solutions which have been already applied with positive results, but they remain behind the challenging path to meet the environment goals.

While carbon neutral or carbon-free fuel production are developing (possibly including carbon capture) the number of possible alternative solutions in the long run is increasing, each of them with pros and cons. The international and national regulations are not yet ready for all technical options, generating shilly-shallying among the maritime and inland navigation industries. Furthermore, regulations usually set the suitable technical arrangements, but they don't provide the constructive dispositions for manufacturing, notably material, components of equipment and tests, and assembling on board.

The classification rules are providing the constructive requirements about each fuel. They refer to the main rule books, NR467 ("Rules for the classification of steel ships") for seagoing ships and NR217 which is applicable to inland navigation vessels. Both are linked to NR216 which provide the requirements about materials and welding. The requirements for approval of equipment in hull and machinery are given in the Rule book NR266 ("Requirements for Survey of materials and Equipment for the Classification of Ships and Offshore Units", complete with NR544 for pure inland navigation vessels (although the latter may refer to the former as far as necessary). Additionally, the Rule note NR320 settles the certification scheme of materials and equipment for classification.

Moreover, the initial conditions for approval of any system must be maintained once it is in service, especially with regard to the specific hazards inherent to the new fuels and technologies. The classification rules settle the periodical inspections as well as the scope of survey for each part of a ship. The pages hereafter would outline the situation of the main technical options regarding the specificity, the regulations and the classification approach.

Thermal engines

Natural gas

LNG is still a fossil fuel, and it poses the challenge of methane slip. Caused by incomplete LNG combustion in the ship engine, methane - a potent greenhouse gas - is emitted into the atmosphere, partly offsetting the CO2 emissions reduction. This is a key area for technological development, as manufacturers are working to improve the design of engines to limit methane slip.

The one main advantage of LNG today is that it is available in large quantities at attractive prices. Another challenge with LNG has been limited bunkering infrastructure and higher CAPEX. However, thanks to huge investment in global LNG bunkering facilities and favourable OPEX conditions, the price of LNG is falling, making it increasingly competitive with existing fuels. This trend is set to continue as global build-up of LNG bunkering infrastructure progresses. As LNG gains traction as a clean fuel solution, greater numbers of LNG-powered vessels are being built; the global order book lists about 20% of newbuild orders as LNG-powered.

Although natural gas is relatively new in inland navigation activities, however it is used in shipping industry for nearly 50 years since the first LNG carrier has been operated.

There are three types of engines:

- *Spark ignited lean burn engine (Otto cycle)*
  LNG engines were developed for land-based power industry with requirements on simplicity and good overall performance with low emissions. It runs with low pressure gas supply, 4 to 5 bars. The gas is injected in the air charge to the cylinder where the mixture is compressed and ignited by a spark.
- *Diesel ignited dual fuel engine (Combined Otto/Diesel cycle)*
  Gas engine with dual fuel capability was developed originally for land-based power plants. Development focused on low NOx emissions at high load, then also for variable speed capability. The diesel-ignited LNG engine is the first type used in the marine industry and it is currently the more common type. It runs with low pressure gas supply, 4 to 5 bars. This type of engine is also suitable to work with diesel only.
- *High pressure direct injection engine (Diesel cycle)*
  It came to use in the offshore industry where its high fuel flexibility and very high-power density are attractive. There is no requirement for the self-ignition stability. The operating principle ensures that the combustion of the gas fuel is very complete but with higher NOx emissions than other gas engine types. Currently, its use in the marine industry is still limited but promising. The operating principle is based on high pressure gas injection, 300 to 350 bars, the air is compressed, and the gas is injected directly into the cylinder at the end of the compression stage.

The IMO regulations are the SOLAS Convention and the IGF Code ("International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels").

The European regulation allows LNG propulsion for inland navigation vessels and the requirements are laid down in the standard ES-TRIN (cf. Chap 30 and Annex 8, section 1).

The Classification Rule Note NR529 ("Gas-Fuelled Ships") applies to ships fitted with internal combustion engine using natural gas as fuel. The gas may be stored in gaseous (CNG) or liquid (LNG) state. This Rule book incorporates the text of the IGF Code and provide some additional requirements and interpretations of the Code. The additional service feature "gasfuel" (or "dualfuel") is added to the classification notations. The specific requirements aim at mitigating risks due to particulars of natural gas, covering especially:

- Risk analysis
- Location and separation of spaces: gas process room, machinery spaces containing gas fuelled engines and tank rooms
- Arrangement of entrances and other opening
- Arrangement of gas piping and liquefied gas piping
- Design of machinery spaces. There are two alternative systems:
    a) Gas safe machinery spaces: arrangements follow the provisions of IGC Code (International Code for the Construction and Equipment of Ships carrying Liquefied Gases in Bulk), Chapter 16, such that the spaces are considered gas safe under all conditions, normal as well as abnormal conditions i.e. inherently gas safe.
    b) ESD protected machinery spaces: arrangements in machinery spaces are such that the space itself acts as the pipe enclosure required by IGC Code, Chapter 16. In the event of abnormal conditions involving gas hazards, emergency shutdown (ESD) of non-safe equipment (ignition sources) and machinery must be automatically executed, and the equipment and machinery in use during these conditions must be certified as safe type.
- Gas supply system in gas machinery spaces (gas safe or ESD)
- Storage tanks used for liquefied gas are designed in accordance with IGC Code, Chapter 4
- Gas fuel bunkering, transfer and distribution systems outside machinery spaces
- Ventilation system (ventilation of hazardous and non-hazardous spaces, gas tank storage room, ESD machinery spaces, process rooms)
- Fire detection and alarm system
- Fire extinction (fire main and water spray, dry chemical powder)
- Electrical systems depending on hazardous areas divided into zones 0, 1 and 2 according to risk of explosive gas atmosphere.
- Monitoring of gas tank, gas process and gas engine
- Gas detection (enclosed spaces and open areas)
- Gas compressors (remote emergency stop)

Petroleum gas

Liquid LPG is supplied to the engine at a pressure of 50 bar. To achieve a full atomization of the liquid LPG when leaving the injection valves nozzles, 600-bar injection pressure is necessary.

The system (ME-LGI, for liquid gas injection) utilizes the fuel booster injection valve (FBIV) that combines hydraulic actuated plunger pump with spring-loaded injection needle valve which opens at given fuel pressure.

Exhaust Gas Recirculation (EGR) or Selective Catalytic Reduction (SCR) system is necessary to fulfil the IMO NOx emission limits.

Regarding safety, the IMO regulation is the IGF Code, although compliance of LPG-fuelled ships should be demonstrated through alternative design. Classification allows assignment of the additional service feature "gasfuel (LPG)", or "dualfuel (LPG)", in either liquid or gaseous state, referring to the note NI647 "LPG-Fuelled Ships". It covers the arrangement, installation, control and monitoring of machinery, equipment and systems using LPG to minimize the risk to the ship, its crew and the environment, mainly:

- Risk assessment
- Fuel containment and fuel piping and protection against mechanical damage, also considering that any released gas is led to a safe location. The provisions of NR529 for material and design of LNG piping systems also apply to LPG.

- Design / working Pressure
- Arrangement of machinery spaces
- LPG preparation room means any space containing pumps, compressors, heat exchangers and vaporizers for LPG preparation purposes. This room must be located on open deck or where it can withstand the maximum pressure in the worst leakage scenario.
- Regulations for bilge systems and drainage arrangements
- Drip trays
- Venting arrangements
- Prevention of phase changes in LPG supply lines
- Arrangement of the bunkering station
- Secondary enclosure for LPG fuel piping
- Fire safety and explosion prevention
- Ventilation systems serving hazardous spaces
- Electrical installations. The provisions of NR529 also apply to LPG
- Control, monitoring and safety systems

Methanol

To use methanol safely, additional CAPEX is required for storage and handling. While the CAPEX gap is smaller than for LNG, fuel costs are less favourable when compared with LNG and LPG.

Methanol can be used in spark-ignition engines. It can offer increased thermal efficiency and power output (as compared to gasoline) due to its high octane ratio (114) and high heat of vaporization. However, methanol's low calorific value also means that ships would need to burn greater quantities than hydrocarbon fuels to travel the same distance. Due to formation of acidic products during combustion, the wearing of valves, valve seats, and cylinders might be higher than with hydrocarbon burning. Certain additives may be added to the fuel in order to neutralize these acids.

As an alternative, methanol can be mixed with ordinary fuel. For instance, some current projects on existing vessels are based on adaptation to existing engine with mixture of methanol (70%) and diesel (30%).

The IMO regulation for use of methanol is the interim guideline MSC.1/Circ.1621 pending final text.

Regarding classification, the new Rule book NR670 has been issued. It is in line with the IMO requirements and it provides additional requirements notably about constructive dispositions.

The specific requirements are relating to:

- Cofferdams surrounding fuel tanks
- Ventilation of void spaces
- Bilge system
- Drip trays
- Design of fuel piping
- Fuel distribution (engine components, double walled pipes, segregation)
- Fuel containment system, tank segregation
- Fire detection and extinguishing system, alarms and heat detectors depending on hazardous areas

Biofuels

Ship managers also need to account for a handful of biofuel-specific technical challenges such as oxidation stability, cold flow properties, and the risk of microbial growth. Also, for certain types of engines, ship managers may need to choose a different lube oil.

For maritime stakeholders who are uncertain about committing to biofuels as a fuel solution, mixed fuels are another possibility. By mixing traditional carbon fuels with biofuels or synthetic fuels, known as "drop-in" fuels, ship owners can take a pragmatic step towards lowering their emissions. Ships can burn mixed fuels without encountering technical, safety or regulatory difficulties, and ship operators can avoid questions of port-by-port biofuel availability. As part of mixed fuels, biofuels can provide a workable entry point into carbon-neutral shipping for shipowners, operators and managers.

The regulations are those applicable to the original matter (diesel, LNG, …). It is same regarding classification but the type approval certificates covering the engine and other components in contact with the biofuel may need to be reconfirmed when the physical and chemical particulars of the product differ from those of the original approval.

Hydrogen

One of the two means for using hydrogen as energy on board is thermal engines. Hydrogen can be injected as a gas in a thermal engine, it may be pure or mixed with diesel (cf. supra). In the latter configuration, 1 kg of hydrogen may replace 2.5 to 3 litres of diesel. The energy efficiency is slightly less than classic engines. The proportion of hydrogen in the mixture would decrease proportionally the direct emission of CO2 but it would increase the NOx emission due to higher burning temperature. The hydrogen combustion engine is simply a modified version of the usual internal combustion engine. The main difference is the stronger design of the engine to withstand the higher pressures.

Three main types of hydrogen engines:

- Direct cylinder injection: it is the most sophisticated system with the fuel-air mixture inside the combustion cylinder after the air intake valve is closed.
- Central injection or Carburetted System: fuel-air mixture during the intake stroke. It is the simplest method for delivering fuel to hydrogen engine, with the same system as gasoil engine, easy to convert to hydrogen. However, it is more subject to irregular combustion due to pre-ignition and backfire.
- Port injection: it injects fuel directly into the intake manifold at each intake port. Air is injected separately at the beginning of the intake stroke to dilute the hot residual gases and cool any hot spots. The risk of premature ignition is reduced.

Since both the carburetted and port injection methods mix the fuel and air prior to entering in the combustion chamber, these systems limit the maximum theoretical power to approximately 85% of that of diesel engine.

For direct injection system, the maximum output of the engine can be approximately 15% higher than that for diesel engine.

The combustion temperature may be very high and a large amount of nitrogen oxides (NOx) may develop. If engine is designed for about twice as much air as required for complete combustion, NOx is reduced to near zero, but the power output is about half that of a similar gasoil engine.

Using hydrogen as fuel requires mitigation of risks. Hydrogen is one of the most flammable products when mixed with air even in small amounts. Ignition can occur due to the oxygen, at a volumetric ratio as low as 4%.

The hazards related to liquefied hydrogen are multiple. Special attention is required due to low ignition energy, wide range of flammability limits, low visibility of flames in case of fire and high flame velocity which may lead to detonation with shockwave. Additionally, low temperature may generate embrittlement compromising the stressed structure's mechanical performance including weld metals. Also, inert gas and constituents of air may come to liquefaction and solidification which may result in an oxygen-enriched atmosphere. As a rule, low temperature hazard implies strict selection of appropriate materials.

In terms of regulation, the IMO resolution MSC.420(97) “interim recommendations for carriage of liquefied hydrogen in bulk” provides guideline for storage.

From classification point of view, the guideline NI547 concerning fuel cells also supplies with requirements concerning containment and use of hydrogen. All pressure vessels, gas pipes, ducting, valves, expansion bellows must be type approved according to the classification rules.

All components in contact with hydrogen should be made of appropriate material, in particular with respect to embrittlement and hydrogen attack phenomena. In the case of compressed gaseous hydrogen, the normal operating temperature range for materials used in hydrogen components should be -40°C to +85°C that must be the gas temperature in normal operating conditions including filling or discharging.

Non-metallic piping carrying hydrogen gas may accumulate electrostatic charge along its exterior surface. Discharges from the external surface of those pipes may be enough to ignite any flammable mixture of gas or vapour in the surrounding environment. When used in hazardous locations, measures to eliminate electrostatic discharges are necessary. This may be achieved by specifying pipe material with sufficient conductivity, or by limiting gas flow velocity below values where electrostatic charge might accumulate. Piping that relies on protective system to eliminate electrostatic discharge (grounding wire or braid) should not be used in major hazardous zone.

Inerting should be performed, with inert gas that cannot freeze to form a plug when exposed to cold hydrogen prior to venting to avoid an explosive atmosphere in tanks and gas pipes.

The inner pressure vessel designed for liquid hydrogen must allow to operate with temperature of -253°C (including fill pipes and piping before vaporizer). An inert gas subsystem is needed for various purging operations. Hydrogen equipment should be purged before and after using hydrogen. The inert gas should have a low melting point to avoid freezing and formation of a plug.

Ammonia

As a zero-carbon fuel when produced from sustainable processes, ammonia has caught the attention of ship owners and operators worldwide. It can be a suitable option for use in ships with modified internal combustion engines. It has several advantages over hydrogen, e.g. it has a greater energy density and it does not need to be stored under compression or at very low temperatures.

It ignites and burns poorly compared to other fuels and combustion could lead to higher NOx emissions unless controlled either by after-treatment or by optimising the engine process.

Challenges embrace toxicity, corrosiveness, slow ignition, and NOx emissions. They require a combination of new engine and fuel gas supply system technologies. Further challenges include developing the technology that ensures a safe combustion process and conducting tests to determine the total fuel consumption necessary to achieve stable combustion. Its lower energy density must be considered when designing the ship. The volume and weight of storage required also have a significant impact on the operating range of vessels. The main items are storage space and bunker station, fuel treatment/HP fuel pump room, engine room to be gas-safe, engine injection systems, vent and safety system including vent mast.

Engine manufacturers need to limit nitrogen oxide (NOx) emissions when using ammonia, in line with applicable regulations (i.e. MARPOL Annex VI for seagoing ships). To achieve the goal, engineers resort to proven technologies, such as Exhaust Gas Recirculation (EGR) and Selective Catalytic Reduction (SCR).

There are strong signals that cryogenic storage will be considered safer when analysing the consequences of a potential leak. Low-pressure fuel tank can be managed with established technologies. Combustion tests have already shown that ammonia can be used as a drop-in fuel with diesel (usual proportion 20%). But ammonia requires extra safety precautions and new materials. Nickle and copper found in seals, gaskets, valves and electrical components would corrode quickly once exposed to ammonia, for example, as would most elastomers.

Using ammonia would need a diesel or dual-fuel engine that was built using materials that can handle the corrosive nature of ammonia. Materials aside, an engine very similar to today's diesel or dual fuel engines – ammonia can be used in both – could use small quantities of ammonia as a drop-in fuel, while later engines will be optimised for use of ammonia as a main fuel. Manufacturers are in the process of defining the engine components and modules that would need to be updated on existing engines to enable the use of high proportions of ammonia.

Currently, aspects of using ammonia are not explicitly covered by the existing regulatory framework – notably IMO's International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (the IGF Code) and require specific attention. The latter does not cover ammonia in detail, therefore an alternative design approach is required.

The classification guideline NI671 is being published. It follows the key principles:

- Prevention of leakages to limit the consequences of ammonia toxicity: tank and pipe design, double wall piping
- Detection and management of possible leakage: leakage detection and management through water mist system, ammonia concentration reduction system
- Manage possible spillage
- Control of ammonia outboard discharge
- Prevent corrosion: selection of materials
- Containment system (same approach as IMO IGC/IGF Codes). Tanks other than fully pressurized IMO type C require boil-off management system
- Classification wants risk mitigation by design:
- Avoid ammonia vapour release to the atmosphere
- Fuel storage based on IGC Code principles
- Materials based on IGC Code principles
- Venting management: several proposals for the safety distances around the vent mast and additional systems are foreseen (e.g. emergency ventilation, ammonia concentration
- reduction system)
- Leakage management: double barrier concept (double wall piping), robust pipe design, dilution through water (various types of systems and layout foreseen) and emergency ventilation maybe required.

There is a general IACS uniform requirement (M57) stating that the area where the ammonia machinery is installed is to be served by a hood with negative ventilation system, so as not to permit any leakage of ammonia from dissipating into other areas in the space.

Fuel cells

Fuel cells is a device which convert chemical energy from hydrogen into electrical energy as direct current. This electrochemical reaction occurs between hydrogen and oxygen from air with efficiency range between 35 and 55% and it emit only heat and water.

Marine stakeholders have begun at developing fuel cells as a source of alternative propulsion. By using fuel cells, ships can run on electrical power, limiting harmful emissions or particulates.

One kilogram of hydrogen can produce same mechanical energy than 4.5 litres of gasoil in thermal engine.

There are different types of fuel cells, depending on the electrolyte and possible fuels, such as:

- PEMFC: Proton Exchange Membrane Fuel Cell, (or Polymer Electrolyte Membrane). It is compact and runs at 80°C, also it benefits from technical advance and decrease in price due to its use in car industry. However, it uses only pure hydrogen and platinum is needed. The axis of improvement would increase the temperature (up to 200°C) for better efficiency, while the lifetime could be increased.
- SOFC: Solid Oxide Fuel Cell, ceramic membrane. It uses either hydrogen or natural gas, and it can be used in cogeneration due to running at high temperature (900°C). However, there is a strong thermal inertia (several hours) and it emits CO2 if natural gas is used. It would need improvement of the lifetime and increase in the number of cycles.

The main advantages of fuel cells compared to thermal engines are:

- High efficiency: between 40 and 50% (instead of 20% or 30%)
- No pollutant emission, no GHG (NOx, Sox, CO2)
- Low noise level
- No vibration
- Compact technology
- Modular (number of cells for voltage and surface of cells for intensity)

Methanol and water can be converted into a hydrogen rich gas using a reformer that is a device that contains a catalyst and heat-exchanging surfaces for process heat transfer. Methanol reforming takes place typically at 220-300°C, it is an endothermic process, it needs additional thermal energy to drive the process. Due to the relative low reforming temperature of methanol, it may be an interesting option to use methanol reformer in combination with a HT-PEM fuel cell (High Temperature Polymer Electrolyte Membrane). Using a mixture with 60% methanol and 40% water is less flammable than pure methanol.

Using methanol requires design to reduce potential risk of fire and leakage because of methanol's low flash point and toxic properties.

There is no regulation yet providing suitable requirements for fuel cells. In Europe, there is currently a draft in preparation for inland navigation vessels that would enter into force in 2024.

According to the Rule Book NR217 for classification of inland navigation vessels, the type and service notation may be completed by the additional service feature "Hydrogencell" when the vessel complies with the Guideline NI 547 "Fuel Cell Systems Onboard Commercial Ships".

It provides criteria for the arrangements and installation of machinery for propulsion and auxiliary purposes to ensure equivalent level of safety and reliability as conventional system.

To achieve this goal, the functional requirements are based on fail-safe design principles:

- Certification of equipment and materials for use in gas system
- Minimize hazardous areas and equipment installed therein
- Minimize ignition sources in hazardous spaces by design, arrangement and suitable equipment
- Arrangements to ensure pockets of gas cannot accumulate under normal and foreseeable failure conditions.
- Arrangements to sustain or restore operation if essential service becomes inoperative
- Ventilation to protect from oxygen deficiency in case of gas leakage
- Gas fuel storage and bunkering arrangements (leakage and overpressure)
- Gas system, piping, containment and over-pressure relief arrangements
- Gas-fuel control engineering arrangement
- Gas detection, alarm and shutdown arrangement
- Protection of compartments from gas storage tank rooms and machinery spaces in case of fire
- Protection against the potential effects of gas-fuel explosion
- fire detection, protection and extinction measures appropriate to the hazards

All requirements from the classification Rule books relating to specific fuels such as LNG, hydrogen and methanol, must be met (cf. supra).

The classification guideline includes instructions regarding the operational aspect. The operational crew should receive appropriate training in gas-related safety, operation and maintenance. The training should be delivered by the manufacturer or the gas provider. The training programme, manual and exercises should be specially designed for each individual vessel and its gas installations.

The system supplier should provide the operator with an operating manual that contains safety information presenting the list of potential hazards and safety instructions. Also, a maintenance manual for the gas supply, fuel cell power and monitoring systems should be available. Gas-related emergency drills should be conducted at regular intervals.

Periodical inspections must be carried out by the classification society once the vessel is in service. It implies that trials and maintenance of gas system are performed in such a way that the level of reliability and safety is maintained.

Batteries

Electric and hybrid ships are currently among the most important developments in the maritime and inland navigation industries. Batteries are the central part of the electric system which store the energy produced by the generators and release it according to the needs of the vessel.

Table 3. Alternative fuel properties – Storage characteristics.

Type	AFC	DMFC	PEMFC	SOFC	Molten carbonate fuel cell	PAFC
Name	Alkaline fuel cell	Direct methanol fuel cell	Proton exchange membrane fuel cell	Solid oxide fuel cell	Liquid Molten salt	Phosphoric acid fuel cell
Electrolyte	Liquid potash	Solid polymer	Solid polymer	Solid ceramic	600 to 650	Liquid Phosphoric acid
Temperature (°C)	70	80 to 130	70 to 160	600 to 1,000	10 to 500	160 to 210
Power (kW)	10 to 100	25 to 5	0 to 200	0 to 200	10 to 500	100 to 400
Combustible	Hydrogen Ammonia	Methanol	Hydrogen	Hydrogen LNG Methanol	Hydrogen LNG Methanol	Hydrogen LNG Methanol
Electrical efficiency (%)	50 to 70	40	30 to 45	50 to 60	40 to 60	40
Lifetime (h)	4,000 to 8,000	4,000	2,000 to 20,000	3,000 to 50,000	20,000 to 50,000	20,000 to 50,000
Starting time	Minute	Minute	Minute	> 10 h	10 h	1. to 3 h

Battery system may be the suitable option for small coastal ships and inland vessels using full electric propulsion.

C Rate is the current which described how fast the cell is charging or discharging, e.g. 1C means the cell can charge/discharge within one hour, 0.5C means charge/discharge within two hours. It is of importance to specify the C rate at design stage.
Battery technology is developing fast, especially Li-ion batteries and it is widely used in current projects. The main interest in batteries is reduction of impact on environment and carbon footprints, providing high power in small volume and low weight with optimized energy production, distribution and consumption. On the other hand, energy is required to produce electricity used for battery charging.

One of the challenges is to increase the energy density and to manage the risk of thermal runaway and explosion. Also, batteries contain several heavy metals and toxic chemicals and recycling can be an issue.

The specific risks must be mitigated and there are some additional safety measures such as appropriate ventilation (especially when hazardous areas may be created), protection against water ingress and leakage in battery compartment, protection against electrostatic hazard, gas detections, fire protection and fire-extinguishing system with regard to battery type.

Li-on batteries are preferred for their light weight, high energy density, low rate of self-discharge and low maintenance. Li-ion batteries design and characteristics depend on need for power or energy. They can be designed to meet demands for high energy/ low current/long discharge applications to those operating with very high-power pulse output, where they can match the performance of supercapacitors. However, Li-on batteries need protection, they suffer from ageing and there are additional safety concerns that require a risk analysis. Also, cost is still an issue. Battery management system (BMS) is an electronic device associated with battery pack. It monitors and manages electric and thermal states by controlling the environment. It provides communication between the battery system and other macro-system controllers, such as a power management system (PMS).

There is no specific regulation for battery system. However, the IEC standards would be applied (notably EC 62619 and IEC 62620, batteries Lithium-ions). In Europe, the standard ES-TRIN 2021 provides the requirements for battery propulsion, especially chapters 10 and 11.

According to the classification Rules NR467 (seagoing ships) and NR217 (inland navigation vessels), the additional notation "Battery System" may be assigned to ships when batteries are used for propulsion or electric power supply. This additional service feature is mandatory when the ship is relying only on batteries for propulsion or electrical power supply for main sources.

Batteries may be lead-acid type, nickel alkaline type or lithium type. Battery cells and battery packs must be type-approved with prototype tests conforming to a national or international standard. The type approval must cover the battery pack and BMS (battery management system). The Rules book NR320 "Certification Scheme of Materials and Equipment for the Classification of Marine Units" must be applied.

For lithium type batteries, a risk analysis covering battery packs, battery compartment and BMS must be submitted. Failure analysis regarding availability of ship propulsion and energy must be submitted. The fire-extinguishing system must be suitable for the battery type. There are also specific requirements for ventilation when using large-vented batteries.

Electrical hybrid

Hybrid system are based on Diesel-electric system coupled with battery system. Hybrid system can be the easiest way in conversion of existing vessels and to reduce fuel consumption.

There are three main types of electrical hybrid:

- Parallel hybrid concept: the electrical engine is fitted in parallel of the propeller shaft. Either the thermal engine or the electrical engine can be used (or both), depending on the needs (e.g. urban operation, manoeuvre). The electrical engine fitted on the reduction gear is small in size.
- The serial electrical hybrid: the electrical engine is fitted in series of the propeller shaft, avoiding mechanical loss due to reduction gear.
- The electrical concept: the generators feed the electrical engine that ensure propulsion in any case. It provides more space in the engine room and it requires less maintenance.

All types can be associated with batteries.

The additional class notation "Electric Hybrid" may be assigned to ships provided with an Energy Storage System (ESS) used to supply the electric propulsion or the main electrical power distribution system of the ship. The ESS aims at assisting the electric propulsion or the main electrical distribution system with the power demand, or to take over from the main source of electrical power. The ESS is a system based on battery packs, semiconductor converter and transformer.

The additional notation "electric hybrid" is completed with (PM) when the power management mode is available as load smoothing mode, peak shaving mode or enhanced dynamic mode. The notation (PB) is assigned when power backup mode is available and (ZE) when zero emission mode can be chosen.

All the requirements for assignment and maintenance of those notations are given in the Rule books NR467 (seagoing ships) and NR 217 (inland navigation vessels).

Hybrid design allows multiple solutions where the alternative fuels and technologies can be combined. The regulations and the classification Rules applicable to each part of the complete system may be superimposed to cover the risks generated by each fuel or technology.

Synthesis and conclusion

There is obviously a large panel of solutions to go toward the environmental goals and to comply with the related regulations to come, if not already in force. None of the solutions is a panacea and the stakeholders must make their choice depending on the type of vessel and the constraints of the area of operation.

LNG, despite fossil fuel and methane slip, is suitable as clean transition fuel, a step to the right direction for CO2/GHG reduction with easy switch towards carbon neutral biogas and synthetic methane (SNG).

Methanol is another growing alternative fuel choice with several advantages for limiting environmental footprint. It is technically attractive but not economically viable yet. Next steps would tell. Bio-methanol engines can be adapted from units running on LNG.

Biofuels are one of the only carbon-neutral fuels readily available today and they become steadily more available. Until biofuel production becomes more uniform and common, it will be difficult to achieve competitive costs. They may be a stepping-stone on the path to decarbonization, offering an accessible carbon-neutral solution in response to growing social pressure to reduce shipping CO2 emissions. However, mass-scale production of biofuels is not sustainable, particularly since other industries already use biofuels. This leaves them in much the same position as LPG, a partial solution pending the next stage of the energy transition.

Regarding hydrogen, storage - liquid or compressed - remains a technical challenge that would be expensive to solve in the short term. So, ammonia, which acts as a hydrogen carrier, currently shows greater promise as a zero-carbon fuel for shipping. Indeed, ammonia is one of the most widely used chemicals in the world. Although the safety issues associated with ammonia's toxicity and caustic properties are still challenging, however it is predicted as the most affordable green zero carbon fuel for long haul trades. LPG could be a step to ammonia since the technology may be compatible. Battery-powered and electric-hybrid vessels are an increasingly favoured solution for small ships that travel fixed routes. Fully and partially electric ships such as inland navigation vessels and short-sea ferries are already operating in some areas such as Europe and North America. Manufacturers are presently improving battery management systems and increasing battery life solutions, but safety and reliability need to be addressed. We may expect installation on larger ships in the near future. Electrical hybrid solution may be a valuable investment on existing vessels by saving on fuel, however the expected reduction in consumption depends on the engine load. It would be more significant during manoeuvres, therefore choice for electrical solution must integrate the manoeuvring time among the operations.

In addition to the technical and economic criteria that path the way to the decision, the regulatory aspect is of major importance. Indeed, technology is used to develop faster than the well-established prescriptive regulations can do, meanwhile alternative design methodologies can be used. Bureau Veritas, as a leading classification society, is committed to partner with shipowners, shipyards and designers and to provide the classification rules covering the new technologies and combination of them. To meet such challenging technical goal, a large panel of experienced specialists and engineers are working hand in hand with the main actors in R&D and development of industrial solutions.

In order to help the decision-makers in opting for a solution pending next stage of development in other fuel or technology are completed, the classification Rules are offering the possibility to validate a design for possible future improvement or conversion. An additional notation mentioning "-prepared" may be assigned (e.g. "Ammonia-prepared").

While many queries come out from the huge number of documents and presentations about the innovative solutions, the set of classification Rules and guidelines aims at providing the answers with regard to the level of safety and reliability that cannot be debatable in any respect.

References

Supplementary to Bureau Veritas' sources and communication:

Friederike Dahlke-Wallat, Benjamin Friedhoff and Sophie Martens, “Assessment of technologies in view of zero-emission IWT“ (Report No. 2293, October 2020), Eidgenössisches Departement für Umwelt, Verkehr, Energie und Kommunikation - Bundesamt für Verkehr (BAV) Abteilung Sicherheit / Sektion Schifffahrt, Switzerland for DST – Development Centre for Ship Technology and Transport Systems, Duisburg, Germany ; part of the overarching study “Financing the energy transition to-wards a zero-emission European IWT sector“

Olivier Ticos and Patrice Domange - Alca Torda Applications, Sept.2020 - “Formation aux notions fondamentales des technologies de l’hydrogène”

VNF, Voies navigables de France, Direction du Développement, 62408 Béthune, France : “Les cahiers techniques de BATELIA“ (Bureau d’Assistance Technique et Logistique pour les Industriels et Artisans), including:
CAHIER TECHNIQUE N°1, Propulsion hybride pour bateaux fluviaux - Édition avril 2018
CAHIER TECHNIQUE N°2, Propulsion hydrogène pour bateaux fluviaux - Édition janvier 2020
CAHIER TECHNIQUE N°3, Propulsion gaz pour bateaux fluviaux - Édition janvier 2020

Editorial Guidelines for Authors

Thematic Interest

The *Ship Science and Technology* Journal accepts for publication original engineering contributions in English language on ship design, hydrodynamics, dynamics of ships, structures and materials, vibrations and noise, technology of ship construction, ocean and marine engineering, standards and regulations, oceanography, maritime and river transport, and port infrastructure, results of scientific and technological researches. Every article shall be subject to consideration of the Editorial Council of The *Ship Science and Technology* Journal deciding on pertinence of its publication.

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- *Scientific and technological research articles*. Documents presenting detailed original results of finished research projects. Generally, the structure used contains four important parts: introduction, methodology, results, and conclusions.
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- *Revision Articles*. Documents resulting from finished research in the field of science or technology in which published or unpublished results are analyzed, systemized, and integrated to present advances and development trends. These are characterized by presenting an attentive bibliographic revision of at least 50 references.

Format

All articles must be sent to the editor of The *Ship Science and Technology* Journal accompanied by a letter from the authors requesting their publication. Every article must be written in *Microsoft Word* in single space and sent in magnetic form.
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File must contain all text and any tabulation and mathematical equations.
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The author's name must be written as follows: last name, initial of first name . Affiliations of author must be specified in the following way and order:

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Abstract
A short essay of no more than one hundred fifty (150) words, specifying content of the work, scope, and results. It must be written in such a way so as to contain key ideas of the document. It must be sent in English and Spanish language.

Key Words
Identify words and/or phrases (at least three) that recover relevant ideas in an index. They must be sent in English and Spanish language.

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The text must be explanatory, clear, simple, precise, and original in presenting ideas. Likewise, it must be organized in a logical sequence of parts or sections, with clear subtitles to guide readers. The first part of the document is the introduction. Its objective is to present the theme, objectives, and justification of why it was selected. It must contain sources consulted and methodology used, as well as a short explanation of the status of the research, if it were the case, and form in which the rest of article is structured.

Body Article
It is made up of the theoretical framework supporting the study, statement of the theme, status of its analysis, results obtained, and conclusions.

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Equations must be numbered on the right hand side of the column containing it, in the same line and in parenthesis. The body of the text must refer to it as "(Equation x)". When the reference starts a sentence it must be made as follows: "Equation x". Equations must be written so that capital letters can be clearly differentiated from lower case letters. Avoid confusions between the letter "l" and the number one or between zero and the lower case letter "o". All sub-indexes, super-indexes, Greek letters, and other symbols must be clearly indicated. All expressions and mathematical analyses must explain all symbols (and unit in which they are measured) that have not been previously defined in the nomenclature. If the work is extremely mathematical by nature, it would be advisable to develop equations and formulas in appendixes instead of including them in the body of the text.

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Acknowledgments may be made to persons or institutions considered to have made important contributions and not mentioned in any other part of the article.

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They must be made in two ways: at the end of the text, in which case the last name of author followed by a comma and year of publication in the following manner:

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UNITED STATED OF AMERICAN. EPA - U.S. Environmental Protection Agency. Profile of the Shipbuilding and Repair Industry. Washington D.C. 1997. P. 135.

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Basic form:
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[1] B. Klaus and P. Horn, *Robot Vision*. Cambridge, MA: MIT Press, 1986.

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[1] *Name of Manual/Handbook*, *x* ed., Abbrev. Name of Co., City of Co., Abbrev. State, year, pp. *xx-xx*.

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[1] E. E. Reber *et al*., "Oxygen absorption in the earth's atmosphere," Aerospace Corp., Los Angeles, CA, Tech. Rep. Angeles, CA, Tech. Rep. TR-0200 (4230-46)-3, Nov. 1988.

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[1] R. J. Vidmar. (1994). *On the use of atmospheric plasmas as electromagnetic reflector*s [Online]. Available FTP: atmnext.usc.edu Directory: pub/etext/1994 File: atmosplasma.txt.

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[1] J. Jones. (1991, May 10). Networks (2nd ed.) [Online]. Available: http://www.atm.com

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[1] J. P. Wilkinson, "Nonlinear resonant circuit devices," U.S. Patent 3 624 125, July 16, 1990.

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Example:
[1] IEEE Criteria for Class IE Electric Systems, IEEE Standard 308, 1969.

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Example:
[1] J. O. Williams, "Narrow-band analyzer," Ph.D. dissertation, Dept. Elect. Eng., Harvard Univ., Cambridge, MA, 1993.

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[1] A. Harrison, private communication, May 1995.
[2] B. Smith, "An approach to graphs of linear forms," unpublished.

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[1] R. E. Kalman, "New results in linear filtering and prediction theory," J. Basic Eng., ser. D, vol. 83, pp. 95-108, Mar. 1961.

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