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COTECMAR

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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.

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Editorial Note

Cartagena de Indias January 31st, 2023.

Welcome everyone to this new edition of our Ship Science and Technology magazine; We start this new year with many expectations and challenges, both scientific and engineering, for our corporation.

The above due to a second semester of 2022 with great milestones for the advancement of engineering and shipbuilding in our Country. In the third quarter, we completed the selection and contracting stage of our technological partner for the co-development of the contractual design of our Surface Strategic Platform (PES). Then, in the last quarter of 2022, we achieved the signing of the largest and most ambitious shipbuilding contract in the history of Colombia, through which we committed to delivering three vessels, a Colombian Ocean Patrol Vessel (POC), a Logistics Support Vessel (BAL) and the first Strategic Surface Platform (PES), all of them the classified as projects of national impact that will undoubtedly promote the development not only of naval engineering, but also progress in the integration with a social focus of the different actors in the supply chain.

For this edition of the magazine we include interesting topics such as: the proposal for the Colombian case of the Identification of economic incentives for the electrification of fluvial and maritime modes, the entry into a new era for electric ships on inland waterways, a Truly Sustainable Digital Transformation Model for the Naval Sector, Numerical analysis of the dynamic behavior of a floating wind platform in regular waves and finally, the development of an engineering tool to analyze spectral fatigue of floating structures by means of hydro-elastic coupling.

I take advantage of this edition to reiterate our invitation to the eighth edition of our International Congress of Naval Engineering CIDIN 2023, to be held in person in Cartagena de Indias between March 8 and 10.

At COTECMAR, "We Keep Moving Forward"

Cordially,

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

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Nota Editorial

Cartagena de Indias, 31 de enero de 2023

Bienvenidos todos a esta nueva edición de nuestra revista Ciencia y Tecnología de Buques; iniciamos este nuevo año con muchas expectativas y retos tanto científicos como de ingeniería para nuestra Corporación COTECMAR.

Lo anterior debido a un segundo semestre de 2022 con grandes hitos para el avance de la ingeniería y la construcción naval en nuestro País. En el tercer trimestre, finalizamos la etapa de selección y contratación de nuestro socio tecnológico para el codesarrollo del diseño contractual de nuestra Plataforma Estratégica de Superficie (PES). Luego en el último trimestre del 2022, logramos la firma del contrato de construcción naval más grande y ambicioso de la historia de Colombia, mediante el cual nos comprometemos a entregar tres embarcaciones, una Patrullera Oceánica Colombiana POC, un Buque de Apoyo Logístico y la primera Plataforma Estratégica de Superficie PES proyectos de País que sin lugar a dudas, impulsaran el desarrollo no solo de la ingeniería naval, sino también el avance en la integración de los diferentes actores de la cadena de suministros con un enfoque social.

Para esta edición de la revista incluimos interesantes temáticas como: la propuesta para el caso colombiano de la Identificación de incentivos económicos para la electrificación de los modos fluvial y marítimos, la entrada en una nueva era para los buques eléctricos en las vías navegables interiores, Un Modelo de Transformación Digital del Sector Naval Realmente Sostenible, Análisis numérico de la respuesta hidrodinámica de una plataforma eólica flotante en olas regulares y finalmente, Desarrollo de una herramienta de ingeniería para el análisis de fatiga espectral de estructuras flotantes mediante acoplamiento hidro-elástico.

Aprovecho esta edición para reiterar nuestra invitación a la octava edición de nuestro Congreso Internacional de Ingeniería Naval CIDIN 2023, a desarrollarse de forma presencial en Cartagena de Indias entre el 8 y el 10 de marzo.

En COTECMAR, "Seguimos Avante"

Cordialmente,

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

Identification of economic incentives for the electrification of river and maritime modes: proposal for the Colombian Case

Identificación de incentivos económicos para la electrificación de los modos fluvial y marítimos: propuesta para el caso colombiano

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Abstract

The transportation sector's significant contribution to greenhouse gas (GHG) emissions, primarily through fossil fuel consumption by motorized vehicles, remains a critical concern. In this industry, maritime transportation independently contributes to 2.89% of total global greenhouse gas emissions, displaying a persistent upward trend even in the face of enhanced efficiency measures implemented in port facilities and vessel operations. In response to this urgent concern, nations and international organizations have been formulating approaches aimed at mitigating greenhouse gas emissions in this transportation sector, encompassing the implementation of economic incentives. This article presents the findings of an exploratory-descriptive research endeavor, which aims to identify incentive policies implemented across various countries to expedite the adoption of electromobility in maritime and river transportation, thereby reducing GHG emissions from vessels. Data was gathered from authorized government websites, various organizations, maritime and river transport companies, and port authorities in each respective nation. Furthermore, this study classifies the incentives according to their methodologies and conducts a comparative analysis with the existing landscape in Colombia regarding the adoption of economic incentives for electrifying river transportation within the country. Through this analysis, some insights and recommendations can be derived to promote sustainable and environmentally-friendly practices in Colombia's river and maritime transportation sectors.

Key words: economic incentives; greenhouse gases; river transportation; maritime transportation; emission reductions.

Resumen

La importante contribución del sector del transporte a las emisiones de gases de efecto invernadero (GEI), principalmente a través del consumo de combustibles fósiles por los vehículos motorizados, sigue siendo una preocupación crítica. En este sector, el transporte marítimo contribuye de forma independiente al 2,89% del total de las emisiones mundiales de gases de efecto invernadero, mostrando una persistente tendencia al alza incluso ante las medidas de mejora de la eficiencia aplicadas en las instalaciones portuarias y las operaciones de los buques. En respuesta a esta urgente preocupación, las naciones y las organizaciones internacionales han venido formulando enfoques destinados a mitigar las emisiones de gases de efecto invernadero en este sector del transporte, que abarcan la aplicación de incentivos económicos. Este artículo presenta los resultados de una investigación exploratoria-descriptiva cuyo objetivo es identificar las políticas de incentivos aplicadas en varios países para acelerar la adopción de la electromovilidad en el transporte marítimo y fluvial, reduciendo así las emisiones de gases de efecto invernadero de los buques. Los datos se recogieron de sitios web gubernamentales autorizados, diversas organizaciones, empresas de transporte marítimo y fluvial y autoridades portuarias de cada nación respectiva. Además, este estudio clasifica los incentivos según sus metodologías y realiza un análisis comparativo con el panorama existente en Colombia en cuanto a la adopción de incentivos económicos para la electrificación del transporte fluvial en el país. A través de este análisis, se pueden derivar valiosas percepciones y recomendaciones para promover prácticas sostenibles y respetuosas con el medio ambiente en los sectores del transporte fluvial y marítimo de Colombia.

Palabras claves: incentivos económicos; gases de efecto invernadero; transporte fluvial; transporte marítimo; reducción de emisiones.

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Introduction

According to a comprehensive report by the International Maritime Organization *(IMO, 2020)*, the transportation of goods and passengers emerges as a prominent source of greenhouse gas emissions worldwide. This crucial sector significantly contributes to approximately 2.89% of the total annual emissions. To address this environmental challenge, sustainable transportation solutions have become a focal point in the quest for mitigating climate change impacts. The Intergovernmental Panel on Climate Change (IPCC) emphasizes the importance of adopting sustainable transport practices to reduce carbon emissions and achieve global climate goals *(IPCC, 2021)*. It is evident that the reduction of emissions in the transportation sector is a critical element in the pursuit of a sustainable and greener future.

Recognizing the urgent need to address these detrimental environmental impacts, multiple initiatives and research sources emphasize the imperative of emission reduction in the transport sector. For instance, the Net Zero Emission by 2050 Scenario proposed by the International Energy Agency underscores the urgency of achieving a 20% reduction in the transport sector's emissions by 2030 and striving for a substantial 50% reduction specifically in maritime transport emissions by 2050 *(IEA, 2022)*. These recommendations align with the global commitment to combat climate change and underline the vital role of the naval sector in achieving sustainable and environmentally friendly transportation solutions.

Due to the increase in fossil fuels, in human industrial activity and the growing energy demands caused by population growth *(United Nations, n.d.)*, this reduction will be possible mainly through the use of technologies aimed at reducing emissions, based on the decarbonization of energy sources, as is the case of the use of alternative energies and electric power in the system *(McKinsey & Company, 2021)*. Although in the fluvial and maritime mode the inclusion of these technologies, such as electric energy is just incipient, due to the low electrification of ships and cargo vessels *(Balcombe, 2019; Xuanet al., 2022)*, to achieve the proposed environmental goals it is necessary to propose initiatives for the inclusion of this technology to encourage and motivate the transition to these new motor sources.

In search of the above, it is possible to find policies and programs around the world, that seek to encourage the inclusion of electric energy in maritime and river transport modes, which can arouse the interest for different actors and entities involved in transport to opt for including these technologies in their processes, such as incentives that grant financial resources *(Kim, 2022; Backer et al., 2020)* for the acquisition of these technologies, the reduction of port tariffs *(Backer et al., 2020)* or obtaining tax subsidies *(Port of Stockholm, 2022)*, among others.

In general terms, subsidies, discounts and project financing programs by governments and private institutions are mechanisms that instead of charging polluters, encourage them to find ways to obtain grants, low-interest loans, discounts or tax exemptions, among others, as a reward for using new methods or technologies to reduce pollutant emissions *(Camargo, C. et al., 2022)*.

To present different alternatives of incentives granted internationally by governments and other private institutions, this paper conducts a search in different countries of such ways to economically encourage the penetration of electric power in maritime and river modes around the world. This work is derived from the research entitled Ferrofluvial 4.0, funded by the Mining and Energy Unit - UPME and the Ministry of Science, Technology and Innovation of Colombia, with the objective of: Formulating a plan for the penetration of electromobility in the rail and river modes for both cargo and passengers, through the evaluation and prioritization of technological alternatives in order to generate a roadmap that strengthens the productive linkages of the country in the medium and long term.

The identification of economic incentives at the global level is fundamental for the Colombian government and other countries to be able to deploy policies and programs aimed at getting stakeholders to appropriate these technologies and thus achieve the environmental commitments agreed upon at the national and international level.

Methodology

To find different financing mechanisms to encourage the use and development of electromobility in Colombia in the maritime and river modes, an analysis was made of these actions in different countries of the world considered as a reference for Colombia and which are recognized for their performance in this area.

The countries in which information was sought were Colombia, Argentina, Brazil, Ecuador, Chile, Uruguay, Costa Rica, Sweden, Norway, Spain, Germany, Holland, the United States, Canada and Japan.

Through extensive research in official government documents, as well as institutions and organizations within the transportation sector, a meticulous analysis has been conducted. Additionally, a wide range of technical reports and scientific articles related to the topic have been considered. This rigorous approach has enabled the identification of various incentives implemented in different countries. Based on these findings, a comprehensive proposal of short-term, medium-term, and long-term incentives has been developed to stimulate the adoption of electromobility solutions in Colombia. These initiatives aim to drive a transition towards a more sustainable transportation system, providing economic and environmental benefits in the process.

It is crucial to recognize that this proposal is built upon successful international experiences and takes into account the specific characteristics and needs of Colombia. By incentivizing the penetration of electromobility in the country, significant economic advantages can be achieved, such as reducing dependence on fossil fuels. Moreover, it will make a substantial contribution to greenhouse gas emissions reduction and climate change mitigation, aligning with global sustainability commitments.

Incentives for electromobility

As a result of the review of possible incentives applicable in the maritime and river mode in 15 countries analyzed, it was not possible to find economic support alternatives in Colombia, Chile, Ecuador and Uruguay. The incentives found in the rest of the countries are:

In the Latin American context, incentives were found granted in Argentina through Resolution No. 50 of 2017: Bonus for sustainable ships[1]-General Ports Administration, which offers discounts between 5% and 10% to vessels that have low gas emissions and are environmentally friendly. In Brazil it was possible to find Discounts for sustainable ships in the Port of Pecém[2], in which up to 10% can be discounted in the rate for the use of berthing facilities for "sustainable ships". In Costa Rica, the Green Hydrogen Law[3], grants tax exemptions, levies, fees or contributions, as well as immigration waivers for foreigners who invest in green h2 and specific credits with terms, interest rates, guarantees and special procedures, with a duration of 15 years from the law's entry into force.

In the U.S. context, there is the FAST Electricity Act 2021[4], which establishes a 30% investment tax credit for any electric propulsion vehicle that is not an on-highway passenger car or truck. In addition, there is the EPA's Port Initiative[5], which provides funding to port authorities and public entities to

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[1] Bonuses for ships (May 2, 2017). Retrieved from Official Portal of the Government of Argentina: https://www.argentina.gob.ar/transporte/administracion-general-puertos-se/puertos/bonificaciones

[2] *Pecém grants discounts for sustainable ships and becomes the first Brazilian port to be recognized by the Dutch foundation* (August 5, 2020). Retrieved from Governo do Estado do Ceará: https://www.ceara.gov.br/2020/06/05/pecem-se-torna-primeiro-porto-brasileiro-reconhecido-por-fundacao-holandesa-ao-conceder-descontos-para-navios-sustentaveis

[3] *Costa Rica: the Green Hydrogen Bill passes a new stage on its way to approval* (December 3, 2021). Retrieved from Strategic Energy: https://www.energiaestrategica.com/costa-rica-el-proyecto-de-ley-de-hidrogeno-verde-supera-una-nueva-instancia-camino-a-su-aprobacion/

[4] *The Fast Electricity Act (2021)*. Retrieved from Web Portal Maria Cantwell United States Senator for Washington: https://www.cantwell.senate.gov/imo/media/doc/FAST%20Electricity%20Act%20Slidedeck%20May%202021.pdf

[5] *Alternative Fuels Data Center: Ports Initiative* (2022). Retrieved from U.S. Department of Energy Web Portal: https://afdc.energy.gov/laws/325

help them overcome barriers to the adoption of cleaner diesel technologies and strategies. There is also the Clean Vessel Incentive Program Port of New York / New Jersey[6], which rewards vessels for using shore power and the cleanest vessels according to the ESI score, values can be found on the Port's Official Port Portal and Public Law 117-58. Port Infrastructure Development Program until 2026[7] that provides financing for projects that allow the development of port infrastructure of GHG polluting ports.

Canada has the Salish Sea Marine Emission Reductions Fund[8] which allows financing the purchase and installation of technology to reduce emissions in the operation of ships. This can be directed to fleet modernization, change of fleet or marine vessel to electric, hybrid or zero-emission technology, hull or propeller modifications, etc. Per fiscal year, funding will not exceed $250,000 per nonprofit recipient and $200,000 per for-profit recipient. In this country there is also the Clean Technology Initiative[9] which allows the financing of pilot projects with clean technologies in maritime mode and the EcoAction Program - Port of Vancouver[10], which offers reductions in port duty rates for shipping companies according to the qualification obtained in the following ranges:

Gold: port duty rate reduced by 47%; Silver: port duty rate reduced by 35% and Bronze: port duty rate reduced by 23%.

In the European context Sweden has the Electricity tax exemption for onshore power supply[11], an incentive that grants an exemption from electricity tax for onshore power supply in ports. The tax rates that would normally be payable are SEK 293 (EUR 33.94) per MWh or SEK 185 (EUR 21.43) per MWh in northern Sweden and the Environmental Discount in the port tariff[12], whereby vessels emitting less pollutant gases pay relatively low navigation fees, while vessels generating more emissions pay relatively higher navigation fees. This changes according to each port's price list. In Norway there is the EPI - Environmental Port Index - Port of Bergen[13], which applies a discount on quay fees, passenger fares and ISPS charges in the port of Bergen.

In Spain there is Directive 2014/94/EU - OPS Master Plan for Spanish ports[14] in which shipowners who switch off their auxiliary engines in port and connect to the electricity grid will receive a subsidy of €9.6/ton of CO2. Ships will pay as a supply tax the symbolic amount of 0.05 euro cents per k/Wh for switching off their auxiliary engines and connecting to the general grid. In the United Kingdom there is the Enviromental Ship Index Program - Port of London Authority[15], in which ships that are registered in the Enviromental Ship Index scheme will receive a discount on their Vessel Conservancy Charges (excluding Estuary Charge) if they comply with the requirement established in the tariff program in force.

The Netherlands has Directive 2003/96/EC[16],

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[6] *Clean Vessel Incentive Program* (2013). Retrieved from Port Authority of New York and New Jersey: https://www.panynj.gov/port/en/our-port/sustainability/clean-vessel-incentive-program.html

[7] *Alternative Fuels Data Center: Port Infrastructure Development Program* (2021). Retrieved from U.S. Department of Energy Portal: https://afdc.energy.gov/laws/12734

[8] *Salish Sea Marine Emission Reductions Fund* (February 1, 2021). Retrieved from Web Portal Government of Canada: https://www.canada.ca/en/environment-climate-change/services/environmental-funding/salish-sea-marine-emission-reductions-fund.html

[9] *Clean Technology Initiative* (2020). Retrieved from Web Portal of the Port of Vancouver: https://www.portvancouver.com/environmental-protection-at-the-port-of-vancouver/climate-action-at-the-port-of-vancouver/clean-technology-initiative/

[10] *EcoAction Program* (January 12, 2022). Retrieved from Web Portal of the Port of Vancouver: https://www.portvancouver.com/environmental-protection-at-the-port-of-vancouver/climate-action-at-the-port-of-vancouver/ecoaction-program/

[11] *Decarbonising Maritime Transport: The Case of Sweden* (March 9, 2018). Retrieved from International Transport Forum: https://www.itf-oecd.org/decarbonising-maritime-transport-sweden

[12] Becqué, R., Fung, F., & Zhu, Z. (2018). *Incentive schemes for promoting green shipping*. Retrieved from Natural Resources Defense Council: https://assets.nrdc.org/sites/default/files/incentive-schemes-promoting-green-shipping-ip.pdf

[13] *Environmental Port Index* (2022). Retrieved from Official Portal Port of Bergen: https://bergenhavn.no/wp-content/uploads/2021/12/Prices-terms-conditions-Port-of-Bergen-2022.pdf

[14] *Puertos del Estado promotes the exemption of the tax on electricity supply to ships at berth* (2018). Retrieved from Portal Web Portal Ministerio de Transportes, Movilidad y Agenda Urbana del Gobierno de España: https://www.puertos.es/es-es/Paginas/Noticias/ProyectoOPS2018.aspx

[15] *ESI Incentives*. Retrieved from the Enviromental Port Index Web Portal. https://www.environmentalshipindex.org/ports

[16] *Reduced tax rate on electricity supplied directly to ships at berth in port* (September 14, 2020). Retrieved from Official European Commission Portal: https://eur-lex.europa.eu/legal-content/ES/TXT/HTML/?uri=CELEX:52020PC0497&from=EN

which is a measure to apply a reduced tax rate of 0.50 EUR/MWh to installations that supply electricity entirely or almost entirely (90% or more) to non-private ships and pleasure craft. There is also the Environmental Ship Index Discount - Port of Rotterdam[17], which gives a 10% discount on the port fee to ships that perform above the legal standard. The discount applies to all ships with an ESI score of 31 or more at the time of arrival (ATA) in Rotterdam. The discount is doubled if the ship also has an individual ESI-NOx score of 31 or more. This discount applies to each call in a quarter, with a maximum of 20 calls per ship per quarter.

The Netherlands also has the Incentive Scheme Climate - Friendly Shipping - Port of Rotterdam[18] which aims to give an incentive contribution and amounts to a maximum of 40% of the costs to support projects that may be difficult to implement without financial assistance. There is also the Port of Rotterdam's Green Award Vessel Discount[19], in which the Port Authority will grant vessels with a Green Award certificate between 15% - 30% discount on port charges when they arrive in Rotterdam and the Port Charge Discounts for electric and low GHG emission vessels in the Port of Amsterdam[20], an incentive where inland vessels with Green Award labels can receive up to 20% discount on port charges for inland navigation.

In Germany there is the Environmental Ship Index Program - Port of Rostock[21] which grants a 5% discount on port fees for ships that score 40 points or more, a 7.5% discount on port fees for ships that score 50 points or more, and a 10% discount on port fees for ships that score 60 points or more. There is also the Blue Angel - Port of Hamburg[22] which grants a 2% discount on the environmental component of the port fee for vessels with Blue Angel certification and the Green Award Program - Port of Hamburg[23] which generates a 3% discount on port fees for oil tankers, chemical tankers and methane tankers of any size that have the Green Award certificate.

In Asia, Japan has the Enviromental Ship Index Program - Port of Tokyo[24] which grants a 30% discount on port fees for vessels with an ESI score between 20.0 and 29.9, a 40% discount on port fees for vessels with an ESI score between 30.0 and 39.9 and a 50% discount on port fees for vessels with an ESI score over 40.0. They also have the Green Award Program - Nagoya Port Authority[25] which offers a 10% discount on port fees for all Green Award certified maritime vessels and the Environmental Ship Index Program - Port of Yokahoma[26] which in turn grants a 15% discount on port fees for vessels with ESI scores over 30 points.

Possible incentives acquired from electric charging infrastructure benefits.

The incentives presented in the previous section are those found specifically to enhance electromobility in river and maritime modes. However, it is possible to find a set of incentives associated with the recharging infrastructure in these countries that, although they are mostly aimed at land transport, can serve as a guide to produce incentives in river and maritime modes. Among the initiatives found along these lines, the most common were:

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[17] *Environmental Ship Index Discount* (2015). Retrieved from Official Portal Port of Rotterdam: https://www.portofrotterdam.com/en/sea-shipping/seaport-dues/environmental-ship-index-discount

[18] *Incentive Scheme Climate-Friendly Shipping* (January 1, 2019). Retrieved from Official Portal Port of Rotterdam: https://www.portofrotterdam.com/en/port-future/energy-transition/incentive-scheme-climate-friendly-shipping

[19] *Green Award Discount* (2022). Retrieved from Official Portal Port of Rotterdam: https://www.portofrotterdam.com/en/sea-shipping/seaport-dues/green-award-discount

[20] *Greenaward* (2021). Retrieved from greenaward: https://www.greenaward.org/inland-shipping/faq/

[21] *ESI Incentives*. Retrieved from the Enviromental Port Index Web Portal. https://www.environmentalshipindex.org/ports

[22] *Special Terms and Conditions applicable to Maritime Shipping* (1 January 2022) Retrieved from the Hamburg Port Authority Web Portal https://www.hamburg-port-authority.de/fileadmin/user_upload/Hafengeld_Seeschifffahrt/Port_of_Hamburg-STC-Maritime-Shipping_as_of_01.01.2022_issued_27.09.2021.pdf

[23] *List of Incentive Providers*. Retrieved from the Green Award Web Portal https://www.greenaward.org/sea-shipping/incentive-providers/list-of-incentive-providers/

[24] *ESI Incentives*. Retrieved from the Enviromental Port Index Web Portal https://www.environmentalshipindex.org/ports

[25] *List of Incentive Providers*. Retrieved from the Green Award Web Portal https://www.greenaward.org/sea-shipping/incentive-providers/list-of-incentive-providers/

[26] *ESI Incentives*. Retrieved from the Enviromental Port Index Web Portal. https://www.environmentalshipindex.org/ports

In Brazil, Resolution 819 of 2018[27] was found, which allows those interested in providing the service (distributors, gas stations, shopping centers, ventures, etc.) to charge for the electric car charging service. In Uruguay, the Regulatory Decree 02/12 of Law 16.906[28] allows the exemption from Wealth Tax of fixed assets included in paragraphs A) and B) of Article 7, acquired as from the effective date of this law. The referred goods will be considered as taxable assets for the purposes of deduction of liabilities and generates an exoneration of the Value Added and Specific Internal Taxes, corresponding to the import of the goods referred to in the previous paragraph, and refund of the Value Added Tax included in the acquisitions of these goods. Decree 57/022 - UTE Commercial Discount[29], which allows the change of the contracted power at no cost, off-peak tariff (0 to 7AM) at 50% in UTE recharge stations, medium consumer and double residential tariffs at 50% in off-peak hours (from 6 to 10 PM).

In Ecuador, the National Finance Corporation[30] will cover 70% of the costs of new projects and up to 100% of expansion projects, while the Organic Energy Efficiency Law (LOEE)[31] offers preferential financing conditions for energy efficiency projects. The regulation will establish preferential rates for public and private electric transportation and incentives for a 10-year period to encourage the use of electric vehicles, such as exempting these vehicles from traffic restrictions due to congestion.

In Costa Rica there is Law 9518 - Law of Incentives and Promotion for Electric Transportation[32] that allows the exemption of the total payment of the selective consumption tax, established in Law No. 4961, Tax Reform Law; Law No. 6826, General Sales Tax Law, and the one percent tax on the customs value established in Law No. 6879, to parts necessary for the installation of recharging centers.° 6826, General Sales Tax Law, and from the one percent tax on the customs value established in Law No. 6879, to the parts necessary for the installation of the recharging centers, duly defined in the list to be prepared via regulation, by the Ministry of Environment and Energy (Minae). This exemption is valid for five years, as from the publication of this law. In addition, there is Decree N° 41092-lMINAE-H-MOPT[33] in which the parts of the recharge centers may be exempted from Selective Consumption Tax, General Sales Tax, Customs Value Tax (Law N° 6879 modified by Law N° 6946).

In the United States, the Energy Efficiency 2021 program was found[34], which is a Zero Emission Airport Vehicle and Infrastructure Pilot that provides financing to airports for up to 50% of the cost to acquire ZEVs and install or modify the supporting infrastructure for the acquired vehicles. It also allows financing of up to 80% of project costs and will be available for both development phase planning activities and the acquisition and installation of alternative fuels or charging infrastructure.

In Canada, the BC Hydro[35] could be found which offers incentives in different categories such as:

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[27] *Regulatory Resolution No. 819*. (June 19, 2018). Retrieved from National Press Portal: https://www.in.gov.br/materia/-/asset_publisher/Kujrw0TZC2Mb/content/id/28737289/do1-2018-07-05-resolucao-normativa-n-819-de-19-de-junho-de-2018-28737273

[28] *Regulation of the methodology for the evaluation of investment projects* (February 2, 2012). Retrieved from Official Information Center: https://www.impo.com.uy/bases/decretos/2-2012

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rebate of up to 50% of the costs to purchase and install an eligible Level 2 EV charger, up to a maximum of $700 for single-family homes, including duplexes and townhouses with private garages or dedicated parking; rebate of up to $3,000 for the creation of an EV Ready plan for Apartment Buildings and condominiums; reimbursement of up to $4,000 per charger, up to a maximum of $14,000, to purchase and install Level 2 on-grid electric vehicle chargers for workplaces; and reimbursement of up to 75% of eligible EV charger purchase and installation costs for Indigenous communities. Also, in this country

The Fortis BC[36] has a rebate of up to 50% of the purchase and installation costs of an eligible Level 2 EV charger, up to a maximum of $700 and a rebate of up to 50% of the eligible purchase and installation costs*, up to $4,000 per station, up to a maximum of $14,000 per application; the Manitoba Hydro[37] with a maximum eligible amount for financing is $3,000 per EV charger, including installation, the Arctic Energy Alliance[38] with A rebate of up to $500 for a Level 2 charger (220 or 240 volt), the Home Energy Loan Program[39] in which Toronto homeowners can obtain a low-interest loan of up to $75,000 to cover the cost of home energy improvements. These include the installation of chargers for their EVs and The Roulez vert Program[40] with rebates of up to $600 for the purchase and installation of a Level 2 EV home charging station.

In Sweden there is the Electric Vehicle Charging Incentive under Commission Regulation (EU) No. 1407/2013[41], which covers the cost of up to 50% of the equipment for powering electric vehicles, up to a maximum cost per charging point of up to SEK 10,000 (€1,000) for individuals and SEK 15,000 (€1,500) for companies, municipalities, councils, and institutions. In Spain there is Royal Decree 569/2020 - Plan MOVES II[42] in which citizens with private vehicles and company vehicles can receive subsidies of between 30-40% (up to a total amount of 100,000€) of the cost of purchase and installation of public or private chargers and Royal Decree 266/2021 - Plan MOVES III[43] with Subsidies of up to 80% for private vehicles, self-employed and for the administration without economic activity and subsidies of up to 60% for companies and public entities with economic activity. There is also Decree 72/2019[44] for electric vehicle charging infrastructure, which offers a subsidy of 30% of the eligible cost for private companies and 40% for individuals.

In Norway you can find Free Charging Chips - Fortum[45] to encourage electric mobility, making it easier for EV owners to experience charging in public parking lots and the Free EV Charging incentive in the municipality of Asker[46] which offers free charging of electric vehicles in parking lots in the center of Asker municipality. There are also EVSE (Charging Station Installation) Grants for Housing Associations in Oslo[47] for a maximum of 20% of the EVSE investment and installation costs, up to NOK 5000 (€450) per charging point and NOK 1 000 000 (€91 000) per housing association

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or co-ownership, where external consultancy and engineering costs can be included in the grant costs; the EVSE (Installation of Charging Stations) Grants for Housing Associations in Skedsmo[48] for a maximum of 20% of the EVSE investment and installation costs, up to NOK 5000 (€450) per charging point and NOK 250,000 (€23,000) per housing association or co-ownership; and EVSE (Charging Station Installation) Grants for Housing Associations in Asker[49] for a maximum of 50% of the cost of and installation of EVSE, up to NOK 5000 (€450) per charging point and NOK 50000 (€4500) per housing association.

In the Netherlands there is the Environmental Investment Allowance for Companies (MIA)[50] which is a subsidy that allows the company to deduct a percentage of its investment costs from taxable profit. This is in addition to regular depreciation. And as a result, the company pays less tax. The percentage of the deduction depends on the company's operating assets and the environmentally friendly investments that qualify on the Environmental List among them. Using the MIA, companies can receive an investment deduction of up to 36% of the amount invested in a charging point.

In Germany you can find the KfW-Bank Incentive for charging stations (private)[51] which grants a subsidy of 900 euros per charging point, the Program: Public charging infrastructure for electric vehicles in Germany (2021 - 2025)[52], which, according to the type of grid connection the financing can vary up to a maximum amount of 10,000 euros. And depending on the type of charging point the installation can be financed up to 60% which is equivalent to 20,000 euros and the NRW-FÖRDERUNG, North Rhine-Westphalia[53] which depending on the type of applicant and the characteristics of the system, the financing can be up to 1,500 euros.

In the UK there is the EV charger grant for homes[54] which offers a subsidy of up to 75% of the total cost of purchasing and installing EV chargers for the home. Company cars and leased cars can also apply for the incentive and the On-Street Residential Charge point Scheme (ORCS)[55] in which local authorities can receive a grant to partially fund (75%) the capital costs associated with the purchase and installation of on-street EV charging point infrastructure in residential areas[56].

In Japan there is a subsidy for the purchase and installation of charging points - Tokyo[57] that allows subsidizing the purchase cost of charging equipment, construction and installation costs, energy conversion equipment, solar energy generation systems and storage batteries, as well as equipment operation costs.

Analysis of possible types of incentives

From the review of incentives, a total of 26 economic incentive programs and initiatives were found to promote electromobility in maritime

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and river modes in the countries analyzed. The country with the highest number of incentives was the Netherlands with a total of 5 initiatives, followed by the United States with 4 and Canada, Germany and Japan with 3 each. Sweden had 2 incentives and the rest of the countries (Argentina, Brazil, Costa Rica, Norway, Spain and the United Kingdom) had 1 initiative.

In these initiatives it was possible to find different types of incentives, which can be grouped into the following typologies:

- A: Discounts to vessels in ports (port taxes/traffic rights)
- B: Financing equipment or infrastructure for electromobility
- C: Tax exemptions/reductions
- D: Guarantees and special procedures for electromobility projects
- E: Financing to port authorities

Table 2 shows the implementation of these incentives in the countries analyzed (using the above notation), from which the most recurrent type of incentive are discounts to vessels in ports (port fees/circulation rights), followed by the financing of equipment or infrastructure for electromobility and tax exemptions/reductions.

Table 1. Incentive proposals for Colombia.

Country/Incentive	**A**	**B**	**C**	**D**	**E**
Argentina	x				
Brazil	x				
Costa Rica		x	x	x	
United States	x	x			x
Canada	x	x			
Sweden	x		x		
Norway	x				
Spain	x				
United Kingdom	x				
Netherlands	x		x		
Germany	x				
Japan	x				

While examining the economic incentives, various certification programs were identified, which serve as evidence of the vessels' ecological contributions. These programs are utilized by authorities to determine eligibility for the aforementioned economic benefits. The identified certification programs include:

Blue Angel

One notable environmental certification is the renowned German label, which serves to assess the ecological performance of services and ensures that transactions are carried out without significant adverse effects on the environment [19]. BlueAngel certification encompasses various activities, including the operational aspects and design considerations of ships *(Blue Angel, n.d.)*. This certification allows stakeholders, including authorities and consumers, to identify and support environmentally friendly shipping practices. Additionally, this certification program holds immense value in the realm of sustainability, transportation, and economics.

Clean Shipping Index (CSI)

The Clean Shipping Index (CSI) serves as a valuable tool in assessing ships based on their air and water emissions, waste management practices, and staff training initiatives. This comprehensive evaluation goes beyond regulatory requirements and measures the environmental performance of vessels. Depending on the scores obtained, ships can receive certification ranging from one to five stars, with five being the highest score *(Clean Shipping Index, 2022)*. This certification system plays a crucial role in promoting sustainability within the shipping industry. It is essential to highlight the significance of the Clean Shipping Index in driving environmental responsibility in maritime operations. By evaluating various aspects of a ship's performance, including emissions and waste management, the CSI incentivizes companies to go above and beyond regulatory compliance. This promotes the adoption of cleaner technologies, fuels, and practices, ultimately contributing to a greener and more sustainable shipping industry.

The Green Award

Green Award is a renowned certification program that prioritizes safety, security, and environmental considerations within the shipping industry. It acknowledges and incentivizes adherence to rigorous environmental and safety standards. The certification process encompasses a wide range of environmental impacts, including air emissions such as sulfur oxide (SOX), nitrogen oxide (NOX), carbon dioxide (CO2), and particulate matter (PM/BC). Additionally, it addresses issues related to energy efficiency, antifouling paints, oil management, lubrication of mooring ropes, and other deck equipment. Furthermore, Green Award evaluates emissions to waters, such as ballast water, sewage, sludge, bilge, and waste management *(Green Award, 2022).*

Environmental Ship Index (ESI)

The Environmental Ship Index (ESI) is a tool that was established by the World Ports Climate Initiative in 2011 to help reduce emissions of NOX, SOX, particulates, and CO2. The scoring in the ESI system is based on the emissions of these gases as well as the vessel's ability to use shore power supply. To receive a score in the ESI system, the vessel must have emissions that are lower than the legal requirement for NOX and SOX. The ESI score ranges from 0 to 100, with a higher score indicating better environmental performance *(ESI, 2022).*

Proposal for economic incentives for Colombia

Colombia is positioned as one of the Latin American countries with more development of electromobility policies and benefits granted to acquire electric vehicles in the road mode. However, this commitment is null for maritime and river modes, since there are no incentives in the country to promote electromobility in these modes of transport, except for a project initiative in the Amazon River that seeks to implement the use of boats powered by electric motors or solar panels. It is therefore necessary that this good practice in the road mode be extended to other modes of transportation.

A good way forward is to adopt the initiatives and incentives that other countries are implementing and that can be applicable to some specific regions of the country or in the country in general, considering the orientation and objectives that Colombia has set for itself in terms of greenhouse gas reduction. Among the aspects to be prioritized in these incentives are the development of infrastructure, modernization of passenger transport fleets, recovery of docks, science, and technology projects. Taking as a basis some of the incentives that are in force or that have been implemented in other countries can represent an advantage to design incentives that can bring benefits for the economy, the environment and society.

Based on this analysis of incentives, the following incentives can be proposed for Colombia (See Table 1), which are presented for different time horizons and include the percentage of financing, discount, or exemption for the aspects to be favored in the maritime and river modes.

Table 2. Incentive proposals for Colombia.

Type of incentive	Short term.	Medium term.	Long term.
Insurance premium discounts.	20%	15%	10%
Discounts on mechanical overhauls	15%	10%	5%
Reduction and exemption of import duties.	100%	70%	50%
Income tax reduction on infrastructure investments.	50%	35%	20%
Reduction in port fees for low-emission vessels.	10%	5%	5%
Reduction or exclusion of VAT on the purchase of goods and services for electromobility projects.	0%	5%	19%
Financing of research projects.	100%	100%	100%
Financing of river projects up to 70% of the project by the national government	70%	70%	70%

Conclusions

In the review different initiatives and actions were found in the analyzed countries aimed at generating incentives for electromobility in river and maritime transportation, thus allowing the migration to environmentally friendly modes of transportation. A total of 26 different initiatives were found, most of which were aimed at generating discounts in ports for the use of environmentally friendly vessels, as well as financing projects for the acquisition of equipment and infrastructure and tax reductions.

This article demonstrates the interest of different countries in promoting electric mobility in maritime and river modes, finding more incentives in one country than in another, but in any case, it is an important commitment to generate sustainable transport systems. In the case of the Latin American countries studied, only in Brazil, Argentina and Costa Rica were initiatives of this kind found, which is an opportunity for the other countries to follow suit.

The regulations and policies on electric mobility in Colombia are oriented towards the electrification of road transport and there are no incentives to promote electric mobility in the maritime and river modes. Nor were any incentives identified that could favor the development of maritime or river electric cargo infrastructure. In order to strengthen this aspect, a set of short-, medium- and long-term incentives were proposed to favor investments in this area in the country.

As future work, there is a potential to expand the analysis to encompass additional countries, thereby uncovering alternative forms of initiatives and incentives. Furthermore, it is crucial to conduct further research to identify the financing mechanisms available to governments, which would facilitate the implementation of these initiatives and incentives. Understanding the avenues through which governments can secure funding is essential for effectively materializing such endeavors.

It is imperative to emphasize the importance of broadening the scope of analysis to gain a comprehensive understanding of the global landscape. Exploring initiatives and incentives implemented in diverse countries can shed light on innovative approaches and best practices that can be adapted to local contexts. Additionally, investigating the financing mechanisms will enable governments to allocate resources effectively and foster the development of sustainable transportation systems.

By expanding the analysis and delving into the financial aspects, researchers and policymakers can foster the creation of a supportive environment that encourages the generation and implementation of impactful initiatives and incentives in the transportation sector.

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Entering a new era for electrical vessels on inland waterways

Entrando en una nueva era para los buques eléctricos en las vías navegables interiores

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Abstract

The shipping industry is moving towards quickly decarbonizing its assets. There is also a growing demand for new urban transportation (passengers, building materials, and equipment) with zero-emission propulsion. Zero-emission propulsion is available today for sustainable transport. The common size of inland navigation vessels offers the opportunity to implement innovative technologies earlier than seagoing ships. There is clearly a wide range of solutions available, with their own set of pros and cons. Batteries and fuel cells are part of a growing list of solutions to carbon-neutral or zero-emissions shipping. They become a strong choice and can be successfully combined with alternative fuels. As a result, electric and hybrid vessels are currently among the most important developments in the inland navigation sector. Bureau Veritas, as one of the major classification societies, proposes a brief review of state-of-the-art electrical solutions, considering available technologies, safety constraints and operational challenges, bringing to light its experience in electrical vessels, both in new constructions and conversions as well as in vessels in service. Although many parameters must be considered, the conclusion confirms that there are electrical solutions already suitable for a range of vessels and it is also possible to pencil the near future in association with new infrastructure and supply chain.

Key words: battery, fuel-cell, hybrid, safety, operations.

Resumen

La industria naviera se está moviendo rápidamente hacia la descarbonización de sus activos. También existe una creciente demanda de nuevos medios de transporte urbano (pasajeros, materiales de construcción y equipos) con propulsión de cero emisiones. La propulsión de cero emisiones está disponible hoy en día para el transporte sostenible. El tamaño común de las embarcaciones de navegación en aguas poco profundas ofrece la oportunidad de implementar tecnologías innovadoras de forma más práctica que en los buques oceánicos. Claramente, hay una amplia gama de soluciones disponibles, cada una con sus propias ventajas y desventajas. Las baterías y las celdas de combustible forman parte de una lista creciente de soluciones para la navegación neutra en carbono o de cero emisiones. Se convierten en una elección sólida y se pueden combinar con éxito con combustibles alternativos. Como resultado, los buques eléctricos e híbridos son actualmente uno de los desarrollos más importantes en el sector de la navegación en aguas poco profundas. Bureau Veritas, como una de las principales sociedades de clasificación, propone una breve revisión de las soluciones eléctricas de vanguardia, teniendo en cuenta las tecnologías disponibles, las limitaciones de seguridad y los desafíos operativos, destacando su experiencia en buques eléctricos, tanto en nuevas construcciones como en conversiones, así como en buques en servicio. Aunque se deben considerar muchos parámetros, la conclusión confirma que ya existen soluciones eléctricas adecuadas para una variedad de buques, y también es posible vislumbrar el futuro cercano en asociación con nuevas infraestructuras y cadenas de suministro.

Palabras claves: batería, celda de combustible, híbrido, seguridad, operaciones.

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Introduction

The need to decarbonise transport is already a priority for international institutions and the shipping industry is moving towards quickly decarbonizing its assets to reduce, or eliminate, greenhouse gas (GHG) emissions from ship operations. Many ferry operators have taken steps toward zero emissions by ordering partial or fully electric ships[1]. Also, there is growing demand for new urban transportation, embracing passengers, goods, materials and even waste, with low air and water emissions.

Zero-emission propulsion is available today for sustainable transport. Potential alternative solutions over the long run embrace thermal engines and fuel cells and batteries, including hybrid installations. There is clearly a broad range of solutions available when it comes to achieving the environmental goals and compliance with future regulation, and each carries its own set of pros and cons.

The common size of inland navigation vessels offers the opportunity to implement innovative technologies earlier than seagoing ships. Batteries and fuel cells are part of a growing list of solutions to carbon-neutral or zero-emissions shipping. They become a strong choice and can be successfully combined with alternative fuels. Batteries may be used alone on board, or in parallel with existing generators (hybrid solution). As a result, electric and hybrid ships are currently among the most important developments in the maritime and inland navigation industries as part of efforts to limit GHG emissions and advance the energy transition.

Fuel cell technology is another expanding application to decarbonize shipping, competing in two weight classes: alternative fuels and clean electricity. Also, supply of electricity to vessels in port (Shore-to-Ship power) has become a key issue in the fight to reduce exhaust emissions in densely populated areas.

The paper proposes a brief review of state-of-the-art electrical solutions, considering technologies, safety and operational challenges, bringing to light the experience of Bureau Veritas[2], as one of the major classification societies, in electrical vessels, in both new constructions and conversions as well as in vessels in service.

Technical Aspects

Battery

Batteries are the central part of the electric system which store the energy and release it according to the needs of the vessel. The main interest in batteries is to provide high power with optimized energy production, distribution, and consumption. (see Fig. 1).

From lead to lithium-ion batteries
Lead batteries have been the traditional batteries used to provide back-up power to ships. They are subject to longstanding rules for installation and maintenance and require low CAPEX investments. Lead batteries are dependable and recyclable, but they have relatively low energy density, they are rather heavy and bulky and there is no option of fast charging.

Battery technology is developing fast, especially Lithium-ion batteries, and it is widely used in current projects. Although they are commonly used as backup power, however they can enable ships to run in zero emissions mode, when batteries temporarily function as the only source of electricity, enabling ships to comply with strict port requirements and travel in environmentally controlled areas (ECA). Additionally, batteries can be used for "peak shaving", taking over from onboard generator sets to deliver the peak load of energy.

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. Lithium-ion

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[1] https://www.electrichybridmarinetechnology.com/online-magazines

[2] https://marine-offshore.bureauveritas.com/

batteries are the best energy density on the market (200Wh/kg, five times lead acid and twice nickel cadmium) with low self-discharge.

Risk of uncontrollable thermal runaway exists, therefore an internal electronic control for thermal protection is needed. The battery management system (BMS) is an electronic system associated with a battery pack which monitors and manages in a safe manner its electric and thermal state by controlling its environment, and which provides communication between the battery system and other macro-system controllers, such as a power management system (PMS). The BMS is to be provided to monitor the modules, sub-packs, packs (voltage, temperature) and to control proper connection / disconnection of battery packs and sub-packs when in critical state.

There are several types of lithium batteries technologies, with various characteristics. Some technologies are known as safe, such as Lithium iron phosphate (LFP) and Lithium titanium oxide (LTO). LFP has high power density (W output / kg) and safety, medium cost and lifecycle, but lower energy density (Wh/kg). LTO presents high safety, long lifecycle, medium power density, but lower energy density and higher cost.

Charging

Energy is required to produce electricity used for battery charging; therefore, the assessment of environmental footprint depends on how the electricity is produced.

C Rate is the current which described how fast the cell is charging or discharging, e.g., in theory, 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 to suit the operational constraints.

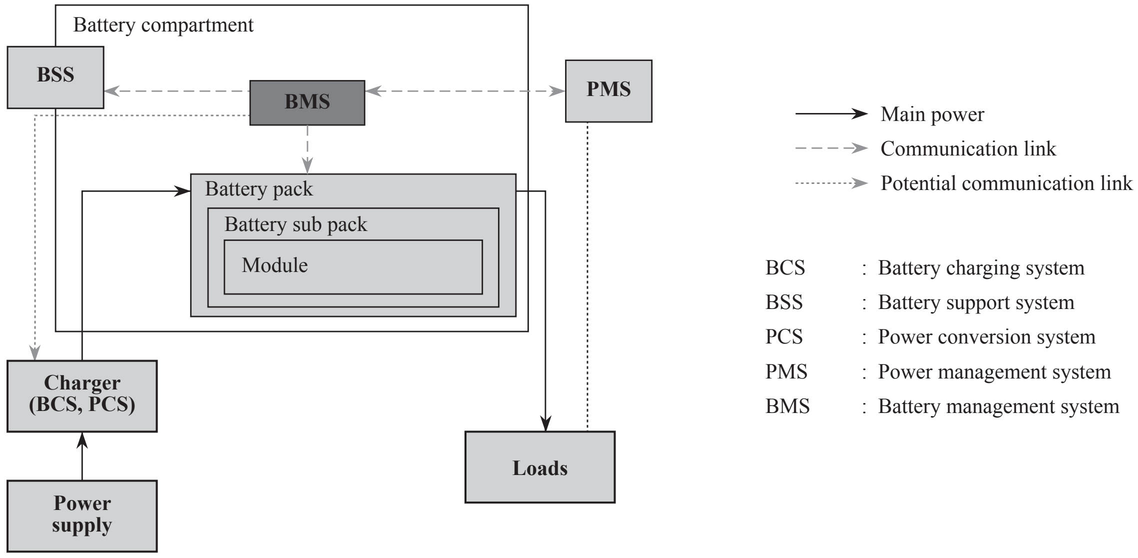
Fuel Cells

Principle

Fuel cells is a device which convert chemical energy from hydrogen ($H2$) into electrical energy to create a direct current through the electrochemical reaction between hydrogen and oxygen from air with efficiency range between 35 and 55%. No energy is stored in the fuel cell but rather in the associated hydrogen container. Fuel cells offer one of the best efficiency-pollutant ratios. It emits only heat and water. If the fuel cell operates at a sufficiently high temperature, its waste heat may also be recovered in onboard heating systems.

To date, fuel cells have seen limited application in the marine industry, and installations and components have still to be adapted for the marine environment and approved for use on vessels to power propulsion or auxiliary power systems.

Fig. 1. Typical battery system.



In view of challenging storage and carriage of hydrogen, Liquid Organic Hydrogen Carriers (LOHC) provide significant advantages in terms of availability, recharging, and safety.

Types of fuel cell

Depending on the fuel and electrolyte, fuel cell technology covers a range of cells such as AFC (Alkaline Fuel Cell), PEMFC (Proton Exchange Membrane Fuel Cell or Polymer Electrolyte Membrane), SOFC (Solid Oxide Fuel Cell) and DMFC (Direct Methanol Fuel Cell). The choice between these technologies will depend on parameters such as starting time, operating temperature, power, and lifetime.

PEMFC is the most used, but it uses only pure hydrogen and requires platinum as a catalyst. It is compact and runs at 80°C. For the time being, PEMFC appears to be the most used option for small applications. The axis of improvement would increase the temperature (up to 200°C) for better efficiency, while the lifetime could be increased.

SOFC is suitable for heavier power requirements. It is operated at high temperatures (800 – 1,000 °C) and requires a significant start-up time. It stands out with the advantageous feature of fuel flexibility since it is not limited to pure hydrogen.

Several possible hydrogen carriers (LOHC)

Methanol (MeOH) can be stored and handled easily at ambient conditions, and it can be produced from various sources such as low-cost biomass on a large scale. Using a mixture with 60% methanol and 40% water is less flammable than pure methanol and it 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. Also, advantage is that methanol has a much higher volumetric energy density than hydrogen and therefore permits fuel tanks of more compact dimensions.

Ammonia (NH3) has a long-term track-record of successful handling and distribution, worldwide. Liquid ammonia can be stored in large tanks at room temperature. Compared to hydrogen, ammonia is easier to be transported. It is much more energy efficient and much lower cost to produce and store. It can be directly used as fuel in SOFC where it is cracked into hydrogen and nitrogen in the anode. The decomposition of ammonia into nitrogen and hydrogen increases with increasing temperature. Already from 400 °C, this decomposition is nearly complete. LNG can be also an option, but it would be suitable to LNG tankers.

Combination of batteries and fuel cells

Usually, fuel cells are not installed alone on board, and a normal main source of power is installed, usually batteries. To date, fuel cell is not able to supply a sizeable ship alone. The dynamic of the fuel cell is not enough and, due to its intrinsically characteristics, it is not able to face the load impact coming from the starting / stopping of large auxiliaries (voltage variation, frequency variation in AC- Alternating current -). In combination of fuel cells and batteries, the high discharge rate of batteries can compensate for the low dynamic of the fuel cell discharge current, the fuel cells deliver a continuous current used to supply the vessel and charge the batteries.

Hybrid solutions

By definition, “hybrid” is of mixed character, a composition of different elements, where each of it can commonly serve propulsion and services.

Apart from common diesel-electric system, there are two main types of electrical hybrid, hybrid propulsion and hybrid production.

Hybrid propulsion

- Parallel hybrid concept: the electrical motor is fitted in parallel of the propeller shaft. Either the thermal engine or the electrical motor can be used (or both), depending on the needs (e.g., urban operation, manoeuvre).
- The serial electrical hybrid: the electrical motor is fitted in series of the propeller shaft, avoiding mechanical loss due to reduction

gear. The vessel can operate at low speed on electric mode only.

Hybrid production
Batteries are associated, wired in parallel with generator. There are three power management modes:

- Load smoothing mode, where the energy storage system (ESS) is charged and discharged all the time to compensate for the network load variations. This will result in limited load fluctuations of the main generating sets, allowing optimized fuel consumptions and reduced exhaust gas emissions.
- Peak shaving mode is dedicated to instant power demand. The purpose is to supply peaks of a highly variable load (e.g., during manoeuvring) and to avoid the connection of an additional main generating set.
- Enhanced dynamic mode is mainly relating to gas fuel or dual fuel generator sets. In case of sudden load increase, the ESS instantaneously supplies the corresponding power demand, thus enhancing the generator dynamic performance, and, for dual fuel engines, preventing the possible switch-over to fuel oil due to ramping-up.

Commonly, hybrid systems are based on diesel-electric system coupled with battery system. To reduce gas emission, diesel engines would be replaced by alternative fuel engine, notably LNG (or CNG) or biofuels, same as vessels fitted with conventional thermal engine propulsion systems.

Safety Aspects

Battery

The challenge of thermal runaway
The primary safety challenge for battery-powered vessels is the issue known as “thermal runaway”. Thermal runaway occurs in situations where an increase in temperature changes the conditions, either from a high current discharge rate or proximity to external heat sources. This can cause a chain reaction, creating a large-scale conflagration that can damage vessels and threaten passengers and crew.

The three major possible consequences in case of thermal runaway:

- Flammable/toxic gas emission, possibly with bursting generating mechanical hazards.
- Flame ignition, and possible flame propagation in the cells or batteries casing and packaging.
- Heat emission and thermal runaway propagation from cell to cell or battery to battery, in absence of flames.

Those 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 suitable to the battery type.

Regulations
To mitigate risk, specific rules and standards are used to test batteries, such as IEC 62619 and 62620, while additional safety measures can be applied, such as Battery Management Systems (BMS). BMS monitors the voltage, current and temperature of battery modules, packs and sub-packs, and controls the proper connection and disconnection of battery packs and sub-packs.

Beyond providing critical safety information, BMS also enable ship operators to optimize energy use and availability, and to increase battery lifetime.

The major IACS[3] classification societies have developed several rules related to battery systems which reflect the latest technical and safety developments in order to limit risk, both for the battery itself and onboard integration.

Manufacturers must carry out a risk analysis, including risk evaluation for sensor failure, internal and external short-circuiting, thermal runaway, fluid leakage, and possibility of gas release (toxic

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[3] https://iacs.org.uk/

or explosive). Shipyards must also perform comprehensive risk analysis, assessing ventilation systems, hazardous areas, and energy storage system spaces, to reduce risk and demonstrate that battery-powered ships are safe.

Bureau Veritas currently offers the notation "Battery System" for battery-powered vessels, covering safe installation and use of batteries, by providing safety testing and risk analysis before integration onboard, and offering a standardized approach to risk management. This notation is mandatory when the ship is relying only on batteries for propulsion or electrical power supply for main sources. Battery cells and battery packs must be type-approved with prototype tests conforming to a national or international standard. The type of approval must cover both the battery pack and the BMS. The Rules book NR320 "Certification Scheme of Materials and Equipment for the Classification of Marine Units" must be applied.

The fire-extinguishing system must be suitable for the battery type. There are also specific requirements for ventilation when using large-vented batteries.

When size of compartment permits, floodable battery compartment, in case of fire, would allow to stop the overheating escalation process. Stability calculation relating to the flooded condition would be required.

Hydrogen fuel cells

Hydrogen has one of the widest explosive/ignition mix ranges with air, falling at the extreme end as low as 4%. Special care is required when handling hydrogen as it is flammable, explosive, and prone to leak. Hydrogen application in shipping entails specific procedures in terms of transportation, bunkering, storage at high pressures or very low temperatures, and use.

Maritime stakeholders developing and using fuel cells must carefully assess the risks associated with their design, construction, installation, and operation. Specific safety requirements must be met to receive certification for fuel cell systems, and a range of risk assessments are required in order to limit the risk of explosion, fire outbreaks, and the spread of toxic chemicals.

As with batteries, specific rules and standards are used to test the fuel cells, and a risk analysis of installation must be performed to assess the ventilation systems, hazardous areas, and fluid leakage. This risk analysis must cover installation, but also gas storage and supply piping.

Bureau Veritas has developed the Rule book NR547, "Ships using Fuel Cells", to cover fuel cell technologies which are adapted to multiple alternative fuel types, each with their own risk profile.

NR547 focuses on the fuel cell system and is to be used in conjunction with several other Rule Notes for alternative hydrogen carriers, including methanol (NR670), LNG (NR529), and ammonia (NR671).

An extensive range of risk assessments must be carried out to be granted the "fuel cell" notation, including HAZID (hazard identification) study of fuel cell spaces, HAZOP (Hazard and Operability) study of fuel cell power system, and FMECA (Failure Mode, Effects & Criticality Analysis) analysis of fuel cell power installation when used for essential services.

The functional requirements are based on fail-safe design principles (minimize hazardous areas and ignition sources, arrangements to sustain or restore operation, shutdown arrangement, fire detection, fire protection, etc.).

Electrical hybrid

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 would be superimposed to cover the risks generated by each fuel or technology.

At Bureau Veritas, all the requirements for assignment and maintenance of each class notation are given in the Rule book NR467 ("Rules for the classification of steel ships").

Thermal engine and batteries

The notation "Electric Hybrid" caters for vessels using a combination of diesel engines and batteries used to supply the electric propulsion and/or the main electrical power distribution system of the vessel.

With "Electric hybrid" notation, the ESS is not considered as forming part of the main source of electrical power and it remains independent of the emergency source or transitional source of power. A Failure Mode and Effects Analysis (FMEA) demonstrates the availability of ship propulsion and main electrical source of power in case of failure of the ESS.

The notation "Electric Hybrid" must be completed with either:

- "PM" for Power Management mode (load smoothing mode, peak shaving mode, enhanced dynamic mode).
- "PB" for Power Back up mode where the ESS is permanently connected to the main electrical power distribution system of the ship and is able to deliver power immediately in case of failure of one main generating set.
- "ZE" for Zero Emission mode where the ESS is temporarily the only source of power connected to electrical network. The ZE mode, unlike the PB mode, is activated intentionally.

Thermal engine and electrical engine

The notation "Hybrid Mechanical Propulsion" may be assigned to vessels provided with a propulsion plant which combines diesel mechanical system and electric system. It provides requirements for remote and local control of both propulsion and switch over from one propulsion type mode to another one. The notation does not require battery.

The additional notation AVM is relevant to systems enabling the ship to carry on limited operations when single failure affects propulsion or auxiliary machinery or when an external event such as fire or flooding involving machinery spaces affects the availability of the machinery. The notation is complete with the system (*i.e.*, Alternative propulsion, Duplicated propulsion or Independent propulsion).

Operational Aspects

Battery

Lithium-ion battery

Shipowners and operators anticipated lower prices thanks to improved technology and increased competition among manufacturers. Indeed, the average cost of lithium-ion batteries has declined by 89% since 2010, falling to just $132/kWh in 2021[4]. It was estimated that the average price for battery packs would fall to $92/kWh by 2024. Presently, that forecast seem increasingly unlikely. The cathode needs lithium, nickel, and cobalt, which prices skyrocketed beginning in late 2021. Some experts expect about a 10% rise in 2022, even a jump of 20% year over year[5].

Ships need to recharge their batteries by connecting to the electrical grid in port. This means ports must have the suitable installations and electrical capacities, coming from renewable sources. Batteries can also be charged using onboard generator sets, using decarbonized fuels.

Li-on batteries are preferred but they suffer from ageing and there are additional safety concerns. One of the challenges is to increase the energy density and to manage the risk of thermal runaway and explosion. There is also the question of sustainable recycling.

Beyond providing critical safety information, BMS also enables ship operators to optimize energy use and availability and increase battery lifetime.

There are other factors that contribute to the cost of lithium-ion systems. The cells make up only 40-50% of overall battery pack cost. BMS is significantly expensive because it requires more flexibility and mechanism to shift energy to and from the battery frequently and in a wide range of operating conditions. These factors increase the specific cost of the battery pack. Large power systems level up in BMS design. For instance, a 1200V system could be monitoring 320 cells

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[4] Source: Full Stack Economics Dec.13, 2021 & BloombergNEF report 2021.

[5] Source: Emerging Tech Brew April 13, 2022.

with multiple stacks in parallel plus an overall management system to aggregate all the stacks into a single system representation. A BMS can cost round $10,000 depending on the nominal voltage of the battery stack and quantity of parallel stacks[6].

Swappable containerized batteries

The swappable containerized batteries system, where the electrical output is either AC voltage or DC voltage, may help accelerate electrification of inland waterway traffic with a lower investment for shipowners and operators. It is notably interesting when operation constraints do not give enough time for recharging.

Roughly, considering the volume of a 20’ container, 1 MWh of batteries - with DC voltage supply - or 3 MWh of batteries - with AC Voltage - can be installed.

A 3 MWh containerized battery pack can be integrated on board within minutes when using a swap-and-carry concept.

A battery container needs to fulfil all regulatory requirements from structural and fire integrity aspects.

The distance between swaps is the key point. There is a necessity to build a network of stations along the route and pay the associated cost for the system. For instance, a battery container with a capacity of 2 MWh could be a solution for an electric vessel that need power about 500-1,000 kW, provided the route allows for 2-4 hours of work between swaps.

Fuel cells

Hydrogen is increasingly viewed as a contender among alternative fuel solutions, receiving increased investment. It has gained momentum in recent years as technology matures, and the price gap with conventional technologies narrows.

The main advantage of fuel cells is the high energy density of hydrogen. In electrical terms, the energy density of hydrogen is equal to 33.6 kWh of usable energy per kg, versus diesel which only holds about 12–14 kWh per kg.

Meanwhile, creating hydrogen by splitting water by electrolysis is a costly process. Approximately, 50 kWh of electricity is needed to produce 1 kg of hydrogen that subsequently yields only 33 kWh of energy[7].

There is a high initial cost of hydrogen installation, and storage and transport are complex due to hydrogen’s low energy density by volume and special pressure/temperature requirements (storage under high pressure, 350 bar even 700 bar, or cryogenic, -253°C).

Green hydrogen produced with renewable resources costs between about $3/kg and $6.55/kg, according to the European Commission's July 2020 hydrogen strategy[8], while the cost of blue hydrogen, which pairs carbon capture with steam methane reformation of natural gas, is estimated at about $2.40/kg[9]. Projections show that renewable hydrogen production costs could decline to $1.4 to $2.3 /kg by 2030[10]. At-scale, international distribution could arrive by 2030 at total costs of $2-3/kg (excluding cost of production).

One must consider the fuel cell system cost and the hydrogen fuel cost. Manufacturers of fuel cell system estimate a current price of € 1,800/kW with a price reduction down to € 1,000/kW towards 2025[11]. The storage tank itself would cost about 400 €/kg in 2024 and 300 €/kg in 2030[12] but in addition to the hydrogen tank, there are costs related to valves and piping, bunkering interface, instrumentation, fire insulation, detectors and firefighting systems. It is assumed

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[6] Source: EDN (https://www.edn.com/)

[7] Source: Prof. Werner Antweiler, University of British Columbia - Sep.18, 2020.

[8] Source: Briefing towards climate neutrality, European Parliament – April 2021 https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/689332/EPRS_BRI(2021)689332_EN.pdf.

[9] Source: Reglobal.co, “The Risks of Investing in Blue Hydrogen for Europe” – May 25, 2022.

[10] Source: Hydrogen Insights Report 2021 - Hydrogen Council, McKinsey & Company.

[11] Source: “Energy and cost analysis of a hydrogen driven high speed passenger ferry” Aarskog Fredrik G., Danebergs Janisa, Strømgren Trondb, Ulleberg Øysteina – July 8, 2020.

[12] Source: Clean Hydrogen Joint Undertaking (EU) - Strategic Research and Innovation - Agenda 2021 – 2027.

that the additional costs are in the same order as the tank itself.

Most of the time, the fuel cells are not marinized yet since they come from the car industry where proven equipment have been developed. Equipment approval and installation on board must be adapted to meet the class requirements.

Once fuel cells are integrated onboard, ship operators must safeguard crew and ensure appropriate training for proper handling of fuel cell equipment.

Hybridization with batteries is expected to increase the lifetime of the fuel cell system significantly.

If one of the LOHC is used instead of pure hydrogen, the technology and equipment must be suitable for the fuel, and the specific regulation must be complied with. Investment depends on the type of equipment corresponding to the fuel, including safety aspects, and operational costs are dependent on availability of bunker stations.

Some manufacturers think also about using a hydrogen version of swappable containers.

Hybrid solutions

There is a multitude of solutions, each of them with its own advantages and disadvantages, depending on the technology and fuel. From an environmental point of view, the efficiency of the solution would imply using biofuel – made from sustainable source – or natural gas.

Electrical hybrid solution may save on fuel, however the expected reduction in consumption depends on the engine load. It would be more significant during manoeuvres (*e.g.*, ferries).

Power in port

Increasingly, ships are connecting to a green energy grid in port, thereby completely eliminating exhaust gas emissions. Power installations at berth are technically sophisticated and must provide enough power to supply several vessels simultaneously. Distribution systems and power receptors must also be harmonized so that a ship can connect in each port with its own onboard equipment, while the installation must also cater for many different types of vessels.

In order to guarantee the effective safety and functionality of installations, there are appropriate technical standards, depending on the nominal power of the shore installation, e.g., European Norms EN15869-1: 2019, EN15869-3, EN16840, as well as Bureau Veritas' Rules. The additional class notation "HVSC" (High-voltage shore connection systems) may be assigned to ships fitted with electrical and control engineering arrangements allowing operation of services by connection to an external high-voltage electrical power supply in port. The requirements for the assignment of this notation are given in NR557 "High-Voltage Shore Connection Systems".

Conclusions

There currently exists no single substitute to the diesel engine. 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. Operators must make their choice depending on vessel type and operational constraints, while also anticipating future fuel alternatives, availability and pricing, and managing challenges of safety and regulatory requirements.

Electrical propulsion is increasingly emerging as an alternative solution. Battery systems, fuel cells, and hybrid are solutions which can be adopted in combination with other technologies and alternative fuels to achieve crucial reductions in pollution, noise, maintenance costs and fuel consumption. Those solutions are set to play an important role in the shift to sustainable shipping, especially on those vessels transiting waterways and estuaries, travelling short and fixed distances, such as ferries and vessels engaged in harbour operations, but also those sailing on waterways benefiting from suitable infrastructure and designed for fast recharging or swappable battery containers.

Battery

The battery market is now nearly mature, and regulations are well established, with both IEC standards and classification rules. The market for battery systems of lithium-type is increasing, with a growing number of vessels in operation or under construction (round 40 vessels have been approved by Bureau Veritas the last two years).

For small-to-medium sized ships on short-haul voyages with multiple port calls – such as passenger ferries, tugs, and specialized vessels – using batteries to store energy may be a viable option.

As progress is made and economies of scale are triggered by the uptake of the technology by terrestrial transportation, the cost of batteries will become more favourable. However, extra cost would remain about safety construction and equipment as well as for battery management.

The positive effect on the environment will depend on how electricity used for charging batteries is produced, either from shore grid or generator on board.

The swappable container solution could be an interesting option, with few adaptations of the deck arrangement, mainly for vessels operating short distances, but it would require an extensive network of stations for vessels sailing long haul.

Fuel cells

Hydrogen fuel cells are also developing quickly, and they could also be serious contenders for vessels that require limited autonomy. So far, the adoption of fuel cells has been hindered by their short service life and price.

Also, the majority of these cells are not adapted yet for marine and the climate for type approval remains challenging. PEMFC seems to offer a better proven time of experience. For the moment, some innovations were approved considering the fuel cells as “non-essential service” and it has been focused on the safety aspect only (risk of gas leakage, explosion). It provides experience in service, and it gives the opportunity to the various manufacturers to prepare for Type Approval Certificate which is the final target.

When it comes to hydrogen, storage remains a technical obstacle that will be expensive to solve in the short term. Currently, there is almost no infrastructure in place for hydrogen bunkering and operations made to date have used custom-made truck bunkering. Cost of green hydrogen would decrease when more production installations are developed.

There are other hydrogen carriers, each of them with their specific safety challenges and regulations. Also, the choice would depend on availability of bunkering stations and price, which is a key parameter that operators have to consider when investigating a fuel to evaluate a vessel’s future OPEX.

While fuel cells are not able to withstand the load impact of activating/deactivating large power consumers and may generate excessive onboard voltage and frequency variations (when AC current is used), the batteries instead can deliver a high current in short time. A combination of batteries and fuel cells may offer great flexibility, with the fuel cells delivering a continuous current which is used to supply the vessel, if maximum power output is needed, or to charge the batteries. This combination also reduces charging time at port.

Hybrid solutions

Electrical hybrid solution may be a valuable investment in conversion of 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.

Combination with batteries can provides flexibility and possibility to operate with zero emission in harbour and urban areas.

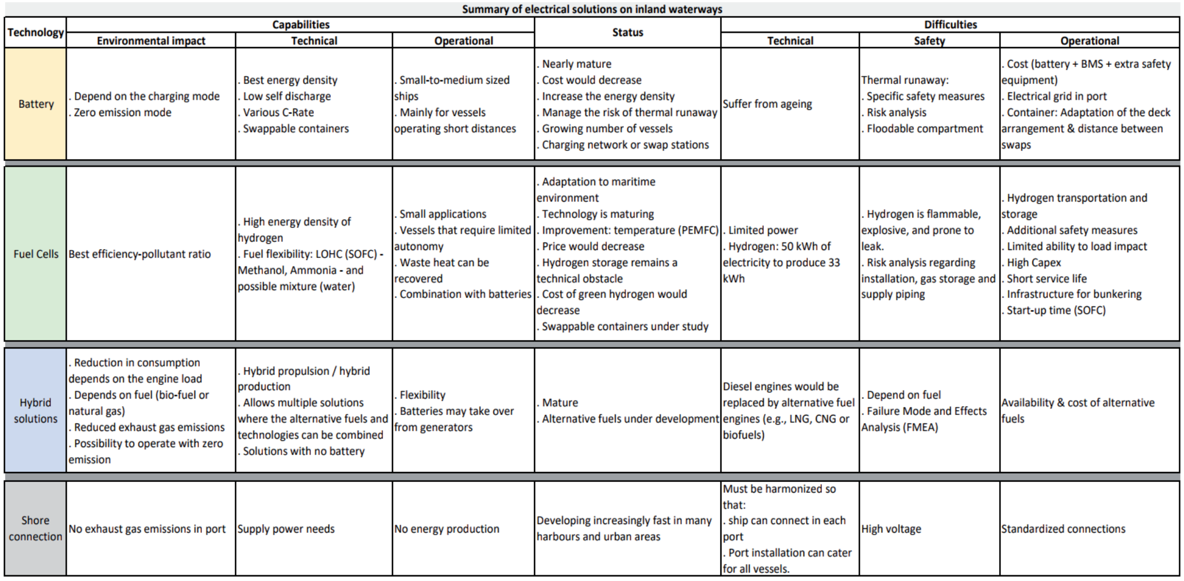
Availability and cost of alternative fuels, to reach the low emissions goal, remain the key point.

Shore connection

It is developing increasingly fast in many harbours and urban areas, following state policy and decision of major municipalities to eliminate easily gas emissions in densely populated zones.

Table 1 is a simplified synoptic summary of the main electrical solutions together with the capabilities offered by the various options and the associated difficulties that generate the challenges to be taken into account when considering a new construction or a conversion.

Table 1. Summary of electrical solutions on inland waterways.



Summary of electrical solutions on inland waterways

Technology	Capabilities			Status	Difficulties		
	Environmental impact	Technical	Operational		Technical	Safety	Operational
Battery	. Depend on the charging mode . Zero emission mode	. Best energy density . Low self discharge . Various C-Rate . Swappable containers	. Small-to-medium sized ships . Mainly for vessels operating short distances	. Nearly mature . Cost would decrease . Increase the energy density . Manage the risk of thermal runaway . Growing number of vessels . Charging network or swap stations	Suffer from ageing	Thermal runaway: . Specific safety measures . Risk analysis . Floodable compartment	. Cost (battery + BMS + extra safety equipment) . Electrical grid in port . Container: Adaptation of the deck arrangement & distance between swaps
Fuel Cells	Best efficiency-pollutant ratio	. High energy density of hydrogen . Fuel flexibility: LOHC (SOFC) - Methanol, Ammonia - and possible mixture (water)	. Small applications . Vessels that require limited autonomy . Waste heat can be recovered . Combination with batteries	. Adaptation to maritime environment . Technology is maturing . Improvement: temperature (PEMFC) . Price would decrease . Hydrogen storage remains a technical obstacle . Cost of green hydrogen would decrease . Swappable containers under study	. Limited power . Hydrogen: 50 kWh of electricity to produce 33 kWh	. Hydrogen is flammable, explosive, and prone to leak. . Risk analysis regarding installation, gas storage and supply piping	. Hydrogen transportation and storage . Additional safety measures . Limited ability to load impact . High Capex . Short service life . Infrastructure for bunkering . Start-up time (SOFC)
Hybrid solutions	. Reduction in consumption depends on the engine load . Depends on fuel (bio-fuel or natural gas) . Reduced exhaust gas emissions . Possibility to operate with zero emission	. Hybrid propulsion / hybrid production . Allows multiple solutions where the alternative fuels and technologies can be combined . Solutions with no battery	. Flexibility . Batteries may take over from generators	. Mature . Alternative fuels under development	Diesel engines would be replaced by alternative fuel engines (e.g., LNG, CNG or biofuels)	. Depend on fuel . Failure Mode and Effects Analysis (FMEA)	Availability & cost of alternative fuels
Shore connection	No exhaust gas emissions in port	Supply power needs	No energy production	Developing increasingly fast in many harbours and urban areas	Must be harmonized so that: . ship can connect in each port . Port installation can cater for all vessels.	High voltage	Standardized connections

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A Truly Sustainable Digital Transformation Model for the Naval Sector

Un Modelo de Transformación Digital del Sector Naval Realmente Sostenible

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Abstract

This document aims to show the meaning and real implications of implementing a Digital Transformation in the naval sector, explaining its three components (People - Processes - Technology), as well as the consequences of the bad practices of its application through real cases of global resonance. Subsequently, an approximation to the requirements to carry it out in an adequate and sustainable manner are stated, by understanding the concepts of the executive level that will help strategic alignment and the application of tools to achieve it, and then explain how to design and execute a Digital Transformation Strategy in any organization. Finally, a model to create a sustainable Digital Naval Industry is offered, leveraged by Industry 4.0 technologies, presenting mechanisms such as the creation of a national and regional naval cluster, which allows free exchange of data and open information in real time, whose enabler will be the Unified NameSpace (UNS).

Key words: Industry 4.0, Digital Transformation, Naval, Digitalization.

Resumen

Se pretende mostrar el significado e implicaciones reales de implementar una Transformación Digital en el sector naval, explicando sus tres componentes (Personas - Procesos - Tecnología), así como las consecuencias de las malas prácticas de su aplicación mediante casos reales de resonancia mundial. Posteriormente se hará una aproximación a los requisitos para llevarla a cabo de manera adecuada y sostenible, mediante el entendimiento de los conceptos del nivel ejecutivo que ayudarán al alineamiento estratégico y la aplicación de herramientas para poder conseguirlo y, seguidamente explicar cómo diseñar y ejecutar la Estrategia de Transformación Digital en cualquier organización. Finalmente, se presentará un modelo para crear una Industria Naval Digital sostenible, apalancada por las tecnologías de la Industria 4.0, exponiendo mecanismos como la creación de un clúster naval nacional y regional, que permita un libre intercambio de datos e información abierta en tiempo real, cuyo habilitador será el Espacio Nominal Unificado (ENU).

Palabras claves: Industria 4.0, Transformación Digital, Naval, Digitalización.

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Introduction

Currently, Latin America is one of the least competitive regions globally, as evidenced in a study conducted by the IMD (International Institute for Management Development) World Competitiveness Center (see Fig. 1). In this sense, the naval sector in Latin America has great opportunities to generate high value in economic growth and increase the competitiveness of the region in general.

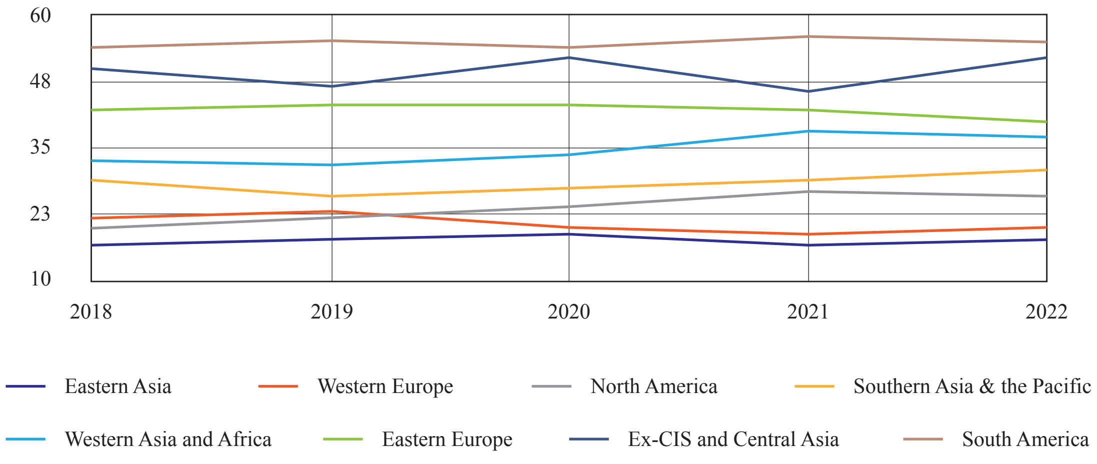
Digital Transformation is called to be the main enabler to allow the constant exchange of reliable, real-time, and valuable data and information across and along all the national and regional naval clusters, to allow the integration of all the efforts inside the sector and pursue a higher global competitiveness.

The naval sector is one of the most complex in the world because of its dependencies, type of projects, need for high investments, highly qualified human capital requirements, highly complex technological solutions, and the need for a global supply chain. This sector is made up of several companies that perform naval architecture, engineering, design, different types of services, economic and sustainable exploitation of the seas, construction and maintenance of ships and vessels of all types, including the design and construction of floating platforms, offshore vessels and systems, naval weapons, propulsion systems and their components, military and civilian communications, radar, sonar and other electronic systems, simulation and modeling systems, and the design and construction of ships, maintenance and repairs of shipyards, and much more.

To be a leading player in this sector, it is essential to be able to count on a high level of integration and collaboration between the different actors. A Digital Transformation of the naval sector is the only way to achieve this goal. A Digital Transformation is based on the use of new technologies to transform the way companies and organizations interact with their customers, employees, and between companies (Business to Business or B2B) inside the cluster. This transformation implies a change in the way companies and organizations work, think, behave, and use technology to do so. It also involves a change in data and information management to make decisions and improves the quality of the products and services.

The approach to this study is carried out through the description of what a successful Digital Transformation process means, through the study of a few failure cases of global resonance and the presentation of statistics and studies of both naval and Digital Transformation aspects. For this reason, the research methodology used is considered a qualitative, descriptive and explanatory study, with a non-experimental, transversal and descriptive design.

Fig. 1. Average ranking positions by region in Overall Competitiveness 2018-2022. (International Institute for Management Development IMD, 2022).



Digital Transformation

What is not Digital Transformation

It is very common to hear people and even read documents, in which the term "Digital Transformation" is carelessly used to describe the adoption of platforms, applications, hardware, software or any other type of initiative, without understanding what it really means, especially in Latin America. It is often confused with other terms such as Digitization or Digitalization. However, the most important thing to know is that there is no Digitalization or Digital Transformation without Digitization of paper, procedures and processes.

Digitization in its most basic meaning, is creating a digital version (bits and bytes) of analog or physical elements; It commonly refers to the transformation of the analog to the digital, whether material or immaterial, such as paper documents, photographs, audio, among others. Schallmo and Williams (2018) define this term in the context of the business process as "... digitally enable analog or physical artifacts to be implemented within business processes, with the ultimate goal of acquiring new knowledge and creating value for stakeholders." (Pag. 36).

Regarding digitalization, the first use of this term was in the essay "The Digitization of Society", published in the North American Review in 1971 by Robert Machal, referring to the limitations and potential of computer-assisted research. The large amount of theory that exists regarding the confusion of this term with digitization, forces to establish the definition for the purposes of this document as "... the fundamental changes made to operations and business models with the new knowledge acquired via high added value digitization initiatives" *(Schallmo and Williams, 2018).*

An example of what digitalization means under this approach, corresponds to the use of technological tools, applications or platforms that renew, transform, facilitate, or replace old processes or procedures, creating an environment in which digital information is the core.

What is Digital Transformation

Regarding Digital Transformation, there are endless definitions that, at their base, are not incorrect. For some people (unfortunately the vast majority), it is related mainly to technology; for others it is the way to get new clients and business opportunities in companies, and others relate it also with a new way of developing their business model. But normally this difference in concepts occurs within the same organization, revealing problems that affect corporate leadership, as they show a misalignment and lack of common vision regarding the future of the companies *(Dorner & Edelman, 2015).*

The most appropriate definition of Digital Transformation, corresponds to what the researchers at Massachusetts Institute of Technology (MIT) Ross, Beath and Mocker (2019) define in the book "Designed for Digital" as Digital Business Design: "… the holistic organizational configuration of people (roles, accountabilities, structures, skills), processes (workflows, routines, procedures), and technology (infrastructure, applications) to define value propositions and deliver offerings made possible by the capabilities of digital technologies" (Pag. 36).

In some circles, Digital Transformation is mistakenly handled as a project since, among other differences, a project has a start and an end. Digital Transformation must be seen as a permanent process and a constantly evolving strategy, thanks to rapid technological changes, which are already beginning to make obsolete the Moore's Law[1]. The implementation of the Digital Transformation should be managed as a project, but the Digital Transformation itself should not.

Components of Digital Transformation

In summary, a successful Digital Transformation carries out a strategy in which the three general components to be transformed are intervened in a sequentially and organized manner: people

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[1] Moore's law is the empirical observation that component density and performance of integrated circuits doubles every two years. (Gustafson, 2011).

(mind and culture), processes (what the company does) and technology (the enabler). Each of these components has a series of methodologies and tools to use that guarantee that it is considered within the Digital Transformation strategy to obtain the greatest possible benefit, as shown in the following table:

Table 1. Digital Transformation components and intervention methodologies.

Digital Transformation Component	Component Intervention Methodology
People (mind and culture)	Organizational Change Management (OCM)
Processes (what the company does)	Organizational Process Reengineering (OPR)
Technology (the enabler)	Organizational Apps. (Apps.)

Statistically, only 30% of companies that embark on their Digital Transformation journey achieve expected value and sustainable change in what is considered the “winners zone”. 44% get some value, but do not reach their goals, or achieve a lasting transformation over time; this area is known as "the zone of concern". The remaining 26% are in the “affliction zone”, those that obtained little or no value and the change was limited in time, (see Fig. 2). The main reason for this high rate of failure, is the fact that many organizations and people consider that the application of technological tools is the component to which they should dedicate the greatest amount of resources, leaving aside, or giving less importance to people and processes, essential aspects to achieve success. *(Forth, Reichert, De Laubier, & Chakraborty, 2020).*

Greatest Digital Transformation failures

As an example of the given statistics, important Digital Transformation failures have been studied, establishing that the most common root cause across these cases is that the companies didn’t make an adequate plan to impact the three components previously described (see Table 2).

This list corresponds to a study carried out by two important Digital Transformation consulting firms. The parameters that were ranked were the severity of the failure and the possibility of it having been avoided *(Kimberling, Third Stage Consultant Group, 2022).*

An example of a Digital Transformation success

Unfortunately, there is currently no real information available about a successful Digital Transformation in the naval sector. However, there have been some notable examples in other industries. One such

Fig. 2. Digital Transformation success statistics. (Forth, et. al., 2020).

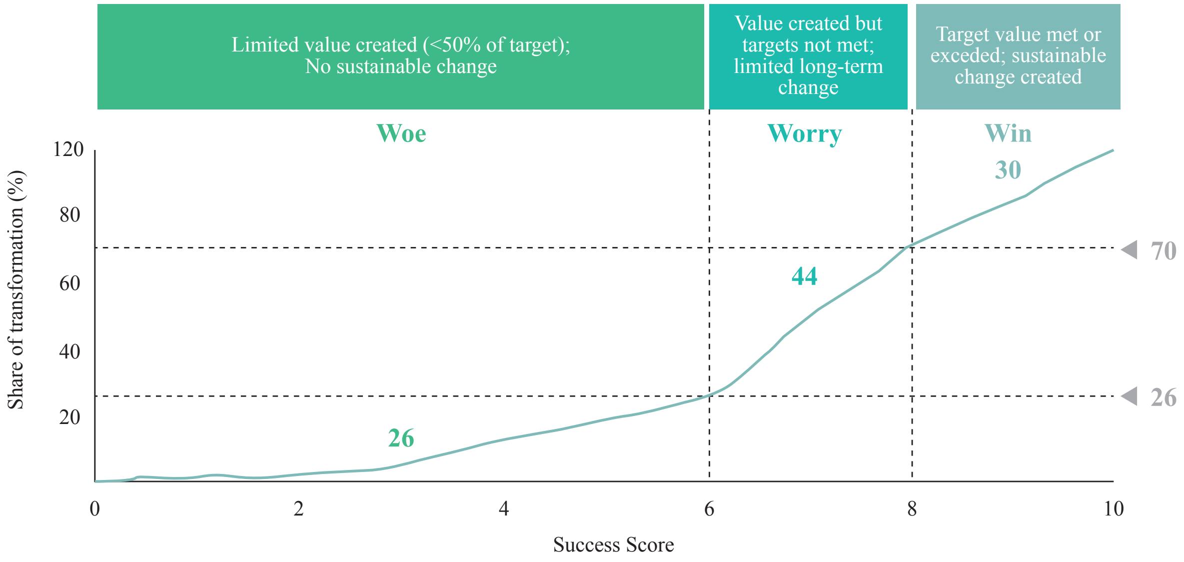


Table 2. Digital Transformation biggest failures.

Rank	Company	Cost in Million USD	Applied Methodology		
			OCM	OPR	Apps.
1	U.S. Air Force	$ 5.000	No	No	Yes
2	U.S. Navy	$ 1.870	No	No	Yes
3	National Grid	$ 1.300	No	No	Yes
4	Nike	$ 900	No	No	Yes
5	Revlon	No data	No	No	No
6	Miller Coors	$ 163	No	No	No
7	Hershey’s	$ 100	No	No	No
8	Waste Management	$ 500	No	No	No
9	Hewlett Packard	$ 160	No	No	Yes
10	Washington Community College	$ 13	No	No	Yes
11	Haribo	No data	No	No	Yes

is Avis Rent a Car. Avis implemented a variety of digital technologies to improve customer experience, such as online booking and mobile check-in. These technologies have allowed Avis to streamline their operations and increase efficiency, resulting in a better experience for its customers.

One of the main reasons for this success, is focusing on improving customer experience, not only implementing a technology (unlike Hertz, its main competitor). By implementing online booking and mobile check-in, Avis made it easier for customers to rent a car and get on the road. This increased convenience and efficiency led to a better customer experience, guaranteeing loyalty. Additionally, by allowing customers to book online and check-in through a mobile app, Avis was able to reduce the time they spend at the rental location, making the process more efficient and convenient.

Another example of a successful Digital Transformation is Amazon. The company has used digital technology to revolutionize the way in which people shop. From their early days as an online bookstore, Amazon has grown to become one of the largest retailers in the world. They have done this by leveraging digital technologies such as data analytics, machine learning and automation to optimize their operations and improve customer experience. They have also expanded into new areas like streaming content and grocery delivery using digital technologies.

This success can also be attributed to several factors. One of the main reasons is the company's focus on data-driven decision making and their use of data analytics and machine learning. Amazon has been able to use data to optimize their operations and improve its customer experience, which has helped them to stay ahead of the competition. Additionally, their use of automation and other technologies has helped to make shopping more convenient and efficient, which has attracted new customers and retained existing ones. Additionally, their strong logistics and delivery network allows them to provide fast and reliable delivery services which helps them stand out in the market. Furthermore, Amazon's willingness to invest in new areas like streaming content and grocery delivery, has helped them to diversify their revenue streams and become a leading player in multiple industries.

Culture, processes, and technology aspects were visibly intervened. Avis focused on improving its customer experience through technology, while Amazon focused on data-driven decision making and automation. Both companies were able to streamline their operations and improve efficiency, which led to a better customer experience and growth in the business. This shows that a successful digital transformation requires a combination of technology, process improvements and cultural changes to drive growth and improve customer engagement.

Naval Cluster

The region requires a high level of collaboration between the stakeholders of the naval sector. This is achieved through a real integration of public, private, and non-governmental organizations that add value to its development. For this, the creation of naval clusters within each of the Latin American countries is fundamental, and then, a great regional naval cluster should be created, which will contribute significantly to increasing continent's competitiveness.

For these clusters to be effective, it is imperative that the actors begin an adequate Digital Transformation process, optimizing the impact of the three components mentioned above. This will enable the exchange of real time, reliable and high value data, and information between actors, both within the cluster and among the national naval clusters. This is a great challenge, since it requires a total change of paradigms; but if done with the right tools and the right partners, it is possible to face this great challenge and obtain the expected benefits, positively impacting on the competitiveness of Latin American countries, and contributing to the continent's economic and social growth.

The organizations called to be part of this cluster should be: the country's Navy, customs and shipping agencies, storage and warehousing, maintenance, spare parts and accessories, engineering certification and inspection, maritime and naval consulting firms, shippers, port companies, exporters and importers, maritime terminals, nautical companies, fishing companies, shipyards and dockyards, transportation, tourism, and any other company that generates value within the maritime sector. The real benefit will be visible after a high level of collaboration and trust is achieved across the cluster, enabled by real-time, reliable, and quality data and information exchange, as a product of the Digital Transformation initiated by each one of the actors.

In the same way, it is possible to create large value chains, where many smaller companies are connected to work and generate value together, taking advantage of technology, which allows them to be more capable and even more competitive. In addition to creating more competent supply chains, business clusters can be used to create more efficient and effective communication and coordination between companies, accelerating the development of new and better operational business models.

How can a naval cluster be created?

The only way for each stakeholder, is to implement Digital Transformation to guarantee new and innovative technologies that allow to share information in real time and in a secure way, so that their activities can be coordinated and generate new value. Technologies such as blockchain, Big Data and analytics, the Internet of Things, and the cloud can be used to connect naval actors and create new business models. In the end, this will generate a high degree of trust within the cluster, being a necessary factor for the joint growth of the entire naval sector. A high level of trust between naval cluster companies is highly relevant because companies often must work together to win tenders or develop new technologies.

The cluster will also contribute to the development of new markets and to the expansion of existing ones, to the development of R&D in the maritime sector by stimulating the investment of companies on this front, as well as to the training and knowledge development of human capital in the sector.

However, the creation of a cluster is not only about connecting companies through technology. The important thing is how the companies use technology and how they can work together to create new value. In this way, each company will have to consider the following:

- How can we guarantee success in Digital Transformation?
- What technology should we use to connect to the cluster?
- What are the expected benefits from the implementation of this technology?
- Who are the other companies that we need to connect with?
- How can we work with the cluster to create new business models?
- What are the advantages of collaborating with the cluster and integrating digitally to create new business models?
- What are the risks of working with the cluster to create new business models?
- What are the risks we face when implementing new technologies?
- How do we ensure data security and data privacy when we share information with clusters?
- What are the policies, processes, and tools that we need to establish to be able to implement the technology successfully?
- How can we create a competitive advantage by collaborating with the cluster?

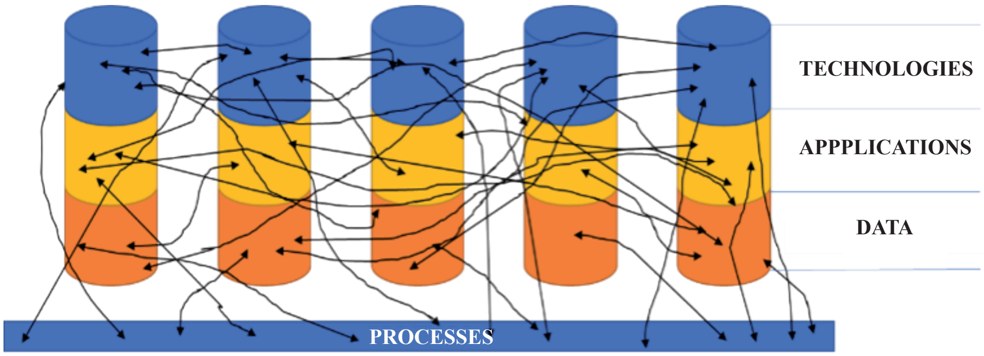
Making the naval cluster sustainable in an Industry 4.0 era

Every business has a unique way of gathering and using data. However, most business data is not accurate or timely enough to be useful for decision-making. Many businesses experience a disconnect between the data they need to make decisions and the data they have at hand. Companies often rely on a colossal mix of unrelated data sources to make decisions. In fact, most businesses rely on multiple data sources that often conflict with each other. The most common data sources are spreadsheets, databases, and Enterprise Resource Planning (ERP) systems.

While these systems may contain useful data, they often don't share a central information hub that can be used to make quick and informed decisions. Even worse, data may be siloed within these systems, each one with lots of discrete connections with others, similarly to a spaghetti diagram, making it difficult to get a holistic view of the business (see Fig. 3).

The lack of a centralized data environment can lead to several problems as incomplete data (when data is siloed in different systems, it's often incomplete. For example, it is common to have customer data in one system and sales data in another. But without a way to link the two, it is impossible to get a complete picture of a customer's buying habits), due to inconsistent data (data inconsistency can lead to errors and inaccuracies). For example, having two different databases with different field names for the same data, will make it difficult to combine the data and get accurate insights), out-of-date data (data that's not up-to-date) can lead to decision-making based on outdated information. For example, using last year's sales data to make decisions about this year's budget, will lead to make least informed

Fig. 3. Siloed systems, data and applications. (Ross, Beth, & Mocker, 2019).



decisions), and difficulty accessing data (if data is siloed in different systems), it can be difficult to access. For example, if pulling data is done from a database that are not connected to the internet, it will be difficult to get it in a timely manner).

The optimal and sustainable way to share information within the naval cluster is for each of its participants to implement two aspects of business management as a result of the Digital Transformation: The Operational Backbone and the Unified NameSpace (UNS).

An operational backbone is a coherent set of enterprise systems, data, and processes supporting a company's core operations to replace the messy legacy systems, processes, and data generated by siloed business units with standardized and shared systems, processes, and data *(Ross, Beth, & Mocker, 2019)*. It is the foundation of a company's Digital Transformation. It enables a company to move away from paper-based processes and manual data entry to automated, real-time processes and data, and enables companies to quickly respond to market changes and customer needs while maintaining high quality standards and compliance. It also reduces the cost of operations by eliminating duplicate and redundant systems and processes (see Fig. 4).

A UNS corresponds to a Platform As A Service (PAAS) solution that works as a central data repository, single source of information and context, or "Single Source Of Truth" (SSOT), where any device, application or user can publish and consume the required information according to their needs. This technology uses the publish/subscribe protocol (PubSub), which allows each node to register with the UNS and receive updates only on the specific topics of interest. Under this model, there will no longer be a disorganized set of discrete connections between independent silos observed in current architectures, but there will be a single explicit connection between the nodes and the UNS (see Fig. 5).

The main benefits of this model are: increased efficiency (by having a central data repository, devices and applications will no longer have to search through multiple silos for the information they need), reduced costs (by eliminating the need for duplicate data storage and the associated costs of maintaining and updating multiple copies), improved quality (with a central data repository, the quality of data improves as there will be only one version of the truth. This reduces errors and inconsistencies), increased agility (the UNS enables organizations to be more agile as they will be able to connect new devices and applications quickly and easily to the central repository and access the data they need), and improved security (organizations will be able to control data access and information stored in the central repository. This will help protect sensitive data and reduce the risk of data breaches).

As the naval clusters are created under this scheme within each country, trust must be generated to share data and information among them under the same pub/sus protocols and then, achieve the

Fig. 4. Operational backbone. (McMahon, 2021).

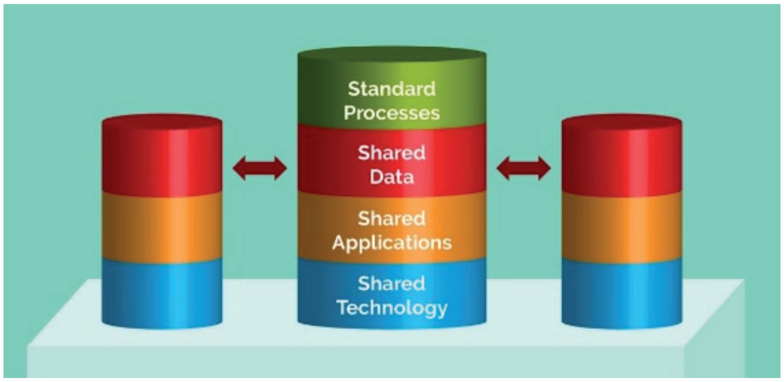


Fig. 5. Unified NameSpace architecture (Velandia, 2022).

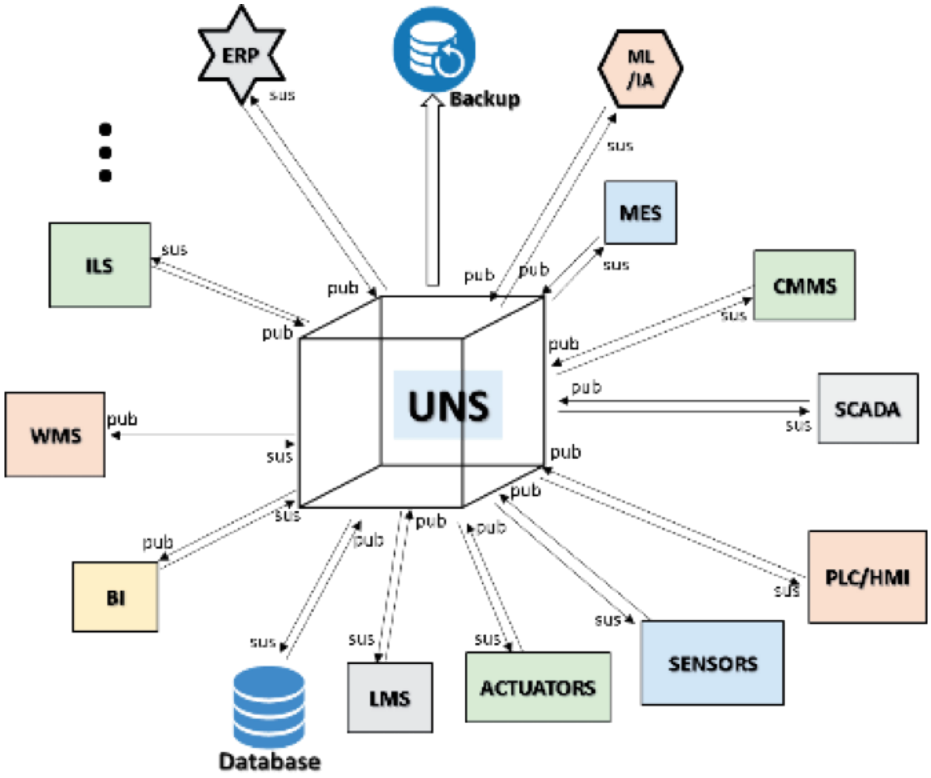
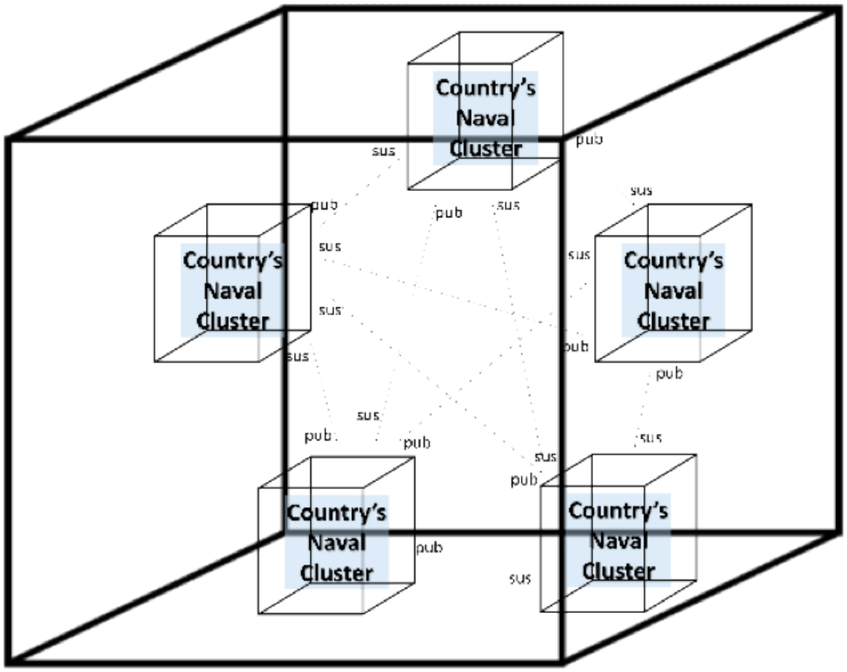


Fig. 6. Regional naval cluster architecture. Own elaboration.



creation of the great Latin American naval cluster (see Fig. 6). This will increase the competitiveness of the sector and, consequently, economic growth in the region.

It is important to consider that in this globalized world, there is no point in competing as separate countries, but rather to compete together. In this way, we build a whole that is stronger than the sum of its parts. The naval cluster is an initiative that shows the way to achieve it.

Conclusions

Digital Transformation of the naval sector in Latin America is a great opportunity to increase the competitiveness of the region. It is a transformation process that should be permanent and in constant evolution, and which requires the intervention of the three components: people, processes, and technology. This transformation will enable the creation of naval clusters within each country, which will contribute to the development of the sector and each country's economic growth.

The Digital Transformation of the naval sector should be based on the use of new technologies to connect the different actors and create new business models. Technologies such as blockchain, Big Data and analytics, the Internet of Things, and the use of the cloud can be used to connect naval actors and create new business models.

The main enablers to do so are the Unified NameSpace and operational backbone, which will allow users to share information in real time, and in a secure way, so that their activities can be coordinated and generate new value. This should be implemented by each of the companies that make up the naval sector, allowing the creation of a great Latin American naval cluster, which will contribute significantly to making the region more competitive.

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Numerical analysis of the dynamic behavior of a Floating Wind Platform in regular waves

Análisis numérico de la respuesta hidrodinámica de una plataforma eólica flotante en olas regulares

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Abstract

The goal of this study is to analyze the hydrodynamic behavior of a Floating Wind Platform (FOWT) under regular wave conditions. The analysis considers three degrees of freedom: Heave, Pitch and Surge. The study was carried out using a CFD (Computational Fluid Dynamics) tool, based on the Navier-Stokes equations and the Finite Volume Method, and results were compared against experimental tests performed at the Wave/Towing Tank at Universidad Austral de Chile (CEH-UACh). For this analysis, a generic scales semi-submersible platform was used under different regular wave conditions, obtaining wave height data at different points of the control volume and translation and rotation movements to obtain the RAO's (Response Amplitude Operator) in each of the considered degrees of freedom. For the CFD simulations, commercial software STAR CCM+ was used, where the flow characteristics were defined through Volume of Fluid (VOF) and their respective boundary conditions. Finally, the results of both methodologies were compared, showing an adequate degree of correlation between them.

Key words: Floating Wind Platform, RAO, CFD, Regular Wave, Potential Wave, Control Volume, DFBI.

Resumen

El objetivo de este estudio es el análisis del comportamiento hidrodinámico de una Plataforma Eólica Flotante (FOWT) bajo oleaje regular. El análisis considera tres grados de libertad: Heave, Pitch y Surge. El estudio se ha realizado mediante una herramienta CFD (Computational Fluid Dynamics), basada en las ecuaciones de Navier-Stokes y el Método de los Volúmenes Finitos, y los resultados se han comparado con ensayos experimentales realizados en el Canal de Ensayos Hidrodinámicos de la Universidad Austral de Chile (CEH-UACh). Para este análisis se utilizó una plataforma semi-sumergible genérica a escala bajo diferentes condiciones de oleaje regular, obteniendo datos de altura de ola en diferentes puntos del volumen de control y movimientos de traslación y rotación para obtener los RAO's (Response Amplitude Operator) en cada uno de los grados de libertad considerados. Para las simulaciones CFD se utiliza el software comercial STAR CCM+, donde las características del flujo se definen a través del Volumen de Fluido (VOF) y sus respectivas condiciones de contorno. Finalmente, se comparan los resultados de ambas metodologías, mostrando un adecuado grado de correlación entre ellas.

Palabras claves: Plataforma eólica flotante, RAO, CFD, Olas regulares, Volumen de Control, DFBI.

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Introduction

It is well known that energy demand has been growing year after year worldwide due, among other things, human overpopulation, and the development of new and increasingly complex technologies that require more energy. However, the supply of resources, especially conventional energy resources such as fossil fuels, is limited and their decrease is evident when projected for the coming decades. Therefore, it has become necessary to develop technologies and devices that produce energy based on natural, renewable and/or perennial resources, such as photovoltaic, wind, wave, and tidal energy, among others.

As far as renewable energies are concerned, in 2019 a maximum installed capacity of 2,537 GW was achieved worldwide [1], with the onshore wind and photovoltaic industries currently leading the way with capacities of 621 and 509.3 GW respectively [2,3]. However, the offshore wind power (FOWT) industry has undergone significant development in recent years, reaching an installed capacity of approximately 30 GW [4], of which 75% is installed in Europe and 23% in China, the main actors in the field [2].

The first FOWT project materialized at full scale is the HyWind Scotland floating wind farm, which has been operating since 2017 and has 5 spar turbines of 253 m height, projected to power 200,000 homes in the United Kingdom [5]. On the other hand, China recently installed its first deep water floating wind turbine called Fuyao, which has a total height of about 72 m equipped with a 6.2 MW anti-typhoon wind turbine. In Latin America, although there are no FOWTs installed, there are onshore wind farms. Countries such as Brazil, Chile and Uruguay stand out as world leaders in wind energy generation, accumulating a power of 8,715 MW, 933 MW and 845 MW respectively [6]. In addition, there is a great investment interest in FOWT in countries such as Colombia [8,9], Brazil [10,11] and Chile [12,13].

Chile has a rather peculiar scenario: in 2021, for the second consecutive year, it was the first country in Latin America to deplete its natural resources, exhausting them only in the month of May [13]. For this reason, the Chilean government and the Ministry of Energy have established through Law 20.698 that 20% of the country's energy must come from renewable sources by 2025 and 70% by 2050 [14]. Such a goal is not unattainable for Chile, the most attractive country for clean energy development followed by India, China, and Colombia [15]. In fact, some of the renewable sources in Chile are estimated to be able to generate between 27 and 103 kW/m for marine energy, 131 GW for fixed offshore wind turbines and 826 GW for floating wind turbines (see Fig. 1) [16].

Within this context, Chile has been increasing the production of renewable energies, reaching in 2021 to obtain 24% of photovoltaic energy and 17% of wind energy (among others) [17] (both with respect to the total energy produced) and, in 2022, for the first time the generation of renewable energies (27.5%) exceeds the generation of coal-based energy (26.5%)[18].

Even though Chile has the great potential and availability of resources described above, the development of FOWT is still in an (increasingly) prospective stage. Therefore, the environmental urgency, the limited availability of conventional energy resources and the usable offshore wind capacity in the country's ocean is what motivates this analysis of a FOWT, as well as the validation of a commercial CFD (Computational Fluid Dynamic) tool, a technique that has gained relevance in recent years due to the possibility of solving the fluid-structure interaction, including viscous effects and nonlinear phenomena.

Background

Floating Offshore Wind Turbines

A FOWT is a simple floating structure with a floater, which is connected to the seabed through the mooring lines with their respective anchoring system. It is coupled to a mast that at its upper point supports the rotor with (usually) 3 blades that rotate when receiving the wind speed, producing the energy (see Fig. 2).

Fig. 1. Offshore wind energy potential off the Chilean coast [16].

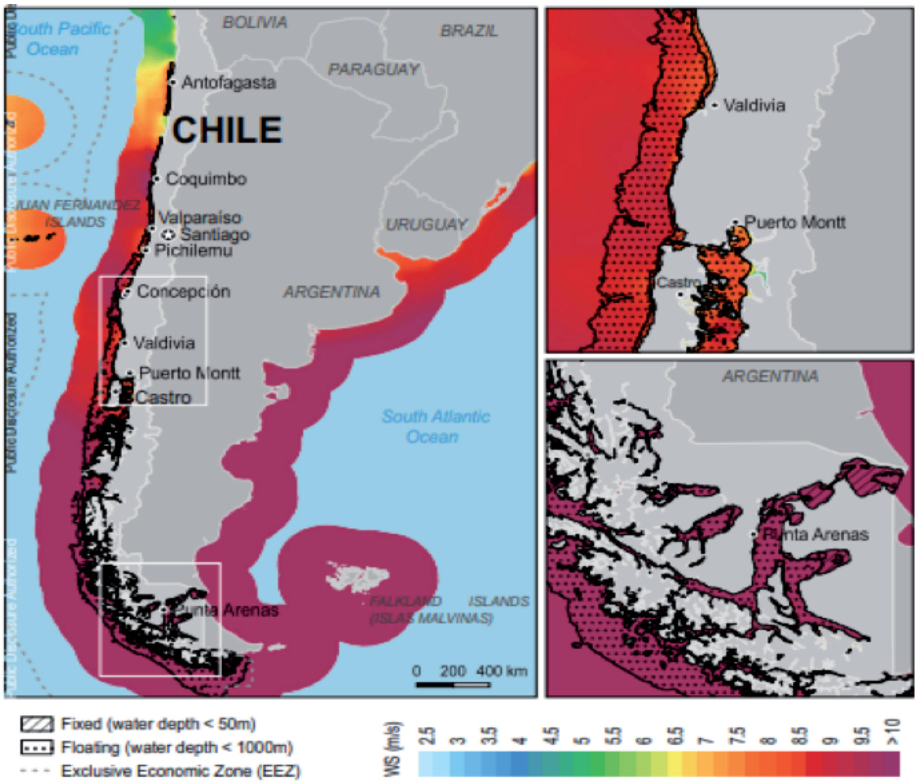
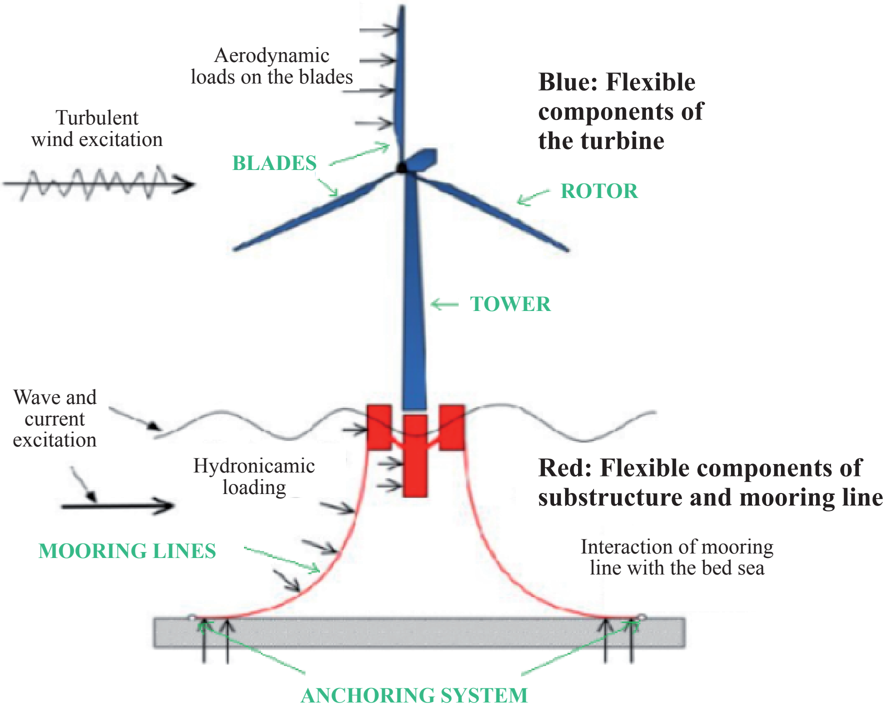


Fig. 2. Parts of a FOWT and the loads it receives [19].



As can be seen in Fig. 2, the wind that hits the turbine not only generates energy, but also, when interacting with the blades, induces aerodynamic loads that destabilize the turbine, causing it to lose its verticality. This, added to the hydrodynamic forces produced by the action of waves and currents, requires a carefully determined float-mooring-anchor configuration to counteract these loads and achieve system stability. In this sense, FOWTs can be classified into 3 main types (see Fig. 3):

Spar Buoy. This type of platform is characterized by having a deep draft, which can be stabilized by means of ballast at the bottom of its structure, causing the center of gravity to be below its center of buoyancy. An example of this type is the previously mentioned HyWind Scotland floating wind farm [20].

Semi-submersible. This system is characterized by having a larger buoyancy plane, causing the center of gravity to be above its center of buoyancy, and can be stabilized by buoyancy. Currently, one such full-scale platform is the WindFloat: developed by Principal Power, it already has an installed capacity of 75 MW [21].

Tension-Leg Platform (TLP). This type of platform is represented has a larger buoyancy/displacement ratio, being stabilized by its highly tensioned tendons. An example of this type of system is the PelaStar TM technology developed by Glosten [22].

Regular wave simulation [24]

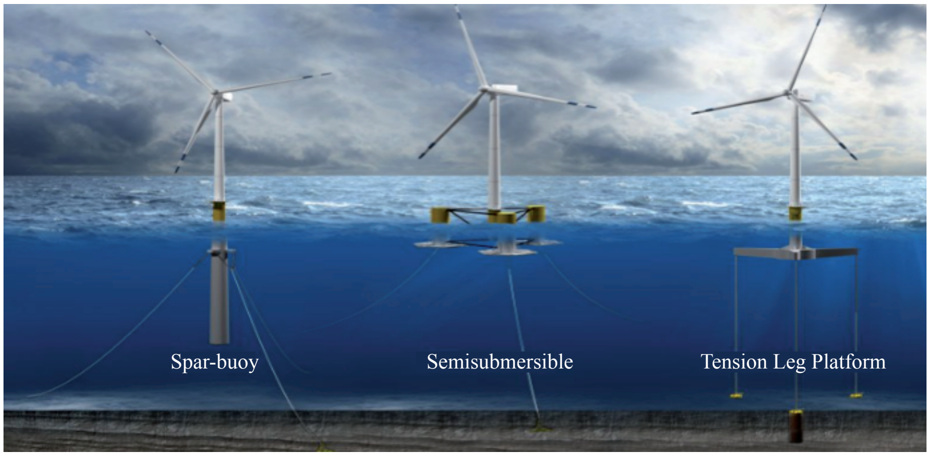
In CFD, the system of Navier-Stokes equations including the continuity equation in three-dimensional space is used to describe the behavior of incompressible Newtonian fluids.

$$\begin{gathered}\nabla\vec{U} = 0\\ \rho(\frac{D\vec{U}}{Dt} + (\vec{U}\bullet\nabla)\vec{U} = -\nabla \mathrm{p} + \rho\vec{g} + \mu\ \nabla^2\vec{U}\end{gathered} \qquad (1)$$

On the other hand, regular wave simulations are initialized from the linear theory. In this theory, to simplify the equation governing the flow, when characterizing the field in the control volume, it assumes that the flow complies with the Potential Flow Theory. That is: a flow without viscosity (no shear stresses), irrotational and incompressible (constant density) that meets the following boundary conditions:

- Continuity condition: constant mass within the control volume.
- Bottom condition: the vertical velocity of the flow at the bottom is zero.
- Dynamic free surface condition: the pressure at the free surface is equal to the atmospheric pressure.
- Kinetic free surface condition: the vertical velocity of a water particle on the flow surface is equal to the vertical velocity of the surface itself.

Fig. 3. FOWT types [23].



Applying the above, the flow behavior reduces to the Laplace (2) and Bernoulli (3) equations:

$$\nabla^2\phi = \frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2} = 0 \tag{2}$$

$$\rho\frac{\partial\phi}{\partial t} + p + \rho g z = p_0 \tag{3}$$

where ϕ is the flow velocity potential, ρ is the flow density, p is the flow pressure, p0 is the atmospheric pressure and z is the depth. By solving those equations for potential, it is possible to describe a regular wave with parameters such as period (T), wavelength (λ), water depth (h), height (H) and amplitude (ζ) (see Fig. 4).

Response Amplitude Operator (RAO)

When a floating body interacts with a regular wave train, the latter induces oscillatory motions in the body, which are produced by hydrodynamic forces including inertial, damping, restoring and external forces. These motions are defined, according to their type of oscillation (Surge, Sway, Heave, Roll, Pitch or Yaw) through the Response Amplitude Operator (RAO), which is a ratio between the maximum amplitude of the object motion (s_0) and the maximum amplitude of the incident regular wave (η_0).

$$RAO = \frac{s_0}{\eta_0} \tag{4}$$

Let s be the amplitude of motion at each degree of freedom, the equation defining the motion of the floating body interacting with a wave train is:

$$(m + A)\ddot{s} + B\dot{s} + Cz = F_{ext} \tag{5}$$

where m is the mass of the body, A is the added mass, B is the damping coefficient, C is the restoration coefficient and Fext is the external excitation force interacting with the body.

Numerical simulations

Problem set-up

A generic floating wind platform is simulated, at scale size, in the STAR CCM+ software. Fig. 5 shows the model designed by using Rhinoceros software where the 3 cylindrical floats, mooring points, deck, and the wind turbine mast can be distinguished. The main characteristics of the platform are shown in Table 1. The simulation reproduces the experimental tests carried out with this platform at the Wave/Towing Tank at Universidad Austral de Chile (CEH-UACh). The tank's main dimensions for LxBxT = 45x3x2 meters equipped with an irregular wave generator is capable of generating regular waves of up to 0.2 m in height.

Fig. 6 shows the configuration of the problem and the dimensions of the control volume. A control volume of dimensions LxBxD = 8x3x3 meters and a depth of 1.73 meters is considered. In addition, the position of each floater on the platform, of the

Fig. 4. Regular wave definitions [24].

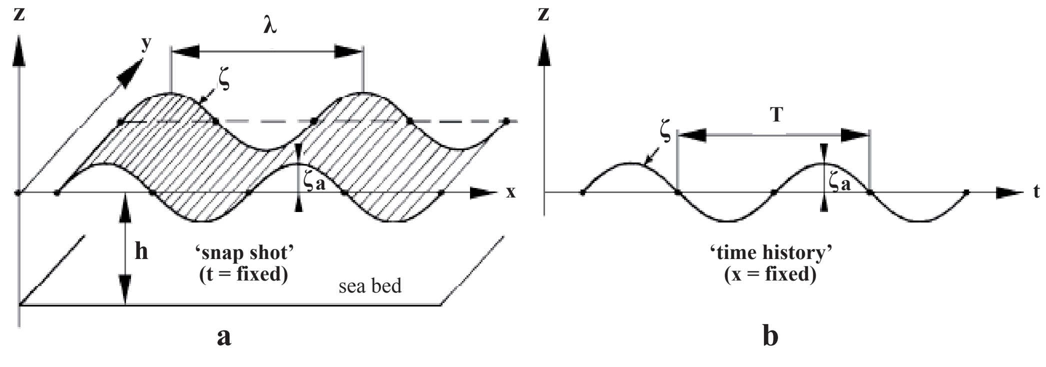


Table 1. Main characteristics of the platform.

Type	Scale	Displacement	Draft (T)	Length (L)	Beam (B)
Semi-submersible	87,2	23,573 [kg]	309 [mm]	630 [mm]	727 [mm]

Fig, 5. Rhinoceros modeling of the generic semi-submersible platform.

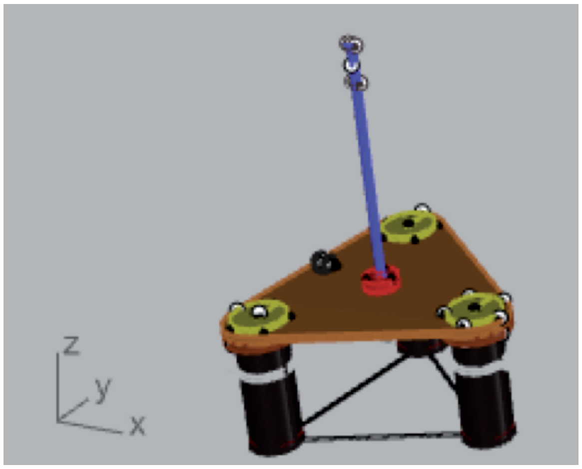


Table 2. Wave characteristics.

	λ/L	Frecuency [rad/s]	Period [s]	Height [mm]
Regular	5,5	4,22	1,49	121
	4,5	4,66	1,348	99
	4,0	4,95	1,27	88
	3,5	5,29	1,188	77

4 wave sensors and of the 3 mooring lines can be seen. It should be noted that for the numerical simulation, the wave generator (flow inlet) is defined to be 3 meters away from the longitudinal center of the platform. This configuration is subjected to 5 wave conditions shown in Table 2.

Boundary conditions

Fig. 7 shows the geometry previously designed in Rhinoceros and imported into STAR CCM+ as a "Surface Mesh" of maximum dimensions LxBxD = 8x1.5x3 meters where only half of the geometry is considered to reduce the calculation time thanks to the existing symmetry in the problem. Then, different regions of the geometry are delimited to make explicit the behavior of the different materials considered in the "Multiphase" model: water and air with their respective constant densities of 997.561 and 1.184 [kg/m3]. The multiphase model defines the interaction of two flows in contact and these, in turn, are coupled using the "Volume Fraction" method to calculate the vertical position of the free surface.

The defined regions are:

- Inlet Region: simulates the wave generator, so

Fig. 6. Configuration of the numerical set-up.

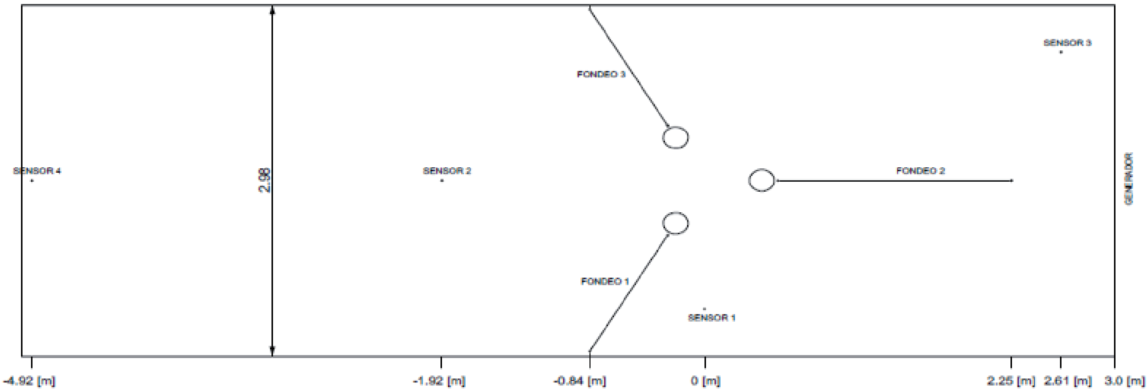
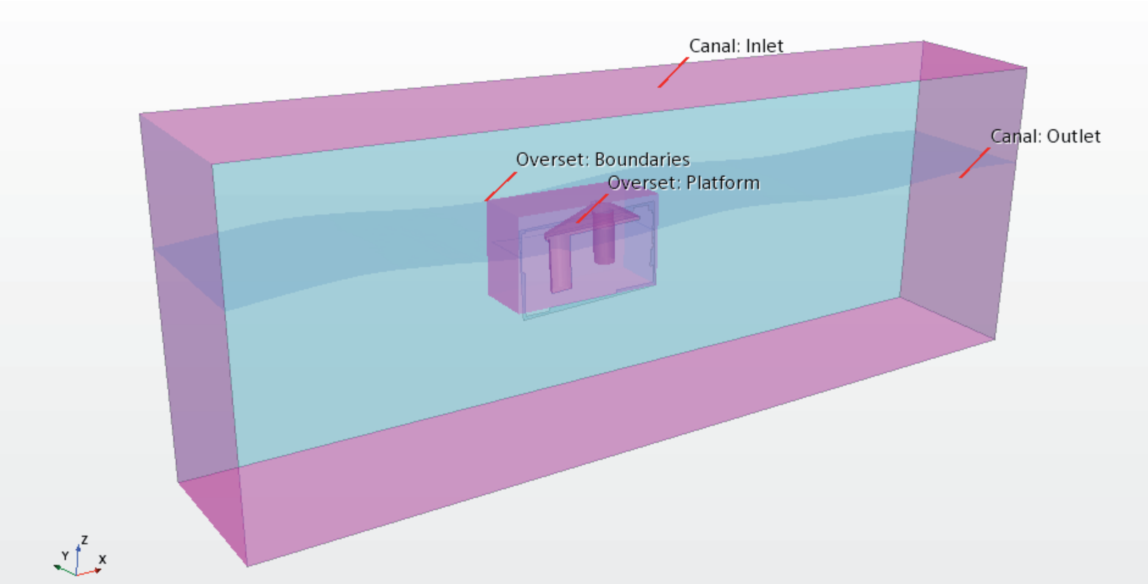


Fig. 7. Geometry and regions of the Control Volume in STAR CCM+.



the boundary condition governing this region is Velocity Inlet defining the inlet surface of the flow.

- Outlet region: Pressure Outlet type where the flow velocity is extrapolated through reconstruction gradients. The flow outlet is defined by means of a damping factor and distance.
- Side Region: simulates the side wall of the test channel and is of Symmetry Plane type, where no shear forces are considered.
- Symmetry Region: simulates the float plane of the problem. Symmetry Plane, where no shear forces are considered.
- Boundaries Region: refines the study in a control volume closer to the platform. Overset Mesh, useful to define a domain that moves within a larger one.
- Platform Region: simulates the platform walls. This is a Wall type where the platform surface is frictionless.

A few other models applied in the STAR CCM+ simulation are shown in Table 3.

Table 3. Boundary conditions for each surface and physical models.

Type	Model
Space	Three-dimensional
Time	Implicit Unsteady
Material	Multiphase
Multiphase	Volume Of Fluid (VOF)
Regimen	Turbulent
Turbulence model	K-Epsilon Turbulence
Flow	VOF Waves

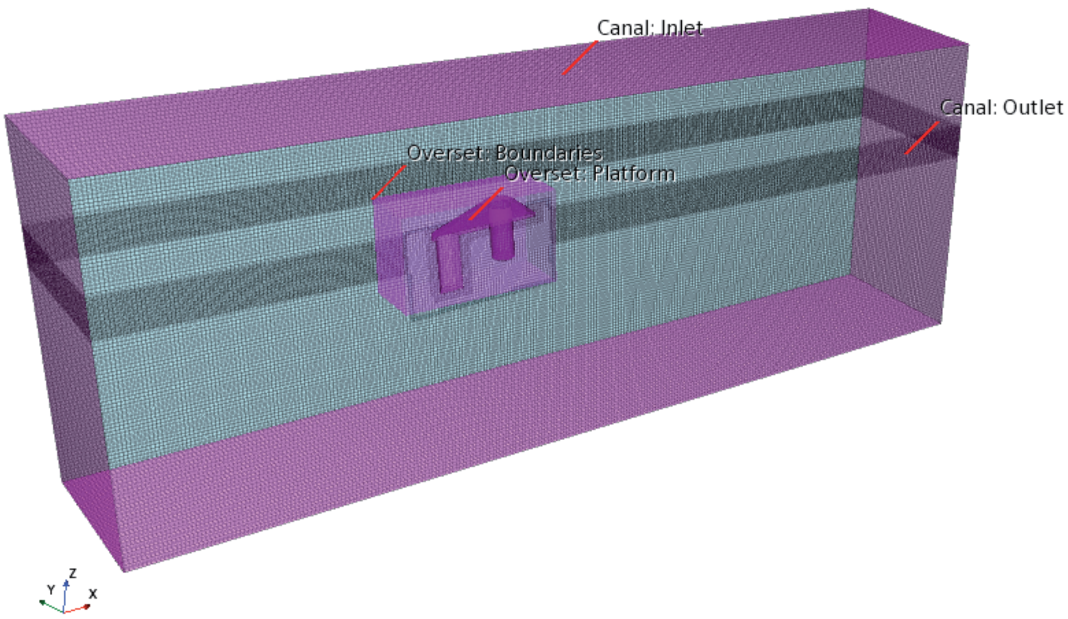
Mesh

Two mesh configurations are studied to solve the problem (see Fig. 8). The first mesh corresponds to the "Channel" control volume and the other to the "Overset" control volume. The Surface Meshers tool is used in both, which allows a re-meshing of the surface to be better adapted to the post-meshing of the volume with the Trimmed Cell Mesher tool. The "Channel" mesh contains a 50% refinement in a volumetric control around the free surface and the "Overset" mesh has a 50% surface refinement on the walls of the platform.

Dynamic Fluid Body Interaction (DFBI)

The DFBI Rotation and Translation module is defined to simulate the motion of the floating

Fig. 8. Three-dimensional meshing of the problem in STAR CCM.



body in interaction with the VoF (Volume of Fluid), solving the forces and moments acting on the body finding solutions to the equations of motion (5). For this, other bodies coupled to the platform that generate external forces on it must be defined. In this case the 3 mooring lines (see Fig. 6) with their respective positions and elastic properties are considered.

In this module the platform is specified as a 6-DOF Body (6 Degrees of Freedom Body) and its properties (mass, center of mass, moments of inertia, velocity) are identified. For this case, the motion of the body is restricted to 3 degrees of freedom: translation in the X-axis, translation in the Z-axis and rotation with respect to the Y-axis.

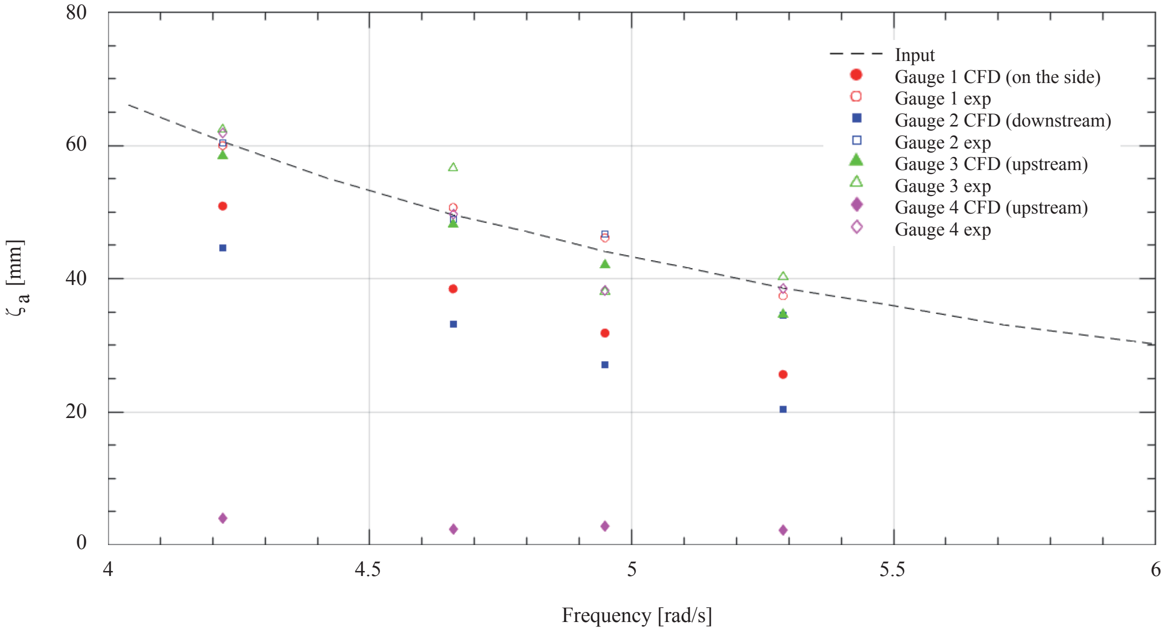
Results and discussion

The results of a first approach to the problem using CFD are shown below. Fig. 9 shows a plot of frequency [rad/s] vs maximum wave amplitude [mm], where the results of wave sensors 1, 2 and 3 are shown. The purpose of this plot is to compare the numerical and experimental results, both with respect to the theoretical input. It is important to mention that the results shown in Fig. 9 represent the wave tests without platform, to avoid interference of the model with the wave train, which would cause alterations in the measured data.

The image shows that the better correlated CFD results (compared to the theoretical input) are obtained for sensor 3, which seems adequate since, being at the flow inlet, there is no numerical diffusion along the spatial domain. Even so, it does differ by a percentage (4-10%) and this could be caused by a lack of precision in the parameters used for the meshing of the problem.

During this research, it became evident that one of the major problems of this type of simulations, which considers wave propagation, is the reflection in the outflow boundary condition. One of the solutions to this problem is to include an artificial dissipation zone in the downstream zone located far from the platform, so as not to interfere with its motion. In the results, when comparing the downstream sensors, it is clearly observed that the numerical results underestimate the wave amplitudes (sensor 4 CFD rhombus magenta), because this zone is governed by an artificial dissipation imposed on the output of

Fig. 9. Comparison between theoretical wave height, experimental sensor measurement and CFD sensor measurement, all without models.



the computational domain with the objective of decreasing or eliminating the wave reflection. The artificial dissipation factor is a function of the wavelength, and during the present work it was approximately 2 times the wavelength.

Comparing the amplitudes obtained by CFD as a function of frequency it is possible to observe that the influence of dissipation increases as the frequency increases, this flow behavior could also be because the mesh element size has an increase relative to the wave lengths, producing an additional numerical dissipation due to the convective propagation of the wave. It is worth mentioning that, although the simulations were performed with a higher order upwind scheme, inherently the convective physical processes discretized by this method produce numerical dissipation.

In this project, the appropriate value of the artificial dissipation parameter as a function of frequency is still under investigation.

As for the RAOs of the different motions, Figs. 10, 11 and 12 show plots of frequency [rad/s] vs Response Amplitude [-] of the Surge, Heave and Pitch motions, respectively. In this case the objective is to compare the results obtained numerically and experimentally.

From this, there is a greater deviation of the results for the natural frequency zone, *i.e.*, environment of ω=4.22 [rad⁄s] in the surge, heave, and pitch motions. However, a clear trend to the empirical results is identified, especially for the higher frequencies. From the plots it is evident that the amplitude of the motion of a floating body is proportional to the amplitude of the wave with which it interacts.

Particularly for the Pitch RAO, there is an outlier at ω=4.22 [rad⁄s], which error exceeds 200%. Since all simulations are identical and only VoF varies, a mesh refinement should be performed and control volume must be extended until a damping zone away from all study points is obtained, i.e., away even from sensor 4. This will improve not only the results of sensor 4 but will also affect the results of the platform motions, expecting more accurate values with respect to the experimental data.

Finally, from the RAO's it can be deduced that the platform does not present major problems when looking for hydrodynamic stability. This is due to the considerable size of the water plane area, as described in section 2.1.

Conclusion

In Chile, floating wind energy devices are in an early stage of research. Therefore, when testing new devices, it is important to obtain support of results through different methodologies (experimental and numerical) to ensure the accuracy of the solutions. In this context, a comparison of experimental results (CEH-UACh) versus CFD results of the

Fig. 10. Experimental and numerical surge RAO.

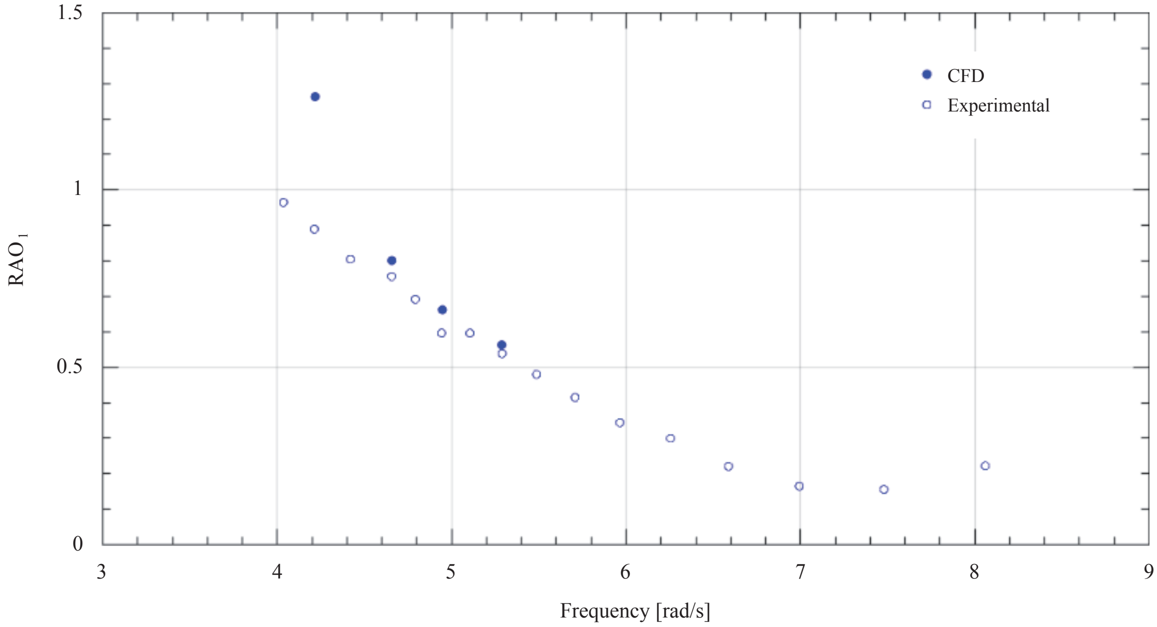


Fig. 11. Experimental and numerical heave RAO.

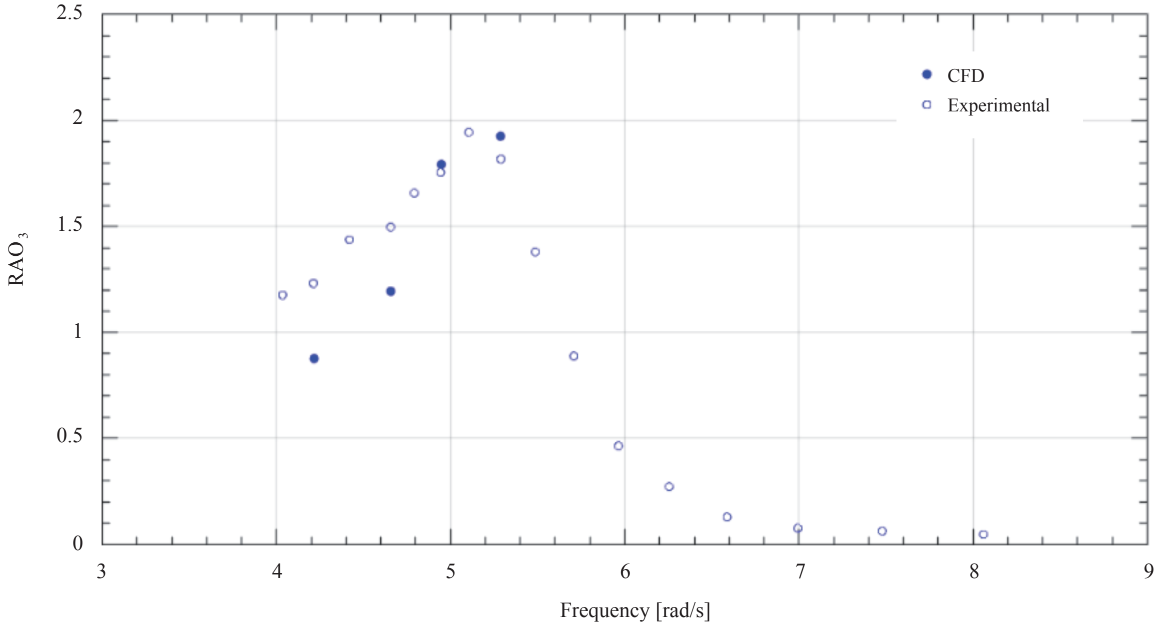
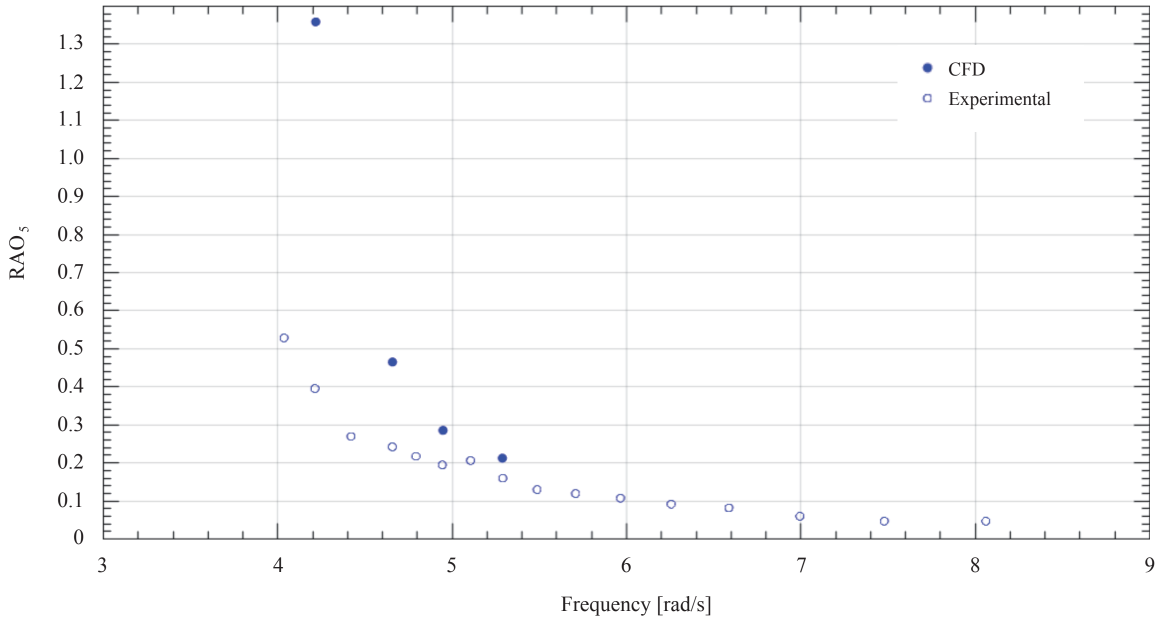


Fig. 12. Experimental and numerical pitch RAO.



same configuration for 4 different regular wave conditions is presented.

The data obtained comply graphically with the trend of the experimental results and the values are close. However, considering the error ranges in the results for both wave amplitude and RAO's (especially those for frequency ω=4.22 [rad/s] that are more than twice), the simulation does not turn out to be satisfactory. Therefore, as a future work, a parametric analysis of the mesh is proposed to improve the accuracy of the results and, thus, give way to the analysis in irregular waves, which is the final objective of the project.

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Development of an engineering tool to analyze spectral fatigue of floating structures by means of hydro-elastic coupling

Desarrollo de una herramienta de ingeniería para el análisis de fatiga espectral de estructuras flotantes mediante acoplamiento hidro-elástico

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Abstract

Navy vessels are relative long and slender ships which must withstand, during their extensive operational life, cyclic loads produced by the seaway. Fatigue is, hence, for those vessels a dominant parameter in the structural ship design and on their operation. Due to the arising complexity of fatigue assessments, an in-house tool is developed to perform automatized spectral fatigue analysis. Tool is called SEAFALT and stands for Long-Term Spectral Fatigue Analysis. This article described the calculation process of SEAFALT, together with results of a case of study. SEAFALT controls automatically the coupling process of the hydrodynamic load calculated on each sea scenario (via ANSYS AQWA), with its correspondent Finite-Element (FE) structural response (via ANSYS MAPDL). SEAFALT calculates: the expected long-term fatigue damage on each node of the FE-model and the minimum required FAT-class.

Key words: Fatigue, Spectral Analysis, Ship Structures, Stress RAO's, ANSYS, MAPDL, AQWA, Pyansys, Damage.

Resumen

Los buques militares son barcos relativamente largos y esbeltos que deben soportar, durante su extensa vida operativa, las cargas cíclicas producidas por el mar. La fatiga es, por lo tanto, para esos buques un parámetro dominante en el diseño estructural del buque y en su operación. Debido a la creciente complejidad de las evaluaciones de fatiga, se desarrolla una herramienta interna para realizar análisis de fatiga espectral automatizados. La herramienta se llama SEAFALT y significa Análisis de Fatiga Espectral a Largo Plazo. Este artículo describe el proceso de cálculo de SEAFALT, junto con los resultados de un caso de estudio. SEAFALT controla automáticamente el proceso de acoplamiento de la carga hidrodinámica calculada en cada escenario de mar (a través de ANSYS AQWA), con su correspondiente respuesta estructural de elementos finitos (FE) (a través de ANSYS MAPDL). SEAFALT calcula: el daño por fatiga esperado a largo plazo en cada nodo del modelo FE y la clase FAT mínima requerida.

Palabras claves: Fatiga, Análisis Espectral, Estructuras Navales, RAO's de tensión, ANSYS, MAPDL, AQWA, Pyansys, Damage.

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Motivation of the Study

Damen Naval (DN) is specialized on the design of naval ships and complex commercial vessels. Navy vessels are relative long and slender ships which must withstand, during their extensive operational life, cyclic loads produced by the seaway. This process triggers the formation of cracks at the structural welds which may reduce the capacity of the structure against further load scenarios. Fatigue is, hence, for those vessel types a dominant parameter in the structural ship design and on their operational usability.

During the last years, DN has been confronting more and more with new requirements for ship fatigue lifetime calculations. Such requirements must be implemented on the ship structural design, which in majority of the cases, due to the complexity of the calculations, requires a major engineering effort. Therefore, to deal efficiently with fatigue assessments on engineering phases approximations and simplifications must be accounted, according to International Recognized Standards.

Nowadays, thanks to the growth of computational power, such approximations can be even implemented in software and/or tools throughout which (even more) complex calculations can be performed, allowing engineers to predict the behavior of the ship's structure on a (more) reliable way.

Hence, to assist structural analysts along the engineering phases on fatigue assessment, it was developed SEAFALT, a software-tool (script) able to perform automated spectral fatigue assessments to establish the coupling between the pressure distribution (calculated on each evaluated sea scenario) with its consequent Finite-Element (FE) structural response (Luna Garcia-Valenzuela, 2019). The used seakeeping tool is ANSYS AQWA, while the chosen FE-software is ANSYS MAPDL (Mechanical APDL). The complete automated process is controlled by a Python-script that was called SEAFALT (Long-Term Spectral Fatigue Analysis).

Fatigue Assessment in Floating Structures

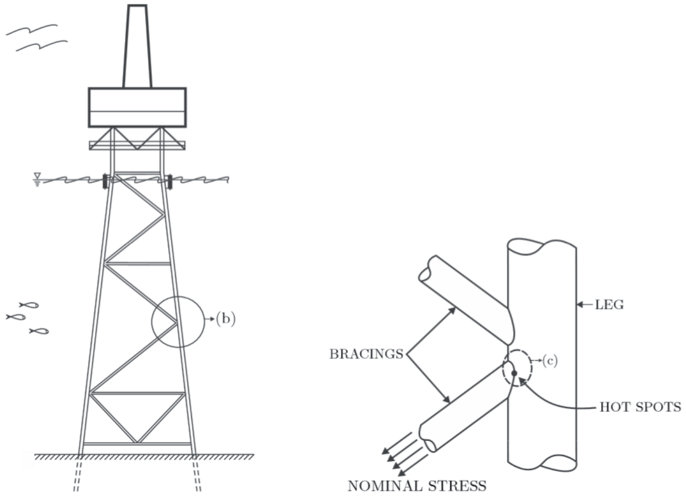
Fatigue occurs as a result of stress or strain reversals, known as cycles, in the time history. It therefore sets the response of the structure or component as the starting point for any fatigue analysis.

Fatigue damage has been traditionally determined from time signals of loading, usually in the form of stress or strain. Such methodology is suitable for periodic loading, nevertheless requires large time records to accurately describe random loading processes. The offshore oil industry faced this problem in the early 1980's, since the offshore platforms are large and complex structures subjected to random wind and wave loading. The analysis becomes complicated because the imposed loads are random and excite dynamically the structure, proving this way the transient dynamic analysis in the time domain as unfeasible (Halfpenny, 1999). On the other hand, for many FE analyses (especially when modelling dynamic resonance), a compact frequency-domain-based fatigue calculation can be utilized alternatively, where the random loading and response are categorized using Power Spectral Density (PSD) functions, and the dynamic structure is modelled as a linear transfer function. In fact, it is often beneficial to carry out a rapid frequency response (transfer function) analysis instead of a computationally intensive transient dynamic analysis in the time domain *(Halfpenny, 1999)*.

Therefore, a FE analysis based in hydrodynamic frequency-domain loads can simplify the problem severally. Such calculation can then be carried out to determine the transfer function between wave height and stress in the structure. Following this, the PSD of wave height is simply multiplied by the transfer function to obtain the PSD of stress response of the structure.

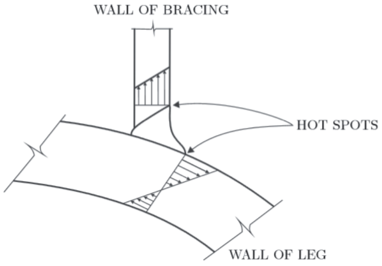
Fatigue in floating structures is mostly driven by moderate sea states, for which linear analyses often suffice *(Naess & Moan, 2013)*. Therefore frequency-domain analyses of wave-induced response for various sea states can then be efficiently carried out

Fig. 1. Fatigue loading in terms of stress ranges. (Naess & Moan, 2013).



(a) Global structure

(b) Hot spots at brace joints



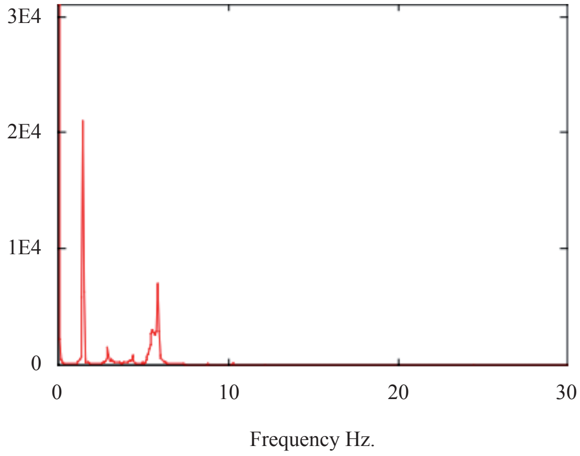
(c) Hot spot stress details

with relatively coarse FE models of the structure, allowing the calculation to be speeded-up in comparison with the time-domain computation. Hence, the calculation of the relevant fatigue loads involves a global analysis and their effects in terms of member forces, and a local analysis to determine the hot spot stress, as illustrated on Fig. 1.

Fatigue Assessment in the Frequency Domain

The frequency domain is another domain in which to view a time signal but losing the phase information, but now the x-axis represents frequency instead of time. In practice, frequency domain is usually represented as a 'Power Spectral Density (PSD)' plot, which consists on a normalized density plot that describes the mean square amplitude of each sinusoidal wave with respect to its frequency. Fig. 2 shows a typical PSD plot, where the mean square amplitude of a constituent sinusoidal wave can be determined by measuring the area under the PSD over the desired frequency range.

Fig, 2. Typical PSD of a random time history.
(Halfpenny, 1999).



The time signal regeneration is performed throughout an 'Inverse Fourier Transformation' on the complex vector of frequency domain results, however, when the starting point is a PSD this method is inappropriate due to the lack of wave phase information of such PSD. However, for certain time stories such as the 'ergodic stationary Gaussian random processes', assumptions about the original phase content can be made for the time series to be regenerated. For fatigue assessments in the frequency domain 'ergodic stationary Gaussian and random' processes are assumed.

For every occurring sea state, the stress response spectrum (or spectral density function) can be easily obtained within the frequency domain approach. For a narrow-banded Gaussian process, every peak is coincident with a cycle and, consequently, the stress amplitudes are Rayleigh-distributed. Now if the Stress-Cycles curve (SN) is formulated in terms of: *N* the number of cycles to failure for stress range *S*, *m* the negative inverse slope of the SN curve and *K - factor* the slope of the curve which governs the relationship between the stress level and the number of cycles, as:

$$N = K\,S^{-m} \tag{1}$$

then the expected fatigue damage *D* is:

$$D = \int_0^\infty \frac{N_T}{K} s^m f_s(s)\,ds = \frac{N_T}{K} E\left[S^m\right] = \frac{N_T}{K}\overline{S}^m \tag{2}$$

where N_T is the total number of stress cycles, *S* is defined by $\overline{S} = \left(E\left[S^m\right]\right)^{1/m}$, and *E[]* denotes the expectation value operator. *S* may be interpreted as a constant amplitude loading that is equivalent to the random loading under the assumption of a single slope SN curve.

If the described Gaussian process has zero mean and variance σ_X^2, the stress range follows a short term Rayleigh distribution, and can be determined from the stress amplitude distribution f_A:

$$f_s(s) = f_A\left(\frac{s}{2}\right)\frac{da}{ds} = \frac{s}{4\sigma_X^2}\exp\left\{-\frac{s^2}{8\sigma_X^2}\right\} \tag{3}$$

The short-term fatigue damage can be therefore expressed as:

$$D = \frac{N_T}{K}E\left[S^m\right] = \frac{N_T}{4\sigma_X^2 K}\int_0^\infty s^{m+1}\exp\left\{-\frac{s^2}{8\sigma_X^2}\right\} \tag{4}$$

$$ds = \frac{N_T}{K}\left(2\sqrt{2}\sigma_X\right)^m \Gamma\left(\frac{m}{2}+1\right)$$

with *Γ(;)* the Euler gamma function.

To perform the long-term fatigue assessment, all or at least the most contributing sea states must be accounted. Long-term fatigue damage can be expressed, in terms of Rayleigh short-term distributed stress ranges, as indicated below *(DNVGL, 2015)*:

$$D = \frac{N_D}{K_2}\Gamma\left(1+\frac{m}{2}\right)\cdot\sum_{j=1}^{n_{LC}}\alpha_j \sum_{i=1,\ \ n=1}^{\substack{all\ seastates\\ all\ headings}} \tag{5}$$

$$r_{inj}\left(2\sqrt{2m_{0_{inj}}}\right)^m$$

where r_{inj} is the relative number of stress cycles in short term condition *i*, *n* for loading condition *j*, a_j is the probability of loading condition *j*, n_{LC} is the total number of loading conditions and m_{0inj} is the zero spectral moment of stress response process in short term condition *i*, *n* and loading condition *j*.

On the other hand, if bi-linear SN curves are to be used, according to (DNVGL, 2015) they can be expressed logarithmically as:

$$logN = logK_2 - mlog\,S \tag{6}$$

with:

$$logK_2 = logK_1 - 2\delta \tag{7}$$

where *δ* is the standard deviation of *logN*, and K_1, K_2 are the constant of mean SN curve (50% probability of survival) and the constant of design SN curve (97.5% probability of survival), respectively. With this, Eq.5 can be expressed as:

$$D = N_D \sum_{i=1,\ j=1}^{\substack{all\ seastates\\ all\ headings}} r_{ij} \left(\frac{\left(2\sqrt{2m_{0_{ij}}}\right)^{m}}{K_2} \Gamma\left(1+\frac{m}{2};\left(\frac{\Delta\sigma_q}{2\sqrt{2m_{0_{ij}}}}\right)^{2}\right) + \frac{\left(2\sqrt{2m_{0_{ij}}}\right)^{m+\Delta m}}{K_3} \gamma\left(1+\frac{m+\Delta m}{2};\left(\frac{\Delta\sigma_q}{2\sqrt{2m_{0_{ij}}}}\right)^{2}\right)\right) \tag{8}$$

with $\Delta\sigma_q$ the stress range in SN curve, where the change of slope occurs (knuckle), K_2, m are the SN fatigue parameters for N<10^7 cycles, K_2= $m + \Delta m$ are the SN fatigue parameters for N>10^7 cycles. SN curves are generally designated by DNVGL with FAT X, where X is the stress range at $2{\cdot}10^6$ cycles.

For floating structures, the (Morison´s) drag force implies super harmonic load components that are normally an order of magnitude smaller than the wave frequency component. However, if the higher-order harmonic load components coincide with the natural frequency, significant amplification occurs, making the high-frequency load effect significant. Slamming and sloshing in tanks can similarly contribute in fatigue loading. This means that the stress history comprises a high- and low-frequency response process and therefore becomes wide banded *(Naess & Moan, 2013)*. As the shape and the variance of the stress-range-response spectrum has a significant effect on the prediction of the induced fatigue damage, a correction factor can be used to consider the band-wideness of the process. Benasciutti and Tovo (2005) proposed an empirical formula of wide-band fatigue damage by using a linear combination of the narrow-band and range counting results that can be obtained by closed-form expressions in the frequency domain:

$$D_{BT} = \left(b + (1-b)\alpha_2^{m-1}\right) D_{NB} = f_{BT}\, D_{NB} \tag{9}$$

where m is the material parameter of the SN curve, D_{NB} is the fatigue damage under the narrow band assumption, f_{BT} is the Benasciutti-Tovo correction factor, and the coefficient b is empirically obtained based on extensive numerical simulations. This formula has been shown to give accurate results in an independent study *(Gao & Moan, 2008)*, and therefore can be applied with good accuracy to all types of wide and narrow band Gaussian processes *(Naess & Moan, 2013)*.

SEAFALT Methodology

Introduction

SEAFALT is meant to be used during a basic engineering phase allowing the user to compute the minimum required characteristics of structural details, to ensure the withstanding of the variety of sea loading cycles during the vessel operation. It could be also used during detail engineering phases to determine the lifetime of the structure, once it has been designed. Fig. 3 shows the logo of SEAFALT.

Fig, 3. SEAFALT Logo.

The development of this tool, was driven by the following key needs:

- Seakeeping Analysis of the vessel, depending on the sea conditions where the vessel has already sailed in or where the vessel will potentially sail.
- Apply loads from Seakeeping Analysis to a (detailed) FE model of the structure.
- Perform Spectral Fatigue Analysis to find the structural elements where crack growth is likely to occur, and to select the minimum required welding details to avoid fatigue

cracking. Also calculate the long-term fatigue damage, provided the FAT-class of the detail.
- Create an exporting tool with which results can be implemented in the FEM model (ANSYS MAPDL), so that the user can check interactively the results.

General Scheme of the Process

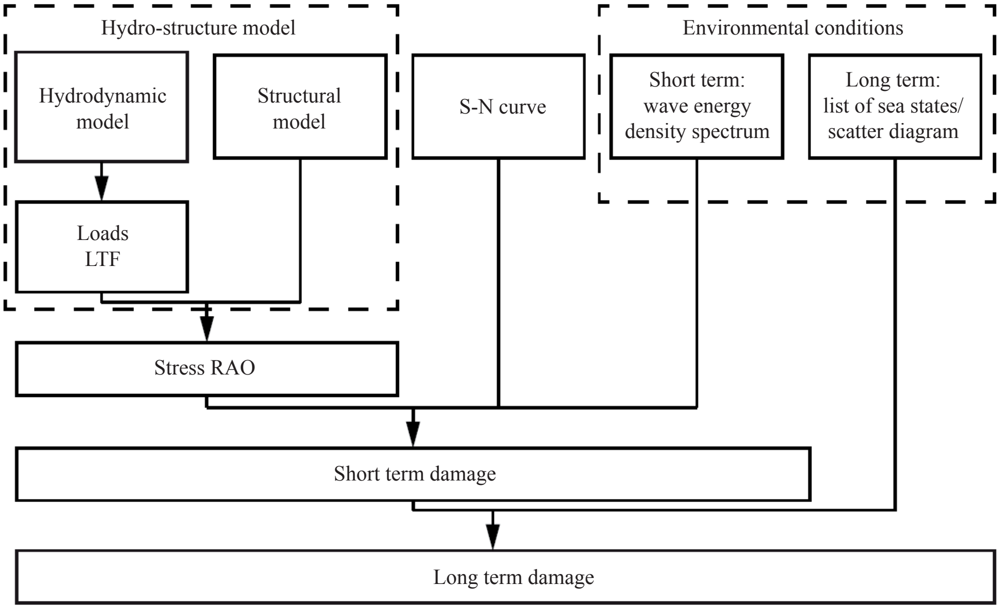
Spectral fatigue analysis is fast, in a lot of cases accurate and, more important, a closed form method *(Zurkinden, A. et al., 2014)*. The aim of the spectral analysis is the determination of the long-term fatigue damage with a direct calculation approach that takes into account the different environmental conditions encountered by the floating structure. So, the core of the analysis is the determination of a Response Amplitude Operator (RAO) between the waves and the stress, for each operating condition. This RAO is obtained by the combination of a frequency-domain-based hydrodynamic model with a linear structural model. Although different hydro-structure coupling schemes are available, it was chosen the process-flow proposed by Bureau-Veritas *(Veritas, 2016)*, as shown in Fig. 4. It is widely used and is based on transferring the wave loads from the hydrodynamic model on a three-dimensional FE model for each wave heading, frequency and speed. Using the stress RAO, a stress response spectrum can be determined for each wave energy density spectrum. Providing short-term wave statistics and considering the fatigue capacity given by the SN curve, a short-term damage is calculated. Finally, the long-term fatigue damage is computed as the summation of short-term damages taking the probability of occurrence of each sea state into account.

This method allows for short computational times as well as a for a direct spectral analysis of the accumulated damage in a given structural detail. On the other hand, the method does not allow for the integration of non-linear effects such as the non-linear hydrostatic force or the non-linear drag forces. To account for such effects a time domain simulation remains necessary. However, as fatigue in floating structures is mostly driven by moderate sea states, a linear analysis often suffice *(Naess & Moan, 2013)*.

Calculation Process

The developed tool controls the solution, pre- and post-processing of the results from the different solvers or modules used to carry out the spectral fatigue analysis of the structure: ANSYS-AQWA and ANSYS-MAPDL. SEAFALT therefore acts

Fig. 4. Spectral fatigue analysis flowchart (Veritas, 2016).



as the “glue” of the complex data management of this process: handling inputs, moving, processing, sending and storing data from the different solvers involved. The calculation flow is then composed by four subprocesses:

Hydrodynamic Loading Data Base

Determines the wave excitation transfer function for different incident wave angles, wave frequencies and ship speed. For the given operational profile, the wave induced load is obtained at a given location per unit wave amplitude, by computing the pressures and rigid body motions of the center of gravity of the structure throughout a linear-diffraction analysis. Response X of a structure subjected to wave loading is therefore calculated by solving the equation of motion in the frequency domain for unit wave amplitude.

FEM Calculation

In this step, the stress transfer functions (STF) or stress Response Amplitude Operator (RAO) are determined by applying the calculated hydrodynamic loads on a 3D FEM structural model. The STF expresses the relationship between the stress at the given structural location and a unit wave amplitude. The procedure is based on computing the linear structural response of the imported hydrodynamic load scenarios. This is done by means of the integration of the pressure values within panels, allowing for the calculation and transfer of discretized loading values inside the same panel, to the detailed FEM mesh. Hence, for each wave frequency ω, heading θ and ship speed v, the hydrodynamic load case scenario is solved via a FEM static structural simulation, and from nodal stress results the stress transfer function $H_{\Delta\sigma}(\omega|\theta|v)$ is obtained. Fig. 5 summarizes graphically the intermediate results of the process to calculate the stress range response. To compute fatigue damage, the effective stress range is computed at each shell-element node of the structural model *(DNVGL, 2015)*, since accounts for the situation with fatigue cracking along a weld toe, but also when principal stress direction is more parallel to it.

Once all load cases are solved, the STF data base is consolidated, from which short-term stresses can be calculated spectrally for different irregular seaway scenarios described in the operational profile.

Postprocessor

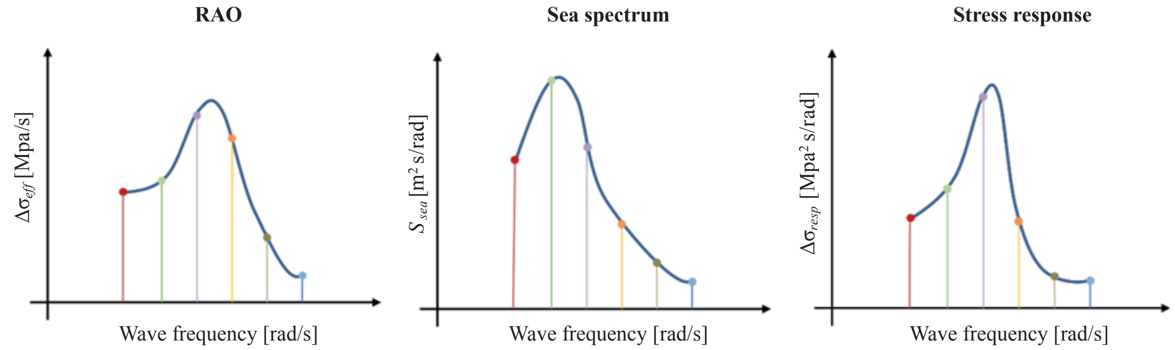
This module calculates the long-term fatigue damage or the minimum required FAT class, at a certain evaluated node of the structural model. To do that, first the short-term stress (range) response spectrum $S_{\Delta\sigma}$ is calculated for sea states described in the operational profile, by accounting for sea spectrum $S_F(\omega|\theta)$ and the respective STF, previously determined.

$$S_{\Delta\sigma}(\omega|\theta|v) = \left|H_{\Delta\sigma}(\omega|\theta|v)\right|^2 \cdot S_F(\omega|\theta) \qquad (10)$$

Then, the spectral moments are calculated by means of the following expression:

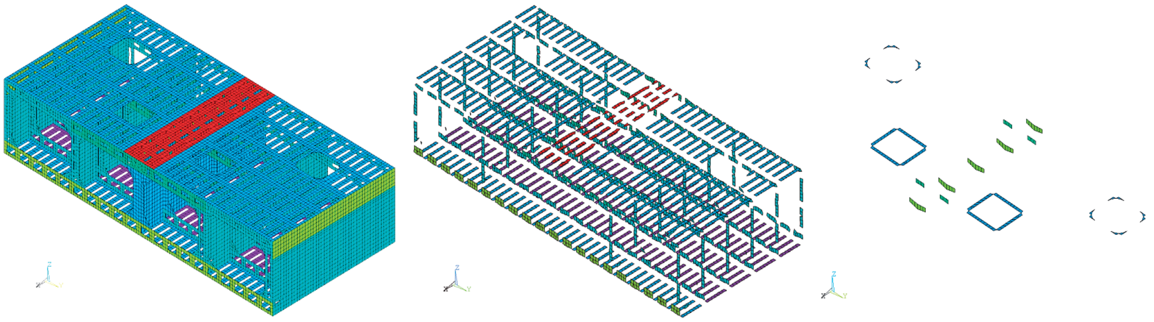
$$m_j = \int_0^\infty \omega^j \, \Delta\sigma_{resp}(\omega)\, d\omega\,, \qquad j = 0, 1, 2,\ldots \qquad (11)$$

Fig. 5. Curves used on the computation of the stress range response: STF (RAO), Sea Spectrum and Stress Response (from left to right).



Now Benasciutti-Tovo correction factor (Eq. 9) is determined. And finally, when all the sea conditions are evaluated (repeating the above described process), the long-term fatigue damage equation (Eq. 8) is solved. To do that, an automatic subroutine classifies the nodes on evaluation in: base-material, welds and free-plate edge (see Fig. 6), for which one reference FAT-class (SN Curve) is assigned according to DNVGL (2015).

Fig. 6. Nodal and element classification: (from left to right) elements attached to weld nodes, base material nodes, and free-plate edge nodes.



Solving Eq. 8 can be done in two different manners, depending on the type of fatigue assessment:

- Minimum required FAT-class (Fig. 7), in which the long-term fatigue damage is set to 1 (maximum allowed according to *(DNVGL, 2015)*), and iteratively the minimum required FAT-class is calculated. Such value is used within engineering phases to check if structural details have FAT-classes above the minimum required.
- Long-term damage (Fig. 8), in which the actual FAT-class of the evaluated structural detailed is known, respective SN-curve parameters are introduced and the equation is solved straight forward.

Fig. 7. Example of SEAFALT Results in APDL: min. required FAT-class assessment. By means of a color-scale, the minimum required FAT is indicated.

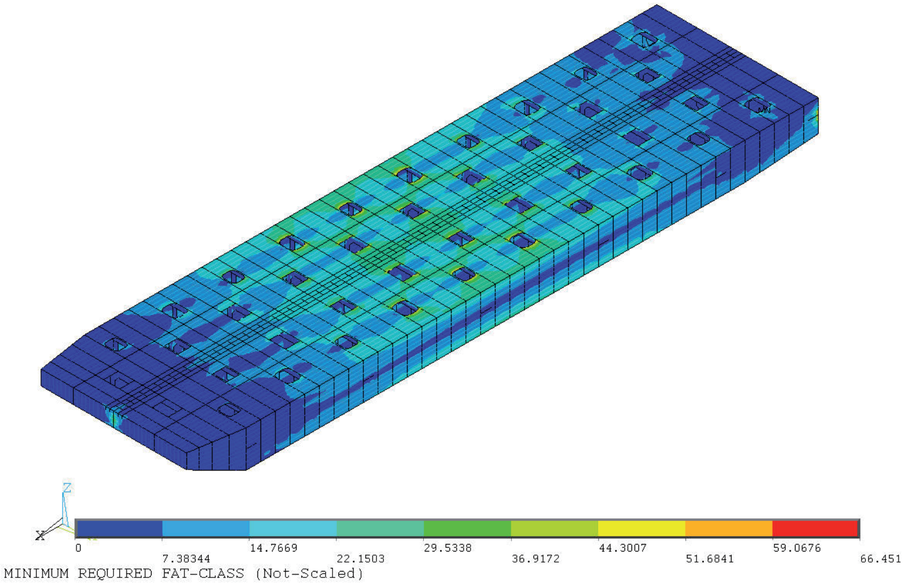
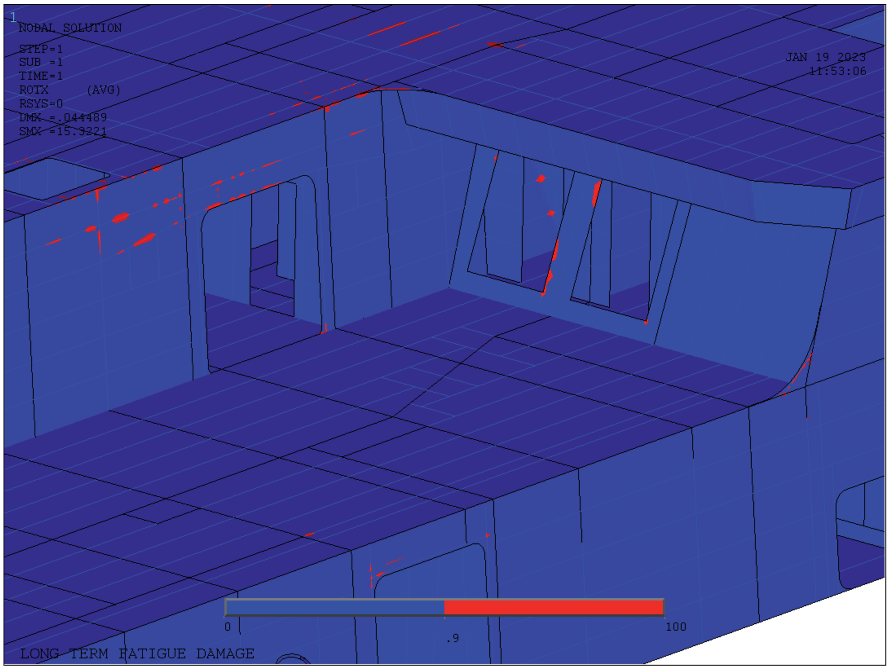


Fig. 8. Example of SEAFALT Results in APDL: long-term damage calculation. In red, details where damage is expected to reach 1 at the end of the lifetime, with current design. In blue, elements for which long-term damage is below 1.



Case of Study

The developed calculation process was tested with a full scale detailed (FE) model of a pontoon-barge designed and built by DAMEN (Fig. 9).

Fig, 9. Pontoon vessel used as study case. (Damen, 2019).

The method to assess global hull-girder structural response is applicable to various hull-shapes, including military-ships. On the other hand, the curved shape of the hull could trigger the buoyancy forces to vary non-linearly with the wave height, inducing weak-nonlinear seakeeping behavior. As the proposed methodology is based on linear hydrodynamics, this non-linear phenomena might not be possible to be directly captured by the seakeeping tool. However as stated in III-C a linear hydrodynamic analysis often suffice for fatigue loading assessments, due to the fact that the expected hydrodynamic response at the recommended rule-based probability of exceedance shows normally a linear trend *(DNVGL, 2015)*. Hence, and for simplicity reasons the above-mentioned barge was chosen as a case of study.

The pontoon is a (relatively simple) barge, with vertical bulkheads and shell, a block coefficient nearby the unit, for which fatigue issues are not expected to appear during its lifetime considering the mild operational profile. The simplicity of the geometrical model to be used in the calculation was hence considered. Main dimensions and hydrostatics of the pontoon model can be summarized in Table 1.

Modelling

In this section the two models used on the computation are described: hydrodynamic and FE model.

Table 1. Main Particulars and Hydrostatics of the Pontoon model.

Parameter	Value
Length	85 m
Breadth	22 m
Height	5 m
Draft Amidships	2.248 m
Center of Gravity from intersection Aft Perpendicular-Base Line (Global Coord System origin)	43.065 m, 0 m, 2.635 m
Longitudinal Center of Buoyancy from origin GCS (LCB)	43.076 m
Longitudinal Center of Floation from origin GCS (LCF)	41.863 m
Trim angle (+ve by stern)	-0.421 deg
Heel	0 deg
Displacement	3999 T

Hydrodynamic Model

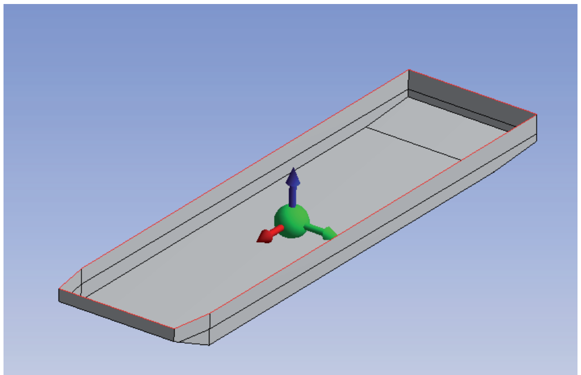
The model used during hydrodynamic simulations consists of a 3D outer-hull-plating model (Fig. 10). Mass and inertia properties are represented through a single mass point with the following characteristics:

Table 2. Mass point properties.

Parameter	Value
Point Mass Location (CoG)	43.065 m, 0 m, -0.316 m
Mass (Displacement)	3999 T
Radii of gyration: Kxx	46.573 m
Radii of gyration: Kyy	25.546 m
Radii of gyration: Kzz	26.412 m

Reader can note that the vertical coordinate of the CoG stated at Table 1 and Table 2 differ from each other. This occurs due to the fact that the origin of the Global Coordinate System of the hydrodynamic model does not coincide with the one of the FE model. The difference is corrected automatically when the coupling is performed.

Fig. 10. Hydrodynamic Model of the Pontoon.

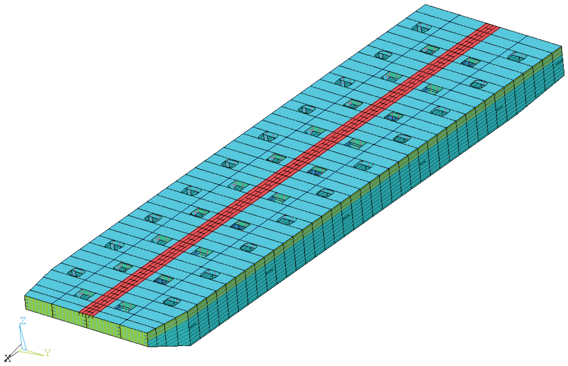


The maximum element size of the panels was set to 3 meters, with a defeaturing tolerance of 0.8 m. With it, it was possible to evaluate wave frequency ranges from 0.25 rad/s to 1.8 rad/s with 50 intermediate values. Different wave heading directions were assessed, from 0 to 180 degrees with steps of 30 degrees. Regarding the pontoon speed, three values were evaluated: 3, 9 and 12 knots.

Structural Model

To carry out FE calculations, a fine mesh of around 256.000 nodes were used to discretize the structure of the pontoon.

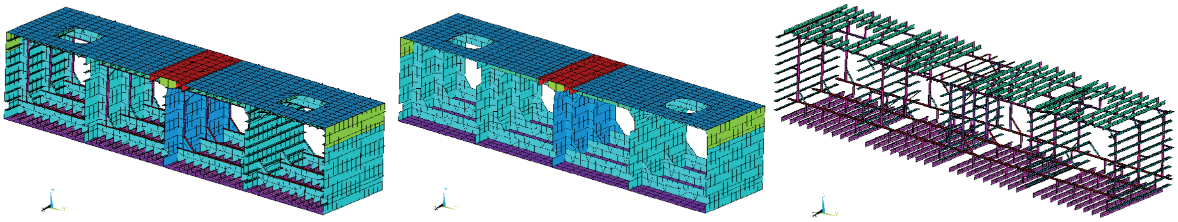
Fig. 11. Pontoon FE Model.



Figs. 11 and 12 shows the geometry of the pontoon, which was modeled by using the following element types:

- Shell: is a four-node element with six degrees of freedom at each node (translations in the x, y and z directions, and rotations about the x, y, and z-axes). In general, primary structural elements were modelled by using shell181 elements.

Fig. 12. Elements within a section of the pontoon model: (from left to right), the complete section, shell and beam elements.



- Beam: is a linear, two-node beam element, based on Timoshenko beam theory. Secondary stiffeners and also face plates on top of primary members were modelled by these elements.

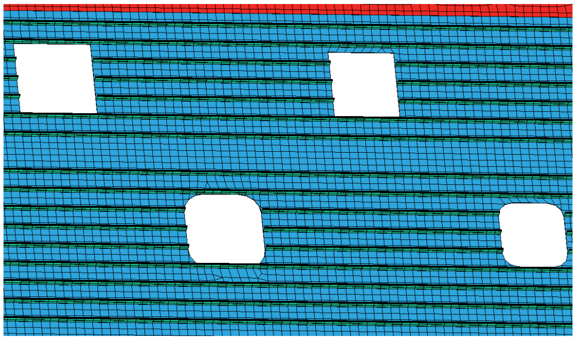
To create fatigue-sensitive locations in the structure, the main deck plating of the structure was penetrated with four different types of holes, as shown in Table 3 and Fig. 13.

Table 3. Dimensions of main deck holes

Hole detail	Dimensions	Corner Radius
Squared with welded edges	2 x 2.2 m	-
Squared without welded edges (free edges)	1.7 x 1.9 m	-
Squared with rounded corners and welded edges	2.2 x 2 m	55 cm
Squared with rounded corners and without welded edges (free edges)	1.7 x 1.9 m	40 cm

In the corners of these holes, high concentration of stresses is expected which will likely create long-term fatigue issues.

Fig. 13. Main Deck holes, detailed view.



Finally, boundary conditions (Fig. 14) were applied to the model so that it can freely deform while keeping the model numerically balanced:

- Forward end: the mid-plane-central node was constrained for vertical (UZ=0) and transversal (UY=0) displacements.
- Aft end: in this area three mid-height nodes were constrained:
  o Side nodes: vertical displacements were restricted (UZ=0)
  o Mid-plane node: longitudinal (UX=0) and transversal (UY=0) displacements were constrained

Fatigue Assessment Settings

Following the process described in Section III-C, the minimum required FAT-class for all the structural nodes in the FE model of the pontoon was calculated.

To do that, the following settings were accounted:

- Reference SN-Curves for structural details *(DNVGL, 2015)*:
  o Base material: Curve B1.
  o Free-plate edge: Curves B, B2, C, C1, C2.
  o Weld: Curves D, E, F.
- Number of cycles above which sea cases contribution is considered (high-cycle fatigue): 104 *(DNVGL, 2015)*.
- Operational Profile (see Table 4).

Fig. 14. Boundary conditions.

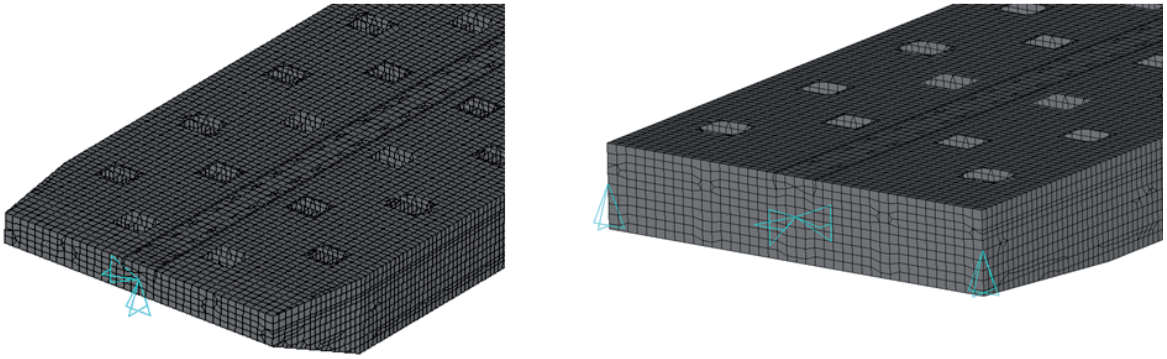


Table 4. Operational Profile.

Total Num.Cycles	2.94E+07	
Wave Scatters	Area 40	North Atlantic (IACS)
Sea Spectrums	JONSWAP	Pierson-Moskowitz
Ship Speed [knots]	3 , 9, 12	
Heading [deg]	0, 30, 60, 90, 120, 150, 180	
Total Sea Scenarios	7224	

- For all the seakeeping assessments, the wave peak is exactly located at the position of the center of gravity of the pontoon, to account for the worst case scenario in regards to the global fatigue behavior of the structure.

A total of 7224 sea scenarios were evaluated by means the described methodology. As an example, the load transfer method is shown in Figs. 15, 16 and 17.

Fig. 15. Wave Loading on FEM Model. Contour-plot of applied pressures.

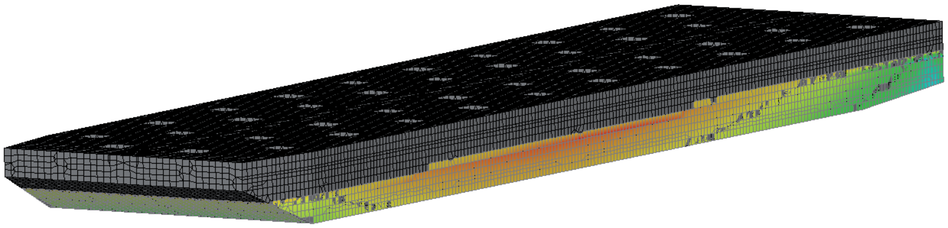


Fig. 16. Wave Loading on FEM Model. Arrow-plot of applied pressures.

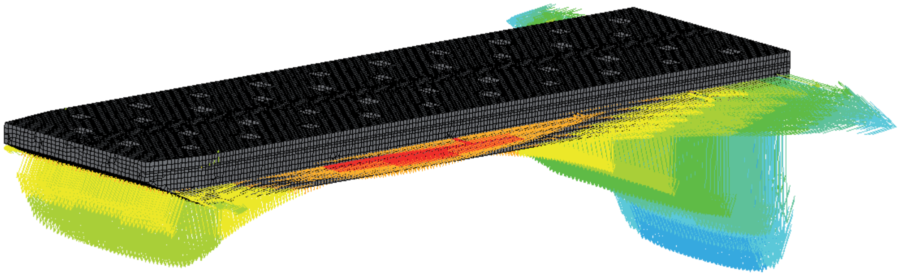
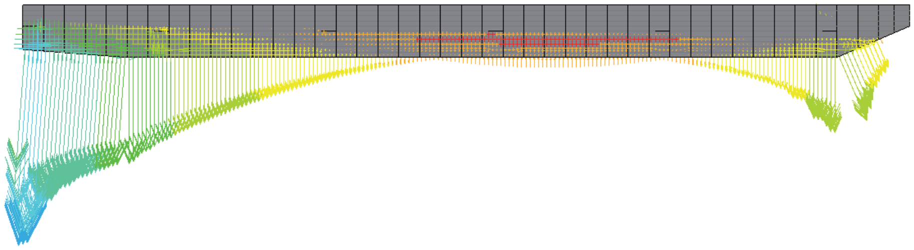


Fig. 17. Wave Loading on FEM Model. Arrow-plot of applied pressures of profile view.



The arrow´s length and color give an idea of the magnitude order. The sign of the pressure value in the legend shows the direction of the pressure vector: positive pressures are applied against the element centroid while negative ones are applied outwards from the element surface. The mid-ship section of the pontoon is situated at the wave crest while the aft and forward region are located at the trough of the wave. Moreover, it can also be noted that the free surface is not perfectly read as a straight line, depending it on the number of elements used on this region of the FEM model. The same applies to the hydrodynamic model and considering the volume calculated through this element discretization, it can be understood that the model will never be completely balanced with regards to the hydrostatic loads. As the calculated volume through elements will be smaller than the actual one, the buoyancy force will be then smaller than the actual weight of the vessel. Therefore at boundary-condition nodes residual stresses and reactions are expected to appear.

Reactions at boundary-condition nodes were monitored. For the worst scenario, the sum of the vertical reaction forces at such nodes was -5.32 kN (0.01% of displacement), thus can be considered that the model was properly balanced.

Results

After the full computation was completed, outputs were analyzed qualitatively, due to the complexity on evaluating long-term results. Intermediate steps were studied and verified *(Luna Garcia-Valenzuela, 2019)*. Quantitative assessment will follow in future work. Results were mapped over the FE model. The following plots were generated:

Fig. 18. Minimum Required FAT-Class (Automatic Coloring Scale): Overview.

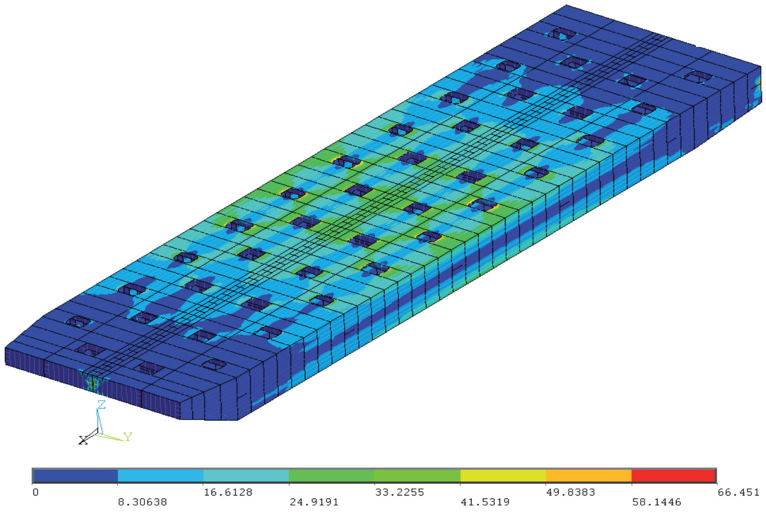
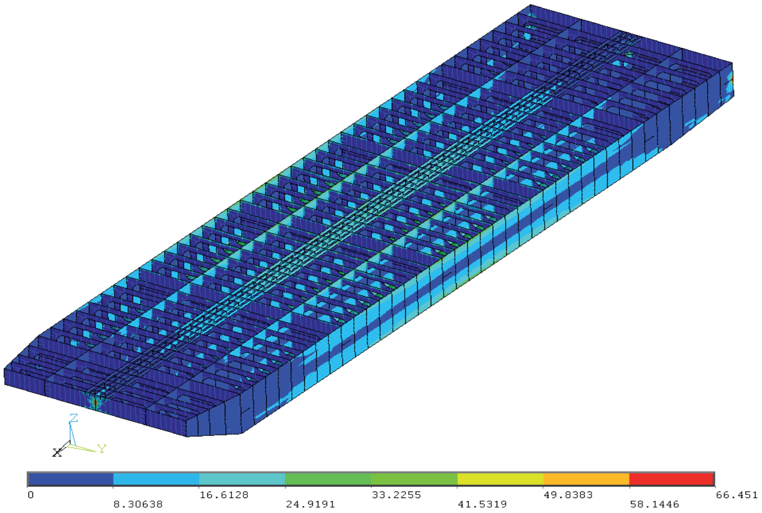


Fig. 19. Minimum Required FAT-Class (Automatic Coloring Scale): Overview without deck plating.



As shown in Fig. 18 and Fig. 19, in the aft- and forward-end regions the minimum required stress range at 2·106 cycles is small (almost 0 MPa) in comparison with the mid-ship region of the vessel, where the minimum required FAT-class for the nodes is about 35 MPa. This structural response was completely expected, due to the mild operational profile. Structural fatigue is known to be dominated by the vertical induced wave bending moment. As the transversal second moment of inertia is higher than the vertical one, then it proves that the transversal bending moment (inversely dependent of the second moment of inertia) is much smaller than the vertical wave bending moment. Consequently, the transversal stress on the structure will be also smaller than the longitudinal stress, therefore setting the importance of the longitudinal stress on fatigue assessment.

Being the extremes of the pontoon constrained by the boundary conditions, the most unfavorable

Fig. 20. Minimum Required FAT-Class (Automatic Coloring Scale): Overview without deck plating.

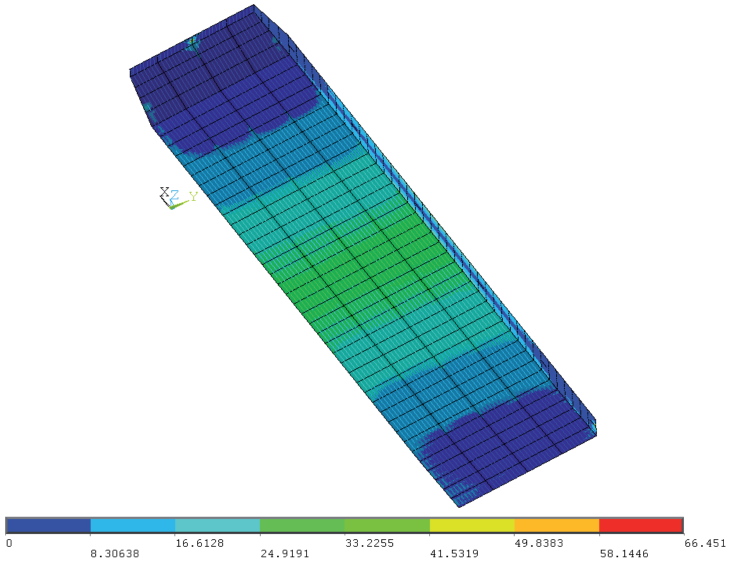
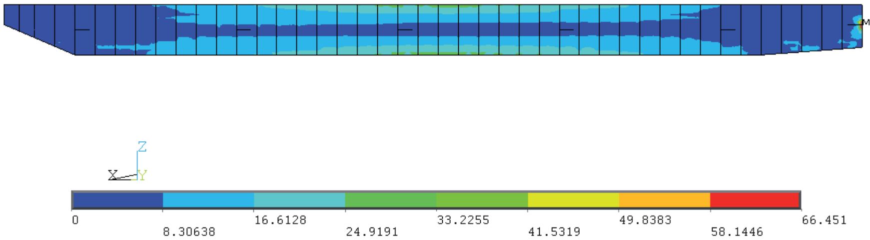


Fig. 21. Minimum Required FAT-Class (Automatic Coloring Scale): Profile view.



condition will be the case in which the wave peak is located at the longitudinal position of the center of gravity, and the wavelength is equal to the pontoon length on head seas. This was the case shown in Fig. 15 where the maximum vertical bending moment occurred in the middle of the vessel. Therefore, it can be understood that the part of the structure in which it is expected to exist fatigue issues it is the midship region of the vessel. This behavior can be also shown in Fig. 20, where the higher minimum required FAT-class again appears on the nodes located at midships. Fig. 19 also shows the expected stress distribution among the different structural members.

In Fig. 21, it is shown on a profile-view the same minimum required FAT-class distribution evaluated previously. Here, it can be noted that in the line of the neutral axis, there is almost no longitudinal stress. This fact triggers that this zone, not only in the hull plating but also in nodes which are nearby the neutral axis line of longitudinal bulkheads, have a low FAT-class requirement. Similarly, in the same view it can be noted that in the deck and bottom regions, minimum required stress range is higher due to the fact that they are subjected to bending moments, which are more significant, as commented, the bigger distance of the neutral axis (in vertical direction) and the closer to the midship region (in longitudinal direction).

Fig. 22 shows the minimum required stress range distribution throughout the main-deck platting of the pontoon. First, it can be noted again the same behavior described previously with regards to the required FAT-class at midships. This response in addition to the effect caused by the structural holes will increment notably the required stress ranges around the edges of such holes. Penetrations consist basically in structural discontinuities which interrupts the stress flow within the plating. That forces the stress to flow around the hole. That will result in stress concentrations around the discontinuity edges.

In Fig. 23, this effect can be noted easily since it is a zoom-in of Fig. 22. Here it can be observed the

Fig. 22. Minimum Required FAT-Class (Automatic Coloring Scale): Plan view.

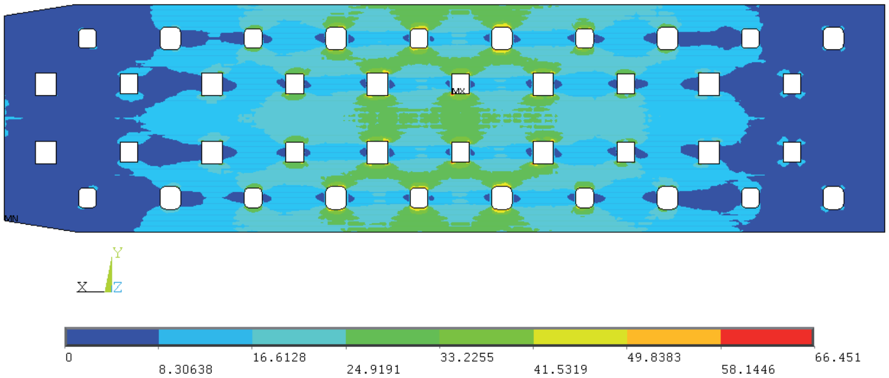
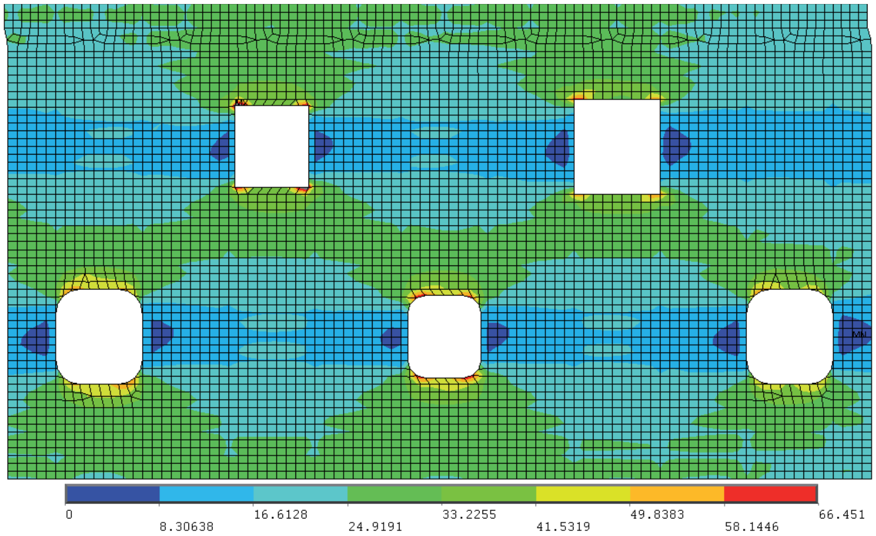


Fig. 23. Minimum Required FAT-Class (Automatic Coloring Scale): Plan-detailed view of deck-platting holes.



stress shadows of the holes (blue colored), where the stress concentration is severely reduced, due to the stress direction towards the hole corners, defining therefore the preferable or allowable areas for deck plating penetrations.

In the squared discontinuities, the stress-flow deviation is bigger than in the one with rounded corners. This effect will increase even more the stress concentration around the squared corners. Red colors therefore arise in the corner edges while only yellow color appear in the rounded corners of the discontinuity.

Fig. 24 shows that none of the nodes of the structure are expected to show fatigue issues during the lifetime of the pontoon, for the considered operational profile. The scale of the figure refers to the stress-range limits of the SN curves (FAT-classes), as defined by DNVGL. The general idea of this plots is checking that the actual FAT-class of the designed detail is equal or higher than the

Fig. 24. Minimum Required FAT-Class (FAT Coloring Scale): Overview.

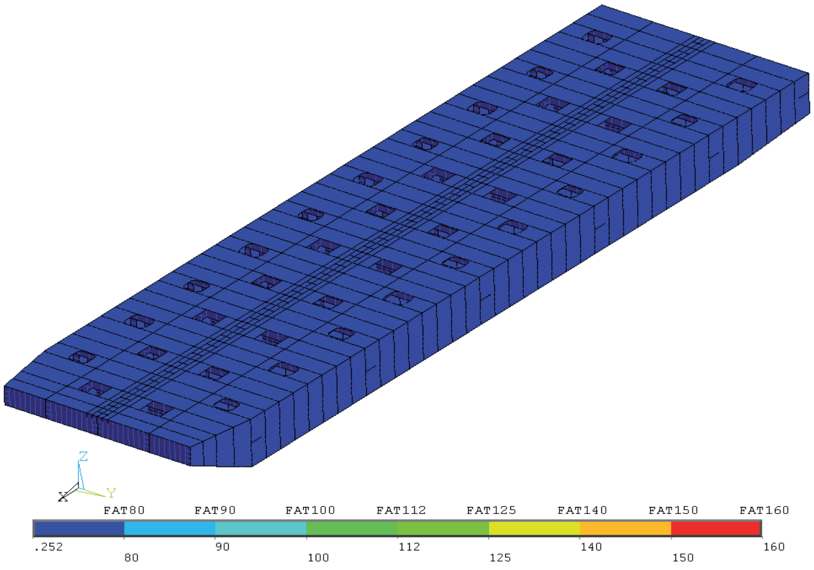
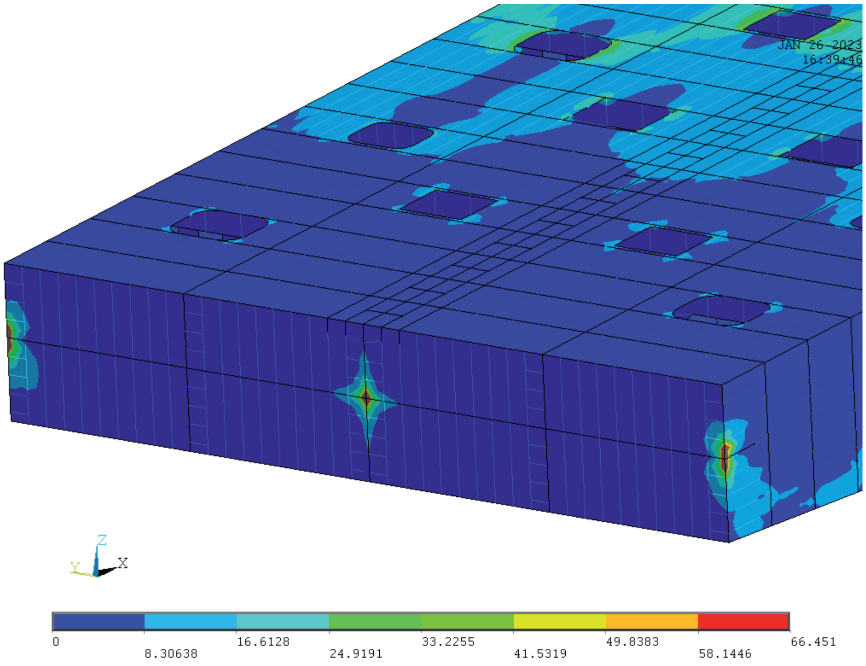


Fig. 25. Minimum Required FAT-Class (Automatic Coloring Scale): Boundary Conditions.



minimum required FAT-Class, for the same detail. Thus, if for instance a node of the structure is classified as base material (SN Curve: B1, FAT-160) and in the plots it is colored in red (FAT-160 threshold), it shows that the minimum required FAT-class falls nearby the limit. Similarly, if a node is classified as FAT-71 weld and has a minimum required FAT-class of 112 MPa, it will be colored in green and therefore, the structural detail should be re-designed since is expected to show fatigue issues. If the structure is then completely painted in dark-blue (FAT-Class below 80) it means that the minimum required FAT-class is below the limits defined of the SN curves and no fatigue problems will be expected.

It should be noted by the reader that if more extreme load cases would have been evaluated, probably different parts of the structure would have been facing fatigue response issues, triggering then such parts to be painted in different color than dark blue.

Finally, Fig. 25 shows the expected stress concentration at boundary conditions. It occurs due to the lightly unbalanced buoyancy forces, creating small non-zero reaction forces at these nodes (and also due to the stress distribution, on surrounding nodes).

Through the previous ts, it can be observed the mid-plane symmetry on the response of the structure. In fact, as the geometry and the wave loading are symmetric, it is to be expected that the structural response of the structure will be similarly symmetric. It should be noted that with a different wave phase delay (than 0 degrees) asymmetric wave loading arises and therefore, asymmetric structure response must be expected.

Also the long-term damage computation was calculated. To do that, an unfavorable case in

Table 5. Sea case of study, for long-term damage evaluation.

Sea Case parameters	Value
Ship Speed	3 knots
Significant Wave Height	3 m
Wave Heading	180 deg (head seas)
Peak Period	7.5 s
Scatter Diagram	North Atlantic (IACS)
Expected Number of Cycles	1.15E+05

terms of fatigue was created and solved (see Table 5). Long-term damage was calculated for all the nodes in the structure, by solving Equation 8.

As shown in Fig. 27, several locations at strength deck amidships showed long-term fatigue damage above or equal to 1. These structural details were in the majority of the cases welds, for which conservatively the chosen FAT-class was 36, normally used for partial penetration butt-welds (DNV-GL, 2015). Red-marked area around the hatch-hole (Fig. 28) showed a stress range of 270 MPa. Fig. 26 represents the long-term stress range distribution. Accounting for the recommended probability of exceedance level for fatigue assessments, 10-2 *(DNV-GL, 2015)*, and also for FAT36 SN-curve parameters, Equation 8 was solved and the long-term fatigue damage yielded to 1.5. Same value was obtained by the developed tool.

Fig. 26. Long-term stress range distribution of evaluated detail.

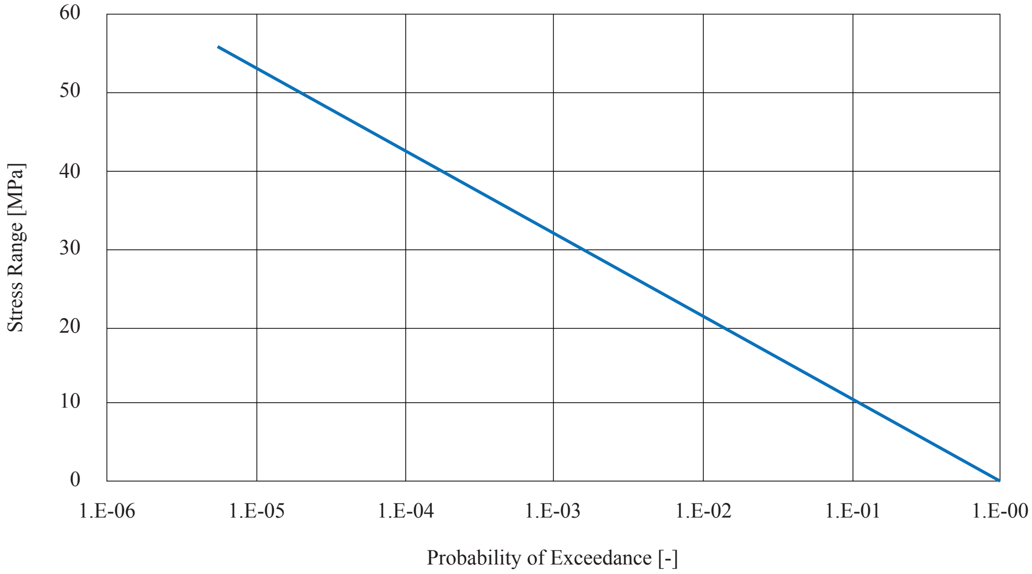


Fig. 27. Long-term fatigue damage for sea case of study. Strength deck nodes at midship.

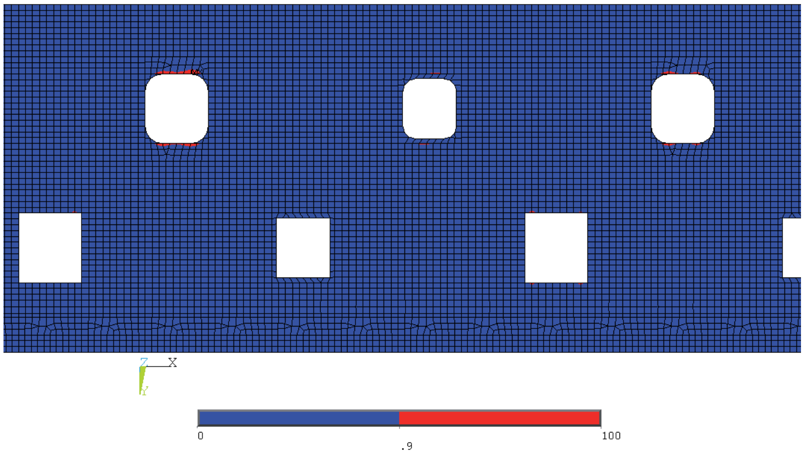
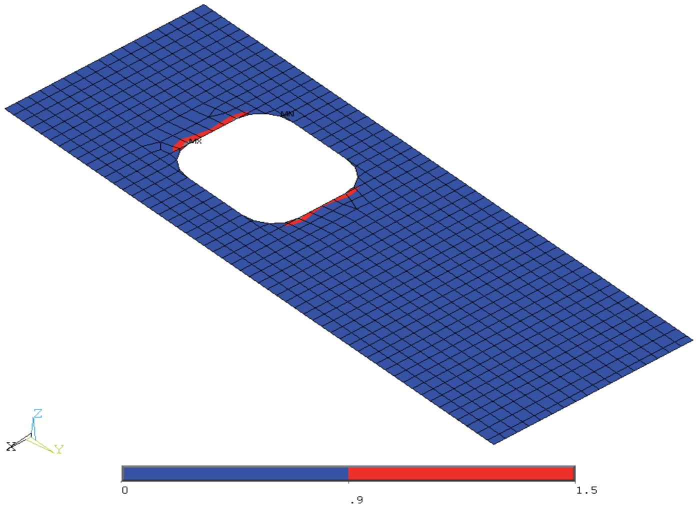


Fig. 28. Long-term fatigue damage for sea case of study. Damage at strength deck nodes, amidships, starboard side.



Conclusions

This article shows a developed process to perform spectral fatigue calculations for floating structures. Such process is implemented on a software-tool, called SEAFALT, dedicated for spectral fatigue analysis based on a coupling of direct calculated loads and the FE method. Hydrodynamic analyses are based on the frequency domain approach and FE computations are static structural assessments. These facts allow to speed-up significantly fatigue lifetime calculations compared to full time-domain methodologies.

The developed tool is pretended to be used during basic and detailed engineering phases and allows the engineer to compute the minimum required characteristics of structural detail, to ensure the withstanding of the variety of sea loading cycles during the vessel his lifetime. Also, long-term fatigue damage can be assessed, once the detail his characteristics are known.

The spectral fatigue assessment is performed in terms of:

- The geometry description throughout a full-length-detailed 3D model of the structure,
- the hydrodynamic BEM model of the outer-hull of the structure,
- the operational profile, which is based on the susceptible sea conditions which are likely to occur during the life cycle of the vessel,
- DNV-GL classification society requirements.

The structure of a pontoon vessel designed and built by Damen DSNS was evaluated through SEAFALT. A full-length-detailed FEM model with 256.000 nodes. Also, a hydrodynamic model was created to evaluate the environmental conditions dictated by the provided operational profile.

For this study, such environmental conditions were quite mild. Hydrodynamically-wise does not trigger the model to develop any fatigue long-term issues, which means that the structure has enough fatigue strength to withstand the potential operational conditions during the entire lifetime and that it has been properly designed. Results were assessed from a qualitative point-of-view and based on engineering experience. Qualitative assessment will be performed in future works. Also future developments will be focused on benchmarking the tool with ships with different hull shapes.

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[3, Th. 1]; [3, Lemma 2]; [3, pp. 5-10]; [3, eq. (2)]; [3, Fig. 1]; [3, Appendix I]; [3, Sec. 4.5]; [3, Ch. 2, pp. 5-10]; [3, Algorithm 5].

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