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Ship Science & Technology is a specialized journal in topics related to naval architecture, and naval, marine and ocean engineering. 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 by exchange or subscription.

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Editorial Note

Cartagena de Indias, July 18th 2017.

In this edition, the Ship Science and Technology Journal initiates a new volume of special publications with the works presented at the Fifth International Congress of Naval Design and Engineering, held in the city of Cartagena from March 15-17, 2017. The key theme was "Contributing to the sustainable technological development of the region" which was broken down into three specific topics, with one topic being discussed per day: 1. Current trends in warship design, 2. Sustainable technological solutions for riverine transportation and 3. Opportunities, outlook and competitiveness of shipyard industry.

The Fifth International Ship Design and Naval Engineering Congress consisted of (6) six lectures, (19) nineteen scientific papers, (7) seven technical presentations, (10) ten commercial presentations and (4) four forums, for a total of 46 academic activities. Attendees from Belgium, Brazil, Colombia, Korea, Chile, Ecuador, Spain, the United States, Mexico, Panama, the Netherlands, Peru and the United Kingdom, in addition to others, were present. Subjects covered and explored in detail included topics related to Design and Engineering, Ship Technology, Combat Systems, Life Cycles, Offshore and Engineering for Sustainable Development.

Based on the above, this edition compiles the works related to optimization of naval structures, numerical simulations, flexible ship design, dynamics, hydrodynamics, system calculations, risk analysis and applicable standards in naval vessels.

We take this opportunity to warmly welcome Professor Hassan Ghassemi, Ph.D from Amirkabir University of Technology in Iran, Captain Oscar Tascón, Ph.D from the Colombian Navy and Professor Adam Vega Saenz, Ph.D. from the Universidad Tecnológica de Panama, who were followers of the journal and now form part of our Editorial Committee. We also thank Captain Jose Maria Riola, Ph.D of the Spanish Navy and Professor Wilson Adarme, Ph.D, from the Universidad Nacional de Colombia, who are now members of the Scientific Committee.

In addition, we thank the students, engineers and general public that participated in the Fifth International Ship Design and Naval Engineering Congress and the followers of the Ship Science and Technology Journal, for being part of this big project through which we want to improve the impact and visibility of the Journal in the scientific community of naval engineering, naval architecture, marine engineering and oceanic engineering. Therefore, we encourage them all to continue to contribute toward the goal of positioning it as one of the best journals specialized in these issues at an international level.

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

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Nota Editorial

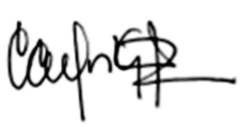
Cartagena de Indias, 18 de Julio de 2017.

En esta edición, la revista Ciencia y Tecnología de Buques abre un nuevo volumen de publicaciones especializadas contando con los trabajos presentados en el V Congreso Internacional de Diseño e Ingeniería Naval, realizado en Cartagena de Indias del 15 al 17 de marzo de 2017. En esta oportunidad se tuvo como temática central "Aportando al desarrollo tecnológico sostenible de la región" y a partir de esta se abrió paso a tres temáticas específicas, las cuales fueron tratadas una por cada día: 1. Actualidad y tendencias del diseño de buques de guerra, 2. Soluciones tecnológicas sostenibles para el transporte fluvial y 3. Oportunidades, perspectivas y competitividad del sector astillero.

El Quinto Congreso Internacional de Diseño e Ingeniería Naval estuvo conformado por (6) seis conferencias magistrales, (19) diecinueve ponencias científicas, (7) siete ponencias técnicas, (10) diez ponencias comerciales y (4) cuatro foros, para un total de 46 actividades académicas. Se contó con asistentes de Alemania, Bélgica, Brasil, Colombia, Corea, Chile, Ecuador, España, Estados Unidos, México, Panamá, Países Bajos, Perú, Reino Unido, entre otros. De esta forma fue posible abarcar y explorar temas asociados al Diseño e Ingeniería, Tecnología de Buques, Sistemas de Combate, Ciclos de vida, Ingeniería para el Desarrollo Sostenible, Offshore, entre otras. Partiendo de lo anterior, en esta edición se recopilan los trabajos relacionados con optimización de estructuras navales, simulaciones numéricas, diseño flexible de buques, dinámica, hidrodinámica, cálculos de sistemas, análisis de riesgos y normas aplicables en buques navales.

Aprovechamos para dar la bienvenida al Profesor Hassan Ghassemi, Ph.D de la Amirkabir University of Technology de Iran, al Capitán de Navío Oscar Tascón, Ph.D de la Armada Nacional de Colombia y al Profesor Adán Vega Saenz, Ph.D de la Universidad Tecnológica de Panamá, quienes se unen a nuestro Comité Editorial. Por su parte, agradecerles al Capitán de Navío José María Riola, Ph.D de la Marina Española y al profesor Wilson Adarme, Ph.D de la Universidad Nacional de Colombia, quienes hoy son nuevos miembros de nuestro Comité Científico.

Además, agradecemos a los estudiantes, ingenieros y público en general participante en el Congreso Internacional de Diseño e Ingeniería Naval y seguidores de la revista Ciencia y Tecnología de Buques, a ser parte del gran proyecto para mejorar el impacto y visibilidad de la revista ante la comunidad científica de ingeniería naval, arquitectura naval, ingeniería marina e ingeniería oceánica. Por lo anterior los exhortamos a aportar hacia la meta de ser posicionada como una de las mejores revistas especializada en estas temáticas a nivel internacional.



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

Optimisation of Ship and Offshore Structures and Effective Waterway Infrastructures to Support the Global Economic Growth of a Country/Region

Optimización de Estructuras Navales y Offshore e Infraestructuras fluviales eficaces para apoyar el crecimiento económico global de un país / región

DOI: 10.25043/19098642.155

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Timothée Pire [4]
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Jean-David Caprace [6]

Abstract

This paper includes the following parts:

- Ship Structure Optimization: methodology to perform ship scantling optimization, decreasing steel weight and keeping the production cost at an acceptable level. We first review the links between "Design" and "Optimization" and secondly define the place of "Ship Structure Optimization" within the general framework of a "Ship Optimization".
- Ship impacts (Collision), with applications to navigation lock and dry dock gates: these gates have to be designed taking into account accidental loads, such as ship collisions. A new simplified analytical method is proposed, based on the so-called super-element method. This method was developed to rapidly assess the crashworthiness of the collided structure and avoid high computational effort of numerical simulations.
- Inland waterway Navigation and the development in South America of Inland Waterway Classifications.
- EMSHIP, European ERASMUS MUNDUS education program (www.emship.eu): the unique master's degree in Ship & Offshore Structures awarded by the prestigious European Erasmus Mundus Program. EMSHIP shares the outstanding experiences of educators, trainers, industrial partners and students in the rapidly developing areas of marine and offshore engineering industry.

Key words: Navigation, inland waterway, optimisation, ship collision, lock gate, ship structure, analytical method, LBR-5, super-element, EMSHIP, waterway classification

Resumen

Este documento incluye las siguientes partes:

- Optimización de Estructuras de Barcos: metodología para realizar la optimización del escantillonado de buques, disminuyendo el peso de acero y manteniendo el costo de producción en un nivel aceptable. Primero se revisa los vínculos entre "Diseño" y "Optimización" y en segundo lugar se define el lugar de "Optimización de Estructuras" dentro del marco general de una "Optimización de Buques".
- Impactos de los buques (Colisión), con aplicaciones en puertas de esclusas: estas puertas deben diseñarse teniendo en cuenta cargas accidentales, tales como colisiones de buques. Considerando el enorme esfuerzo computacional de las simulaciones numéricas, se propone un nuevo método analítico simplificado, basado en el denominado método de super-elementos. Este método fue desarrollado para evaluar rápidamente la resistencia a impactos de la estructura colisionada.
- Navegación fluvial y el desarrollo en América del Sur de las Clasificaciones de la Vía Fluvial.
- EMSHIP, programa europeo de educación ERASMUS MUNDUS (www.emship.eu): único programa de maestría en Estructuras Navales y Offshore otorgado por el prestigioso Programa Europeo Erasmus Mundus. EMSHIP comparte las experiencias sobresalientes de los educadores, entrenadores, socios industriales y estudiantes en las áreas de rápido desarrollo de la industria de ingeniería marina y offshore.

Palabras claves: Navegación, navegación interior, optimización, colisión de buques, puerta de esclusa, estructura de buque, método analítico, LBR-5, super-elemento, EMSHIP, clasificación de vías navegables.

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Introduction

After presenting of the main research activities at ANAST, ULG, we discuss the way to improve the effectiveness of waterway infrastructures to support the global economic growth of a country/region.

The paper includes four sections, which cover:

- Ship Structure Optimization;
- Ship impacts (Collision), with application on IW infrastructures including navigation lock gates;
- Inland waterway navigation and the development in South America of Inland Waterway Classifications;
- The European EMSHIP education program in Naval Architecture *(www.EMSHIP.EU)*.

These 4 parts are in fact the pillars of the research and expertise of ANAST, University of Liege; combining naval architecture, ocean engineering, ship and offshore structure with unique expertise in inland waterways as well as in transport system analysis and logistics. All the aspects related to marine and inland waterways aspects are covered, from the ship design and operation, the waterway infrastructure and the transportation economic analysis.

A benchmark international association in which Ph. RIGO disseminates his expertise is PIANC (www.pianc.org). This is the world Association for Waterborne Transport Infrastructure and its forum is where professionals around the world join forces to provide expert advice on cost effective, reliable and sustainable infrastructures to facilitate the growth of waterborne transport. Established in 1885, PIANC continues to be the leading partner for the government and private sectors in the design, development and maintenance of ports, waterways and coastal areas.

PIANC brings together the best international experts on technical, economic and environmental is-sues pertaining to waterborne transport infrastructures. Members include national governments and public authorities, corporations, private companies and interested individuals.

Prof. Ph. Rigo is the chairperson of the PIANC InCom (Inland Navigation Commission) and is the author of several PIANC Reports on Inland Waterway infrastructures *(PIANC WG106 - 2009, PIANC WG26 - 2016)*.

What is new in ship structure optimization?

Links between “Design” and “Optimization” (Rigo, Caprace, 2011)

It is impossible to talk about optimization without a clear definition of the design stage(s) which are considered during the design of a ship. If the target is the conceptual design stage, the optimization (tools and objectives) will be completely different from those used for an optimization carried out at the detailed design stage.

“Ship Design” is usually presented through the “Design Loop” or “Design Spiral” (Fig. 1). Each of these design tasks is mandatory to obtain a reliable design of the targeted ship. None of these tasks can be omitted, irrespective of whether the design is for a large cruise vessel, cargo ship, pleasure yacht, tug boat, barge, fishing vessel or navy ship.

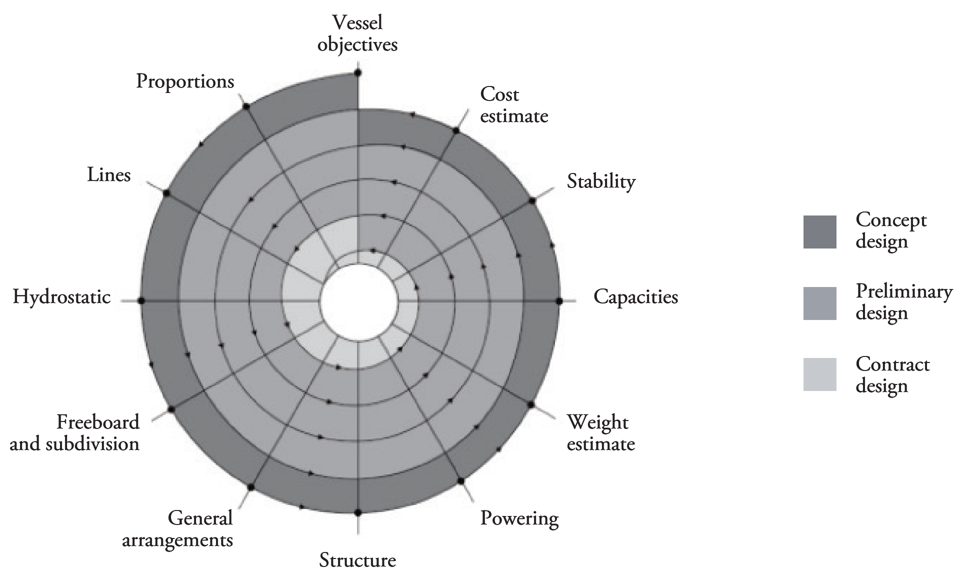
These design tasks can be achieved sequentially or simultaneously. In the past, these tasks were performed sequentially but now, for the sake of production efficiency and to reduce the delivery time, most of these tasks are achieved through a concurrent engineering process *(Caprace, 2010)*.

In 2017, performing concurrent design tasks is the current practice. However, today, is it possible to perform concurrent design optimization tasks? Our an-swer to this question is given below.

Ship design optimization is a type of normal task that the naval architect tries to perform during the var-ious loops of the design spiral (whether done sequentially or concurrently). The “Spiral” (Fig. 1) is definitively an optimization process. Each loop can be considered as an iteration of the optimization process. Nevertheless, when the specialists are called in, as is usually the case at the contract design stage and even more so at the detailed design stage, the optimization becomes definitively local optimization.

Local optimization is understood as optimization that tackles a single specific issue (hydrodynamics, propulsion, structure, manoeuvrability, etc.), with the other design aspects being suspended. For instance, it is common to consider the hull form and the General Arrangement (GA) as fixed when we optimize the ship structure (scantling) in order to reduce the weight and/or production cost.

Fig. 1. Typical Design Spiral (Eyres 2001)



Similarly, in CFD optimization we often consider the structure (scantling, weight, gravity centre, etc.) to be fixed. Alternatively, rules of thumb or statistical curves [weight = Fct *(Δ, L, B, T, Cb, etc.)*] are used to adjust the weight according to the hull form.

There is also the ship production team which tries to optimize workflow and workload to reduce the delivery time. They are working in the field of *Design for Production* and the aim is to optimize the ship focusing on the production keeping the other parameters fixed (hull form, scantling, etc.) *(Caprace 2008).*

It is clear and obvious that it is not efficient to perform sequential local optimization. Nevertheless, even today, it is still the industrial practice used to achieve an improved ship design. Engineers know that they do meet the global optimum but they are moving in the right direction.

Therefore, the solution is definitively to move to a global optimization, by which we mean towards a holistic optimisation *(Holiship, 2016)*. The challenge for tomorrow is therefore to move to a concurrent optimization. That means that several tools will run simultaneously, using the same database and the same design (geometry, loads, hull form, scantlings, etc.).

There were some tentative moves to initiate this procedure [such as VIRTUE (CFD), IMPROVE *(RINA 2009)* and BESTT *(Bayatfar, 2013)* for Structure], which are former EU projects. Today, the promising HOLISHIP (2016) EU project has been launched with its target to demonstrate the feasibility of a holistic optimisation using CAESES® (Friendship Systems) as the support environment.

All these prior and new projects are facing the same challenges:

- Difficulty in sharing data. Standard formats are required and must be accepted by the different developers, which are in fact often competitors. Currently, maintaining a different format (standard) is a way to avoid competitors and repulse new developers with alternative modules (which can be more effective than their own module).
- Difficulty in moving from CAD data to CFD, from CAD to structural models (FEM) and above all, from CFD to structural models, and vice versa.
- The level of accuracy of the CAD data is rather different than the expected level required for struc-ture analysis (FEM). Some data may be missing. Nevertheless, more often than not, too much CAD data are available to easily and automatically produce a coarse mesh for FEA. In this case, how can we automatically generate a simplified model from a detailed CAD model, and later, when the optimization is achieved, how can we update a detailed CAD model with data (usually geometric) coming from a coarse mesh FEM? The key issue is to avoid remeshing and manual data transfer, or even worse, retyping the data.
- Most of the tools are in fact "black boxes" for the other developers. Therefore, data exchange is ra-ther slow and cumbersome.

In conclusion, a promising direction of research is the development of a concurrent optimization platform *(Holiship, 2016)*, which could be the intermediate step between a series of sequential local optimization and a full global optimization (which remains a rather long term goal).

In the framework of this targeted holistic and multidisciplinary ship optimization, the next section presents the author views on "multiobjective optimization of ship scantling", the least weight and least cost methods (section 2.2) as well as some outcomes of the BESST project (section 2.3).

LBR-5, a Least Cost Structural Optimization Method

To be attractive to shipyards, scantling optimization has to be performed at the preliminary design stage. It is indeed the most relevant period to assess the construction cost, in order to compare fabrication sequences and to find the best frame/stiffener spacings and most suitable scantlings to minimize the life cycle cost of the ship. However at this stage of the project, few parameters (dimensions) have been definitively fixed and standard FEM is often unusable, particularly for design offices and modestsized shipyards. Therefore, an optimization tool at this design stage can provide precious help. This is precisely the purpose of the LBR-5 optimization software, Rigo (2001) and Rigo & Fleury (2001).

The structural analysis is performed on a model based on an extrusion of the cross section of the structure (2D+) solving the stiffened plate differential equations with Fourier series expansions, Rigo (2003).

The LBR-5 structural optimization model is com-posed of several modules and is made up of 3 key modules (objective function, optimization algorithm and structural constraints), which forms the framework of the optimisation tool.

Around the objective function and constraints modules, there are a large number of submodules. Each of these submodules is specific to a type of constraint.

Fig. 2 shows the basic configuration of the LBR-5 software with the 3 fundamental modules (objective function, optimization algorithm and constraints).

As an example of application, we present the structural optimization of a cruise ship (Fig. 3). The length (Lpp) is about 280 m.

Load cases

For each section, the following load cases were considered:

- sagging and hogging wave vertical bending moments with a probability of 10^{-8}; still water pressures; static deck loads;
- sagging and hogging wave vertical bending moments with a probability of 10^{-5}; still water and wave pressures; static deck loads;

Fig. 2. Flow chart of the LBR-5 optimization software (Rigo 2001, and Rigo 2003)

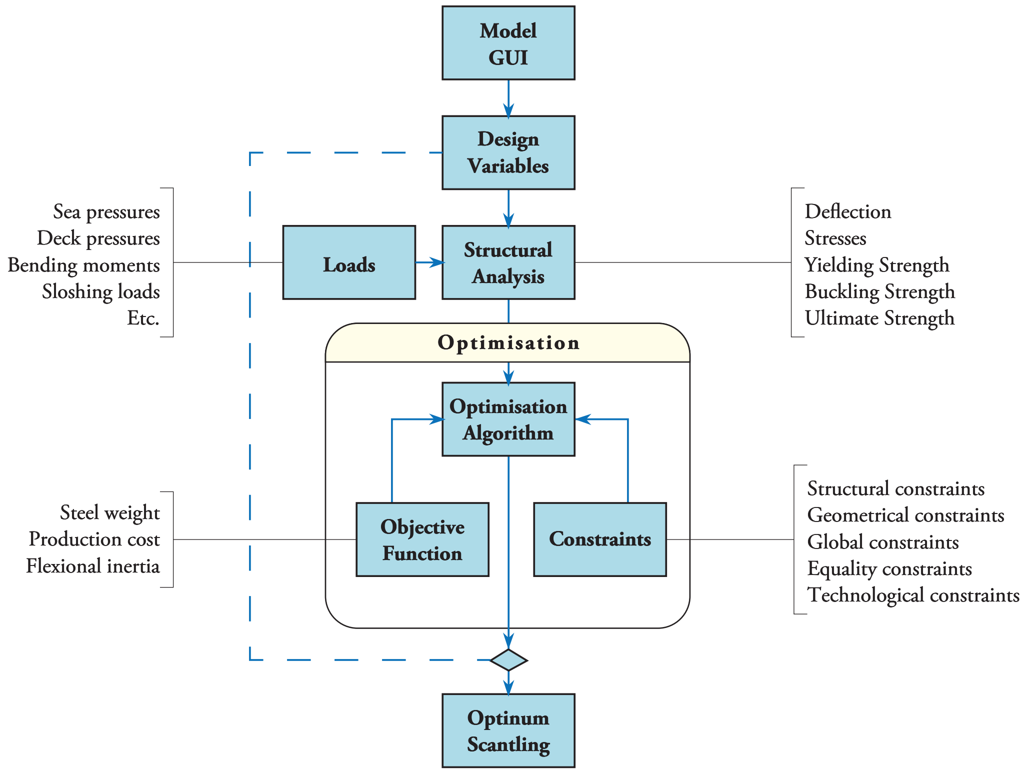
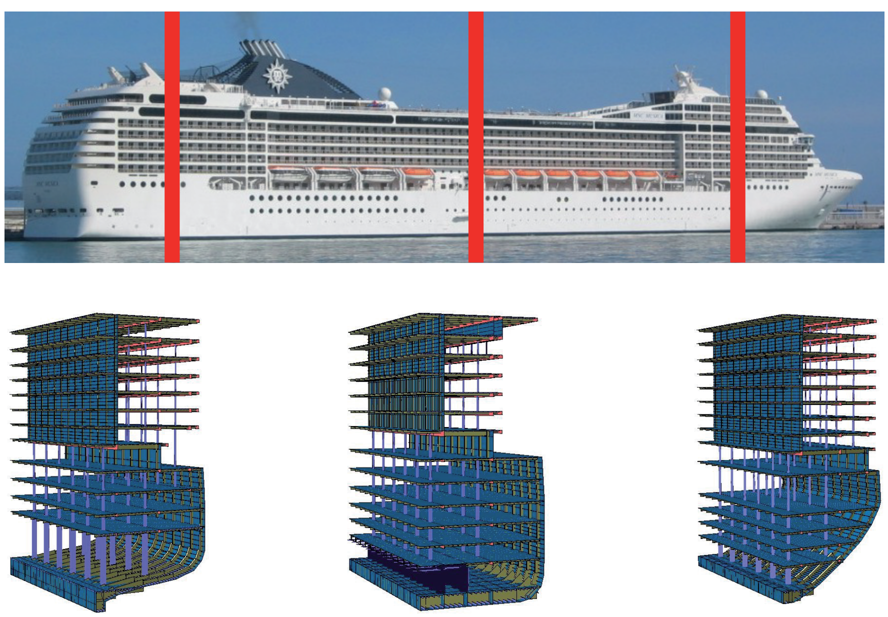


Fig. 3. Three amidships sections of a cruise ship (STX-France)



81 panels	*78 panels*	*93 panels*
24 pillars	*25 pillars*	*28 pillars*
Aft ship section [A]	***Amidships section [M]***	***Fore ship section [F]***

- maximum still water and wave pressures, without hull bending moment.

Optimization - Design variables

The three ship sections are modelled with 81, 78 and 93 stiffened plate elements respectively. The structural response of the model is solved with the resolution of the nonlinear differential equations of each stiffened plate element, Rigo (2001). For each element, 9 design variables are available:

- Plate thickness.
- For longitudinal members (stiffeners, crossbars, girders, etc.),
  - web height and thickness,
  - flange width,
  - spacing between 2 longitudinal members.
- For transverse members (frames, transverse stiffeners, etc.),
  - web height and thickness,
  - flange width,
  - spacing between 2 transverse members (frames).

In this case, 1694 design variables were activated for the whole ship model (3 ship sections) which represents an average of 6-7 design variables per stiffened panel.

To deal with this huge number of design variables the LBR-5 optimization algorithm solving nonlinear constrained problems has been used. It is based on both a convex linearization of the nonlinear functions and a dual approach, Fleury *et al.* (1986). It is especially effective because only few FEM reanalyses are required; typically less than 10.

Optimization - Objective functions

Production cost and minimum weight constitute the two objectives considered in this application.

Production costs (PC) has been subdivided into three categories:

- the cost of raw materials (MC) – The evaluation of material costs consists in quantifying volumes required for construction and obtaining prices from suppliers and subcontractors.
- the labour costs (LC) – This means the labour cost (LC) of a stiffened panel: welding of two as-semblies, the tacking of steel profiles, etc. The production cost has been calculated with an ad-vanced cost module taking into account a detailed shipyard database. Around 60 fabrication operations are considered, covering the different construction stages, such as girders and webframes prefabrication, plate panels assembling, blocks preassembling and assembling, as well as 30 types of welding and their unitary costs, Toderan *et al.* (2007).
- the overhead costs (OC).

Optimization - Design constraints

Constraints are linear or nonlinear functions of the design variables which are either explicit or implicit. These constraints are analytical relationships of the limitations that the user wants to impose on the design variables or parameters such as displacement, stress, ultimate strength, etc.

The problem is highly constrained (Table 1) and the adequacy of these constraints can greatly influence the solution provided. In this specific case study,

Fig. 3. Three amidships sections of a cruise ship (STX-France)

	Aft ship section	**Amid ships section**	**Fore ship section**	Total
Number of strake elements	81	78	93	252
Design variables	550	460	684	1694
Technological constraints	1100	920	1368	3388
Geometrical constraints	558	446	692	1696
Structural constraints	5734	4035	7040	16809
Global constraints	2	2	2	6
Equality constraints	0	0	0	0
Total constraints	**7394**	**5403**	**9792**	**21899**

3388 technological constraints, 1696 geometrical constraints, 16809 structural constraints and 6 global constraints have been used.

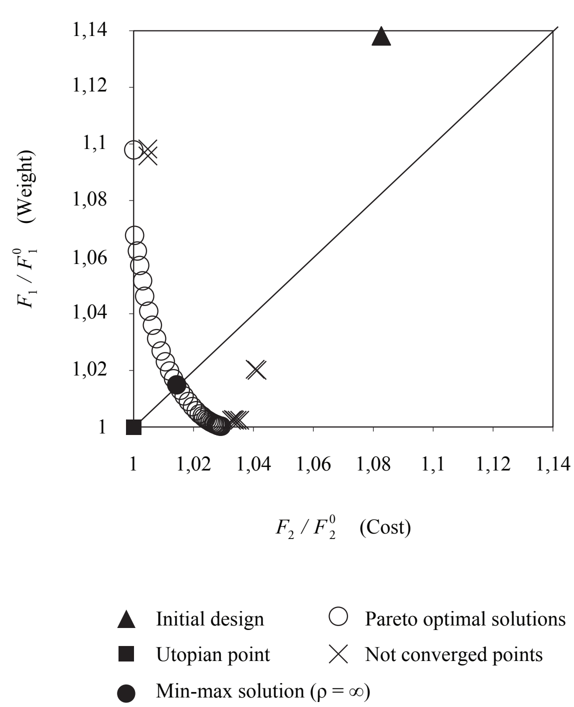
Pareto front

For this application case, two objective functions are considered. This results in Eq. 1 where P is the objective function and F_1, F_2 which are both analysed in this paper (the steel weight and the production cost respectively). Furthermore, F_1^0 represents the value of the criterion F_1 (*i.e.* steel weight) obtained when the optimization is performed with only this criterion in the objective function (single objective), while F_2^0 represents the value of the criterion F_2 (*i.e.* production cost) obtained when the optimization is performed with only this criterion in the objective function (single objective).

$$P = \left[\left[w_1 \left| \frac{F_1 - F_1^0}{F_1^0} \right| \right]^{\rho} + \left[w_2 \left| \frac{F_2 - F_2^0}{F_2^0} \right| \right]^{\rho} \right]^{1/\rho} \tag{1}$$

Thanks to the optimization algorithm, all scantlings presented in Fig. 4 are feasible solutions, which mean that all of the constraints imposed on the optimization are being satisfied.

Fig. 4. Pareto front of the cruise ship optimization



The utopian point, the min-max solution ($\rho=\infty$), and the initial solution are also shown in Fig. 4. Min-Max solution has been obtained for a weighting factor equal to 0.59 for the production cost and 0.41 for the weight. This analysis has highlighted that the initial design is relatively far from the Pareto front. Using Fig. 4, the design team is now able to choose a compromise solution from the Pareto front, by considering additional factors and constraints that could not be included in the optimization problem.

Table 2. Cost and Steel Weight Savings

	Weight Optimization	**Cost Optimization**	**Min-Max Solution**
	Saving (%)	Saving (%)	Saving (%)
Steel weight	**-12.72%**	**+5.1%**	**-11.3%**
Production cost	**-0.88%**	**-4.52%**	**-1.58%**
Material cost	-8.5%	+0.89%	-8.38%
Labour cost	+4.22%	-8.8%	+2.96%

Conclusions

The future challenge in the field of ship structure optimization does not concern the optimization algorithm itself but the development of some specific modules and principally their integration.

The identified challenges and needs are as follows:

- Development of fast and reliable modules to assess structural constraints such as fatigue and loads, at the early design stage (conceptual design stage but more probably at the basic design stage).
- Develop interfaces and/or open platforms for an easy plug and play (integration) of external modules. An initiative started by the IMPROVE user group *(RINA, 2009)* must be encouraged together with the development of open platforms such as the Holiship (2016) platform.
- Integrate the optimization tools in design chains, with direct links to the major CAD/CAM tools and FE software to avoid data retyping and time consuming remeshing.

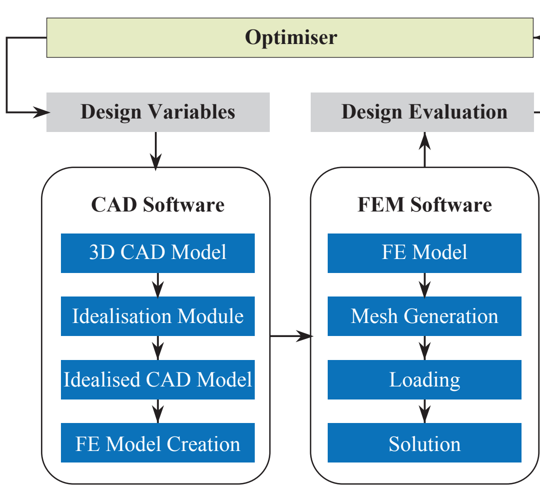
- Implement multi stakeholders and multi objectives approaches to better converge towards reliable industrial solutions, which are always a fact of comprise between the objectives of the different stakeholders.
- Integrate life cycle cost, and particularly the maintenance and operation costs within the global cost assessment for the entire life of the ship. In that case, optimization will be a supportive design tool toward the “Design for Maintenance” and “Design for operation”.

Toward a Ship Structural Optimization Methodology at the Contract Design Stage

This section presents an innovative workflow toward a ship structure optimisation loop based on the Integrated CAD tool (AVEVA), FEA (ANSYS) and Optimizer *(ModeFrontier, 2016)*. The work was performed in the framework of the research activity carried out by the European Project BESST *"Breakthrough in European Ship and Shipbuilding Technologies" (Bayatfar 2013)*. The focus concerns the development of an optimisation workflow supported by CAD/FEM integration that works automatically without any manual intervention.

In this regard, a typical deck structure was taken into consideration to evaluate the iterative process in the workflow. As shown in Fig. 5, the 3D CAD model is first transferred from the CAD software

Fig. 5. Schematic of optimisation workflow



to the idealisation module. Then, the idealisation module generates a simplified geometry which satisfies the FEM needs. After that, the idealised CAD model is transferred to the FEM software to create the meshed and loaded structural model.

Finally, the FE analysis is performed and the results obtained for the objective function and the previously defined con-straints are transferred to the optimiser tool to be evaluated, in order to update the design variables (plate thickness, stiffener dimensions, stiffener spacing, etc.) and to create a new structural model. The optimisation iteration process continues until the convergence is reached.

The deck structure model was created by CAD AVEVA Marine software (2017). The structure is constituted by deck plate, longitudinal girders, transversal frames, longitudinal stiffeners placed between girders, and two longitudinal walls along with its stiffeners. In the AVEVA Marine model, the longitudinal stiffeners placed between girders and the stiffen-ers placed on two longitudinal walls were taken into consideration as beam members (Fig. 6).

Results and discussions

The AVEVA Marine based optimisation workflow was successfully validated and the obtained results are presented in this section. The communication between all integrated software and tools are a fully automatic process, without any manual intervention on the graphical user interface.

The convergence of the solution is obtained after 246 iterations. The total calculation time for one run is about one minute (the total run takes about 4 hours).

Fig. 8 shows the structural models along with its FE results for various iterations for the AVEVA Marine case study, and shows the convergence histories of the objective function (*i.e.* the total weight of the structure) and the structural constraint (*i.e.* the maximum Von Mises stress) with a multihistory chart. The optimum is reached after 209 iterations.

Fig. 6. Deck structure model - AVEVA Marine

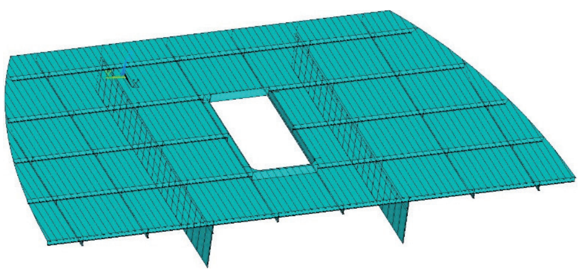
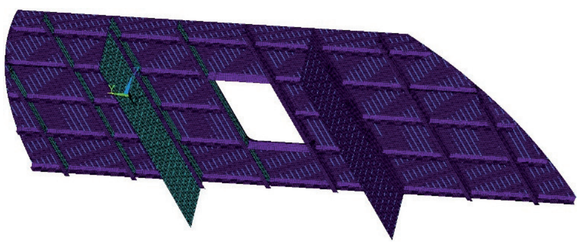


Fig. 7. Typical FE mesh model – Ansys



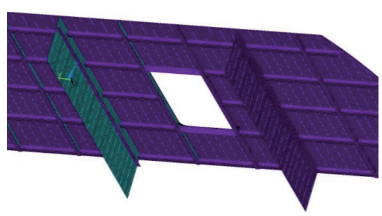
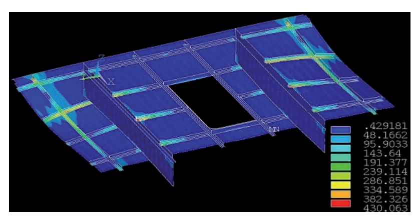
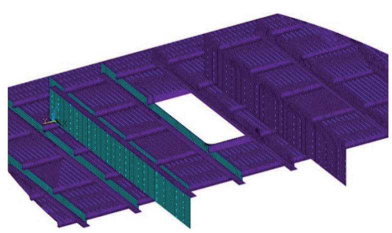
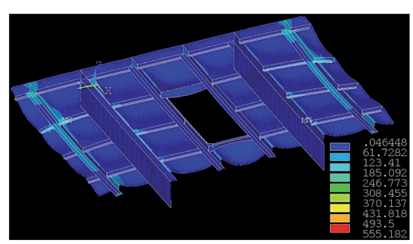
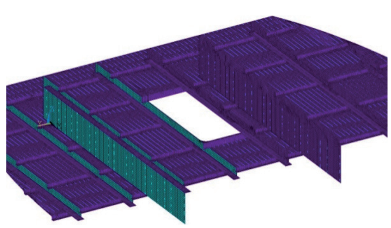
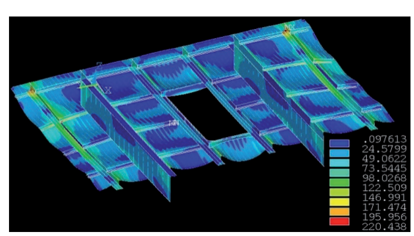
Holiship, an holistic framework for ship optimization (EU project, H2020, 2016-2020)

Holiship (2016): the aim is to develop tools and optimization methodologies for the initial and contract design phase in terms of structure and producibility aspects.

In the detail design phase (Fig 9), CAD and FEM models are available and can be used by Holiship simulation kits to assess and update (optimize) the design considering the owner's and yard requirements.

The Holiship project, in addition to "Hydro" and "Life Cycle", addresses the structural and functional simulation and optimization (Fig. 9). To go into further details there would be development/ workflow for structural simulation/optimization

Fig. 8. Structural models with FE results for different iterations (AVEVA / Ansys)

Iteration	Structural Model (AVEVA)	FE Results (ANSYS)
Initial Design High Stress Level		
Iteration 176		
Iteration 210 Optimum (Lower stress)		

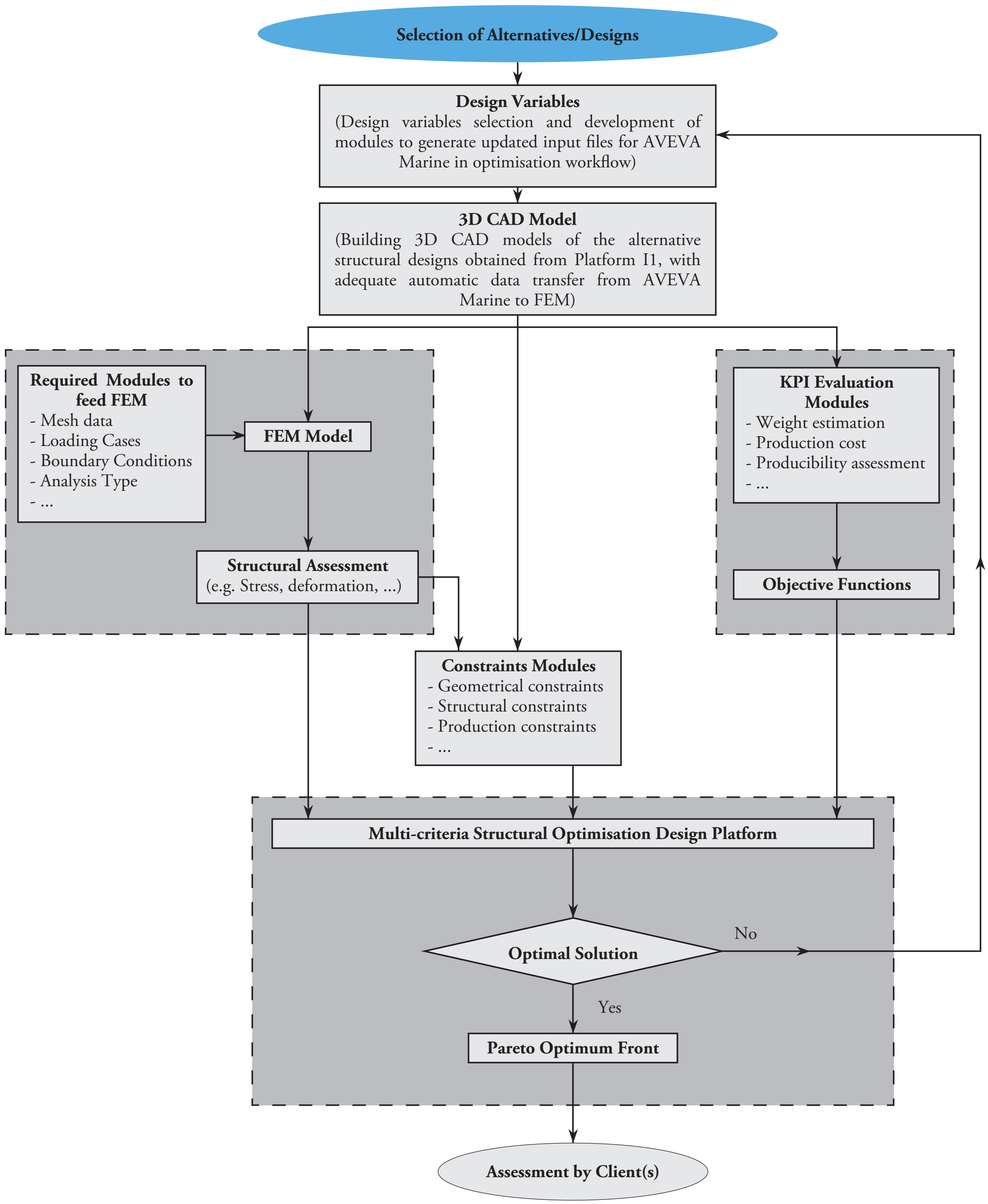
and functional optimization, interacting with each other's in some points.

Here it should be noted that the workflow provided in Fig. 9 is the continuation of the development started in BESST project (FP7).

Acknowledgment

The authors thank the members of the IMPROVE, BESTT and HOLISHIP European projects. The work was performed in the framework of the research activity carried out by the European

Fig. 9. Structural and functional optimization of the HOLISHIP Integrated Platform (Contract Stage)



Project BESST. In this regard, the authors wish to acknowledge the support given by European Community's 7th Framework Programme (FP7/2007-2013) under grant agreement N° 233980 which has been led to the results presented in this paper.

Similarly, Holiship project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme under Grant Agreement N °689074.

Ship impact on inland waterway gate infrastructures

Worldwide statistical data showed that the freight transport demand has been increasing constantly over years. Currently most of the transit is via roads, but its capacity is reaching the maximum in many parts of the world. Transportation by waterways represents an interesting alternative due to several factors, such as environmental impact (pollution and noise), road congestion, carrying capacity or cost of transport. Transportation by waterways is increasing and is expected to develop further in the near future *(PIANC WG139, 2016)*.

In addition, most international design standards must consider accidental loads when calculating structures such as navigation lock and dry dock gates *(PIANC WG106, 2009)*. This includes, in addition to others, the creation of a ship collision risk analysis, which is the product of the probability of an accident occurring and the related damage *(PIANC WG 151, 2014)*. The occurrence of a ship/lock gate collision event is low but will increase with the evolution of waterways traffic. However, failure may lead to important consequences on environmental (flood), economic (traffic is stopped, need of repairs, etc.) and social aspects.

Nowadays, design offices mainly use finite element simulations to compute the resistance of a gate impacted by a ship. This method provides accurate results but is time-demanding and therefore is not suitable for the predesign stage and risk based analysis. In any cases, many collisions scenarios have to be investigated as it is difficult to predict the most critical one.

To overcome this issue, simplified analytical methods were developed by the authors to rapidly compute the crushing force of a ship striking a lock gate. The results are validated by comparison with numerical simulations results performed with the finite elements software LSDYNA.

Super-element (SE) method

The super-element (SE) method *(Buldgen, 2014; Le Sourne, 2007)* is an analytical method that allows the computing of the behaviour of a structure submitted to a specific loading case, for which the SE was developed.

First, the global structure is decomposed into large structural units, called super-element (SE). Then, analytical formulations are derived to characterise the behaviour of each SE. Finally, an algorithm is developed to combine the effect of all the SE and get the total resistance of the structure.

This methodology was already used for offshore collisions application, in addition to others, by Le Sourne *et al*. (2012) for ship-ship collisions, by Buldgen, Rigo *et al*. (2012) for ship/lock gate collisions and by Le Sourne, Rigo *et al*. (2016) for ship/wind offshore wind turbine (OWT) collisions.

Applications for navigation lock and dry dock gates

Simplified analytical formulations were developed for plane lock gates with a single plating and an orthog-onal stiffening system, suitable for lifting gates, sin-gle leaf gates or horizontally moving gates, but also for mitre gates which is one of the oldest gate types *(Buldgen, 2014; PIANC WG139, 2016)*.

The impact location varies with the ship's direction (upward or downward) and the type of gate (upstream or downstream gate).

When the ship strikes a gate, at the beginning the structure suffers local deformations, as the penetration value is low (Fig. 13). The collided area can suffer plastic deformations which might lead to a rupture of some structural elements. As the penetration increases, large out of plane displacements occur to the entire structure and a global deformation appears (Figs. 12, 13).

In order to apply the super-element method, the lock gate must be decomposed into large structural units called "Super-Element (SE)". For a plane lock gate, different types of SE are required, as presented in Fig. 10:

- Type (1) is a plate SE clamped on its four edges which is submitted to out-of-plane displacement. This SE is used to model the plating of the gate which is limited by two horizontal girders and two vertical frames.
- Type (2) is a girder SE used to model parts of frames limited by two girders (vertical elements) or parts of girders limited by two frames (horizontal elements). These SE are considered as plates supported on three edges.
- Type (3) are X or T-shaped SE elements used to model the intersection of the vertical frames with the horizontal girders.

The resistance of the gate P (δ) can be evaluated by combining the local resistance $P_{1.}$ (δ) and the global resistance $P_{r.}$ (δ). The local resistance $P_{1.}$ (δ) is defined as the reaction of the gate when only local deformations occur due to ship collision and is only derived for a rigid plastic material, without considering the overall motion of the gate. The global resistance $P_{r.}$ (δ) is defined as the

Fig. 10. The geometry of the gate and the three super-element types considered for modelling

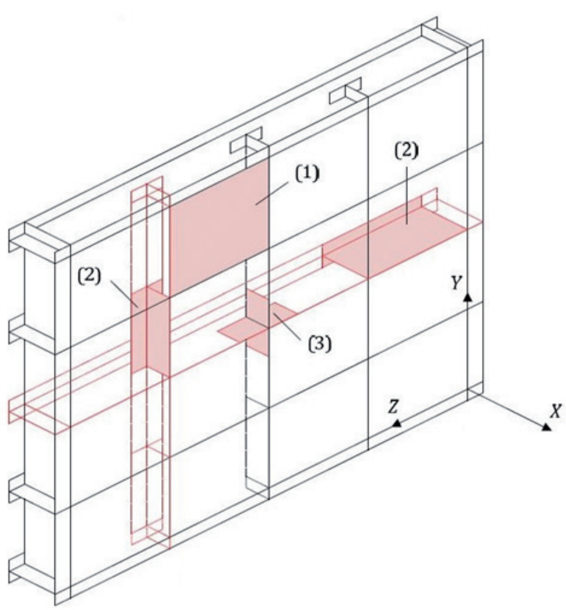


Fig. 11. Local deformations of a SE Type 3 (Von Mises stresses)

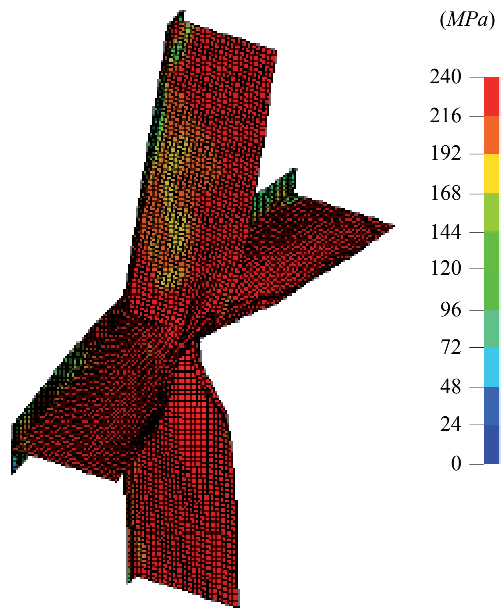
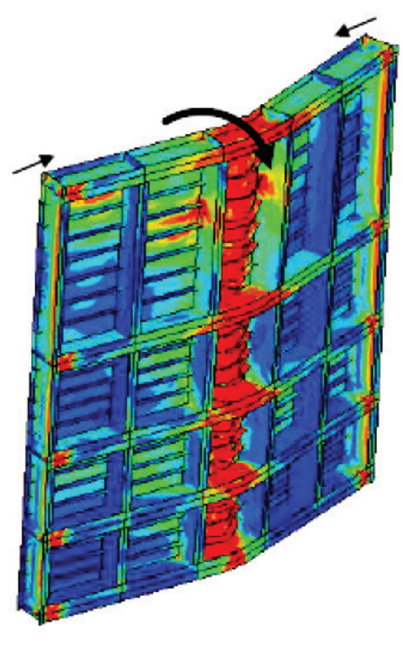


Fig. 12. Global deformation of a plane gate



reaction of the lock gate when the striking ship moves forward imposing an overall bending of the structure. First an elastic plastic solution is derived which is combined with the local resistance $P_{1.}$ (δ) in order to obtain the resistance during the local deformation mode. Second, the resistance during the global deformation mode is evaluated by using a rigid plastic solution of the global resistance.

The total resistance computed with this analytical method is compared with the results obtained with finite element simulations performed with the LS-DYNA software. The comparison in terms of crushing force and dissipated energy with regard to the vessel penetration for a collision of a typical vessel on a plane lock gate are plotted in Fig. 13.

Development of inland waterway classifications in South America

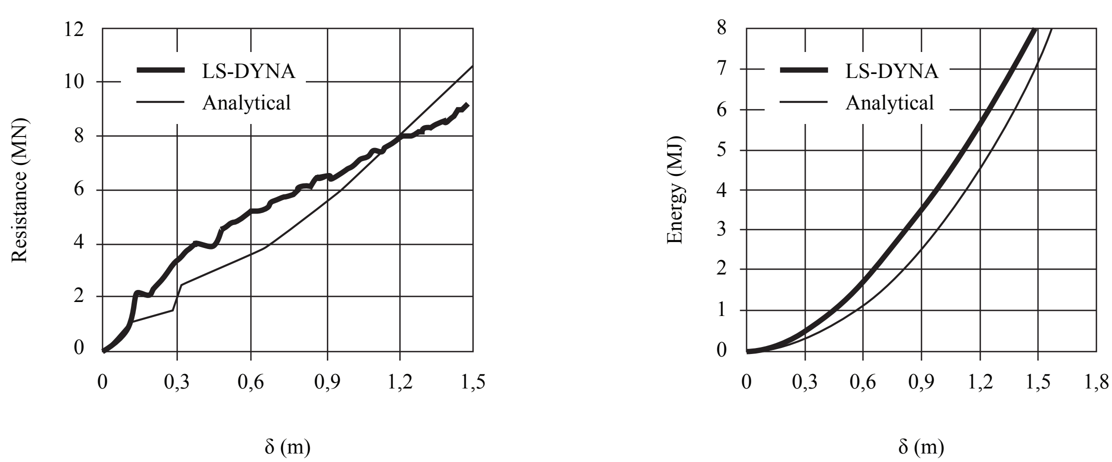
South America has to take full advantage of its extensive system of naturally navigable waterways or to integrate them into the region's transport network to cater for the ever-increasing demand for cargo and human mobility. The modal shares of inland shipping in the region's international transport are less than one percent in terms of value and volume *(Wilmsmeier and Spengler, 2015)*. Nevertheless, the evolution of international transport in inland navigation has been positive over the last decade.

Inland waterways are not only used for transport between the countries of the region, located along the river basins, but are also the first leg of international transport flows with other regions of the world. Examples of the latter are natural resource exports (soybean products, aluminium, and oil related products) from the Paraguay-Paraná, Orinoco and Magdalena river basins that are destined for the Europe, the US or Asia. In these cases, seagoing vessels are directly deployed from the ports along these river systems. While the values of these exports have more than tripled since 2002, in some waterways the volumes have shown a decreasing tendency over the last years but hopefully not everywhere as in Paraguay-Paraná IW.

In South America, there are several independent inland waterway systems, which have different levels of development. For some of these systems, and from a macro perspective view, the uses of the inland waterway systems in the region are challenged by various factors. These factors include:

- Incomplete, outdated or absent national and regional norms and regulatory frameworks;
- Lack of common inland waterways classifications in South America standardizing the inland navigation at national and 'supranational' levels;
- Lack of standardization of fleets, vessel, and control procedures.
- Lack or absence of investment in the construc-tion and maintenance of waterway infrastructure and inland ports;

Fig. 13. Crushing force and dissipated energy for a ship - plane lock gate collision



- Delay and lack of administrative structures and building of institutional capacity (capacity in this case refers to human and financial capital);
- Lack or absence of navigation aids, including updated maps, electronic charts, signals, and other navigational services as RIS;
- Lack of qualified labour and institutions for capacity building and training of qualified labour

These challenges limit the past, current, and future potential of inland navigation and the current situation affects not only the wider use of this mode of transport, but also its integration with other modes, generates inefficiencies, such as cargo losses, and results in relatively high costs of transport at local, regional, and national level.

A shared inland waterway classification for South America can be a first milestone in developing inland shipping prospects. Indeed, past experiences such as CEMT'92 (1992) have shown that such classifications are far from being a formality or a purely academic exercise, but an essential, powerful and dynamic tool for supporting and implementing inland waterways policies and projects as they allow the limitations and the economic potential of navigable waterways in the region to be identified and to encourage and monitor the development of their capacity for the transport of goods and people *(Jaimurzina et al., 2016)*.

In October 2016, at the ECLAC/PIANC/ ANTAQ Seminar on Inland navigation and a more sustainable use of natural resources: networks, challenges, and opportunities for South America (Rio de Janeiro, Brazil), the representatives of the South American countries (including Colombia) with interest in inland navigation and the PIANC experts (PIANC 1990, 1996, 1999 and 2019 from Europe, Northern America and Asia supported the idea of creating a regional classification for inland waterways in South America and recommended the creation of a dedicated working group on the issue.

Objectives

The main objective of this initiative *(ECLAC, PIANC, 2016)* is to develop and implement a strategy for a common supra-national inland waterway classification for South America, combining the knowledge of ECLAC (CEPAL) and PIANC and drawing on the experience of other regions of the world.

EMShip, a unique european master's programme in ship & offshore structures

The EMShip programme (www.eship.eu) is unique and it is the only master's degree in *"Advance Design in Ship & Offshore Structures"* awarded by the prestigious European Erasmus Mundus Program. Indeed, EMShip shares the outstanding experiences of educa-tors, trainers, industrial partners and students in the rapidly developing areas of marine and offshore engineering industry.

The EMShip Master Course "*Integrated Advanced Ship Design* - www.EMSHIP.eu" was developed and is run by seven universities in six different European countries (Fig. 14). After 1.5 years (3 semesters) with a total of 90 credits, graduates earn a Dual Degree: one Master Degree awarded by the University of Liege in Belgium: *"Advanced Master in Naval Architecture"* and the second by the Ecole Central in Nantes, France: *"Master of Sciences in Applied Mechanics, specialization in Hydrodynamics, Energetics and Propulsion"*.

Students enrolled have the opportunity to take lectures in three European countries: after the first semester in Belgium and the second in France, they can decide to either complete their degree at University of Galati in Romania, University of Genoa in Italy, University of Rostock in Germany, West Pomeranian University of Technology in Po-land or at the ICAM (Engineering School) in France (and many others).

Fig. 14. EMShip Partners – www.EMShip.eu

Mobility Scheme

The mobility scheme, being a fundamental component of the programme, gives the students the opportunity to experience a variety of academic and cultural environments and to greatly benefit from the multicultural nature of the student population in the master's degree course and the networking instruments for students and staff. An internship forms an integral part of the programme for which many leading European maritime companies offer positions as they strongly support the international EMShip EMMC. In reality this setup means that students have to take residence at four locations in Europe (and sometimes worldwide) while being enrolled in the EMShip programme.

Industry Relevance

Shipbuilding is a fundamentally interdisciplinary discipline which has always been global and provides the means for an economically and ecologically highly efficient and safe transport. Europe has developed a clear perspective on maritime technologies as waterborne transport is regarded as being essential for economic and ecologically sustainable growth. The European maritime industry holds a firm market position; the need fot competent partners worldwide with a sound knowledge of European culture and values, with valuable experiences achieved in Europe is regarded as being inevitable.

Europe for example holds the leading position in developing and supplying ship design consultancy, complex ship onboard systems, passenger vessel and mega yacht design and production with many famous shipyards in Italy, France, Germany, Holland and Finland. A similar situation is observed in the offshore market. This business has been booming for several years in Norway and the UK (oil and gas), Denmark and Germany (wind energy turbines). Innovative, modern ships (PSV, OSV) and offshore installations are designed, repaired and produced in Norway and Poland.

Global Network

To be able to recruit the best students, to be aware about the demands of the students from all over the world and to continuously develop the quality of the program, 8 additional associated partner universities have joined the consortium (Fig. 14). These are the University of Michigan (NA&ME, USA), University of Osaka (NAOE, Japan), Federal University of Rio de Janeiro (UFRJ, Brazil), University of New South Wales (UNSW, Australia) and the Pusan National University (NPU, Korea)…..

Recruitment Statistics

In February 2017, after 7 intakes, more than 170 students will have graduated from the EMSHIP program, including 6 Colombians (two from COTECMAR). These students have been selected from almost 2000 applicants strictly following a selection scheme, mainly based on the students' skills and results achieved in their previous Education program (MSc, MSc). Additionally the consortium selects students in such a way that each yearly cohort is an international group with a large diversity of ori-gins and backgrounds, guaranteeing a study environment which fully supports a qualification on an inter-national level (Fig.15).

Acknowledgments

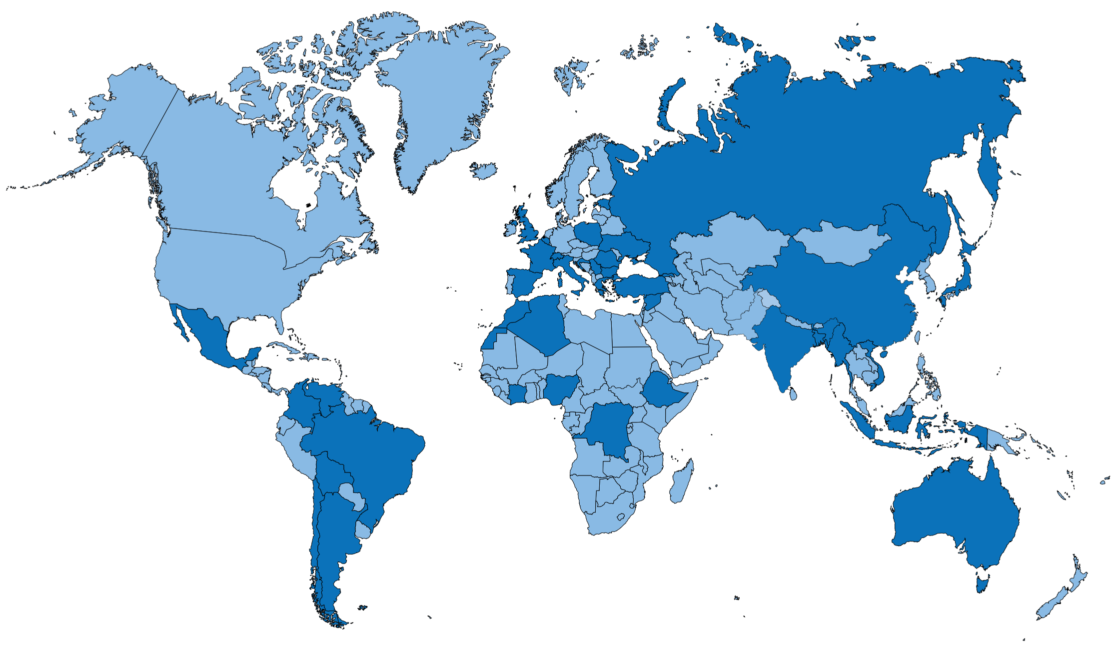
The EMSHIP Consortium Universities warmly thank the Erasmus+ Programme of the European Union for their support.

Conclusion & promotion of an effective waterway infrastructures to support the global economic growth in South America

Rivers and waterways are natural transportation modes and we should use them more extensively to sustain the future world economic development, and particularly in South America.

The economic development of a country or a re-gion always requires effective transportation modes. Our purpose is not to promote Inland Waterways (IW) versus road or train, but to claim that a sustainable future development requires the sustainable transportation of goods and persons. This can only occur by using multi modal transportation, combining sea transport, Inland navigation, road, train (and air).

Fig. 15. Nationalities of EMSHIP students



To reach said sustainable development, the share of the inland navigation must be increased, as it is much more environmental friendly than other modes.

Inland navigation and their associated waterways infrastructure elements (port, quay, navigation, lock, flow regulation weirs, dredging, etc.) are not only important for transportation but also for:

- Hydro-electricity → power plant;
- Environment protection (fishes, plants, etc.) → fish passages and natural bank protection;
- Tourism (along the rivers, and on the river, yachting), walk paths along rivers and parks, ports and marinas, etc.;
- Fishing activities (quay, port, etc.);
- and of course, flood protection (dredging, flood-ing areas, etc.).

In the modern cities, all these activities related to waterways must be considered, none can be neglected, otherwise the "public, the media, and lobbies" will not accept it.

Therefore, our recommendation is to develop a strategic plan to develop natural waterways and move to a *"waterway of the future"*, which will be multidisciplinary tools to promote the economic but also social, living and sustainable environment. The proposal of CEPAL and PIANC to establish specific waterway classifications in South America could be the first step.

In parallel to that, specific studies on waterway in-frastructures must be performed (for more information see www.PIANC.org) and also on the design of specific inland waterway ships/vessels (cargo, LNG, passengers, etc.) and the associated facilities (ports and multimodal platforms), for inland navigation, in universities, research centres, public administrations, and various associations such as COTECMAR.

Inland navigation requires multidisciplinary knowledges and expertise [technical (for ship and infrastructures), economic (transport model), social and environmental]. Ship designers and ship owners cannot improve the navigation (and economic growth) by themselves, they should collaborate with waterway managers responsible for infrastructures and with the persons/companies/associations who are living, using and working along/on the waterways.

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EMSHIP and EMSHIP+; www.emship.eu, coordinated by ULg, Dr. Rigo Ph, ph.rigo@ulg.ac.be

Numerical hull resistance calculation of a catamarán using OpenFOAM

Simulación numérica de la resistencia al avance de un catamarán usando OpenFOAM

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Rubén J. Paredes Alvarado [2]

Abstract

In the present study, numerical resistance predictions using OpenFOAM were performed considering the Cormorant Evolution Catamaran, which provides travel services in the Galapagos Islands. These predictions were compared with experimental data published by Chávez and Lucín [1] and with systematic series [2]. Simulations were made at model scale of 2 [m] in two load conditions, considering demi and twin hull (s=0.56 [m]) configurations. A mesh convergence study was performed with 3 different meshes for V=1.05 [m/s] at Light Condition (T=0.086 [m]). The converged mesh, with 1 million of cells approximately, has the lower standard deviation and a 5% error when compared to its experimental value of 1.79 [N]. The errors between the experimental data and the numerical simulations for demi hull configuration were 43% and 36% for Light and Full conditions, respectively. Besides, for twin hull configuration the errors were around 14% and 32% for Light and Full conditions, respectively.

Key words: Catamaran, CFD, resistance, interference.

Resumen

En el presente estudio, predicciones numéricas de resistencia usando OpenFOAM fueron realizadas considerando el Catamarán “Cormorant Evolution”, que ofrece servicios turísticos en las Islas Galápagos. Las predicciones numéricas fueron comparadas con datos experimentales publicados por Chávez y Lucín [1], y con métodos estadísticos [2]. Las simulaciones fueron realizadas con un modelo de 2[m] en dos condiciones de carga, considerando uno y los dos cascos (s=0.56 [m]). Se realizó un estudio de convergencia con tres mallas para V=1.05 [m/s] en condición ligera (T=0.086 [m]). La malla seleccionada contiene alrededor de 1 millón de celdas y presenta un error del 5% frente a una resistencia experimental de 1.79 [N]. El promedio de los errores entre datos experimentales y simulaciones numéricas para un casco son del 43% y 36% para condición ligera y cargada, respectivamente. Por otro lado, los errores para dos cascos son del 14% y 32% para condición ligera y cargada, respectivamente.

Palabras claves: Catamarán, CFD, resistencia, interferencia.

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Abbreviations

CFD Computational Fluid Dynamics
Exp Experimental
OF OpenFoam
RANS Reynolds Average Navier-Stokes
Rt Total Resistance in Newtons [N]
S Separation distance between the hulls (m).
Sta. Dev. Standard Deviation
T Model draft (m)
V Velocity of the simulation fluid (m/s)

Introduction

The resistance of a ship at a given speed is the force required to tow the ship at that speed in calm water, assuming no interference from the towing ship [3]. The ship must provide the minimum shaft horsepower to cruise at required velocity.

Ship resistance estimation is a complex task. It can be broken down into frictional and residual components. In addition, there is an additional component in the case of catamarans, such as the interference between the demi-hulls. There are three different methods to predict ship resistance: empirical methods, model testing and numerical simulations.

In the last years, numerical simulations using CFD have become a third alternative used in the industry. The CFD solution is a numerical method to solve the nonlinear differential equations governing the fluid flow. However, it cannot be used as a black box because it can produce spurious results if not set correctly. It is required to perform a verification and validation procedure, usually using experimental data.

In this work, numerical simulations were performed to predict total resistance of a catamaran and results were validated using experimental data obtained by Chávez and Lucín [1]. OpenFOAM is used to predict the catamaran resistance. It was chosen because of its customization options, online training and support, and it is open source.

Geometry and test conditions

The "Cormorant Evolution" Catamaran was built in Ecuador in 2011 by "Astilleros y Marina BOTTO CIA. LTDA", and operates through "Cormorant Cruise" in Galapagos Islands [4]. It is a 32.5 [m] length fiberglass touristic vessel; with a "V" middle section, a bulbous bow, separation of 9.11[m] between the centerlines of hulls and a design velocity of 5.14 meters per second (10 knots). Subsequently a 2 [m] length model was built using Cormorant Evolution hull-shape, to measure experimental resistance in the lake of "Escuela Superior Politécnica del Litoral" (ESPOL) [1]. The scale factor was λ=16.25. The experiment velocity range of the model was from 1.05 to 1.45 meter per second. Table 1 shows the main characteristics of the catamaran at two load conditions.

Computational method

Open Source Field Operation and Manipulation (OpenFOAM) is a free source code with C++ programing language. This code creates executable

Fig. 1. Experimental test at ESPOL Lake

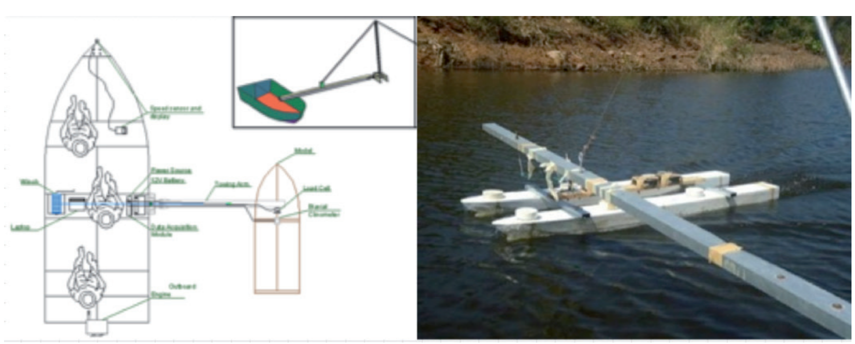


Table 1. Catamaran scale model dimensions

	Light Load	Full Load
L [m]	2.00	2.00
Bcat [m]	1.87	1.89
S [m]	0.561	0.561
T[m]	0.086	0.103
Δ [ton]	0.018	0.024

scripts, called applications that are divided in two categories: solvers developed for specific problems in continuum mechanics, and utilities developed to manipulate data. Fig. 2 shows the workflow of OpenFOAM.

There are three physical laws that govern a fluid flow: Conservation of Mass, Conservation of momentum, and Newton's Second Law. However, these equations cannot be solved analytically for all types of problems.

One alternative is to solve them numerically using Computational Fluid Dynamics (CFD). In real applications, fluids flow is turbulent and it can be modeled by RANS technique. The governing equations are:

Reynolds Average Navier-Stokes

$$\rho\frac{\partial U_i}{\partial t}+\rho U_i\frac{\partial U_i}{\partial x_j}=-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left(2\mu s_{ij}-\rho\overline{u_j'}\,\overline{u_l'}\right) \quad (1)$$

For linear eddy viscosity models, RANS need some extra terms (transport properties) to represent the turbulence properties of the flows. In this work turbulence is modeled using the k-Omega SST method, which is a two-equation linear eddy-viscosity model.

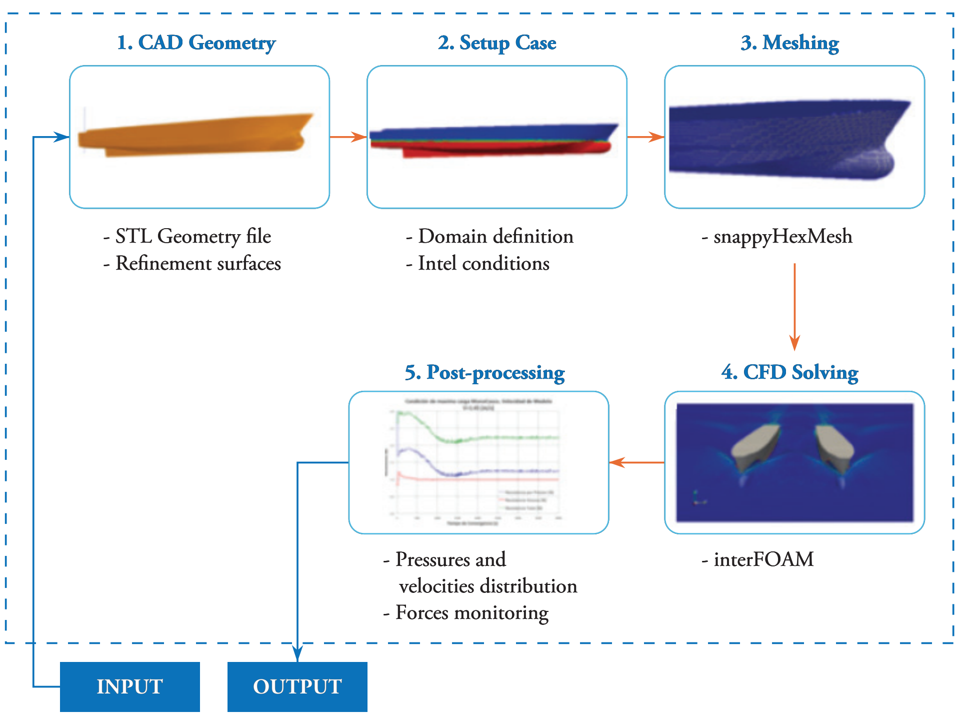
Turbulence kinetic energy

$$\frac{\partial k}{\partial t}+U_j\frac{\partial k}{\partial x_j}=P_k-\beta^*k\omega+\frac{\partial}{\partial x_j}\left[(\nu+\sigma_k\nu_T)\frac{\partial k}{\partial x_j}\right] \quad (2)$$

Specific dissipation rate

$$\frac{\partial \omega}{\partial t}+U_j\frac{\partial \omega}{\partial x_j}=\alpha S^2-\beta\omega^2+\frac{\partial}{\partial x_j}\left[(\nu+\sigma_\omega\nu_T)\frac{\partial \omega}{\partial x_j}\right]+2(1-F_1)\,\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_i}\frac{\partial \omega}{\partial x_i} \quad (3)$$

Fig. 2. OpenFoam Workflow



The following assumptions about the numerical model to be implemented are considered:

i. Steady, turbulent and three-dimensional flow.
ii. Single-phase flow.
iii. Uniform velocity.
iv. Constant air and water properties.

For marine applications, two solvers can be used for multiphase flows, interFoam and interDyFoam. In this thesis, the InterFoam solver is applied because only ship resistances are measured in experiments. InterFoam is a solver for two incompressible, isothermal immiscible fluids using a volume of fluid phase-fraction based interface capturing approach [8]. The computational domain includes fresh water and atmosphere.

y^+ is the non dimensional distance and OpenFOAM is a post processing tool applied to near-wall cells of all wall patches. The value obtained by y^+ can describe the places where the mesh has to have a greater number of cells. y^+ is defined by:

$$y^+ = \frac{u_* y}{v} \tag{4}$$

Where u_* is the frictional velocity at the nearest wall, y is the distance to the nearest wall and v is the local kinematic viscosity of the fluid.

Results

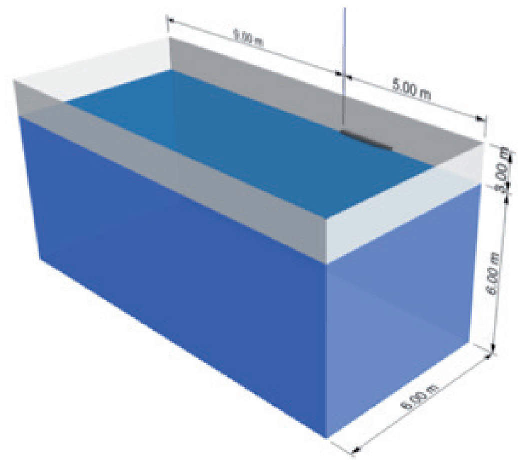
3D Generation model

The 3D surface model was generated with the body and profile plan in the Computer Aided Design (CAD) software Rhinoceros 3D [5] and positioned after the perpendicular line at the origin axes before exporting as a STL file to import into the CFD code, OpenFOAM. Fig. 3 shows the 3D Rhinoceros scaled demi-hull model.

Domain, grids and boundary conditions

The computational domain was built as a rectangular block around the hull (demi and twin hulls) in deep water; Fig. 4 shows the principal dimensions in meters.

Fig. 4. Catamaran domain size



Verification and validation

To identify the mesh density needed for the Catamaran cases a mesh convergence study was perform. The domain was divided into six blocks with different mesh densities. Table 2 shows the number of cells for each mesh.

To visualize the convergence of the simulations, Fig. 5 shows the force time history (4,000

Fig. 3. Scale Cat. 3D model

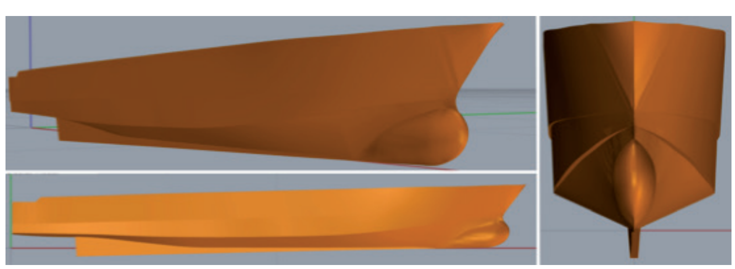


Fig. 5. Total Resistance along the setting time of convergence for different mesh densities

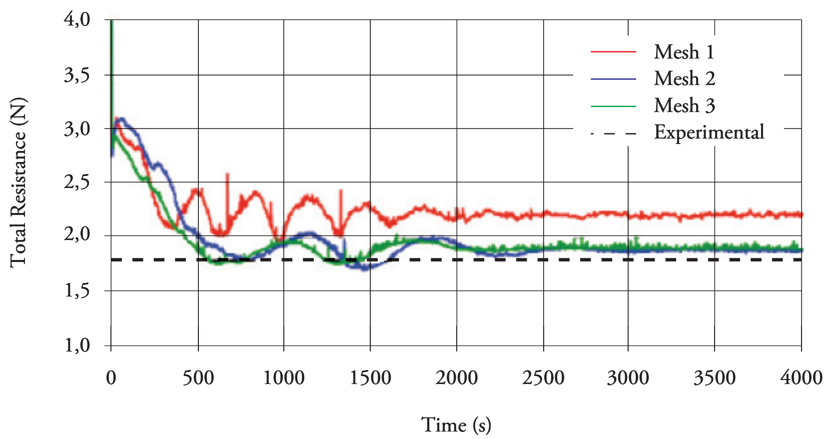


Table 2. Number of cells by each types of mesh

Type of Mesh	Nº of Cells
Coarse - Mesh1	250,599
Medium - Mesh2	1'000,278
Fine - Mesh3	1'566,579

seconds – Fixed time step 1 per second) for each mesh.

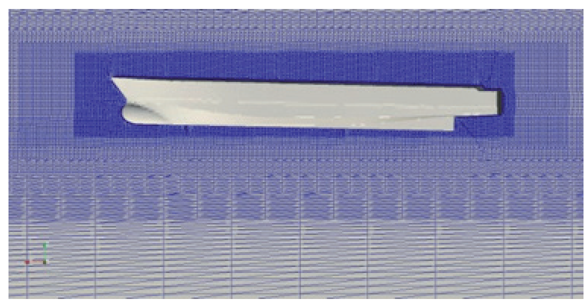
Four thousand values of resistance were generated at the Light Load condition at v=1.05 [m/s]. Table 3 shows the average of the last five hundred values for the resistance of each mesh and its error when compared with an experimental value of $R_{t\,exp}$=1.79 [N].

Table 3. Catamaran scale model dimensions

	Resistance Average	% Error	Sta. Dev.
Mesh 1	2.22	24%	0.71
Mesh 2	1.88	5%	0.34
Mesh 3	1.91	6%	0.50

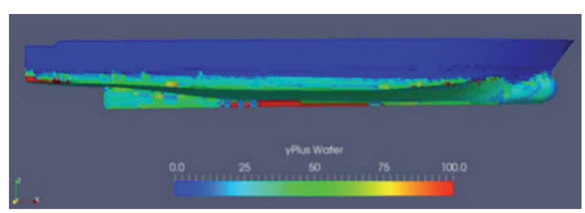
The errors between meshes 2 and 3 are closer. But, analyzing the standard deviation, Mesh 2 has less variation of resistance in the analyzed steps. Mesh 2 was selected to set up the other simulations. Fig. 6 represent the mesh 2 configuration around the hull.

Fig. 6. Mesh around the catamaran hull



As a post-processing tool, y^+, was calculated to verify the mesh quality near the hull. A value of y^+ ≤100 is acceptable for the case of the catamaran. Fig. 7 shows the wall y^+ parameter for the submerged hull.

Fig. 7. y+ of water, for ligth condition at v=1.05 [m/s]

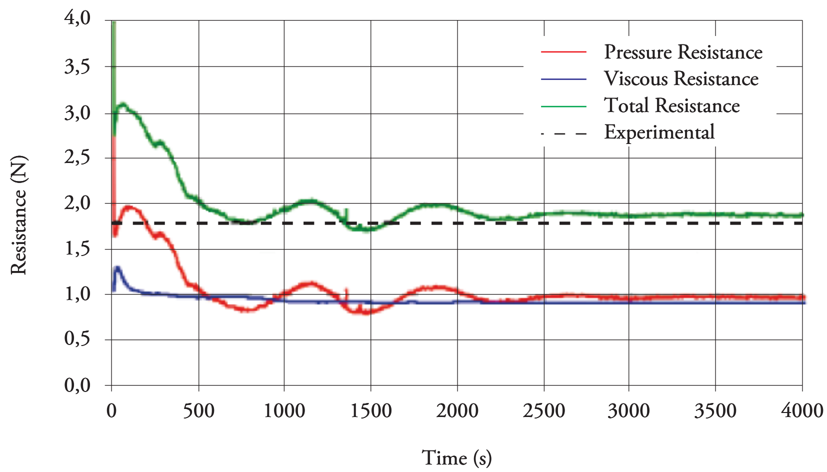


Bow, Stern and central keel are zones that required a grater mesh density.

Resistance

OpenFOAM calculate the forces components acting in Catamaran hull, namely pressure and

Fig. 8. Resistance components at v=1.05 [m/s]



viscous. Fig. 8 shows Pressure and Viscous force components for the case of demi-hull in Light Condition at a velocity of V=1.05 [m/s]. The experimental resistance is 1.79 [N] at Fn=0.2453.

Total resistance was obtained by adding pressure and viscous forces.

Demi Hull Catamaran Resistance

The model was simulated following the experimental data [1], and compared with Maxsurf-Resistance. For demi hull Maxsurf-Resistance case, Holtrop method was used.

Table 4 and 5 present the data obtained by OpenFOAM simulations at different velocities in two Load Conditions. The percentage of standard deviation was obtained by [1]:

$$Sta.Dev. = \frac{Standard\ Deviation}{OpenFOAM\ average\ R_t} \tag{5}$$

Figs. 9 and 10 shows the total resistance by OpenFOAM, experimental data and Maxsurf for demi hull. The simulation standard deviation it's about 0.63%, due this cannot be displayed.

Twin Hull Catamaran Resistance

The model was simulated following the experimental data [1], and compared with Maxsurf-Resistance. To simulate the catamaran structure in OpenFOAM, the hull was displaced into the computational domain a distance S=0.2805 [m], measured from the centerline of ship to centerline of the hull, Fig. 11 shows the distribution.

Table 4. OpenFoam Resistance data for demi hull in light condition

Fn	V [m/s]	OF. Rt [N]	Exp. Rt [N]	% Err
0.2453	1.05	1.88	1.79	5
0.2663	1.14	2.15	3.91	45
0.2803	1.20	1.16	3.60	68
0.3037	1.30	2.81	5.26	47
0.3387	1.4	3.54	7.01	49

Table 5. OpenFoam Resistance data for demi hull in load condition

Fn	V [m/s]	OF. Rt [N]	Exp. Rt [N]	% Err
0.2393	1.03	2.08	3.08	33
0.2556	1.10	2.39	4.12	42
0.2858	1.23	2.92	4.57	36
0.3137	1.35	3.78	5.58	32
0.3369	1.45	4.43	7.00	37

Fig. 9. Total resistance for demi hull in light condition

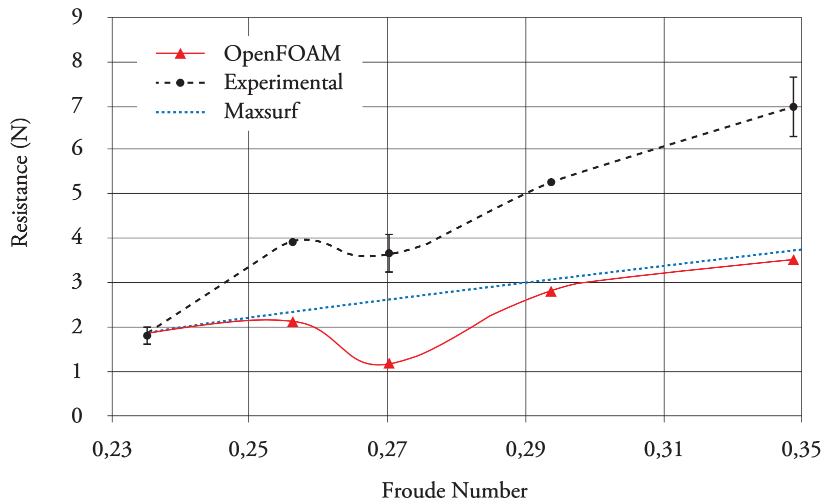


Fig. 10. Total resistance for demi hull in load condition

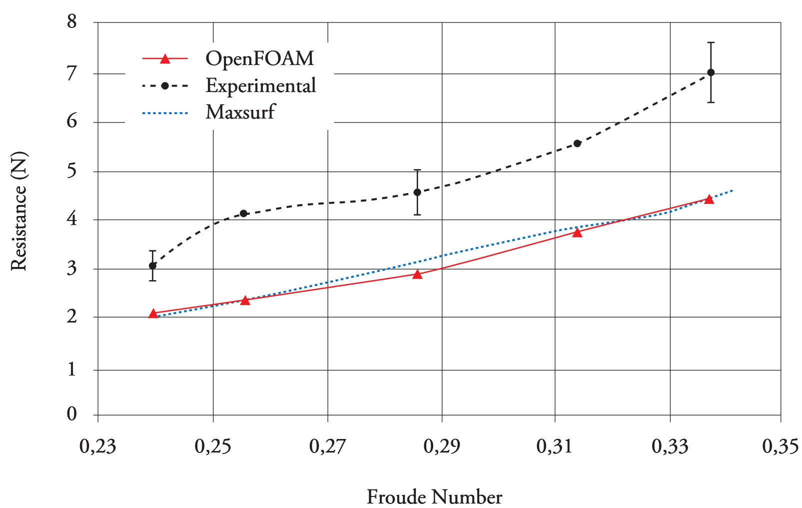


Fig. 11. Total resistance for demi hull in load condition

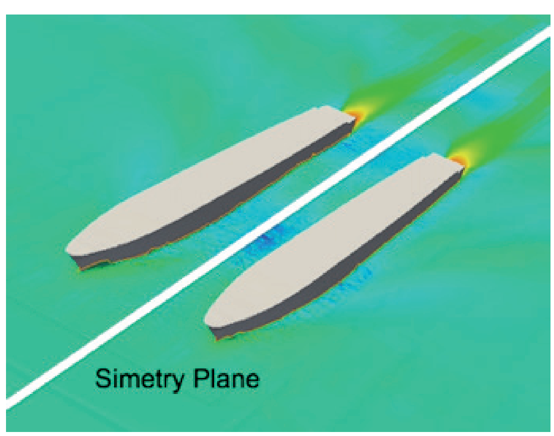


Table 6 and 7 present the data obtained by OpenFOAM simulations at different velocities in two Load Conditions.

Figs. 12 and 13 shows the total resistance by OpenFOAM, experimental data and Maxsurf for demi hull.

Table 6. OpenFoam resistance data for twin hull in light condition

Fn	V [m/s]	OF. Rt [N]	Exp. Rt [N]	% Err
0.2453	1.05	3.87	5.11	24
0.2663	1.14	4.51	4.80	6
0.2943	1.26	5.36	6.14	13
0.3083	1.32	6.08	7.76	22
0.3574	1.53	8.01	10.32	22
0.4111	1.76	11.97	12.07	1
0.4532	1.94	15.40	13.29	16

Table 7. OpenFoam resistance data for twin hull in load condition

Fn	V [m/s]	OF. Rt [N]	Exp. Rt [N]	% Err
0.2440	1.05	4.36	7.91	45
0.2602	1.12	4.87	6.88	29
0.2904	1.25	6.13	10.06	39
0.3090	1.33	7.52	10.54	29
0.3392	1.46	9.64	12.14	21
0.3602	1.55	10.20	14.54	30
0.4066	1.75	14.24	20.62	31

Fig. 12. Total resistance for twin hull in light condition

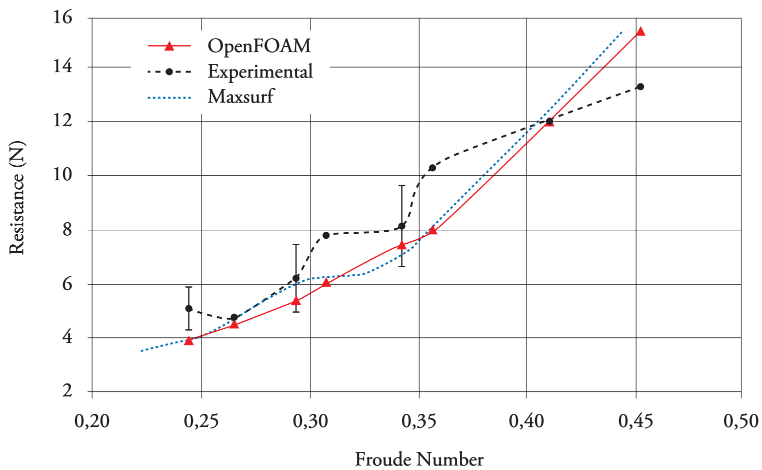
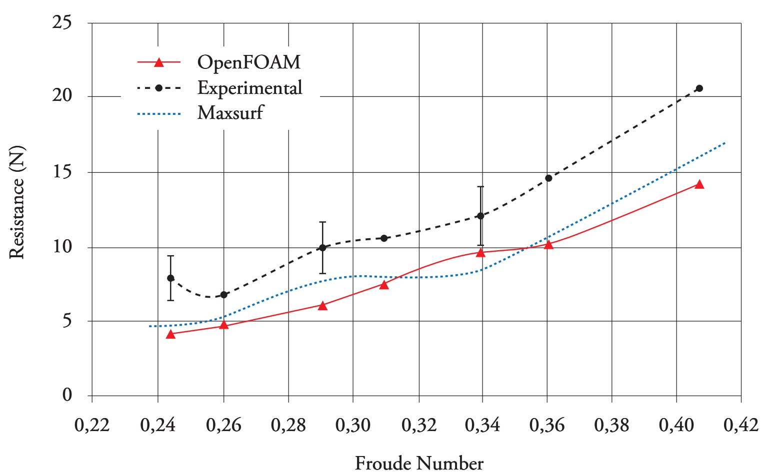


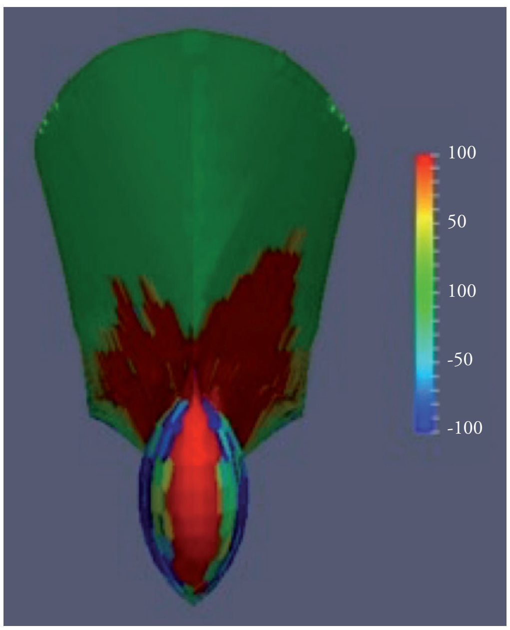
Fig. 13. Total resistance for twin hull in load condition



The errors between experimental data and numerical simulations are lower in light condition of catamaran. However none of the curves follows the same trend.

Fig. 14 shows the pressure distribution the hull for Fn=0.34 (v=1.45 m/s). The labels of dynamic pressure was setting to capture as blue ones the zones with negative pressure and red ones the zones with positive pressure. For twin hulls, the pressure in the inner side of the hull is slightly greater than the pressure on the outside of the hull; this is due to the interference caused by the other hull.

Fig. 14. Pressure around the bulbous for twin hull



Interference

The catamaran interference was estimated following the expression [1]:

$$R_W = \frac{R_{T\,CAT} - 2R_T}{2} \qquad (6)$$

Where:

R_W is the demi hull interference in Newton
$R_{T\,CAT}$ is the total resistance of twin hulls in Newton
R_T is the total resistance of demi hull in Newton

Figs. 15 and 16 shows the interference factor for original hull separation at Light and Full load conditions.

The interference factor obtained by numerical simulations is linear contrasting with the experimental interference published by Chávez and Lucín [1]. The positive interference corresponds to increased interference (unfavorable) and the negative values to decrease (favorable).

Wave pattern

Figs. 17 to 19 shows the wave pattern for different Froude numbers in Full load condition.

The blue areas correspond to the hollow of the wave and the red areas to the hump. Of these three

Fig. 15. Interference for light condition

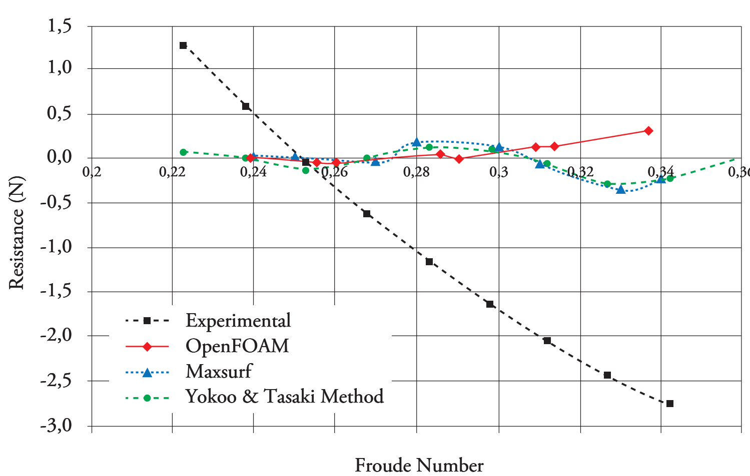


Fig. 16. Interference for load condition

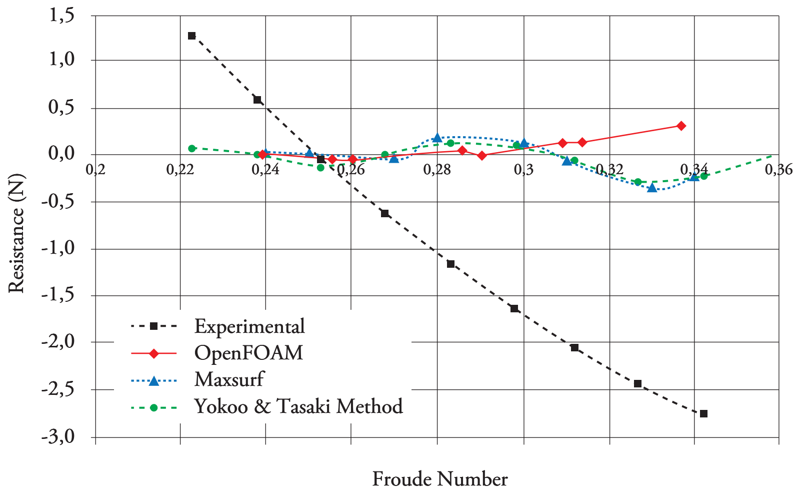


Fig. 17. Wave pattern at Fn=0.24

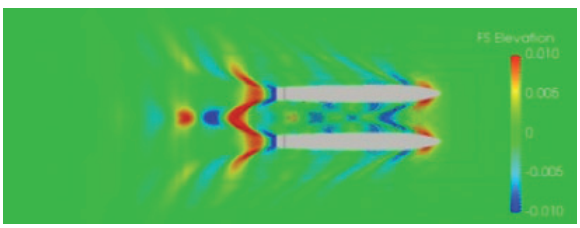


Fig. 18. Wave pattern at Fn=0.31

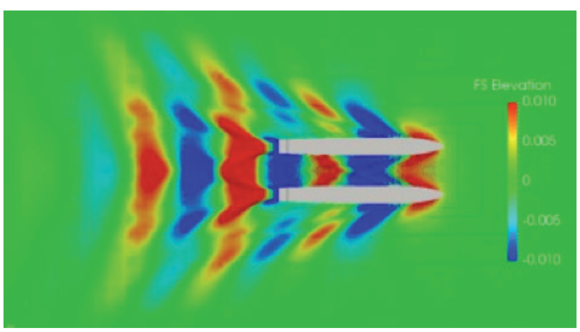
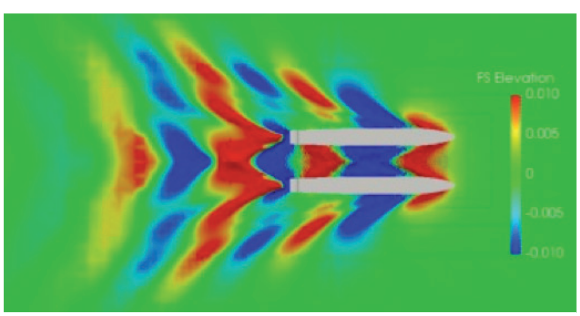


Fig. 19. Wave pattern at Fn=0.34



figures it is emphasized that as the speed of the simulation increases the amplitude and the length of the wave increase. Also, the wakes pattern from the lowest to the highest velocity produce the increase in zone of interference.

Conclusions

Before starting the Catamaran numerical resistance, several tutorials were carried out using the OpenFOAM user manual [6]. These tutorials were of great help to understand the capabilities and limitations of the software. *Cavity* was the first made tutorial, for laminar and incompressible flows. The user manual gives an overview of the workflow of OpenFOAM: Pre-processing, solution and Post-processing. ParaView is a post-processing tool; the user manual also gives an introduction of its operation. This was an important step for understanding OpenFOAM and the principles of fluid analysis.

A catamaran mesh convergence study was developed first, with 3 types of mesh for a demi hull at Fn=0.2453. Mesh 2, with 1 million of cells, was chosen to the simulation because had the lowest error and standard deviation at R_{texp}=1.79 [N], error=5% and Sta. Dev.=0.34 [N]. Due the extensive time of resolution, the interDyMFOAM solver was not taken into consideration in the Catamaran hull. Two load conditions were implemented for demi and twin hulls. The errors for Light Load Condition were: 42.8% in Demi Hull and 14.0% in Twin Hull configurations. The errors for Full Load Condition were: 36.0% in Demi Hull and 32.0% in Twin Hull configurations.

Numerical simulations using OpenFOAM are a feasible method for predicting the resistance of the Cormorant Evolution catamaran, despite the difference between experimental data and numerical simulation resistance. However, numerical results are close to statistical methods, such as Holtrop and Molland, estimated with Maxsurf Resistance software.

The interference component between the twin hulls was estimated for Full and light Load conditions for Fn between 0.24 and 0.34. But these results were not those expected, because the curves of interference did not display the same trend. Also, the interference factor was calculated using the Maxsurf data and even though it was not very close, the Maxsurf interference had the same trend compared to numerical data.

These variations between experimental results and numerical simulations may be due to external factors, that can not be controlled or measured, such as: wind, water temperature, interference between the method of drag, towing velocity uncertainly, differences between the model and the catamaran, and range of work of Data Card available in our college.

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On the use of time-domain simulation in the design of Remotely Operated Submergible Vehicles

Uso de herramientas de simulación en el dominio del tiempo para el diseño de vehículos sumergibles operados remotamente

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Rafael E. Vásquez [3]

Abstract

Designing a Remotely Operated Vehicle (ROV) is a complicated task in which the design team deals with a considerable amount of uncertainty before the device is able to be tested at full scale. A way to cope with such uncertainty is to use simulation software to evaluate design concepts along the different levels of abstraction of the process. In this work, the use of aNySIM, the Maritime Research Institute Netherlands (MARIN) multibody time-domain simulation tool, as a part of the design process of an ROV is addressed. The simulation software is able to solve the equations of motion of the vehicle based on rigid body dynamics, including features such as hydrodynamics, hydrostatics, thrusters, thrust allocation, and PID control. Different simulation scenarios are proposed to evaluate different concept solutions to the design, including thruster parameters and distribution. The results are further used to select the concept solutions to be implemented in the final design.

Key words: Remotely Operated Vehicle Design, Time-domain simulation.

Resumen

El diseño de vehículos operados remotamente (ROV) es una tarea complicada en la cual el equipo de diseño trabaja con una cantidad importante de incertidumbres antes de que el dispositivo pueda ser probado a escala real. Una forma de reducir esta incertidumbre es usar software de simulación para evaluar conceptos de diseño a lo largo de los diferentes niveles de abstracción del proceso. En este trabajo se usa aNySIM dentro del proceso de diseño del ROV; esta es una herramienta de simulación multicuerpo en el dominio del tiempo desarrollada por el Maritime Research Institute Netherlands (MARIN). El software de simulación es capaz de resolver las ecuaciones de movimiento del vehículo con base en la dinámica del cuerpo rígido, incluyendo elementos de hidrodinámica, hidrostática, propulsores, distribución de fuerza de propulsión y control PID. Se proponen diferentes escenarios para evaluar diferentes conceptos en las soluciones de diseño, tales como los parámetros y distribución de los propulsores. Estos resultados son usados luego para para seleccionar las soluciones que son implementadas en el diseño final.

Palabras claves: Diseño de Vehículos Operados Remotamente, Simulación en el dominio del tiempo.

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Introduction

Because of the importance of the ocean for several industries such as fisheries, transportation, tourism, and offshore industry, among others, there is an increase on the use of marine-related technologies around the world. Among such technologies, different crafts and vessels are used to perform several operations, including underwater remotely operated vehicles (ROVs) that allow people to stay safe on the surface while surveying the seabed, for instance [1].

There are works in the specialized literature regarding the design and development of underwater vehicles which state that during the early stages of the design process information is scarce [2][3][4]. As in any other marine craft design process, assessing that the designed vehicle will be able to withstand the operational conditions is of paramount importance. There are multiple interactions between subsystems, hence, the naval design process of an ROV requires several iterations and has to be done considering interdisciplinary team work [4].

The design spiral is a classical empirical approach that proposes a sequence for the design of the different subsystems. For instance, for a manned submersible [5], the sequence starts with the mission and performance requirements and then the different subsystems are approached in the following manner: component arrangement, geometry and displacement, hull and structure, propulsion plant, electrical plant, command and surveillance, auxiliary systems, outfit and furnishings, energy summary and energy storage system, weight displacement centre summary, and cost estimate summary. Once this sequence is finished, a new loop must be followed with greater level of detail. This is repeated until the design is sufficiently detailed.

Using computational tools allows the marine craft design process to be speeded up, at early stages when there is no detailed information about components and geometry or when it is not possible to perform experiments. For instance, Toxopeus *et al*. [6] developed tools to simulate the manoeuvrability and seakeeping of sea vehicles. Wang et al. [7] obtained the mathematical model for an underwater vehicle based on CFD calculations. Ramírez-Macías et al. [8] performed the hydrodynamic modelling of the ROV Visor3 using a viscous flow solver for the accurate prediction of manoeuvring coefficients needed for the development of control algorithms.

In this work, we address the use of aNySIM, a multibody time-domain simulation tool developed by the Maritime Research Institute Netherlands (MARIN), as a part of the design process of an ROV when the geometry is not well known but choices must be made regarding motion-related components, focusing on the features of the ROV. The first section contains the design problem statement. Then the simulation software is described and the simulation framework is explained. After, the use of the software is exemplified using different scenarios to evaluate different concept solutions to the design of an observation class for remotely operated vehicle. Finally, some conclusions are stated.

Formulation of the design problem

The design problem stated here focuses on the propulsion subsystem. Here, it is assumed that there is knowledge about the ROV's overall geometry and component distribution; it is desired to make decisions on propulsion and motion-related components; and further information about other components such as the power plant is not taken into account. More specifically, the propulsion subsystem is considered as the one responsible for transforming available power into motion. Furthermore, at the stage design in question, decisions about the components involved such as thrusters and control system are to be taken.

This problem is relevant because for ROVs ocean currents impose important operational limitations. Commonly, given that the operational envelope is small, ROVs are to be operated only at calm or near to calm water conditions. If the operational envelope is to be assessed and/or optimised, during this design stage, for instance, it is convenient to perform comparison and evaluation of different propulsion system alternatives. These alternatives may include the selection of thruster's particulars such as propeller diameters, thrusters' configuration, and control strategies.

In this work, it is proposed to use time-domain simulation as a virtual prototyping tool where many features of the ROV can be modelled and non-available features can be implemented. The simulation results, then, can be used to make design decisions. For instance, a CAD 3D modelling tool allows the geometry and component distribution to be foreseen, to predict interferences, and calculate mass and volume properties. Here, aNySIM is proposed to be used to foresee the performance of the propulsion system and predict the operational envelope.

Different simulation scenarios to test variation of performance indices are proposed. These scenarios correspond to evaluating full thrust surge, sway, heave and yaw, forward and backward. And, for each scenario, it is proposed to test the performance of the ROV in terms of efficiency, power consumption, and operation speed. The scenarios are proposed to evaluate the following designs parameters:

- Propeller parameters: diameter, pitch-diameter ratio, and number of blades. The propeller is selected under the assumption that each thruster is required to consume less than 1 kW.
- Propeller configuration, from two possibilities: 1) three thrusters for horizontal and three for vertical motion, and 2) four thrusters for horizontal and two for vertical motion.

Simulation tools

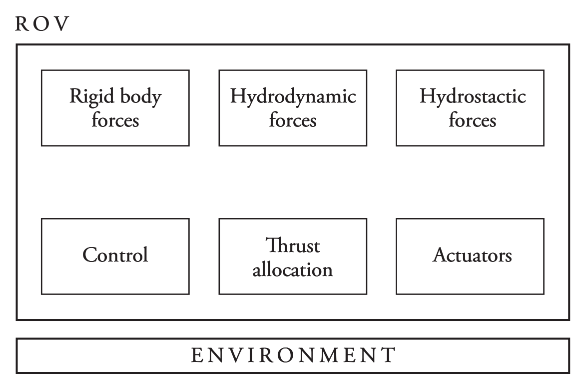
aNySIM is a modular time-domain simulation program able to compute the behaviour of multiple (floating) bodies under the action of combined environmental loads such as swell, wind seas, current and wind and operation-related loads. It is used for offshore applications including coupled mooring analysis, Dynamic Positioning, multiple-body lifting operations, riser dynamics, offloading operations, etc. For instance, in [9] the positioning capabilities of a DP-controlled mono-hull deep-water drillship including a Kalman filter, PID controller and thruster interaction effects were studied. The program integrates the equation of motion for multiple bodies taking into account their own inertia, added inertia, wave loads, damping loads and hydrostatic restoring forces, as well as loads due to interactions, actuators and other mechanical components.

The simulation tool has been developed and validated over years at MARIN, and its capabilities can be extended using Lua. Lua is an extension programming language, developed at the Pontifical Catholic University of Rio de Janeiro (PUC-Rio) in Brazil that functions embedded in a host [10]. In this case aNySIM works as the host and can invoke functions to execute pieces of Lua code, as well as writing and reading Lua variables and writing and reading aNySIM's objects properties.

Simulation framework

In order to develop a virtual representation of the motion problem, a framework including the building blocks, illustrated in Fig. 1, is proposed. It includes a representation of the ROV and its surrounding environment. The ROV is modelled as a rigid body, defined by its mass, moments of inertia, and centre of mass. Other components of the simulation model are: hydrodynamic forces such as displacement and restoring moments; hydrodynamic forces such as drag and added mass; control algorithms; thrust allocation strategies; and actuator forces and moments. The environment representation mainly includes current effects, but effects such as waves may be included as well.

Fig. 1. Simplified framework



When the motion problem is implemented in aNySIM a more detailed framework may be described (see Fig. 2). Here, each model feature is represented by an object inside the aNySIM simulation scenario. The simulation scenario includes two main objects: the ROV and the environmental conditions, as well as the parameters of the numerical solver such as time step, integration algorithm, and variables to register in the file of simulation results.

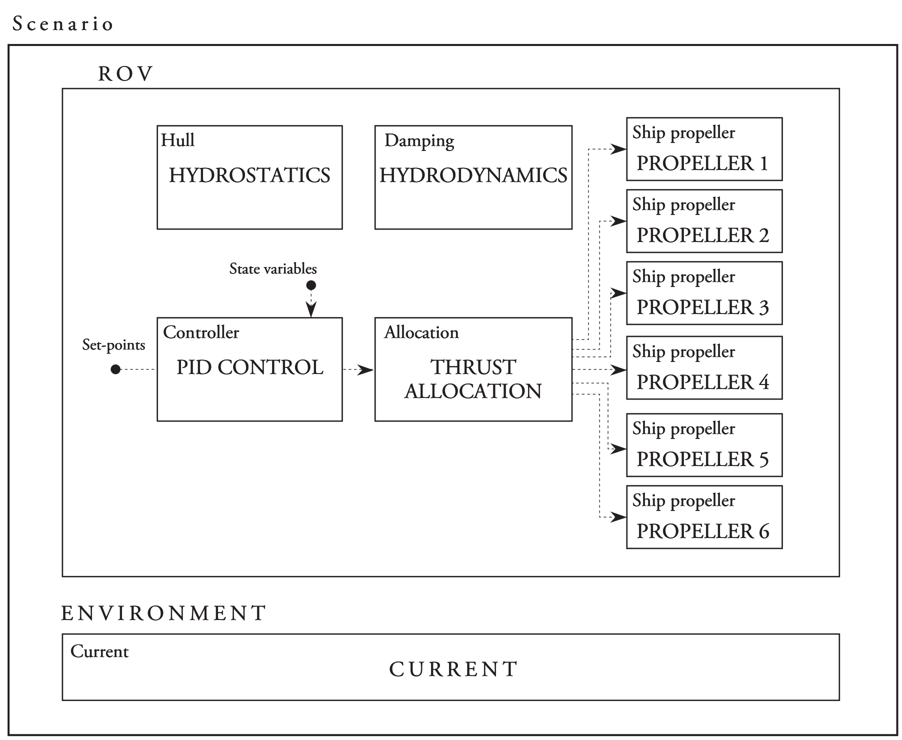
The simulation framework uses an inertial Earth-fixed (EF) global system of coordinates, with an East-North-Up convention. The origin of the system coincides with the waterline. The x-direction is coincident with the initial heading of the ROV and the y-direction is directed towards portside. The z-direction is positive upwards and all rotations are right handed [11].

In aNySIM each defined body has a body-fixed frame where the x-direction, surge, is directed from stern to bow, the y-direction, sway, is directed from starboard to portside, and the z-direction, heave, is directed downwards. Roll is the rotation around the surge axis and is starboard down positive. Pitch is the rotation about the sway axis and is bow down positive. Yaw is the rotation about the heave axis and is bow to portside positive [11].

In this framework the ROV is the main body and is represented by a BodyOde rigid and defined by its mass, moments of inertia, and centre of mass. This object also wraps the objects which represent the remaining model features such as hydrostatics, hydrodynamics, actuators, and control. When parametrising the body, the position of the centre of mass is given in the body-fixed frame using the previously stated convention. The moments of inertia could be defined either by a full 6×6 matrix or by 6×1 vector that represents a diagonal inertia tensor.

Hydrostatic loads are defined using a hull object whose volume creates a neutrally buoyant submersible at the specified water density. Using these conditions, the object calculates non-linear hydrostatics from a water-tight 3D model (e.g. a geometry specified by a .3ds file). This captures the effects of the restoring moments produced by

Fig. 2. Detailed framework



the relative position of the centre of buoyancy and centre of mass.

Hydrostatic loads include drag and added mass. The added mass is directly added to the mass matrix. Drag can be defined as linear or quadratic damping objects. These objects require the definition of a matrix of coefficients which relate velocities to forces and moments, *i.e.*

$$\begin{bmatrix} F_b \\ M_b \end{bmatrix} = D \begin{bmatrix} v_b \\ \omega_b \end{bmatrix} \quad (1)$$

where D is a 6×6 constant matrix in the linear damping case, F_b is the body-forces vector, M_b is the body-moments vector, v_b is the linear velocity vector, and ω_b is the angular velocities vector. In the quadratic damping case the velocity vector is replaced of an element-wise multiplication between the velocity vector and a vector of its absolute values.

The propulsion system requires the definition of two features: the thrusters' configuration and the propeller properties. This is modelled by a propeller object. Here, the configuration is parametrised by the position and orientation of the propeller. These use the X-Y-Z position and roll-pitch-yaw orientation convention previously stated. The propeller is parametrised using the diameter, diameter-pitch ratio, and number of blades.

The control system uses PID algorithms for the control of surge, sway, heave and yaw motions. Given that an ROV's motion is always pilot-assisted, the level of automation is variable among different systems. This means that at its minimum only the thrust allocation algorithm is required and more advanced algorithms are not included. In this case, yaw and heave positions and surge and sway velocities are controlled using PID controllers. It is desired to keep constant heading and depth; surge and sway control function in a fly-by-wire fashion.

For a ROV current is the most relevant environmental variable. Two options for modelling current are considered: constant current and current layer objects. The former is useful when ignoring cable effects; the latter is useful when drag accumulation along the cable is to be considered. For each case current magnitude and orientation parametrise the object. If the cable effect is to be included a dynamic line object may be defined.

Model implementations and parameter estimation

In this section model particulars are considered. Parameters related to the ROV's geometry and component distribution are obtained from existing information. Parameters related to the propulsion system are assumed unknown but bounded. How these parameters are included into the model is presented in the following paragraphs.

Rigid body properties such as mass, moments of inertia and centre of mass and hydrostatics properties such as displacement and centre of buoyancy are known in this problem. The values are calculated from the available data of mass, volume and distribution of the different ROV components. It this case, a database of the different components, including their mass, volume and position in the ROV, is used to estimate the overall mass, moments of inertia, volume, centre of mass, and centre of buoyancy. These are calculated using conventional mechanics principles; details of these calculations are outside the scope of this paper.

It is assumed that the hydrodynamic loads follow Morison's equation structure, similarly as in [12]. This means that the in-line force due to hydrodynamic forces is given by

$$f_H(t) = \frac{1}{2}\rho_W C_D A_p u(t)\left|u(t)\right| + C_A \rho_W \nabla \dot{u}(t) \quad (2)$$

where C_D is the drag coefficient, C_A is the added mass coefficient, A_P is the projected area, ρ_W is the water density, ∇ is the volume, u is the velocity, and $\dot{u}$ is the acceleration. This means that quadratic drag is assumed. It is also considered that the added mass is frequency independent and may be added to the ROV's mass matrix. The drag coefficients are obtained from [1], assuming the drag coefficient of a cube.

The propulsion system forces are obtained from the four-quadrant propeller theory, where ambient flow and propeller rpm determine the hydrodynamic pitch angle. This is used for table interpolation to determine non-dimensional thrust and torque coefficients. The propeller tables are dependent of the propeller's diameter, pitch-diameter ratio and number of blades. These parameters are design unknowns. The ranges shown in Table 1 are considered for these variables.

Table 1. Propeller parameters

Parameter	Min	Max
Diameter (mm)	100	130
Pitch-diameter ratio	0.8	1.6
Number of blades	3	5

Regarding the thrusters' configuration, two different six-thruster configurations are studied: 1) three thrusters for horizontal and three for vertical movement, and 2) four thrusters for horizontal and two for vertical movement. In this study only the horizontal plane motion is considered. The position and orientation considered for horizontal motion thrusters at each configuration are shown in Table 2.

For the environmental conditions only current is considered. Here, a depth-independent generic condition where current is assumed as a constant in magnitude and orientation is used throughout all simulations. Regarding wave conditions, usually wave-effects are not considered because usually ROVs work below the wave zone. Nevertheless, if the ROV is set to work in the wave zone, these effects should be considered; this is out of the scope of this paper.

Results

Propeller parameters

To select an adequate set of propeller parameters, full forward thrust was simulated under the assumption that only two thrusters aligned with the direction of movement were used, and the propeller speed can go up to 3000 rpm. The evaluated parameters are as follows:

- D = 100, 110, 120, and 130 mm,
- P/D = 0.8, 1.0, 1.2, 1.3, 1.4, and 1.6, and
- Number of blades = 3, 4, and 5.

All possible combinations were simulated and data at 3000 rpm are used for evaluating the parameters. Preliminary results showed that the most sensitive variable is the diameter, and the least sensitive variable one is the number of blades. Some results, as a function of diameter, are shown in Fig. 3; here, each line represents a different pitch-diameter ratio. From the plots it is apparent that higher velocities are attained for higher values of the diameter; nevertheless, higher values of power are consumed as well. If a restriction of 1 kW is enforced, an adequate value of the diameter is 120 mm.

Supposing that the diameter is 120 mm, the behaviour of the remaining variables is analysed as a function of the P/D ratio. The results are shown in Fig. 4, where different lines are plotted representing different number of blades.

Table 2. Thrusters configuration

Parameters	3-3			4-2			
	1	2	3	1	2	3	4
Position x (m)	-0.37	-0.37	0.39	0.37	-0.37	0.37	-0.37
Position y (m)	0.25	-0.25	0	0.25	0.25	-0.25	-0.25
Position z (m)	0	0	0	0	0	0	0
Orientation roll (deg)	0	0	0	0	0	0	0
Orientation pitch (deg)	0	0	0	0	0	0	0
Orientation yaw (deg)	20	-20	90	35	-35	-35	35

Fig. 3. Propeller parameters as a function of diameter

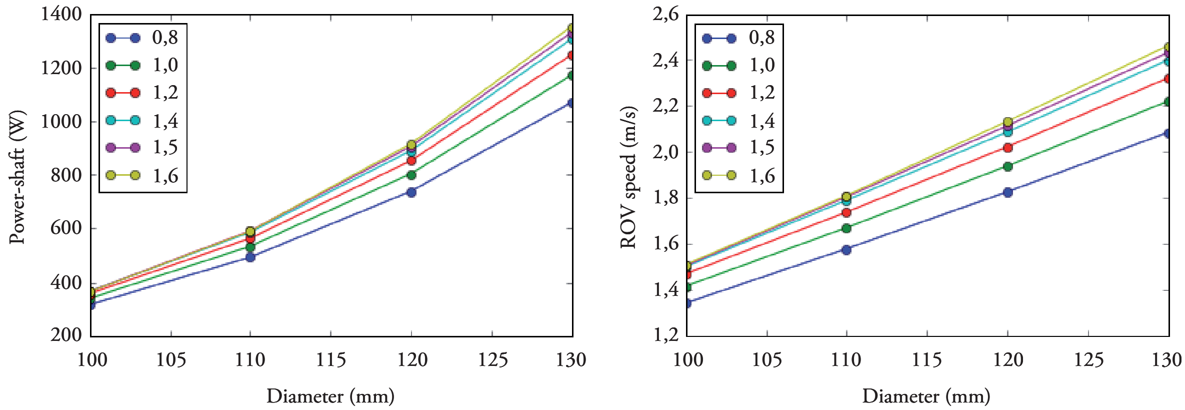
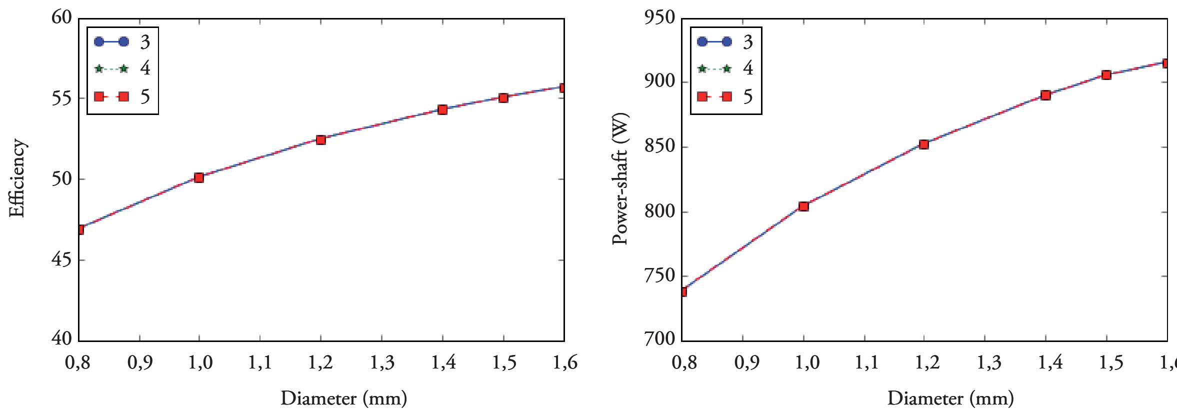


Fig. 4. Propeller parameters as a function of P/D



From Fig. 4 it is apparent that efficiency increases with the P/D ratio; however, the increase ratio of this efficiency decreases above 1.4. It could be theorised that it is desirable to continue increasing the P/D ratio, but, given that consumed power increases as well, a value of 1.5 is chosen. The number of blades does not modify the behaviour significantly.

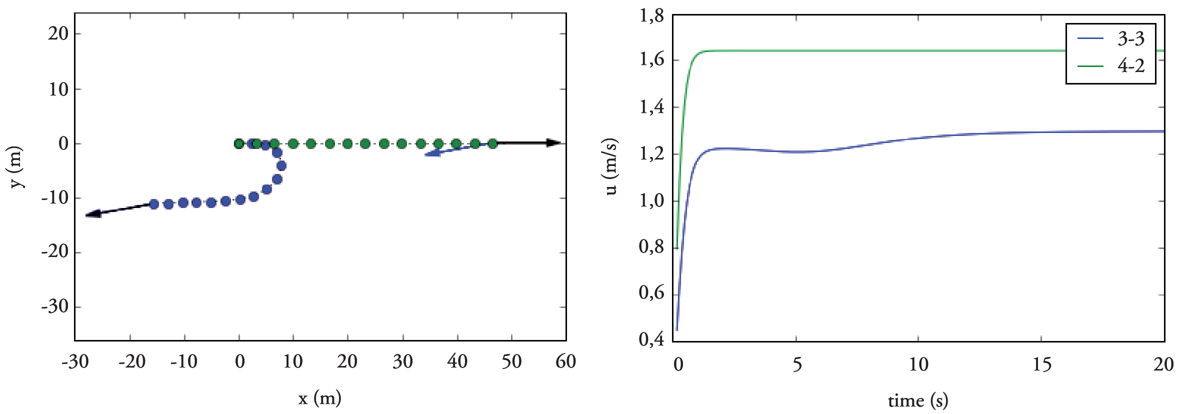
Thruster configuration

To illustrate the two proposed thruster configurations a simple scenario is proposed. Here, full forward thrust in open-loop control conditions is evaluated when a 0.6 m/s current is at 10 degree relative to the surge direction. From the results in Fig. 5 a) it can be seen that the 4-4 configuration keeps its course and the 3-3 configuration does not. There, the black arrow represents heading, the blue arrow the direction of current, and the dots different ROV positions; green dots represent the 4-2 configuration and blue dots the 3-3 configuration. It is apparent that the 3-3 configuration may work better with closed-loop control e.g. yaw control. Also, from Fig. 5 b) it can be see that, because the 4-4 configuration uses one more thruster for horizontal plane motion than the 3-3 configuration, there is a difference of 0.4 m/s in surge speed.

Conclusions

This paper addressed the use of a multibody time-domain simulation tool for the design process of an ROV. aNySIM was used in different scenarios to evaluate full thrust in different directions in order to test the performance of the ROV in terms of efficiency, power consumption, and operation speed. The proposed scenarios allowed the designers

Fig. 5. Thruster configuration comparison: a) trajectories and b) surge speed



to evaluate different design propeller parameters: diameter, pitch-diameter ratio, and number of blades, as well as different propeller configurations. Using simulation tools such as aNySIM allows the marine crafts designers and naval architects to speed-up the design process, when the geometry is not well known but choices must be done regarding motion-related components.

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Flexible Design as an Acquisition Opportunity

Diseño Flexible como Oportunidad de Adquisición

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Abstract

Navies around the world adopt different ways of acquiring ships. Using a single large prime contractor, placing individual contracts for design, build and integration, or employing a state-owned shipyard with external support are all procurement options that we see today.
'Flexibility' in warship design is normally perceived as provision of extra empty space, weight and power, which could be filled with new equipment at some point in the future. However, this idea can be extended to describe a design that achieves true flexibility by exploiting the synergy with different acquisition strategies, adaptability allowing a choice of balanced capability and options for incremental acquisition to control cost and risk profiles. This leads to a design that will deliver a class of warships able to meet the evolving roles and threats throughout its life, whilst not introducing additional risk and cost into the programmes of any modern Navy around the world which adopts it.
To achieve this flexibility BMT have created a single base design with multiple configurations; a warship with a functional arrangement that is able to be tailored to meet the specific requirements and budget of each Navy, minimising the initial cost penalty in a programme, and maximising commonality. It also allows for modular construction techniques which not only apply to single yard construction, including small and medium shipyards, but enables blocks to be built in several shipyards.
This paper will describe the underlying considerations behind this flexibility, including incremental acquisition as a cost mitigation in procurement programmes, and the different potential partnership models between shipyard, designer and integrator in effective acquisition programmes which work to the strengths of each party.

Key words: Flexibility, Frigates, Acquisition, Strategy, Procurement, Adaptation, Capability, Cost, Risk.

Resumen

Las armadas nacionales alrededor del mundo adoptan diferentes maneras de adquirir barcos. El uso de un solo contratista principal de gran tamaño, la asignación de contratos individuales para el diseño, la construcción y la integración, o el empleo de un astillero de propiedad estatal con apoyo externo son todas opciones de adquisición que vemos hoy en día.
La "flexibilidad" en el diseño de buques de guerra se percibe normalmente como la provisión de espacios vacíos, peso y potencia adicionales, que podrían ser utilizados con nuevo equipo en algún momento en el futuro. Sin embargo, esta idea puede ampliarse con el fin describir un diseño que logre una verdadera flexibilidad al explotar la sinergia entre diferentes estrategias de adquisición y adaptabilidad permitiendo la posibilidad de una capacidad equilibrada y opciones para la adquisición incremental con el fin de controlar los perfiles de costos y riesgos. Esto conduce a un diseño que ofrecerá un tipo de buques de guerra capaces de cumplir con los cambiantes roles y amenazas a lo largo de su vida útil, sin generar riesgos y costos adicionales en los programas de cualquier Marina moderna alrededor del mundo que los adopte.
Con el fin lograr esta flexibilidad, BMT ha creado un diseño de base única con múltiples configuraciones; un buque de guerra con un arreglo funcional que puede ser adaptado para cumplir con los requisitos específicos y el presupuesto de cada Armada, minimizando la penalización del costo inicial en un programa y maximizando la homogeneidad. También permite las técnicas de construcción modular que no sólo se aplican a la construcción de astilleros únicos, incluidos los astilleros pequeños y medianos, sino que permite la construcción de bloques en varios astilleros.
Este documento describirá las consideraciones subyacentes detrás de esta flexibilidad, incluyendo la adquisición incremental como una forma de mitigar costos en los programas de adquisición y los diferentes modelos potenciales de asociación entre astillero, diseñador e integrador en programas efectivos de adquisición que trabajen enfocándose en las fortalezas de cada parte.

Palabras claves: Flexibilidad, Fragatas, Compra, Estrategia, Adquisición, Adaptación, Capacidad, Costo, Riesgo.

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Introduction

A warship is a significant investment for any nation. The level of capability and cost inherent of the warship design chosen will depend on the roles and requirements selected by the Navy in order to support wider goals; whether this is to provide maritime security to a vulnerable coastline, influence global events in support of the nation's interests or to secure energy, food and trade routes upon which the nation is fundamentally dependent. These wider goals, and the roles of a warship which are derived from them, can sometimes be fluid and ambiguous; the threat environment and geo-strategic situation undoubtedly change over time. Flexibility throughout a warship, considered from the very inception of the design, can provide a route to deliver a cost-effective procurement programme able to meet this changing capability need.

This paper outlines the synergies and common design characteristics that enable different build strategies, different customer requirements and budgets and incremental or 'spiral' acquisition to be achieved from a single base design.

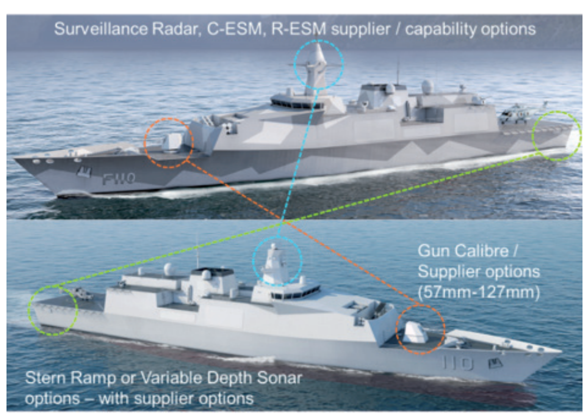
'Flexibility' in warship design has typically been perceived as provision of extra empty space, weight and power in a design, which could be filled with new equipment or modules at some point in the future. However a design that achieves true flexibility is better placed to be delivered through a range of different acquisition strategies for different Navies through adaptability. This allows choice of combat system and other design features, and includes options for spiral or incremental acquisition to control cost profiles. A truly flexible warship is able to meet the evolving roles and threats throughout its life, whilst also minimising cost for this flexibility and overall ship size of the design for any one Navy. This means that no matter which acquisition strategy is chosen by each Navy, the design will adapt to deliver a capable warship without introducing additional risk and cost into the programme. A platform design which is adopted by a number of different Navies also brings wider support benefits, especially to deployed ships operating around the world as they are able to call upon a common supply chain.

Considerations

The complexity of the combat system, along with the environmental operating conditions, accommodation numbers and standards are amongst the influential drivers on the design of a warship. These areas can drive significant cost into the programme if they are not carefully considered from the start of the design process. The requirements associated with these aspects will also differ between each Navy. This means the cost of reworking a design that is originally intended for one Navy may make it unaffordable, or introduce greater risk or compromise to other Navies on the wider export market. If there is too much change required in a design the benefit of re-using the design itself is lost.

For example, a Navy may have an incumbent or indigenous supplier of combat system equipment. For a variety of reasons, including commonality with other platforms, existing training pipelines, personnel experience and economic benefits, a Navy may have a strong preference (or a requirement) to incorporate the equipment from this supplier in their future warship. Conversely, the shipyard or designer may have constrained their platform design around a single combat system due to strategic relationships, or a requirement to use a specific supplier from the Navy for which the ship was originally designed.

Fig. 1. A single base platform can be designed to suit the combat systems produced by a range of manufacturers, and a range of capabilities



For a platform design to be attractive to a number of Navies it needs to have the flexibility to incorporate a variety of combat system equipments from different suppliers, all without increasing the risk within the design or the cost of each individual programme.

This is also the case with regard to the operating environment requirements from each Navy. For example, a ship optimised for Gulf summer operations could potentially struggle with the conditions in the north Atlantic winter, and vice-versa. Again, flexibility within the platform design to accommodate these requirements can mean a single design is suited to the widest possible range of conditions, and mean that a Navy adopting this existing design will incur less additional cost and risk converting the platform to their own environmental requirements. The sizing of environmental systems to address the requirements of many different Navies also provides further benefits of through-life growth and adaptation for any one individual Navy.

A further example of this flexibility affects the manning philosophy adopted (such as conscription or lean manning) and associated accommodation standards. Within the BMT Aegir® platform design developed for the UK as the Tide Class Fleet Tanker, the design was configured to meet Royal Fleet Auxiliary (RFA) accommodation standards. Features of the design included unmanned machinery control rooms and en-suite cabins, to meet the requirements of the RFA manning philosophy and standards. The Aegir® platform design developed for the Royal Norwegian Navy and built as the HNoMS Maud was configured to accommodate both enlisted and conscripted personnel, to Norwegian standards, with other bespoke habitability features including a sauna; alongside a 40-bed hospital complex with operating theatres, isolation/intensive care wards and CT scanner. This provides a demonstration of the flexibility of a single base design to accommodate different requirements, without adding cost or risk into either the UK or Norwegian programmes in order to allow the design to conform to the other's standards.

Flexibility in a design also extends to the classification society and standards adopted. A Navy that takes a design that was created for another Navy, designed to their particular set of standards and class rules, may incur a cost, risk or schedule penalty when attempting to convert this design to suit their own policies, regulations and legal requirements. However, a platform can be designed from the start to be flexible enough to switch between the rules of different classification societies and standards to reduce this risk. This is again demonstrated by the BMT Aegir® design. Aegir® was designed and built to Lloyds Register naval rules and UK Defence Standards for the UK Tide Class programme, whilst the Aegir® design for the Royal Norwegian Navy was designed and built to Det Norske Veritas (DNV) naval rules and Norwegian standards.

Fig. 2. (top) BMT Aegir® design for the UK Tide Class designed to Lloyds Register naval rules. (below) BMT Aegir® design for the Royal Norwegian Navy designed to DNV naval rules

Flexibility in Platform Design

The proliferation of modular space onboard modern warships is indicative of the requirement to incorporate the latest developments in technology. From the vehicle deck within the Danish Absalon Class to the provision of dedicated space for 20-foot containers onboard modern OPV designs such as the 20 De Julio Class of

Colombia, warships now have the ability to host equipment, such as unmanned vehicles, which are constantly being updated and upgraded. This flexible space is essential to quickly adapt to meet new roles and requirements, and to facilitate higher technology refresh rates necessary to keep pace with developments.

However, flexibility can also extend to other aspects of the platform design, bringing with it other benefits alongside spare space for enhanced capability. Through considerations around hydrodynamics, military capability, the arrangement of the platform itself and designing for potential spiral or incremental acquisition true flexibility in warship design can be achieved.

Instead of starting the design of a warship to meet a single particular cost constraint, which has very little relevance to the spectrum of Navies around the world with different industrial bases, the design is instead tailored for cost, maximising the capability against the available budget.

When BMT started the design of a Light Frigate in 2012, the platform was not designed to any one particular requirements set, or for any one particular Navy, or for construction in any one particular country. Indeed, in 2012 the Navy of BMT's home country (UK) did not have a programme for a Light Frigate, upon which costs or requirements could be based; and so it had to be designed for the full range of costs inherent in the industrial bases of the global market of Navies which require a Light Frigate. This drove a flexible 'tailoring for cost' philosophy. This is unlike the origin of Frigate designs in the past, where the ship is designed for a particular Navy, and their particular requirements set, and then subsequently marketed to other Navies. These other Navies may then have to live with certain compromises in the design made by the original Navy, which may not necessarily fit with their own requirements.

Ship Sizing

Where the design is based on a single set of defined requirements, for a single Navy, the ship is obviously sized according to the dimensions needed to fulfil these requirements. However, for a flexible design with a range of potential customers, this cannot be addressed in the same way; specific requirements cannot be detailed at the start of the process in order to drive the overall size of the ship. Without this single set of requirements there is a danger that the design may become too large and expensive for any one customer. Therefore the approach adopted by BMT was to decide on a minimum viable size of vessel, in order to manage cost, whilst using flexibility to tailor closely to differing requirements.

For the Light Frigate design, having decided upon a genuine global "blue water ocean" capable vessel (i.e. a Frigate rather than a Corvette or OPV derived hull), this defined a suitable minimum ship size based on the required and tested hydrodynamic performance. This work is described further in the paper at Reference 1.

The only firm requirements at the start of the project were based around these overall dimensions of the ship. To prevent the gradual growth of additional military requirements being added to the ship, which would result in a rapidly increasing size and price tag, the ship was not allowed to grow beyond these dimensions within this hullform in the initial stages. Balanced military capability could be provided within the ship, with the ability to provide bespoke capabilities via options, flexibility or modular upgrades. However this balanced capability was not allowed to drive up the dimensions of the ship itself, as an exploration of what could be achieved within this affordable Frigate design. Scope to enlarge this design, or 'stretch' the hullform exist; this allows the design team further flexibility to tailor to the specific requirements of each customer if required and permitted by the available budget.

Military Capability

Starting the design without one particular Navy, or one particular requirement set in mind forced the BMT design team to consider a very broad range of capabilities and potential requirements, in order to deliver balanced capability overall.

BMT analysed the doctrine and concepts of operation of a number of nations, in order to understand the diverse picture of the range of activities that the ship may be called on to perform. Reinforced by engagement with several Navies, and support from operators from a number of countries, a list of roles and activities was drawn up. These roles were then broken down into their underlying requirements, with other important aspects such as the threat environment also considered.

Most importantly, the requirements distilled from this analysis were not specific to the doctrine of any one Navy or nation. For example, Anti-Submarine Warfare (ASW) can mean different things to a nation that is primarily required to provide a passive screen to a carrier task group, versus another nation where ASW can mean the protection of territorial waters or critical trade routes, chiefly by active means, from the covert submarine activity of a neighbour or the smuggling activities of 'narco-submarines'. Both are considered valid ASW policies by their respective Navies; however they have a disparate impact on the platform design itself.

Armed with these requirements, applicable to a range of Navies, the design team then generated the design itself with a range of capabilities tailored for cost, identifying which roles and activities were compatible with each other. Some of these roles had a number of options. For example, a number of options for the Hangar arrangement were generated, able to accommodate the range of manned helicopters operated by different Navies around the world; this was coherent with the design of the air weapons magazine arrangements to cater for the weapons carried by these different helicopters.

Other potential roles and activities of the ship that were not compatible with each other were identified as further capability options. For example, the design can either incorporate a stern ramp launched RHIB Interceptor, a Variable Depth Sonar (VDS) or a simple low cost open quarterdeck option.

Through the use of capability modelling tools and analysis over a period of several years appropriately balanced capability across surface, sub-surface and air domains was optimised for a range of budgets, with the constraint of the hull size an effective method of controlling the overall cost. This was tested against real costing of the design from external organisations including leading Combat System Integrators.

It is critical that the capability of a warship is balanced to prevent size and cost escalation. There is always a temptation within the requirements of a warship to add more capability, such as additional Vertical Launch Silos (VLS), larger mission bays, additional sensors, greater coverage for close in weapon systems (CIWS) or more medium calibre ammunition, amongst others. However these military features have to be balanced with the more mundane areas of a ship. Accommodation, HVAC, electrical generation and distribution, galley, stores, sewage treatment, data processing, chilled water and medical spaces; survivability features in areas such as shock, redundancy and a citadel; sufficient tankage for fuel, AVCAT, black/grey/fresh water, lube oil, urea and ballast, with the associated cofferdams, required to provide an adequate range and endurance are all amongst those features that need to be located within the fine hullform and subsequent weight of a Frigate. For instance, a large mission bay within the ship is attractive from a future flexibility point of view. However, in order to maintain tolerable temperatures in very hot or cold environments the HVAC requirements for such a large open space are significant. Notwithstanding the requirement for far larger ATUs, this adds a much greater electrical load to the ship itself. Additional accommodation is required for the operators and maintainers of the equipment stowed in a large mission bay, who in turn require a greater payload of stores and fresh water, with the extra equipment in the large mission bay requiring its own support of fuel and stores. A large, open and sometimes empty space within the ship also has a fundamental impact on the buoyancy and stability (including damaged stability) of the ship itself, which has to meet both class rules and the standards of the Navy for which it is designed. It should be noted that this is particularly prevalent when increasing the number of warfighting systems onboard a warship, such as weapons and sensors, as they are placed high on the ship and have a significant impact on the top weight, the stability and the through-life growth margin of a Frigate; the fine hullform of which is necessary to achieve the expected end-of-life speed and manoeuvrability requirements.

From this example of a large mission bay alone it can be seen how quickly the wider requirements of a ship are driven up when the capability of the ship is not balanced. This in turn rapidly drives up the size and cost of a ship significantly. This is why BMT devoted so much effort to achieve optimised capability balances across all of these aspects discussed within the hydrodynamically tested hullform of a Light Frigate, tailored for the available budget. Flexible mission space can be provided, but it must be balanced and proportionate over the whole ship design.

This design process, known as 'Middle-Out Design' is described further in the paper at Reference 2. A key tenet of this process is the in-stride development of the design and the requirements at the same time. The fundamental understanding of the capability between the design team and the requirements team from the start has been found to produce a more coherent design.

Functional Arrangement

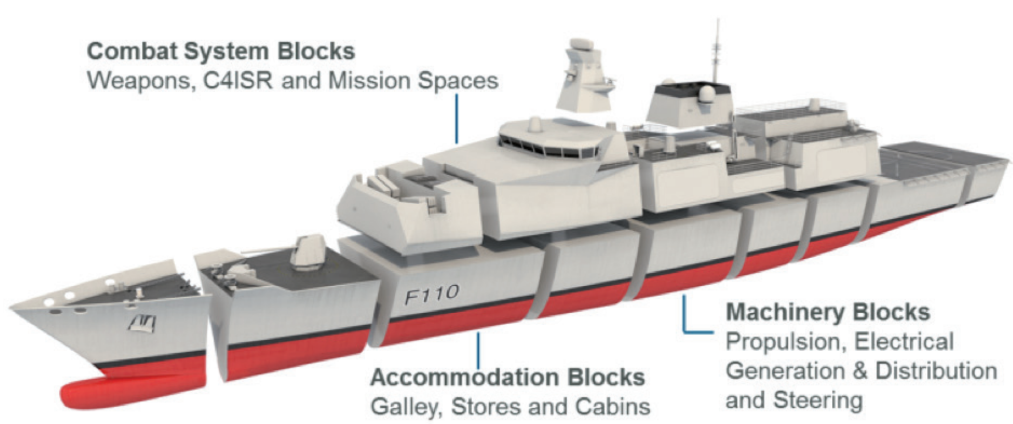
Flexibility does not only extend to the equipment choices and provision of military capability. Flexibility designed into a platform by way of a functional arrangement brings a number of benefits during the design and build of a warship, which can result in a lower procurement cost.

A functional, or zonal, arrangement is where systems and spaces are concentrated within particular areas or construction blocks of the ship, in order to reduce complexity where dispersal is not required for survivability. It is critical that a functional arrangement is considered from the outset of a platform design, and forms the overarching philosophy throughout the process. A high level indication of what is meant by a functional arrangement is shown in Fig. 3 below.

This means that during the design and build of the ship the shipyard, platform or combat system integrators can concentrate on a particular form of outfit within each block. This avoids attempting to fit out a main machinery space, combat system processing compartments, accommodation and main weapon systems such as missile silos in a single block for example, reducing the build complexity, and deconflicting the schedule between the different trades and outfit sub-contractors.

This also means that the interfaces between the blocks, such as cable runs and pipework, are reduced as much as possible within a warship. Each individual block can be outfitted to a higher degree prior to the blocks being brought together for final assembly, leading to a higher degree of concurrent activity during the build programme, assisting the schedule and cost & risk profiles.

Fig. 3. The functional arrangement of a warship, within 15 build blocks



A functional arrangement also brings a higher level of flexibility to the design process, and the ability to amend a design to meet a Navy's requirements if they were to evolve during the design, due to operational reasons or a change in the threat environment. By using a functional arrangement the different sections of the ship can be amended to suit the updated requirements without impacting on the rest of the design. For example changes could be made to the accommodation blocks, whether this is to increase the number of personnel borne or to alter the accommodation standard adopted, without resulting in costly changes to other areas of the ship such as machinery or operations rooms. This reduces the whole ship design effort required, reducing the design cost within the procurement programme.

Removal routes aligned with the combat system equipment compartments mean these systems can be installed later the schedule or following build, reducing the impact of long lead items for the combat system on the build schedule. Concurrent shore-based integration and testing on the complex combat system can also take place later and occupy a longer period in the programme, further aiding the schedule and risk of the build. The combat system spaces were also designed within the BMT Light Frigate with technical design information and significant assistance from a number of different combat system equipment suppliers. This supports the ability to tailor the design to accommodate the requirements of each Navy, and tackle through-life obsolescence. This flexibility around the design of combat system equipment spaces is one feature that allows a procurement programme to follow an incremental or 'spiral' acquisition.

Spiral Acquisition

The investment that a government is willing to make in a warship programme may not entirely match the total need of a Navy, or encompass the entirety of the roles that the platform is required to perform throughout its life. In contemporary programmes this has resulted in either:

1. A cut to the number of platforms procured, a measure that itself has significant ramifications for a Navy as a whole due to force generation; or,
2. Equipment being considered 'fit to receive', where space, weight and power allowances are made for individual items of equipment in the design with some ambition to fit these at a later date; or
3. Entire capabilities lost from the programme as it becomes unaffordable.

This is most prevalent in programmes where the first of class ship is immediately required to provide the full capability identified by policy for the class upon delivery. Car and aircraft manufacturers, and even defence companies building complex military vehicles such as Main Battle Tanks, first build a significant number of prototype machines; ironing out the issues and risks within the design prior to starting a full production run for a customer. The very first warship prototype built is delivered to the customer as the first of class, and expected to provide the full capability demanded. The risks inherent in getting all of aspects of a modern warship to function together correctly, in time, in the first example of the class add significant cost to a procurement programme in the early years. This can lead to the financial pressures which result in the three courses of action described in the paragraph above.

To avoid this high initial cost and high risk for the first of class in the early years a spiral, or incremental, acquisition policy could be followed. However, for this to be successful a flexible design, including a functional arrangement, is required.

An incremental procurement is where the first of class prototype is delivered with a reduced capability against the full capability required for the class. The designer, builder and combat system integrator can then concentrate on the fundamental platform aspects such as hullform, propulsion and power generation, and certain aspects of the warfighting capability so that the vessel still meets at least the minimum level of utility when delivered. Once tests, commissioning and acceptance have been conducted on a concentrated range of aspects within this first of class, the lessons for these aspects will have been fed back into the later ships of the class.

Subsequent ships can then concentrate on delivering the higher end capability required, without the risk and cost of having to prove the entire platform at once. It is important however that the base platform for these later ships is still the same as the first of class. This initial prototype ship of a class cannot be designed to a low cost for affordability, with subsequent ships fundamentally re-designed to incorporate higher levels of capability as all benefit of commonality and the risk-reduction effort is lost, and the overall programme will be far more expensive.

A good example of this incremental strategy is that adopted during the Danish Iver Huitfeldt Class Frigate acquisition, described later within this paper. In this Danish example the first of class prototype was later refitted with the additional capability to bring her up to the full class requirement, and only entered service at full capability after all other ships in the class were delivered.

This incremental acquisition, together with the functional arrangement, also raises other opportunities for the capability that the Navy can acquire. As the design itself has the flexibility and space to be reconfigured without incurring significant costs, additional capability can be added to later ships of a class if the threat environment or roles change during the build programme, or more funding becomes available.

For example, the stern sections could be changed to a Variable Depth Sonar option, or the number of cells in the Vertical Launch Silo (VLS) could be increased, or swapped out for a different type of silo. These capability upgrades on later ships are a more cost effective method of acquiring this capability, reducing the risk overall by spreading out the design, build, test and acceptance risk for different aspects of the programme over time. The functional arrangement means that only certain individual blocks require this re-design effort, which would not affect the overall platform, reducing the associated cost and maximising commonality. If a Navy wished to procure an initial batch of ASW specialised Frigates, followed by a second batch of AAW specialised Frigates, this functional arrangement means that the commonality of the base platform is also accentuated between the two batches, contributing to a lower through-life cost.

This concept can also be extended to incorporate the latest technologies and equipment, to mitigate the risk of obsolescence. For instance, the internal layouts of individual main machinery blocks could be re-designed with energy storage solutions when the technology matures, used for both electric propulsion systems and Directed Energy Weapons or Railguns. Hangar and flight facilities could be adapted to new helicopters or unmanned vehicles as the existing solutions go out of service. Finally combat system equipment, such as multifunction radars, communications or anti-ship missiles could be changed for future solutions that are relevant against the evolving threat, all with minimal impact on other parts of the ship outside the functional block in question; retaining the maximum level of commonality across the fleet

During the design of the Light Frigate, BMT found that this form of spiral acquisition and flexibility has to be considered very carefully, which has informed the latest variant of the design. This is

Fig. 4. Example of VLS options within a Light Frigate design, which could be adopted over a class of ships to provide greater capability once the initial risks are resolved or mitigated

Option 1: 24 Cells VLS

Option 2: 48 Cells VLS

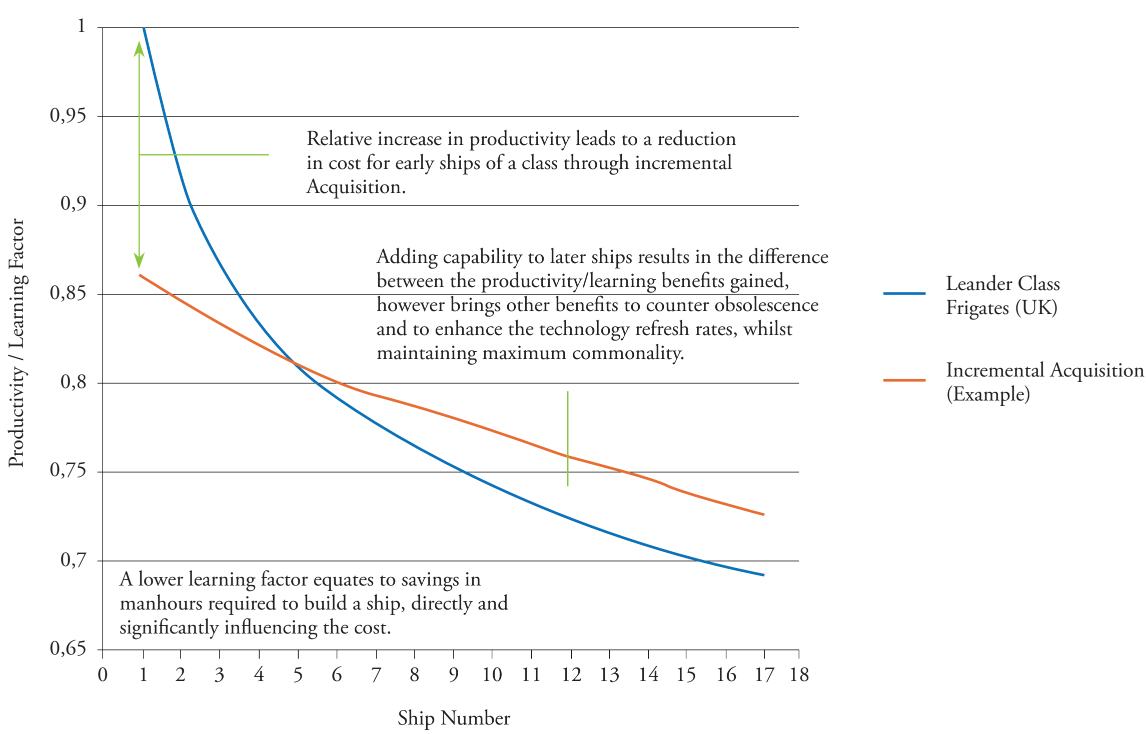
Option 3: 24 Cells VLS, with 8 cell Strike Lenght VLS to avoid adding too much extra space and power margin in the initial design, bringing in unwanted additional cost to the first of class. Overall, this is a drive to consider adaptability, and the tailoring of a warship for cost, at a whole ship level.

Fig. 5. Spiral, or incremental acquisition. This can lead to the introduction of new technology or roles in later ships of a class, or potential to adapt to an evolving threat environment, in a programme with a smoother cost and risk profile

The effect of this spiral development could also be seen on the learning curve experienced during the build programme over a class of ships. Fig. 6 below shows the learning curve that was experienced during the Royal Navy Leander Class Frigates programme built in the UK. The reduction in cost for each platform during that programme can be seen, due to the learning experienced by the shipbuilder and therefore the manhours saved, once the first few ships of the class (the prototypes) were completed. The second line shown is an example of the effect a spiral or incremental development could have on a programme. The initial costs of the programme are lower due to the installation and de-risking activity on a more concentrated range of platform aspects, which is balanced by inserting this capability back into the early ships later in the programme once the de-risking activity has taken place on the initial vessels. This also leads to a smoother cost profile over the course of the entire programme, especially in the difficult early years.

Overall however, despite delivering these benefits discussed, including enabling a variety of different capability configurations within a single base design, the BMT Light Frigate is actually a straightforward design. The propulsion and power generation system is proven and already at sea, and

Fig. 6. Learning Curve Comparison



a great deal of intelligent effort over several years has been put into the arrangement and layout to meet naval class rules and standards, and to provide survivability. Significant effort has been devoted by BMT, along with platform system integrators and combat system integrators, to develop a warship which can meet the requirements of a modern Navy but is not complicated for a shipbuilder to construct. This simplifies the build and minimises the cost and risk within the base design.

Flexibility in Acquisition Strategy

The flexibility to tailor the design to meet the operational needs and budgets of a range of Navies also opens up applicability to a variety of acquisition strategies; in a way that a more constrained design developed for a single Navy within a conventional acquisition strategy may not without bringing additional unwanted change, risk and cost.

The acquisition strategy for a new warship can take several different paths. The strategy selected will depend on the policy of the government, the available infrastructure within the country and the needs and budget of their Navy, amongst other factors. There is also a rapidly increasing demand from a number of countries for warships to be built bespoke to their own requirements, and built within their own country, rather than follow the previous strategy of buying second-hand ships. A Navy may also wish to specify individual systems or equipment produced by manufacturers in their own country. This is where a flexible design, and a functional arrangement, is required so as not to introduce a high level of re-design work to accommodate these new system choices, which would add risk and cost into the programme and make the design itself unattractive or unaffordable. For reference, Lamb (2013) (Reference 3) outlined a number of acquisition strategies that could be taken, and Tascon (2015) (Reference 4) further analysed these different potential approaches.

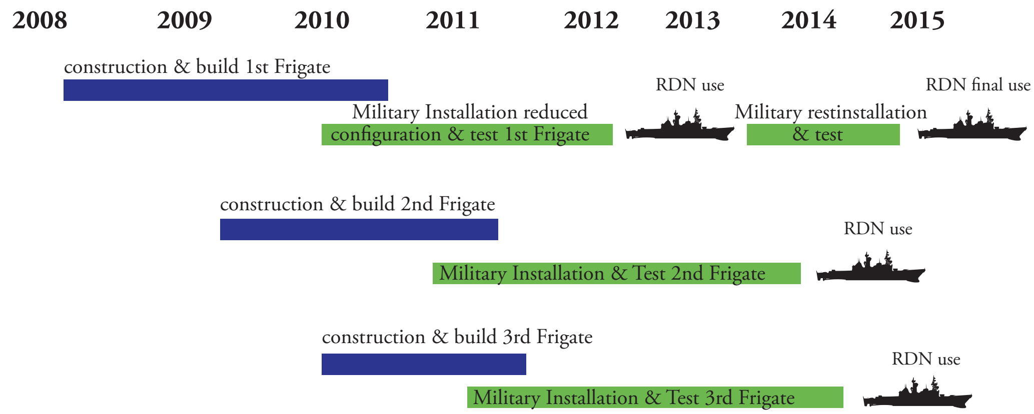
One acquisition strategy to highlight is that used to acquire the *Iver Huitfeldt* Class Frigate. The acquisition of the *Iver Huitfeldt* Class by the Danish Defence and Logistics Organisation (DALO) used a model that had strong parallels with the commercial procurement of ships by companies such as Maersk. This also provides a good example of a flexible design, based on the earlier *Absalon* Class, and was designed by the Royal Danish Navy and the Odense Steel Shipyard working in close co-operation. The platform, combat system and integration of the *Iver Huitfeldt* Class were split, with the DALO organisation itself effectively taking responsibility as the prime over all these elements. All of the blocks for the three ships of the class were constructed by Baltija Shipyard (Lithuania) and Loksa Shipyard (Estonia), before final assembly in Odense Shipyard (Denmark), taking advantage of the lower overheads presented by these commercial shipyards.

Fig. 7. The three Frigates of the Royal Danish Navy Iver Huitfeldt Class

Once the platforms themselves were complete, the installation of the military equipment and testing took place. Procurement of this combat system equipment was also undertaken ('primed') by the DALO itself. The incremental, or spiral, acquisition and testing within the programme is demonstrated in the image of the Iver Huitfeldt Class shown in Fig. 7. The ship at sea in the foreground is not fitted with air/surface search radar (Thales APAR) and satcomms on the main mast, and with several weapon systems yet to be installed.

A high level diagram of the project plan for the Iver Huitfeldt class is included in Fig. 8 below, extracted from a briefing produced by the Royal Danish Navy (Reference 5). This shows the de-risking activity that took place on the first of class ship, where the installation of the combat system was split. This resulted in this first of class 'prototype' vessel only entering service at full capability after all other platforms in the class were

Fig. 8. Danish Frigate Programme Main Plan (extract from Reference 5)



introduced. In addition, the installation of SM-2 missiles across the entire class, to enable the full capability requirement to be met, was conducted after the ships had entered service; shorter range air defence Evolved Sea Sparrow Missiles (ESSM) were used initially as an interim capability. This demonstrates a form of spiral or incremental acquisition as described earlier within this paper.

It is claimed that this split procurement model, where platform and combat system were procured, built, integrated and tested separately and incrementally saved around USD 65 million per vessel overall (Reference 6), with the allocation of risk within the programme a contributory factor. This resulted in a low procurement cost of these vessels, when compared to contemporary Frigate programmes. A breakdown of the cost for these Frigates has also been published (Reference 6), showing almost a 50/50 split in costs between the platform and combat system elements. However, it is important to note that for this type of acquisition strategy to be successful it is vital that the platform design itself is flexible enough to allow the selection and fit of the combat system once the ship itself has been built. This was aided in this case by the Danish Stanflex modular system, overall supporting the separate and parallel construction of blocks.

Acquisition Strategy – Alliance Approach

Not all governments will have the capability and capacity to undertake the prime integration role as taken by the DALO in the Danish example described above. However, many of the benefits of the approach can be delivered through a strategy based on the engagement of an alliance. The Navy or procurement body can work as closely with alliance members as they wish, depending on their capabilities and desire to learn through participation in the project, tailoring the levels of technology transfer to suit all parties.

The flexible alliance incorporates a Shipbuilder, a Platform Designer, a Combat System Integrator (CSI) and a Platform System Integrator (PSI). The level of involvement each party plays depends on the nature of the acquisition strategy, and some roles may be fulfilled by the same company. The focus of effort will change between these parties as the programme proceeds.

The Shipbuilder: The shipbuilder can be abroad or in the customer's own country. In cases where the customer wishes to build the warship in their own country, but lacks experience, a shipyard consultant may be part of the alliance providing expertise and support to the local shipbuilder. This consultant party may be a shipyard itself but the advice could come from suitably experienced consultants.

More than one build facility may be used with blocks being built in different locations and integrated together by the lead Shipbuilder. A design specifically developed to support such an approach is needed to avoid significant additional costs being incurred. This allows the progressive development of industrial capabilities, and can speed up delivery.

In the early stages of the project the Shipbuilder's role will be in providing comment on the developing design to ensure that construction issues are addressed. They will also commence engagement with potential equipment suppliers, obtaining prices and data (including space, weight and power requirements) to support design development and trade-off decisions. This will also support planning for construction. If applicable, any requirements for development of facilities will also be identified. As the project proceeds the Shipbuilder will be increasingly involved in planning and procurement of long lead items. The shipbuilder will again be supported by the shipyard consultant as needed.

Depending on Shipbuilder capability they may also become progressively involved in developing the detailed and production design, under supervision of the Designer, to ensure that the original design intent is maintained.

The Designer

The Designer will take the lead in the early stages, working with the customer to explore options to focus the design on a reasonable compromise that best meets the balanced operational requirements and budgetary constraints. Working from a flexible baseline design as discussed earlier in this paper prevents high levels of re-work, significantly speeding up this process and reducing cost. Whilst input will be required from the Combat System Integrator, the level of detail needed is kept low allowing work to continue on development of the combat system design itself within defined boundaries, without causing change to the rest of the overall design. Development of the design can also recognise customer requirements for variations between vessels in the same class, either to meet a fleet capability mix requirement or to facilitate future upgrades.

As the design matures, detailed design, drawing work and production outputs may be undertaken by the shipyard or other in-country contractors under the supervision of the designer, as required by the industrial policy.

The Combat System Integrator

The Combat System Integrator is responsible for the delivery of key capabilities of a warship. This includes design, equipment procurement, system integration, testing and demonstration of the combat system. They may also undertake installation, as demonstrated by Saab with the Royal Thai Navy Frigate currently under construction by DSME, or by Thales integrating the combat system within *Project Khareef* for the Royal Navy of Oman.

Regardless of whether all equipment chosen is already in-service, the integration of the equipment with each other and the command system requires significant effort. It is good practice to integrate systems ashore before installing on the ship, simplifying the physical work and deconflicting interference between ship construction and combat system installation, integration and testing. The down side of this is that they system may not be ready for installation as early as the build schedule would permit. The flexible design with a functional arrangement, described above, allows ship construction and potentially testing to be completed before the Combat System Integrator takes responsibility for installation and testing of the Combat System, working with the shipbuilder or in a separate naval dockyard.

The Platform System Integrator

Depending on the complexity of the propulsion and power generation systems, and the sophistication of the control systems required for these and the auxiliary systems, there may be a need for a Platform System Integrator to take responsibility for the design and integration these systems. Including the Platform Management System and the power and propulsion equipment, this is similar to the Combat System Integrator with the Combat System. Again, the flexible design with a functional arrangement allows the Platform System Integrator to develop their aspects of the design, within defined boundaries, with minimal risk that design development will cause changes and disruption to development of the rest of the overall platform design.

For requirements at the more straightforward end of the spectrum this role will normally be fulfilled by the Designer with procurement by the Shipbuilder.

Summary

Flexibility in warships has a greater meaning than the provision of empty space for modular upgrade at some point in the future. True flexibility throughout is a critical feature of warship designs which can provide a balanced capability, tailored for cost, and able to mitigate the risks of obsolescence and the changing threat environment. With the ability to evolve into new roles as the global situation develops, this flexibility can also maximise commonality within the fleet, and with the fleets of other nations that tailor to the same design, delivering through-life cost benefits.

Flexibility in warship design has to be considered carefully from the start of the design process, in a way that does not bring extra cost into the platform design itself; so that a Navy is not penalised by paying for additional features, or a larger warship than they require.

Through the design of a Light Frigate over the past few years, BMT have found that a functional arrangement is a way of managing this flexibility. This functional arrangement can simplify the build of a ship, by limiting the interactions between the blocks, leading to a greater degree of pre-outfitting before final assembly. This functional, or zonal, arrangement also serves as a method of keeping control of costs during the design phase if the Navy adds or changes requirements, and provides a cost effective method of adopting new technologies as they develop.

Spiral development over a class of warships, through the use of a cost-effective functional arrangement, can ease affordability versus capability conflicts. Delivering full capability over a number of ships in the class can reduce the risk inherent within the first of class prototype vessel, and reduce the impact of obsolescence. This is especially the case if the class is to be built over a long time period, where advancements in technology mean that if the last ship in a class were to be built to the same specification as the first it would suffer significant shortfalls against the evolved threat and intended roles.

A warship designed in this way supports adaptation for different Navies no matter what acquisition strategy is chosen. In particular it facilitates the adoption of an Alliance based acquisition strategy, which allows flexibility in customer involvement and home nation industry involvement and learning. Shipbuilder, Designer, Combat System Integrator and Platform System Integrator can work in parallel with clear interfaces with reduced risk of re-work and options for spiral development. The combination of a truly flexible design, readily adaptable to meet a range of balanced requirements and tailored for cost, with an arrangement that minimises the cost impact of change, and a flexible alliance engaging the optimum mix of government and contractors offers true flexibility in acquisition.

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An interference risk–based approach for naval vessels

Enfoque basado en riesgo para la interferencia sobre buques navales

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Abstract

Price development of naval ships has forced the industry to search for smarter solutions. Until recently this was not possible because the rule based approach demanded the use of maritime Eletromagnetic Compatibility Standards (EMC) that focused on equipment level. With the new Lloyd's Naval Register EMC Rules (Register, 2016), a modern risk-based approach can be followed. This enables the use of commercial Off-the-Shelf (COTS) equipment, which is more cost-effective than dedicated maritime equipment, by using the ship's structure and the installation as protection. This paper explains how these new Lloyd's Naval EMC rules can be applied for modern naval shipbuilding.

Key words: Risk based EMI approach; naval ships; Lloyd's Register; EMC management; EMC control.

Resumen

La evolución de precios de los buques navales ha obligado a la industria a buscar soluciones más inteligentes. Hasta hace poco lo anterior no era posible debido a que el enfoque basado en reglas exigía el uso de Estándares Marítimos de Compatibilidad Electromagnética (EMC, por sus siglas en inglés) los cuales se centraban en la maquinaria. Con las nuevas reglas EMC de Lloyd's Naval Register (Register, 2016), es posible seguir un enfoque moderno basado en el riesgo. Esto permite el uso de equipos comerciales de venta libre (COTS, por sus siglas en inglés), lo que resulta más rentable que el equipo marítimo dedicado, utilizando la estructura del buque y la instalación como protección. Este documento explica cómo estas nuevas reglas EMC Lloyd's Naval pueden aplicarse a la construcción naval moderna.

Palabras claves: Enfoque EMI basado en el riesgo; buques navales; Lloyd's Register; Gestión de EMC; Control de EMC.

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Introduction

Introduction on costs of naval ships

The costs for naval ships are escalating at an unsustainable rate as can be seen in Fig. 1. The data in this figure shows the price development of surface combatants of the US Navy between 1950 and 1999. If the estimated combined procurement costs of the DDG1000, DDG1001 and DDG 1002 in 2017 are added, it turns out that these ships will cost 12,738.2 M US $ *(O'Rourke, 2016)*, which is well over 4 Billion US $ a piece. This is in line with the logarithmic price development between 1950 and 1999. Several factors contribute to this rapid increase in procurement costs of ships, but according to *(Neradka, et al., 2010)*, 3 of them out of the top 10 of cost-drivers are EMC related standards being:

- MIL-STD-461E Electromagnetic Interference (EMI),
- MIL-STD 464A Electromagnetic Environmental Effects (E3) Requirements for Systems
- MIL-STD-469B Radar Engineering Interface Requirements, Electromagnetic Compatibility – Frequency Spectrum Guide for Radar.

Introduction on EMC

According to IEC (Electropedia, 2017) EMC stands for:

> *"The ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment"*

On board ships there is a range of sources generating high levels of ElectroMagnetic (EM) emission, such as radio transmitters and radar systems, for which the emissions are integral to their function. However, there are also many systems that produce EM emissions as a side effect of their functions, examples are LED-drivers and Variable Frequency Drives (VFDs). These emissions require additional mitigation measures, which increase the overall cost. If appropriate measures are not taken, the EM-emissions may cause Electromagnetic Interference (EMI) in susceptible systems such as radio receivers or sensor systems. An important aspect of EMI is the coupling path between the disturbance source and the susceptible victim, which can be through air (magnetic coupling, electric coupling or EM waves) or conductive materials (voltages and currents). Fig. 2 shows a schematic representation of how EMI may occur.

Three options are available to prevent EMI:

1. Reduce the EM-emission (only possible for unintentional transmitters),
2. Increase the immunity level of the victim,
3. Interrupt or attenuate the coupling path.

Fig. 1. Cost Escalation for selected surface combatants according (Arena, et al., 2006) , DDG: Guided missile destroyer, FFG: Guided missile frigate, DD: Destroyer

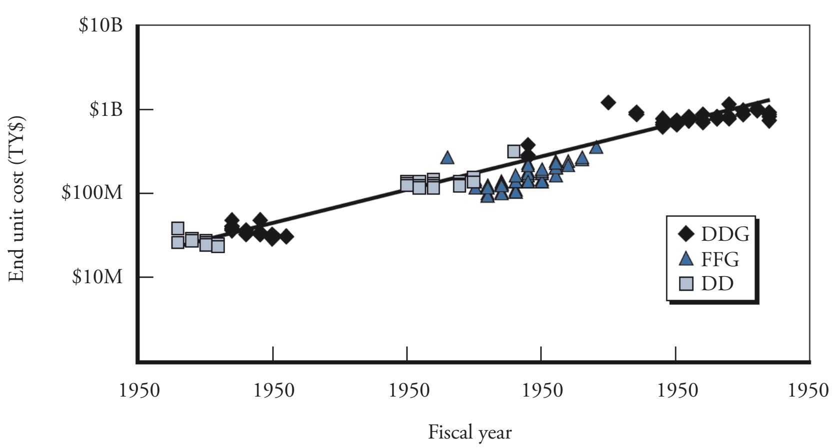
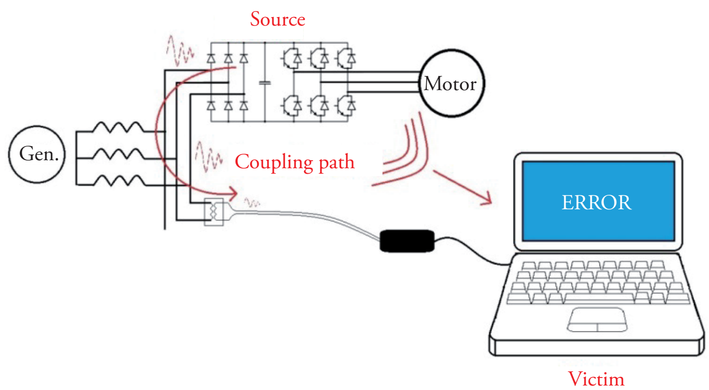


Fig. 2. Electromagnetic interference



EMC and standards

The traditional approach focuses on limiting EM emission levels and establishing minimum EM (ElectroMagnetic) immunity levels. The high-tech defence and space industry has developed products suitable for naval ships and meeting these emission and immunity levels. These products are robust, produce little unintentional emission and comply with military EMC standards such as MIL-STD-461-F *(MIL-STD-461F, 2007)* or NATO AECTP 500 series *(NATO, 2016)*. Over time, the cutting edge electronics from this high-tech industry have also become available outside the military domain: COTS products. Because of the legal requirements posed worldwide on electronic products, like the EMC Directive in Europe *(Council, 2014)*, the EM quality of COTS is much, much better than ever before, without any additional measures, or costs. But also, today's civil development has led to rapid mass production of reliable new technology at a much faster pace than in the defence industry. As a result of this reversal, military grade equipment today is often outdated, expensive and difficult to obtain. However, these COTS products are not designed for naval applications, and consequently could cause problems, producing higher levels of unintentional EM-emissions and may not have the immunity required by naval EMC standards. As a result, and in line with the traditional approach, today's COTS equipment is hardened to allow its use on board naval vessels. This is expensive, requires extensive testing and causes problems when equipment has to be replaced and the same type of COTS equipment is no longer available. The same applies for equipment specifically developed for the maritime market in compliance with IEC 60533 *(IEC, 2015)*.

Until last year, if a ship was built under Lloyds Register Naval rules, only two options to comply with the EMC requirements were available ("IEC 60533" or "a naval EMC standard"), as stated in the Lloyd's Register Rulefinder *(Lloyd's Register, 2015)* Volume 2, Part 1, Chapter 3, Section 4.13.2.:

> *"An EMC test plan is to be established, an EMC analysis carried out and a test report produced in accordance with the requirements and guidelines of IEC 60533 Electrical Installations in Ships, Electromagnetic Compatibility or equivalent requirements of the Naval Administration as defined in a specified standard."*

With this requirement shipbuilders were forced to apply difficult to obtain, expensive, and often outdated equipment, because equipment which complies with IEC 60533 *(IEC, 2015)* is rare. The hardening of COTS equipment to have them fulfill the specific requirement at equipment level is costly, while not adding quality to the EMC performance at platform level. However with the updated Lloyd's Register Naval Rules a third option becomes available, as can be read in Notice No.4 *(Register, 2016)*. This option has been effected as from January 1, 2017 and includes EMC related clauses in Volume 2, Part 1, Chapter 3, Section 3.3 and section 4.13 of the Lloyd's Register Naval Rules.

Apart from following military or maritime EMC standards it is now also allowed to use a risk based ElectroMagnetic Interference[1] (EMI) approach. This gives the possibility to focus less on emission and immunity levels and more on interruption of / attenuation by the coupling path. The Rules give some guidance on how this should be done and this paper will elaborate on it.

The risk based approach

Introduction

A couple of years ago several companies, knowledge institutes and the government decided to tackle the challenge of high EMC-related costs on board Naval Vessels together. This resulted in the "EMC for Future Ships" consortium which incorporated:

- a navy (Royal Netherlands Navy),
- a Classification Society (Lloyd's Register of Shipping),
- a shipbuilder (Damen Shipyards),
- a combined combat-system-integrator (CSI) and equipment manufacturer (Thales Nederland),
- a combined E-system integrator (ESI) and installer as well as equipment manufacturer (RH Marine Netherlands) and
- a university (University of Twente).

Together they could optimize on ship level instead of on equipment level and substantiate this approach with thorough research which is summarized in the PhD thesis: "Requirements with rationale and quantitative rules for EMC on future ships" *(Leersum, 2016)*. A major aspect of the thesis is the substantiation of attenuation of interference that can be obtained by proper installation methods. This was an important precondition for Lloyd's Register to allow a Risk based approach.

Future requirements as a result of the risk based approach of Lloyd's Register Naval Rules

The risk based approach makes it harder for Lloyd's Register to validate compliance. In the past they just had to check if all equipment complied with the proper EMC standards, but now they need to make an assessment if the EMC engineering was done properly. In summary: Risk Management, instead of the Risk Avoidance when following the Rule-Based approach. To overcome this disadvantage Lloyd's Naval Rules requires at least the following documents:

- an EMC Management plan,
- an EMC Control Plan,
- an EMC Implementation Plan and
- an EMC Test Plan.

The following four paragraphs will elaborate on these plans.

EMC Management plan

The EMC management plan has two important goals. The first one is to define the electromagnetic environment (EME) in which the ship will operate. In other words what does the customer want with his ship and what kind of EM threats follow from these requirements? Examples are: Impact from direct or indirect lightning strikes, Emcon[2] requirements, Nuclear ElectroMagnetic Pulse[3] (NEMP), Skyline[4], Will the ship be sailing in convoys, Intentional ElectroMagnetic Interference (IEMI). What requirements does the customer have, for example:

- A STANAG 1008 *(STANAG, 2004)* power grid requires a power supply grid where the neutral point is not connected to earth (IT system) in contrary with shore based power grids which usually have an earthed neutral point (TN or TT system). In general equipment will be developed for power grids with an earthed neutral point which means that the expected overvoltages for this kind of equipment are lower and filtering with capacitors to earth is allowed. So applying equipment developed for an earthed grid in an unearthed grid involves a number of risks.
- The use of mobile radios (walkie-talkies) on board introduces a disturbance source

[1] EMI is the opposite of EMC. Where EMC means there is electromagnetic compatibility, EMI means there is electromagnetic interference

[2] Emission control or radio silence.

[3] When a nuclear device is detonated outside earth's atmosphere it results in very high electromagnetic field strengths at ground level.

[4] What kind of radar systems and radio transmitters are used onboard and by allies.

which can create significant field strengths at any location on board, possibly causing interference. Nowadays there are devices that require much less field strength.
- Powerful transmitters and VFDs can be very useful but they can also cause high disturbance levels.

The second goal is to share the responsibilities between all parties involved: the contractor, sub-contractors, and suppliers. EMC can be obtained at almost any level. The component producer can make sure the components can withstand all the disturbances to which they will be exposed, for example by filtering on the printed circuit boards or proper conductive enclosures. The same applies for the equipment manufacturers. If these parties make sure their delivery complies with IEC 60533 or naval standards, a rule based approach is chosen. However, companies that integrate equipment into systems and the electrical / combat system integrators can take measures to make sure the systems run satisfactorily. For example by applying cable segregation, using power filters, using shielded cables etc. Even the yard can do a lot to reach EMC. E.g. a proper top deck design, shielded windows, and different EM-zones separated with bulkheads.

If all contractors, sub-contractors, system- and equipment suppliers, and component manufacturers take all necessary steps that whatever purchased parts they use, their delivery is completely suited to be used in a Naval environment, the ship will be too expensive. If none of these parties take these steps, there is a high risk on interference resulting in malfunctions. The challenge is to make sure that the party that can prevent EMI in the naval environment against the lowest overall costs, will do so. The problem is that in practice parties often assume that one of the other parties will take the necessary steps and at the end of the day nobody did it. In the management plan responsibilities are designated to the different contracting parties to make sure one of the parties is responsible for this job. Examples of these kinds of tasks are: writing an EMC control plan, creating a top side design, performing an THD (Total Harmonic Distortion) calculation, define the earthing philosophy and so on.

Other topics to be dealt with in the EMC management plan are the legal and contractual EMC obligations. If there are standards to be adhered to, what kind of standards are they and under what conditions are they applicable. Since cooperation between all partners is important to reach EMC and a reliable ship at the lowest costs, it is important to facilitate this cooperation for example by means of an EMC team. Several procedures need to be established, for example how to deal with differences in insights between the involved companies and how to record why certain decisions were taken or solutions were chosen. Finally some thought should already be given on what kind of inspection, verification and validation is required to convince classification society and customer of the reliability of the delivered installation. Inspection, verification and validation can be real cost drivers so all involved parties should roughly know what is expected from them if they make their offer.

To summarize the management plan defines the EM-threats that follow from the requirements of the customer and states who is responsible for what.

EMC control plan

The EMC control plan is all about: controlling the identified risks, defining measures (best practices [5]) to mitigate those risks, and translating them into purchase specifications for sub-contractors and system- / equipment suppliers.

The input of the EMC control plan consists of the EM-threats and operational requirements from the customer combined with the equipment that will be used on board. An easy tool to identify the risks is a "source victim matrix". In a source victim matrix interference risks are identified and mitigated with best practices. On the right side of the page a simplified example is given which consists of a few best practices and Table 1 up to Table 3.

5 A best practice is a method or technique that has consistently shown results superior to those achieved with other means, and that is used as a benchmark

If a mitigation measure is not recognized as "best practice", proof will need to be delivered with respect to the effectiveness of the mitigation measure. However, once this is done this mitigation measure can be used in future projects.

In Table 1 the risks are identified. This is done by placing all potential disturbance sources on the left side and all possible victims on the top side. At the cross section of victim and disturbance source

- a green cell indicates there is hardly any risk on interference, *e.g.* the conducted emission from LED lighting on the bridge will not influence the propulsion VFD.
- An orange cell indicates there is a risk of interference, *e.g.* a lightning strike could damage the propulsion VFD, and
- A black cell is not considered because this is intrasystem and up to the supplier of the system.

Table 1. Source victim matrix, step 1

Best Practices
1) Metal hull, EMC MCT's
2) Surge arrestors
3) Screened cables
4) Harmonic suppression
5) EM zoning
6) Top deck design
7) Procedures

Victim:	EMCON	Propulsion VFD	VHF transmitter	VHF receiver	Distribution transformer	LED lighting bridge
Lightning						
Skyline						
Propulsion VFD						
VHF transmitter						
VHF receiver						
Distr. transformer						
LED lighting bridge						

The idea is to mitigate risks so the orange cells should disappear and become green. This can be done by applying best practices, for instance a metal hull is used with EMC Multi Cable Transits (MCTs). This will prevent that currents induced by a lightning strike can reach the propulsion VFD which is placed deep within the ship. So a "1" is added to the cell at the intersection of lightning and propulsion VFD and it turns green, see Table 2. This best practice will also help to protect the VHF transmitter so a "1" is also added to that cell, but it stays orange because not all risks are mitigated. There is still an antenna sticking out of the hull which is exposed to lightning and through the antenna cable the transmitter can be exposed to high currents. However by adding surge arrestors (best practice 2) it is also possible to mitigate this risk and the cell at the intersection of lightning and VHF receiver becomes green and a "2" is added to this cell as shown in Table 3. This process can be repeated until all cells become green.

Based on the risk analysis the output of the control plan will be a number of documents and instruction which can contain, but are not limited to:

- The source victim matrix.
- A list of best practices that can be distributed to all stakeholders.
- An EM-zoning plan to be used to allocate equipment developed for the same EM-

Table 2. Source victim matrix, step 2

Victim:	EMCON	Propulsion VFD	VHF transmitter	VHF receiver	Distribution transformer	LED lighting bridge
Lightning		1	1	1		1
Skyline		1	1	1		
Propulsion VFD	1			1		
VHF transmitter		1				1
VHF receiver						
Distr. transformer						
LED lighting bridge				1		

Table 3. Source victim matrix, final step

Victim:	EMCON	Propulsion VFD	VHF transmitter	VHF receiver	Distribution transformer	LED lighting bridge
Lightning		1	1,2	1,2		1
Skyline		1	1	1		5
Propulsion VFD	1,3		3,5	1,3,5	4	3,5
VHF transmitter	7	1		6		1,3,5
VHF receiver						
Distr. transformer						
LED lighting bridge				1,3	4	

environment next to one another and separate this equipment from equipment developed for another EM-environment.

- An earthing strategy, if a zoning plan is used cable screens need to be earthed where they pass from one EM-zone to another. This needs to be communicated to suppliers of equipment since not all systems are developed for connecting cable screens at multiple points to earth. Also the choice of power grid (with earthed neutral point or without) needs to be communicated to the suppliers, equipment will be developed for either one of them and suppliers need to select suitable equipment.
- A top deck design, to prevent interference between the different transmitters, receivers, and equipment placed in the vicinity of antennas.
- THD budgets for all equipment in order to prevent that the overall THD levels will become unacceptable.

Implementation

The control plan states "what needs to be done to prevent interference", but not in detail "how this should be done". This subject will be dealt with in the implementation plan. An implementation plan gives, for example, information about: how to arrange cables into different groups with roughly the same disturbance levels, separation distances between those cable groups, preferred communication busses and so on. With this information installers / system manufacturers can create electrician's manuals / instructions. An electrician's manual states in detail "how the components that will be used need to be installed". Items to be discussed: whether earth connections should be made inside or outside a cabinet, how an EMC gland needs to be mounted, where to earth cable screens and so on. It is important that requirements are specific and measurable, so it is easy to verify whether the work has been performed correctly.

The equipment manufacturer's installation instructions can conflict with the requirements from the EMC control plan. In this case a memo will be added to the implementation plan. This memo explains: how the conflict is to be dealt with, what the chosen solution is, what the consequences are and who is responsible for implementing the solution. An example is when the equipment manufacturer requires the earthing of the cable screens at only one point, whilst the EMC control plan states that they are to be earthed at multiple points.

EMC test plan

The test plan exists of two major parts a verification part, primarily performed during construction phase and a validation part, primarily performed during harbor acceptance and sea acceptance trials. The verification is all about checking if the best practices are implemented correctly and if the instructions from the electrician's manual are lived up to. This needs to be done during the construction phase because for example: "after an EMC gland is mounted, it hard to see if this was done properly". The same applies for topics like: creating earth connections, cable separation and so on.

The validation is performed to check if the best practices are as effective as expected. Simple tests can determine this like checking the goodput of data busses, checking reception of radio signals, measuring noise levels in the VHF band, and things like that.

Time schedule

If the risk based approach is chosen it is important to do this very early in the project.

The management plan needs to be created immediately after the moment the contract is signed since many aspects will be part of the contract negotiations. In an early stage of engineering the control plan needs to be created. This is necessary because the engineering department needs to know which best practices to apply and the information from the control plan is required in order to purchase systems and equipment. Then, before the detail engineering starts, the implementation plan needs to be available. Finally the verification and validation plans need to be ready before the building phase starts, since part of the verification is for example checking if the right type of frames (stainless steel) are mounted for MCTs.

Conclusion

This paper explains how the new Lloyd's Register Naval Rules with respect to EMC can help to reduce EMC related costs and use state of the art technology, by applying a risk based EMI approach instead of a rule based EMI approach. A rule based EMI approach requires expensive dedicated equipment, while a risk based approach allows the use of COTS equipment if the correct ship building process is chosen. An EMC management-, control-, implementation-, verification- and validation plan combined with source victim matrices and other documents will help to implement the risk based approach properly in the ship building process.

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An Introduction to NATO Standard ANEP (Allied Naval Engineering Publication) 77 and Its Application to Naval Ships

Introducción a la Norma de la OTAN ANEP (Publicación de Ingeniería Naval Aliada) 77 y su aplicación a los buques navales

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Abstract

In a dynamic world of continuously evolving design and application of innovative new technologies, it is proving increasingly challenging to apply the traditional approach of prescriptive-based standards. As a result, attention has focused on the increased use of a goal based philosophy over the detailed technical standards often incorporated in rules and regulations. A successful application of this approach has been witnessed in providing goal based requirements to the design of safety for naval vessels.

Key words: ABS, ANEP, GBS, goal based standard, INSA, NATO, NSCA, naval, safety.

Resumen

En un mundo dinámico de constante evolución en diseño y aplicación de nuevas tecnologías innovadoras, está resultando cada vez más difícil aplicar el enfoque tradicional de los estándares basados en normas prescriptivas. Como resultado, la atención se ha centrado en el uso creciente de una filosofía basada en objetivos por encima de los estándares técnicos detallados que a menudo se incorporan en reglas y regulaciones. Una aplicación exitosa de este enfoque se ha evidenciado en la proporción de requisitos basados en objetivos al diseño de la seguridad para los buques navales.

Palabras claves: ABS, ANEP, GBS, estándar basado en objetivos, INSA, OTAN, NSCA, naval, seguridad.

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Introduction

Our current environment of increasing computational speeds, along with the many complex analytical methods available to naval architects and marine engineers, has resulted in many novel approaches to ship design. Some of these design innovations are on a system scale, while others address the overall arrangement of the marine platform. In a dynamic world of evolving design, it is proving increasingly challenging to apply the traditional approach of prescriptive based standards. As a result, attention has focused on the increased use of a goal based philosophy over the detailed technical standards more typically incorporated in rules and regulations.

Typical goal based standards (GBS) contain tiers that provide progressively more detailed information. In essence, GBS are intended for developers of standards, not as the standard itself. Once a comprehensive standard is created, designers apply it to their ship. Using a goal based philosophy for naval ship safety, NATO ANEP 77 (known as the Naval Ship Code) provides the first high-level comprehensive safety standard for combatant and noncombatant military ships. Put simply, ANEP 77 is a sort of naval version of IMO SOLAS (Safety of Life at Sea, a convention of the International Maritime Organization) and is being applied to many NATO and non- NATO warships around the world.

This document presents the genesis of goal based standards in the commercial maritime industry and discusses the existing maritime treaty (IMO SOLAS) that forms the basis for the Naval Ship Code. It describes the historical evolution leading to the current standard – which was created as a product of both navies and classification societies engaged in naval and maritime defense work – providing a short overview of the governing bodies for ANEP 77, namely the International Naval Safety Association (INSA) and the Naval Ship Classification Association (NSCA).

Finally, this paper suggests a process for applying the Naval Ship Code to a naval combatant and provides guidance on how that process would be applied.

The trend toward goal based standards

Most of the standards used in technical fields are prescriptive in nature; for example, they may cite specific materials to be used; numerical tolerances to be adhered to; building plans to be followed; or test criteria that must be satisfied. Of course, many more examples can be cited. Among the thousands of industry, governmental, national and international standards that exist, these are by far the most prevalent. Prescriptive standards list what to do to achieve compliance and, in many cases, how to do it as well.

Goal based standards (GBS) differ from a prescriptive standards in their approach to compliance, by describing what must be achieved, rather than what must specifically be done to successfully achieve it. They do not specify the means of achieving compliance, but set tiered layers of goals that allow alternative and creative means to be compliant. While it can be argued that prescriptive standards offer a more predictable result, they also tend to restrict alternatives that may prove superior to the prescribed result. This is principally because prescriptive requirements tend to be a representation of past experience, which could become less relevant over time. As a result, they could hold back ship designers from being able to properly address future design challenges by employing evolving new technologies.

Goal-based standards are generally high-level standards and procedures, and may be described as a 'standard of standards' since these high level requirements are met through regulations, rules and standards. GBS are typically comprised of at least one goal; functional requirements associated with that goal; and verification of conformity that rules/regulations/standards meet the functional requirements and goal or goals. In order to meet the goals and functional requirements, third party certifiers, generally made up of 'recognized organizations' (ROs) and/or national agencies (typically Naval Administrations), work to choose and develop the requirements. These detailed requirements eventually become a part of the overall GBS framework.

This is particularly advantageous when considering designs incorporating novel concepts or new innovations that have not been previously envisioned. Perhaps the most prevalent example where prescriptive standards were no longer adequate to satisfactorily address design challenges was during the revolution in shipboard control systems. As these systems transitioned from cable connected electronics networks, with modules in enclosed operating stations containing fixed circuit control cards, to programmable logic controllers (PLCs) and computer based networks, and eventually towards wireless and cloud based integration with centers external to the ship itself, classification society[1] rule sets were continually challenged to keep pace. Rule requirements for these types of control systems, which were progressively melding fixed purpose electronic circuits with programmable information networks, were becoming outdated quicker than the rules were being updated. For this reason, these rules moved away from prescriptive standards towards performance and goal based rules that relied more on failure mode and effects analyses (FMEA) and verification and validation techniques (V&V).

To illustrate, the American Bureau of Shipping (ABS) now offers ABS CyberSafety® notations that include Integrated Software Quality Management (ISQM) services. Rather than the previous traditional focus on individual equipment and system components, this notation helps to deliver efficient, uninterrupted operation by providing a framework for coordinating and controlling the way software development, integration and maintenance are managed throughout the life of the asset. The software provider participates in a rigorous review of its software quality engineering process and procedures as documented; the program also includes an onsite assessment of execution of those processes by the development staff to verify integrity and compatibility with other software systems installed on board.

[1] Since the 1700s, the commercial shipping industry has employed the process of ship classification for ship design, construction and lifecycle maintenance, using the independent third-party services of recognized Classification Societies (also known as 'Class Societies'). Classification societies establish and apply technical standards (known as 'Rules') in relation to the design, construction and periodic survey of marine related facilities (including ships, craft and offshore structures). Classification addresses the life cycle of a ship or offshore unit from design to decommissioning; only classification societies are able to class ships and other marine structures. As independent arbiters of standards, these organizations are a major stakeholder in the international network of maritime safety.

Efforts to address safety in the global maritime and naval world using GBS practices

IMO

The International Maritime Organization (IMO) is the United Nations specialized agency with responsibility for the safety and security of commercial shipping and the prevention of marine pollution by ships. As a specialized agency of the United Nations, IMO is the global standard-setting authority for the safety, security and environmental performance of international shipping. Its main role is to create a regulatory framework for the shipping industry that is fair and effective, universally adopted and universally implemented.

Formed by the United Nations in 1948, IMO is the first ever international body devoted exclusively to maritime matters.

Headquartered in the United Kingdom, it has 170 Member States and three Associate Members. Its governing body, the Assembly, meets once every two years. Between sessions the Council, consisting of 40 Member Governments elected by the Assembly, acts as the governing body of the IMO. IMO is a technical organization and most of its work is carried out in a number of committees and sub-committees.

The first conference organized by IMO in 1960 was addressing maritime safety. That conference adopted the International Convention on Safety of Life at Sea (SOLAS), which came into force in 1965, replacing a version adopted in 1948. The 1960 SOLAS Convention covered a wide range of measures designed to improve the safety of shipping. They included subdivision and stability; machinery and electrical installations; fire protection, detection and extinction; life-saving appliances; radiotelegraphy and radiotelephony; safety of navigation; carriage of grain; carriage of dangerous goods; and nuclear ships. IMO adopted a new version of SOLAS in 1974, which entered into force on 25 May 1980. This, along with a series of amendments developed since then, is still the governing version today.[2]

IMO Moves toward GBS Practices

In the 1990s, IMO's Maritime Safety Committee recognized that prescriptive requirements were unable to cope with the challenges posed by new ship designs, and attempted to incorporate a goal based philosophy into the technical requirements found in SOLAS. As experienced with ship electronics controls and computer based systems, safety regulations also need to be frequently updated to keep pace with lessons learned and the latest technologies.

The concept of goal based ship construction standards was introduced in IMO at the 89th Session of the Council in November 2002 through a joint proposal from the Governments of Bahamas and Greece (IMO MSC 77). In this proposal, it was recommended that IMO play a larger role in determining the standards to which new ships are built. Traditionally, these standards were developed by shipyards, classification societies and in some cases flag states. These ship construction standards need to be written in such a way as to permit innovative designs; but at the same time, the ships should be built so that, with proper maintenance and adequate allowance in the design for ease of inspection and survey, they will remain safe for their entire economic life.

Over the next 2 years the matter was considered by the Maritime Safety Committee, the Council and finally the IMO Assembly. At its 23rd session in November 2003, "Goal-based new ship construction standards" was included in the strategic plan and the long-term work plan of the Organization. The MSC commenced detailed technical work on the development of GBS at its 78th session in May 2004, and a working group on GBS was established (MSC 79 and MSC 80) to address the research. In May 2005, it was agreed the basic principles of the IMO goal based standards would be:

- Broad, over-arching safety, environmental and/or security standards that ships are required to meet during their lifecycle;
- The required level to be achieved by the requirements applied by class societies and other recognized organizations, Administrations and IMO;
- Clear, demonstrable, verifiable, implementable, long standing, and achievable, irrespective of ship design and technology; and
- Specific enough in order not to be open to differing interpretations

These basic principles were developed to be applicable to all goal based standards developed by IMO and not only to ship construction standards. For example, the latest IMO instruments using the GBS approach (besides the "Common Structural Rules for Bulk Carriers and Oil Tankers", called the 'Common Structural Rules' or CSR BC & OT developed by IACS[3]) are the Polar Code, as well as the International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF Code).

The Maritime Safety Committee, at its eighty-seventh session in May 2010, adopted a new SOLAS regulation (reg. II-1/3-10) on *"Goal-based ship construction standards for bulk carriers and oil tankers"* (resolution MSC.290(87)). This regulation, which entered into force on 1 January 2012, requires that all oil tankers and bulk carriers of 150 m in length and above, for which the building contract is placed on or after 1 July 2016, satisfy applicable structural requirements conforming to

[2] In the commercial shipping industry, marine safety has long been addressed in a global context since the mid-nineteenth century through international conventions. This practice became more urgent after the sinking of the Titanic in 1912. This effort resulted in the first International Convention for the Safety of Life at Sea (SOLAS). Successive versions of SOLAS were released in 1929 and 1948. Soon after, the International Maritime Organization was formed. The IMO subsequently became the responsible body for SOLAS. The SOLAS Convention is generally regarded as the most important of all international treaties concerning the safety of merchant ships.

[3] International Association of Classification Societies.

the functional requirements of the International Goal-based Ship Construction Standards for Bulk Carriers and Oil Tankers (GBS Standards). Under the GBS Standards, construction rules for bulk carriers and oil tankers of classification societies (which act as recognized organizations) or national Administrations, will be verified by international GBS Audit Teams established by IMO's Secretary-General. This scheme is based on the *"Guidelines for the verification of conformity with goal-based ship construction standards for bulk carriers and oil tankers"* (MSC.296(87)), or the GBS Verification Guidelines.

The basic principles and methodology that IMO would use to develop these GBS utilize 5 tiers:

Tier I – Goal(s)

- One or more high-level objective(s) to be met

Tier II – Functional Requirements

- Criteria to be satisfied in order to conform to the goal(s)

Tier III – Verification of conformity

- Procedures for verifying that the rules and regulations used conform to Tiers 1 and 2

Tier IV – Rules and Regulations (for ship design and construction)

- Detailed requirements applied by national Administrations and/or recognized organizations acting on their behalf to the design and construction of a ship in order to address Tiers 1 and 2

Tier V – Industry practices and standards

- Industry standards, codes of practice and safety and quality systems for shipbuilding, ship operation, maintenance, training, manning, etc., which may be incorporated or referenced in Tier 4

Parallel Naval Efforts toward a GBS Safety Code

At about the same time that IMO was working towards the publishing of goal based standards (from the late 1990's to the present), an ongoing effort within the global naval community – one that would see a nexus between the increased application of commercial practices for naval design and construction, along with the need for commonality of naval safety measures – was underway, one that would result in the development of naval safety requirements contained in the first Naval Safety Code.

Since before the Second World War, many navies have gained familiarity with the commercial process of classification through naval construction programs using commercial standards and processes. While most of these ships were of a non-combatant nature, such as for auxiliary support vessels, oilers and stores ships, some navies have moved into using this process of classification for combatant ships as well. Since 2000, several classification societies developed Rules to address a wide range of naval combatants. Among them are American Bureau of Shipping (ABS), Bureau Veritas (BV), Det Norske Veritas - Germanisher Lloyd (DNV-GL), Indian Register (IRS), Lloyd's Register (LR), Polish Register (PRS), Registro Italiano Navale (RINA) and Türk Loydu (TL). These rules have been applied to navy ships built for the navies around the world. However, while navies extensively employed classification society rules for hull, mechanical and electrical aspects of their ships, naval ship safety requirements were typically maintained through standards and guidance unique to each naval organization, and applied on a ship class by class basis. The challenge before them was to apply this same commercial model to develop common naval safety requirements that could be used across not only classes within a navy, but also applied across many fleets.

Starting in the late 1990's, while several classification societies worked independently with various navies to develop naval classification rules, a few approached NATO's (North Atlantic Treaty Organization) Naval Group 6 on Ship Design to suggest possible opportunities for collaboration. Both the societies and NATO NG6 agreed that the societies would be better served to coordinate their efforts, and by 2000 the Terms of Reference (ToR) was signed forming the Naval Ship Classification Association (NSCA), an organization dedicated to addressing naval design issues specific to class societies. As a sort of naval-oriented counterpart to the International Association of Classification Societies (IACS), NSCA's goal was to cooperate in areas related to the safe operation of naval ships. Today, the NSCA is composed of eight classification societies; ABS, BV, DNV-GL, HRS, LR, PRS, RINA, and TL.

One of the first tasks for NSCA was to investigate some recent accidents on navy ships, comparing them to similar experiences on commercial ships. The NSCA determined that one of the principal reasons for these accidents was that the navy ships were not subject to the requirements of the Safety of Life at Sea Convention (SOLAS), as are commercial ships, since Chapter 1, Regulation 3 to IMO SOLAS specifically exempts 'ships of war and troopships'.

Historically, it was never envisioned to apply SOLAS to naval designs or operations. It was recognized by the Societies that many of the requirements contained in IMO SOLAS were incompatible with navy ships for many reasons. For example, commercial ships typically have much smaller crews than comparably sized naval ships; this larger crew is to support the naval mission, which may include operation of combat systems, or repair of damage sustained in combat. In addition, there may be additional personnel onboard for marine contingents and air support crews. For these and other reasons, IMO added the Exception Clause noted in the previous paragraph.

To address this need, NSCA began work on a set of rules for addressing safety issues, to be named the Naval Ship Code. To better support this effort, as well as create an open forum between the NSCA and interested navies, the International Naval Safety Association (INSA) was established in 2008. In addition to the classification societies composing the NSCA, participants of INSA include several Navies. Today, the members consist of: Royal Australian, Canadian, Danish, French, Italian, Netherlands, Norwegian, Singaporean, South African, Swedish and UK (Royal) Navies. Today, the principal function of INSA is to continue to develop and maintain the Naval Ship Code, as well as track its application to designs around the world.

The naval ship code

Introduction and Application

The Naval Ship Code, or NSC, is intended to be a code addressing naval surface ship safety, which is based on IMO conventions, resolutions and other sources that are applicable for the majority of government ships. NSC is published by the North Atlantic Treaty Organization (NATO) as ANEP (Allied Naval Engineering Publication) 77, and approved by the nations in the NATO Naval Armaments Group. NSC was developed from the start as a goal based standard, considering what the ultimate safety intent of the designer is, and considering a range of alternative design approaches that will reach this safety goal. The goals should represent the top tiers of the framework, against which a ship is verified both at design and construction stages, and during ship operation.

The Code is applicable to all surface craft used for government, non-commercial service, such as navy, coast guard, border patrol, customs etc. It applies principally to conventional powered vessels (non-nuclear) using conventional fuels such as diesel (for example NATO F76 fuel) or intermediate fuel oils.

The Code requires that a Concept of Operations Statement (or ConOpS) be developed to compare the applicability of the criteria and standards chosen. It is noted that the ConOpS may change, perhaps several times, over the service life of a government ship. Accordingly, the criteria may need to be reconsidered over the life of the ship as the ConOpS evolves. Once this is determined, the Code can provide a path for a ship to be certified by a Naval Administration[4], along with recognized organizations (RO) such as classification societies, to establish that a vessel is safe (within the limits of those aspects

[4] The 'Naval Administration' is the agency within a Government or Nation responsible for the safe operation of government ships. The Naval Administration may be assisted or supported by other government departments, or it may delegate this duty to another agency within the Government. For the purposes of the Naval Ship Code, the Naval Administration is that agency that is charged with the implementation of the Code (or the delegation of specific duties to a recognized organization) as part of the safety management systems for a ship.

addressed by the Code) to operate in accordance with the ConOpS provided, as well as within the safety policies, and safety organization, of the government organization in which it will operate.

While the goal based nature of the Code allows the Naval Administration and ROs to consider alternatives to the typical safety requirements applied to commercial ships, it is important to emphasize two limitations:

1. The Naval Ship Code is not intended to be viewed as a complete and entire safety management system for a ship or fleet. It is, rather, a 'tool in the toolbox' of overall and safe operation for a fleet, and may fill an important role in the fleet or administration's safety policy.
2. It includes processes and potential solutions for the defined technical areas which can be applied to any naval ship, within the context of its operational requirements. While fully intended to apply to operating conditions and foreseeable damage scenarios applicable to peacetime and maritime security (as determined in the ConOpS), the Code is NOT intended to apply to combat operations, or its associated threat conditions. While an important part of a government operated ship intended for military or defense related operations, these are outside of the scope of the Code, and intended to be addressed separately by the appropriate departments within an Administration.

The Naval Ship Code need NOT be invoked in full; it is not mandatory (unless made mandatory in the context of a build specification or through a Naval Administration), and any nation is free to implement all - or part - of the Code as part of their national regulations applied to government ships. In addition, when applying the Code, consideration is needed to determine how the ship will continue to be verified to the Code for recertification during its service operation, in order to avoid unintended safety degradation due to modifications or modernization measures applied to the ship over its life.

Framework of the NSC

The Naval Ship Code includes three distinct Parts:

Part 1: NSC Requirements
Part 2: Solutions
Part 3: Justification and Guidance

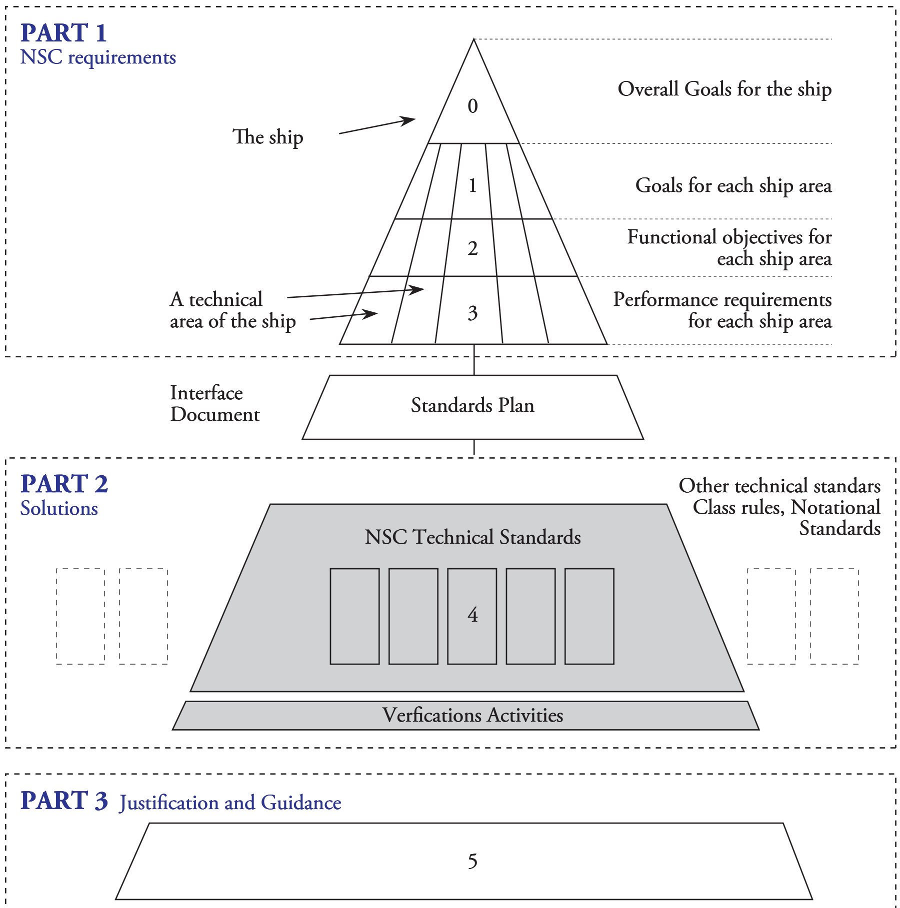
See Fig. 1, Arrangement of the Naval Ship Code. The tiers are similar to the IMO GBS structure (See "IMO Moves toward GBS Practices"). The increasing width of the triangle as the Naval Ship Code descends through the tiers implies an increasing level of detail. In addition, the vertical diagonals within the triangle refer to different technical areas within the ship, as addressed within the chapters.

Each Part of the NSC contains essentially the same Chapters:

Chapter 0 – Using the Naval Ship Code
Chapter I – Naval Ship Safety Certification
Chapter II – Structure
Chapter III - Buoyancy, Stability and Controllability
Chapter IV - Engineering Systems
Chapter V - Seamanship Systems
Chapter VI - Fire Safety
Chapter VII - Escape, Evacuation and Rescue
Chapter VIII - Communications
Chapter IX - Navigation
Chapter X - Dangerous Goods

Part 1 contains the overall goals for the ship, and are found in Regulation 1 of Part 1, Chapter 1 ("Naval Ship Safety Certification"). In short, the ship is to be designed, built and maintained so that when operated within the determined ConOpS, the ship is (1) safe to operate and prevents injury of crew onboard; and (2) the ship still has essential safety functions for crew in foreseeable damage circumstances. It is important to note that, for "special ship concepts", these goals may be modified if agreed by the Naval Administration; but risks must still be kept as low as practicable. However, in addition to these stated goals, the Naval Administration may add additional goals.

Fig. 1. Arrangement of the Naval Ship Code



As visually demonstrated by the pyramid in Fig. 1, the top Goal is achieved through the achievement of the goals found in each chapter; these in turn are met through the successful completion of the Functional Objectives and Performance Requirements for each ship technical area. This scheme provides flexibility as to how certification may be achieved. And, while it is emphasized that the Code is not mandatory, nor must it be invoked in its entirety, use of only parts of the Code are not recommended as hazards can be interdependent on one another.

It is noted that between Part 1 and Part 2, the Figure refers to an 'interface document' described as the "Standards Plan"; this item will be discussed below in the section titled "The Process for NSC Certification".

Part 2 contains suggested solutions for the functional objectives and performance requirements in Part 1. For example, in Part 1, Chapter VII (Escape, Evacuation and Rescue), Regulation 27 addresses 'Rescue Arrangements'. The Functional Objective simply states that these arrangements shall permit persons to be rescued from the sea, whether it be from the water or some form of survival craft. The Performance Requirements add the need for these rescue arrangements to retrieve persons overboard, while minimizing risk to the crew rescuing the person. In addition, there should be a means to permit the mass rescue of persons from another vessel. This is the limit of Part 1. Meanwhile, Part 2, containing the recommended Solutions, provides far more detail. It mandates that rescue craft arrangements comply with either IMO Resolution A.656(16) *"Guidelines for Fast Rescue Boats"*, LSA [5] Code Chapter 5 "Rescue boats", or IMO MSC/Circ.809

[5] Lifesaving Appliances Code.

"Recommendation for canopied reversible liferafts, or automatically self-righting life-rafts and fast rescue boats, including testing, on ro-ro passenger ships". It describes the number of craft to have onboard and how it is to be used; requirements applicable for the ship to be adequate to recover overboard persons; how rescue craft and lifeboats shall be launched and under what conditions; Swimmer of the Watch requirements and their equipment; Mass Rescue requirements; as well as needs for line-throwing appliance lifebuoys. As can easily be seen from this example, the solutions tend to be prescriptive as a response to the performance requirements; but even in the solutions, alternatives are presented and considered.

> *[Note: As shown in this example, industry, government, military or international standards (such as IMO) may be invoked as possible solutions to the performance requirements. In addition, classification society rules may be used; this exemplifies why a goal based standard is best described as a 'standard of standards' as noted earlier. This also best explains the boxes shown within Tier 2 in Fig. 1; these represent the many standards invoked to be used as solutions for Tier 1.]*

Options are also provided for verification. The solutions provided (such as those listed above) may be followed; as an alternative, the rules of a classification society, international convention (such as IMO SOLAS), or a suitable alternative or additional standard may be used to facilitate verification of the performance requirements. In stating this, the Code allows the Naval Administration to continue to use the existing standards, systems and equipment used previously, should these items be verified to meet the requirements. In most cases in Part 2, these solutions may either be verified by the Naval Administration, or by an RO (such as a classification society).

Part 3 contains the final tier of the pyramid, and provides justification and guidance to support the Naval Ship Code Performance Requirements and Solutions to adequately satisfy the Goals. In addition, and perhaps even more critical, this Part provides the history and reference data provided by all applicable parties who contributed to each part and chapter. It discusses the derivation of many of the sections, presented in tabular format. For example, referring back to our example on Rescue Arrangements, it gives the sources of the requirements (such as IMO and classification society documents and rules), as well as references provided by navy members of INSA. In this way, the guidance lays down the foundation for future development to be accomplished for the NSC.

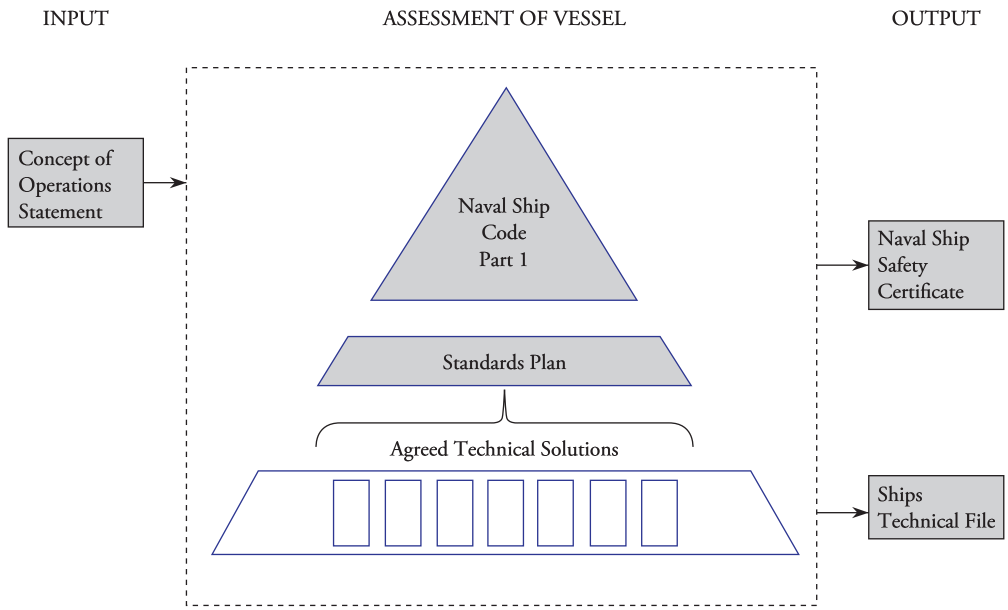
The Process for NSC Certification

The process for certification of a government ship begins with the concept of operations statement, or ConOpS. The ConOpS defines the ship's function, operational areas and characteristics, and serves as the basis for the certification. The ConOpS is composed of a table listing the following:

- Vessel particulars, such as:
- Mission or roles of the ship
- Dimensions
- Displacement measurements
- Speed and endurance
- Post damage capability (non-combat or threat related)
- Operational area
- Crew description
- Environmental operational limits:
- Including navigation in ice
- NSC related engineering equipment:
- Propulsion machinery/equipment
- Fire safety related systems and gear
- Communications and navigation equipment
- Maintenance and survey schemes/periodicities
- Etc.

This is the primary input to the assessment of the ship (see Fig. 2). Once established, the ConOpS is used to begin assessing the ship to Part 1 of the NSC (from Goals to Performance Requirements). Part 2 may be applied to determine agreed upon Solutions to satisfy Tier 1. An example of a ConOpS form may be found in Part 3, Chapter I, Annex A of the NSC.

Fig. 2. Main Regulatory Elements in the Certification Process of Ships



The **Standards Plan** is comprised of a listing of technical standards. These are used to verify that the ship meets the Goals, Functional Objectives, and Performance Requirements as verified by the Naval Administration or its recognized organization(s), within the defining parameters of the ConOpS. These may include (as examples): industry or government design standards for safety equipment; IMO conventions either applied in part or in whole; the applicable rules of a classification society; or other options for solutions deemed appropriate for use as determined by the Naval Administration. This plan (essentially a list or spreadsheet) forms the basis for the Tier 4 Solutions. An example of a Standards Plan form may be found in Part 3, Chapter I, Annex B of the NSC.

As the NSC certification process is in progress, documents are being created to maintain configuration control of the overall process. These documents will eventually be collected to create the Technical File.

A Ship's Technical File contains information as to how the requirements of the Code have been applied for the ship design and construction. The file shall be complete at delivery of a new ship, provided all aspects of the Code being invoked for this design have been addressed. A typical Technical File may include:

- A Copy of ConOpS;
- Applicable NSC Parts/Chapters being invoked
- Applicable NSC Tier level being invoked
- The complete Standards Plan
- Interpretations/Justifications made during the NSC certification process
- Classification Society information (rulesets, notations, etc.)
- Statutory certificates
- Other information as needed

The Technical File is a living document; it must be updated to address events such as modifications and modernization initiatives along the life of the ship's operation.

Naval Ship Safety Certification (NSSC)

Once the verification process is completed, the ship is issued the Naval Ship Safety Certificate (NSSC). This may be issued by the Naval Administration, or jointly with the Recognized Organization. The NSSC shall refer to information found in the ConOpS, Standards Plan, and ship construction files maintained by the classification society or Naval Administration. The NSSC contains the certificate itself, an Annex containing key design and verification information, and supporting data related to design information. Once completed, the NSSC then becomes part of the Technical File.

Much like a class certificate issued by a classification society, the NSSC is endorsed and renewed at regular intervals as determined by the Naval Administration.

The NSSC should be as clear as practicable in describing the technical standards used and any determinations or major assumptions made during the NSC process. An example of a NSSC form may be found in Part 3, Chapter I, Annex C of the NSC.

Applying ANEP 77 to new construction and existing ships

ANEP 77 and the Acquisition Process

Most modern government ship acquisition programs employ some form of a certification matrix. A 'Certification Matrix' is a table that addresses all aspects of the ship (using a system/ equipment level approach, such as the Ships Work Breakdown Structure or 'SWBS' format). Each row of the table presents a system or equipment description, subtopic within that item, applicable standard, type of certification required for that topic, and the certification agent (or certifier). For example:

SWBS code:	555
Description:	Fire Extinguishing Systems
Subtopic:	Fire Pumps
Standard:	ABS INSG [6], sections 4-6-1/3.7 and 4-7-3
Certification:	Certified per ABS INSG 4-6-1/7.3.1
Certifier:	ABS

Using a typical acquisition strategy, the NSC process would begin soon after the Capability Development Document (CDD) is generated, as which point the ConOpS may be developed. Some items of the ConOpS (such as propulsion and safety equipment) may not be able to be completed until the completion of the Capability Production Document (CPD) or perhaps not even until detailed design is well in progress. In any case, the NSC certification process should be developed in parallel with the design and construction of the ship, as it is essentially a subset of the total ship certification matrix.

Existing Ships

It is preferable to conduct the process for Naval Ship Safety Certification at new construction; however, with adequate documentation and access to the ship, it may also be applied retroactively after the ship has begun operation.

For existing ships that are classed by a classification society, one way to begin the process (after development of a detailed ConOpS), is to build a draft Standards Plan that includes reference to the rules to which it was built, or currently applicable rules (as agreed between the classification society and the Naval Administration). Then, compare the rules to the applicable Performance Requirements found in the Code. Once this is done, there will be a number of 'gaps' between where the classification society's rule alone could not meet, or could only partially meet, the Performance Requirements. To these gaps are then applied more standards into the Standards Plan. At this point, the ship should have all of the requirements in the Code addressed, and a formal survey of the ship can begin.

Developing a Standards Plan for Existing Ships

Based on recent ABS experience with applying the NSC to two separate classes of existing naval vessels, some key insights are provided below that detail potential issues, their solutions, and additional guidance that may assist in practical implementation of the Code.

Chapter 0 – Using the Naval Ship Code

The foregoing discussion describes the purpose,

[6] ABS Guide for Building and Classing International Naval Ships (2017)

scope, limitations, roles, arrangement, principles, required documentation and exemptions provided in the Code.

Chapter I – Naval Ship Safety Certification
A detailed and up to date ConOpS provided by the Naval Administration (Owner) is crucial to guiding the selection of applicable technical standards. The ConOpS should include details of how the ship will be operated and maintained throughout its service life including details of the ship attributes, survivability, operating environment etc.

Chapter II – Structure
Although the Code does not specify prescriptive structural design requirements, it broadly defines the design goal for safe operations as:

Structural capacity ≥ Structural demand x Safety Margin

Several IACS classification societies, including ABS, have well developed and established naval ship rules that form a sound basis to verify the goals of this chapter are met.

Chapter III - Buoyancy, Stability and Controllability
In general, the subdivision arrangement, watertight integrity and intact & damage stability requirements of applicable IMO regulations and classification society rules cover or exceed the ANEP 77 Tier 3 performance requirements.

Chapter IV - Engineering Systems
In general, the engineering system requirements of classification society rules cover or exceed the ANEP 77 Tier 3 performance requirements.

It is to be noted that certain requirements in this section may be additional to what Class Rules or IMO requirements specify for commercial vessels. These requirements may be evaluated based on the ConOpS and criticality of the safety function supported in discussion with the Naval Administration.Some examples of such requirements are listed below:

- An uninterrupted power system (UPS) for essential safety functions;
- Requirements for backup illumination of spaces;
- Redundancy of electrical distribution systems across main fire zones;
- Procedures for setting and overriding alarms and safety systems
- Software integrity (this is offered by Class as an optional notation, ISQM)

Chapter V - Seamanship Systems
The seamanship systems requirements such as for anchoring and mooring arrangements, embarkation and accessibility, etc., of the applicable IMO and IACS requirements cover or exceed the ANEP 77 Tier 3 performance requirements.

Chapter VI - Fire Safety
The fire safety requirements concerning structural fire integrity, containment of fire and active and passive means of firefighting are well covered by the extensive fire protection requirements of SOLAS and related IMO publications such as the FTP[7] Code, HSC[8] Code or the FSS[9] Code.

Certain requirements related to casualty threshold, safe return to port and safe areas specified in ANEP 77 are more typically applicable per SOLAS to large commercial passenger vessels. The related prescriptive requirements are specified in detail within SOLAS; the applicability to the naval vessel under consideration may be decided based on the vessel ConOpS and in discussion with the Naval Administration.

Chapter VII - Escape, Evacuation and Rescue
The requirements related to escape, evacuation and rescue, etc., of SOLAS and related IMO publications such as the LSA Code, HSC code, etc., cover or exceed the ANEP 77 Tier 3 performance requirements.

A few requirements with regard to the number and position of the general alarm system and emergency lighting systems as well as the requirement to include these in the FMEA analysis may not fully fall within the scope of typical IMO and Class requirements

7 International Code for the Application of Fire Test Procedures.
8 International Code of Safety for High-Speed Craft.
9 International Code for Fire Safety Systems

and may need to be evaluated based on the ConOpS and criticality of the safety functions supported in discussion with the Naval Administration.

Chapter VIII – Communications

Most requirements in this section are equivalent to those as specified in SOLAS with a few additional requirements sampled below:

- Internal communications systems need to be provided with a backup independent of the ship's power supply
- Capability for sea-to-air 2-way radio communications
- GMDSS[10] system to be provided with facilities to inhibit transmission for Emissions Control (EMCON) and Electromagnetic Radiation Hazard (RADHAZ) purposes.

Chapter IX – Navigation

The Navigation requirements are equivalent to the applicable SOLAS and Class requirements, however, ANEP 77 requires mandatory compliance with the recommendatory IMO Resolution MSC/Circ. 982 *"Guidelines on Ergonomic Criteria for Bridge Equipment and Layout"*. Further, additional design and arrangement requirements are specified in ANEP 77 for the alternative and emergency conning positions.

Chapter X - Dangerous Goods

Where compliance with SOLAS or the IMDG[11] code, in whole or part, is not compatible with the ConOpS, issues of stowage, personal protection and emergency procedures when dangerous goods are carried must be made using equivalent arrangements within the scope of SOLAS/IMDG (ex. ammunition); or using additional arrangement outside the scope of SOLAS IMDG (such as a navy specific ammunition standard); or through a risk assessment acceptable to the Naval Administration.

Conclusions

Goal based standards have enabled both commercial and government ships to maintain acceptable levels of safety for operators, Flag Administrations and Naval Administrations, while allowing for novel design innovation and technological advances related to ship design.

Typical goal based standards (GBS) contain tiers that provide progressively more detailed information. In essence, GBS are intended for developers of standards, not as the standard itself. Once a governing standard is created, designers apply it to their ship. By applying this goal based philosophy for naval ship safety, NATO ANEP 77 (Naval Ship Code) provides a comprehensive safety standard for combatant and noncombatant military ships for both NATO and non- NATO warships around the world.

As the Naval Ship Code has only been in existence for a few years, it is too early to determine how effective it has been in adequately addressing safety on new naval ships. However, the standard has gained enthusiastic support from the naval participants of INSA, and several have employed all or parts of the standard in the design and construction of their newer designs. In addition, some have initiated the process of applying the NSC to their existing classes as well. The NSC remains a living document, and both NSCA and INSA continue to improve the document to increase its effectiveness as a worldwide naval safety standard.

[10] Global Maritime Distress and Safety System.

[11] International Maritime Dangerous Goods Code.

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Figure Credits

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Design and development of route planner for Unmanned Surface Vehicles

Diseño y desarrollo de un planificador de rutas para vehículos de superficie no tripulados

DOI: 10.25043/19098642.151

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Abstract

This paper describes the development of a route planner for Unmanned Surface Vehicles (USVs) focused on the study of an operational scenario for a specific mission – Anti-Submarine Warfare (ASW). Through the design and implementation of a simulation model, the effect of the different factors that particularly influence ASW is analyzed, such as search pattern, speed and sensor type; dipping sonar or towed array sonar (TAS). By obtaining a measurement of effectiveness, the USV's response in the deployment of this type of mission can be defined using time to detect the threat in a search area, as parameters to measure the performance.

Key words: Unmanned Vehicles, USV, Searching Patterns, ASW, Sonar, Dipping Sonar, TAS, Effectiveness, Navy.

Resumen

En este artículo se presenta el desarrollo de un planificador de rutas para vehículos no tripulados de superficie (USVs) orientado al estudio de un escenario operacional para una misión en particular – la guerra antisubmarina (ASW). Por medio del diseño e implementación de un modelo de simulación, se analiza el efecto de los diferentes factores que influyen particularmente en la ASW, como son el patrón de búsqueda, la velocidad y el tipo de sensor; sonar de profundidad o sonar remolcado. Se aprecia mediante la obtención de una medida de efectividad, la respuesta de los USVs en el desarrollo de este tipo de misión, usando el tiempo para detectar la amenaza y la detección de la amenaza en un área de búsqueda, como parámetros para medir el desempeño.

Palabras claves: Vehículos no tripulados, USV, Patrones de búsqueda, ASW, Sonar, Dipping Sonar, TAS, Efectividad, Armada.

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Introduction

For the accomplishment of missions with unmanned surface vehicles (USVs), it is very important to have tools that allow the prediction or estimation of the time, trajectory, performance and effectiveness in the accomplishment of tasks, and even more so when taking into account the complexity of performing specific missions such as Mine Countermeasures (MCM), Anti-Submarine Warfare (ASW), Maritime Security, Surface Warfare (SUW), Special Operations Forces (SOF) Support, Electronic Warfare (EW) and Maritime Interdiction Operations, which are common for this type of vehicles. [1].

This research focuses on the development of a model to replicate a particular ASW scenario using different computational tools such as Matlab® and Labview®. Expert assessment identifies a possible operational scenario and different factors that could influence the increase or decrease of mission effectiveness, including search patterns, the type of sonar, speed, direction of search, the starting point of the search and the number of USVs. Based on these factors, a method of evaluating effectiveness is explored and the relative impact of the different factors on the success of the mission is investigated through experiment design and different sensitivity analyzes.

Development

Anti-Submarine Warfare – ASW

ASW consists of the purpose of finding, tracking and damaging or destroying enemy submarines. To perform the detection of an ASW threat, equipment such as sonobuoys and different types of sonars that differ in their mode of operation are used; Helmet sonar, Dipping Sonar, TAS - Towed Array Sonar [2]. These sensors perform the first detection, then using specialized equipment the classification of the type of unit and subsequent monitoring and neutralization is performed using torpedoes or mines. Within the detection of a submarine, there are parameters such as the speed of sound in the water, temperature and salinity profile, type of background, depth, among others, that must be taken into account to achieve a high detection probability.

According to the assessment of experts an operational scenario is determined, which consists of the port exit with submarine opposition, where the threat is greater due to the complex conditions of sonar detection in shallow waters. The submarine will always be in an advantageous position for an attack because the surface units will not be able to start ASW operations until they have crossed the channel or completed the port exit.

Unmanned surface vehicles in ASW

General Dynamics has been designing USVs since 2006, using sonar sensing equipment specially modified for this type of craft [3]. In 2004 Thales implemented the FLASH Dipping Sonar in the ACTD Spartan USV, see below, and it was tested in Brest Bay in mid-2006 where it demonstrated its ability in shallow waters in sprint & dip operations which means to advance and submerge. See Fig. 1.

Fig. 1. FLASH sonar in Spartan USV [4]

On the other hand, it is important to highlight the USV Darco, which is a USV with a multi-configuration for Antisubmarine warfare. This USV can be equipped with torpedo launchers, depth sounder, Active Source and towed Sonar. The USV Darco is a development proposed by the company General Dynamics that seeks to supply this type of USV for the Litoral Combat Ship - LCS type ships of the US Navy. [5]

Movement patterns for naval missions

Search patterns are commonly used in different scenarios where it is required to optimize and follow an established order in order to optimize time and increase the probability of detecting the target, whether they are threats or any element of interest. The patterns are very specific according to the doctrines and necessity of each country's Navy, however the patterns, as shown in Fig. 2, correspond to those commonly used for different scenarios and which serve as input for the generation of ASW search patterns. Each pattern has a trajectory starting point that is CSP, leg lengths or trajectory with no change of "s" course and courses preset through a previous phase of mission planning.

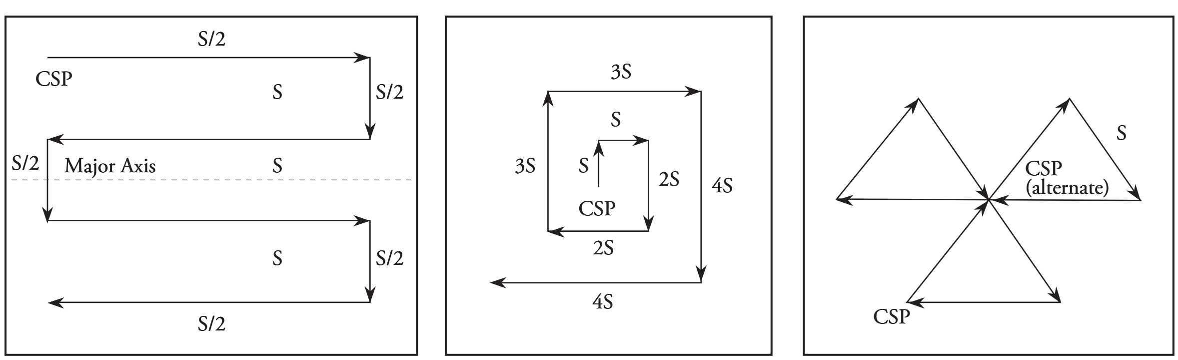
Pattern assessment methodology

In accordance with the methodology proposed by [7] and [8] to develop models that are able to be evaluated by simulation of discrete events, the following process is proposed:

- *Define mission requirements*
  It is necessary to have the objective to be accomplished within the mission defined, to know the threat to be faced, the operating environment and to specify an operational situation (OPSIT1) as a validation point. Based on the above, the blockade of a maritime route by an enemy submarine force type 212 [9] is defined and USVs stand out as support units to carry out the mission. Spartan Scout USVs [10] are equipped with the necessary sensor to detect and track submarine type threats in an area near a fuel refueling point.
- *Identify evaluation requirements and metrics*
  Adapted from [7], it is proposed to use the following parameters for evaluation:
  - The factors or variables are simulation parameters which can be manipulated, such as the number of USVs, the search pattern, sonar type, search direction and search start point.
  - Measures of Performance (MOPs) will be used as metrics related to the tasks required for a particular mission.
  - Measures of Effectiveness (MOE) are measures of mission operational performance and are calculated on the basis of MOPs.
- *Development of computational models*
- *Evaluation of the characteristics of the simulation and its impact on the performance of the mission*

For the evaluation of the impact of the different factors of the model on the effectiveness of the mission, a tool for statistical development and analysis like JMP ® is used, which allows an Experimental Design process to be performed. Likewise, an evaluation module is developed to simulate, program and evaluate a set of experiments to determine the best effectiveness in the mission of interest.

Fig. 2. Search and rescue patterns [6]



Simulation factors

The aim is to analyze different variables of the USV in the ASW, such as speed and sonar type. Also, some scenario factors correspond to simulation input parameters such as the type of search pattern, the search entry point, the search direction and the number of USVs. These are described individually below.

USV speed
Speed has a direct relationship with the autonomy of the USV; greater speed produces more fuel consumption, causing the decrease of hours that the USV can be maintained in the area of operation executing the mission. On the other hand, the speed directly impacts the detection range of the TAS sonar; which means that as speed increases, the amount of radiated noise produced by the propulsion system and other components significantly impacts the threat detection range.

The goal is to analyze, through the variation of this factor, the incidence in the reduction of the detection time of the threat and to determine if the autonomy is enough to culminate the exploration in an area. With the speed variation, it will be possible to analyze the behavior of the sonar detection range and the impact it generates on the autonomy of the USVs when performing the ASW mission.

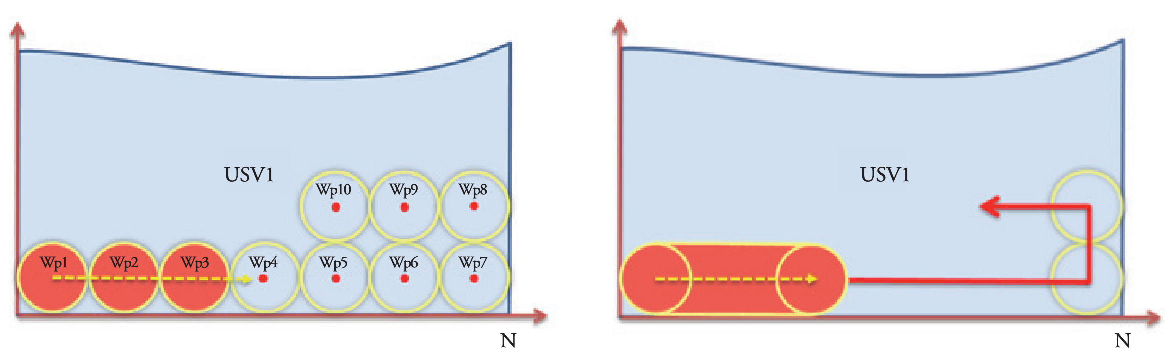
Sonar type
Two possible sonar types are implemented in the experiments, Dipping Sonar (DpS) or Dive Sonar and Towed Array Sonar (TAS) or Trailing Array Sonar. The main difference is in the way the threat is searched; while with the DpS maneuvers must be performed to advance, stop at a point, submerge the sonar, perform the search and raise the sonar again before advancing, with the TAS the search can be performed from the first moment the sonar is launched at a defined depth, which means continuously, see Fig. 3. On the left side of this image the different unfilled discs can be seen, where the USV must submerge the DpS. Each circle symbolizes the range of detection that sonar can achieve; the filled areas symbolize the scan performed. On the other hand, the right side of this image shows the continuous thin line that symbolizes the unexpanded trajectory of the USV, while the filled area displays the area that has already been continuously scanned using the TAS sonar. A threat can only be detected at the last exploration point of the trajectory.

In accordance with [8], the value of the Sonar Range of the results obtained in this research project are taken, thus reducing the complexity of the model and the development of sonar theory.

The objective is to analyze the behavior of the search for the threat and to observe the variation of effectiveness using these two types of sonars.

Number of USVs
Due to the size of the scanning area, the difference of using one or two USVs to perform ASW missions is analyzed, showing the contrast of the

Fig. 3. Scanning with Dipping Sonar (left) – Towed Array Sonar (right)



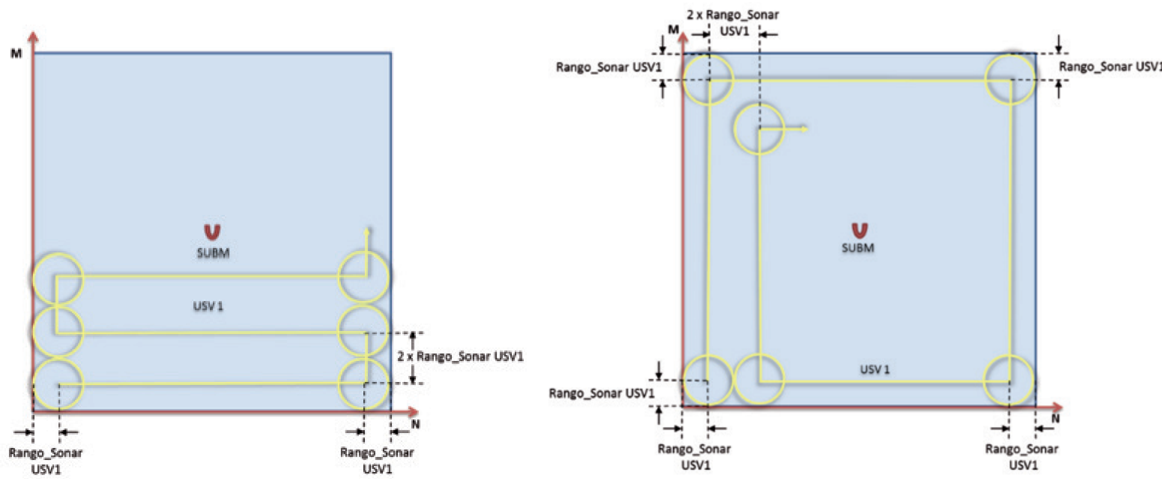
detection time and the total effectiveness for the development of the mission.

Submarine Search Patterns

Based on the operational requirement to search for a threat in an area, four patterns are established adapted from different sources for the search of the submarine according to the OPSIT1 operational scenario. Standard, Diagonal, Expansive, and Evolutive are movement patterns implemented for one or two USVs looking at a specified area of NxM nautical miles, adapted from worldwide fleet procedures for search and rescue; the US Coast Guard and for submarine search in an area taken from NATO, documents of the Antisubmarine War of the Colombian Navy [11], [12] and other reviewed documents that due to their publication restrictions are not named in this document. Each of the different patterns implemented are listed below; each circle symbolizes the detection area ofeach USV.

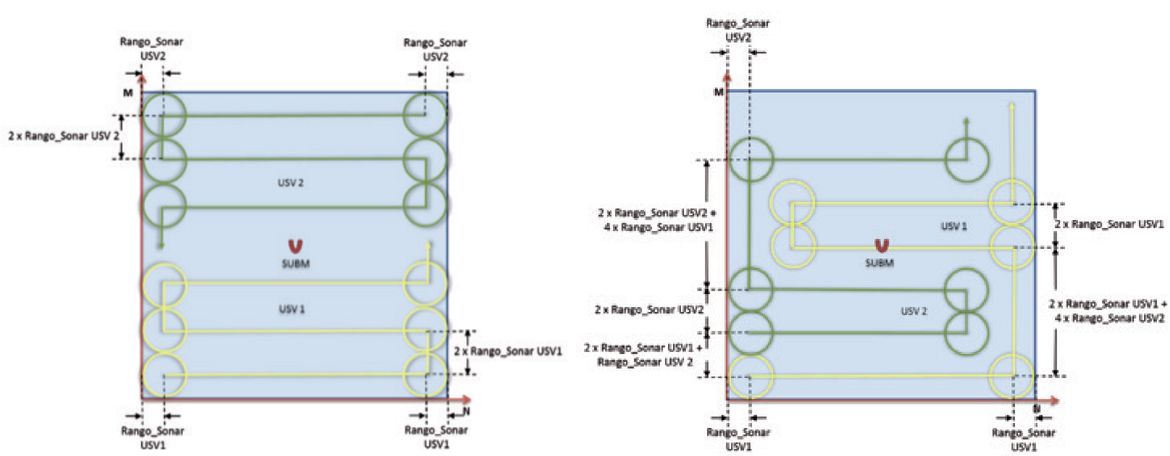
- Standard and Evolutive ASW pattern for 1 USV

Fig. 4. Scanning for Sonar – Standard (left) – Evolutive (right) – 1 USV



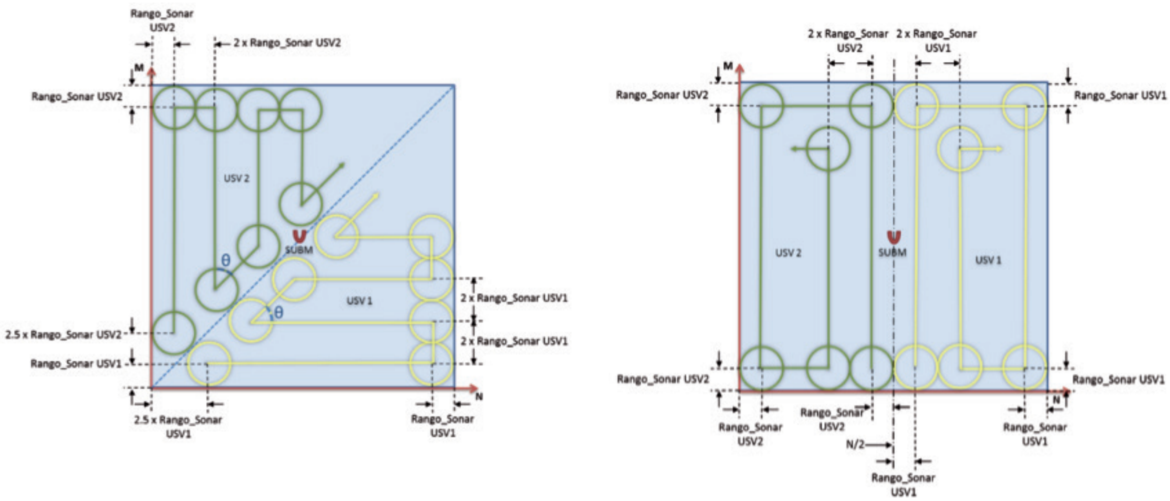
- Standard and Evolutive ASW pattern for 2 USVs

Fig. 5. Scanning using Sonar – Standard (left) – Expanded (right) - 2 USVs



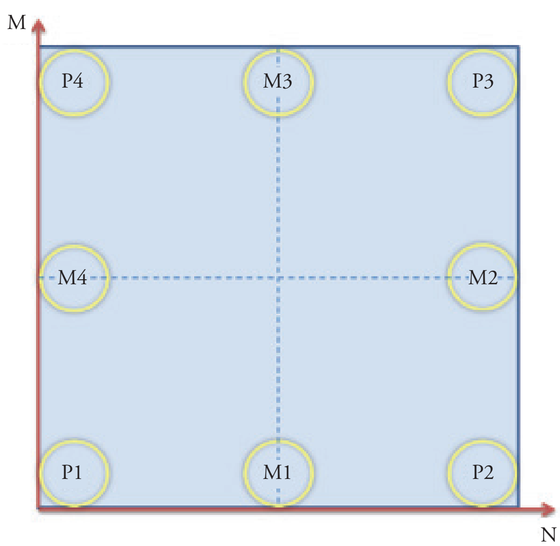
- Diagonal and Evolutive ASW pattern for 2 USVs

Fig. 6. Scanning using Sonar – Diagonal (left) – Evolutive (right) - 2 USVs



For a NxM area there are different start points according to the executed pattern. For the vertices of the area, the starting points P1, P2, P3 and P4 are defined. For the middle sections of each side of the area the points M1, M2, M3, M4 are defined. See Fig. 7.

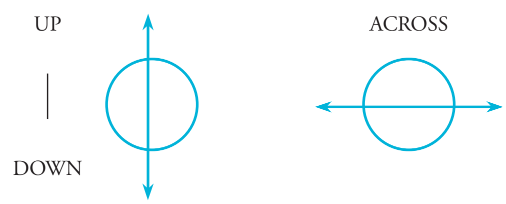
Fig. 7. Scanning starting points



- Direction of the search starting point

To perform the exploration of the area the initial directions of exploration are defined, with Vertical and Horizontal as the options. See Fig. 8.

Fig. 8. Scanning start direction



Response of the models

According to the operational scenario, two measures of performance (MOP - Measures of Performance) are established to determine the success of the mission; the time to detect the submarine and the detection of the submarine in the search area.

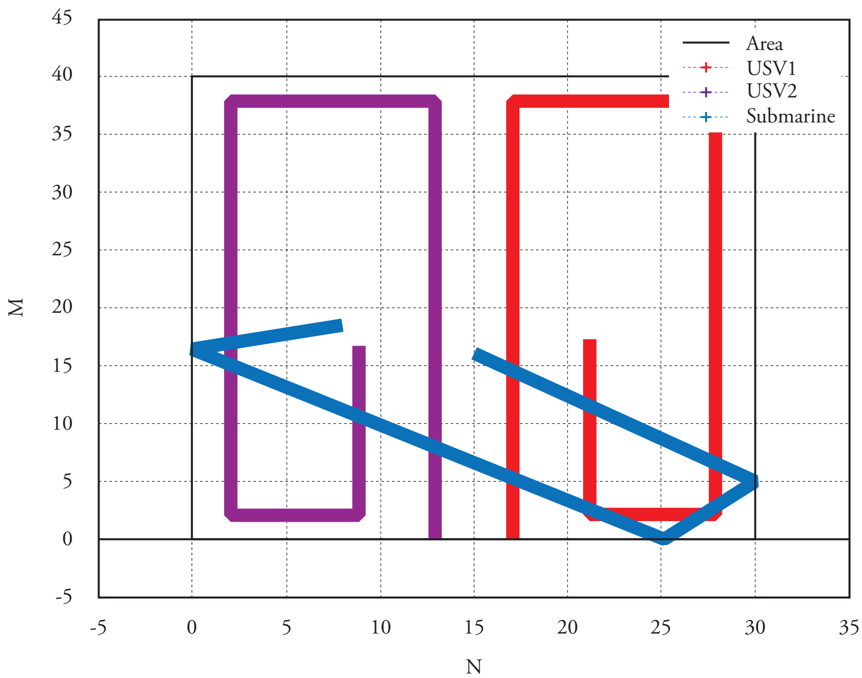
- MOP_1 = Time to detect the submarine.
- MOP_2 = Detection of the submarine in the search area

The mission's measure of effectiveness (MOE) will be defined by the weighted sum of the established MOPs, where the simulation response will finally be.

$$MOE_{ASW} = {}_{w1}{*}MOP1 + {}_{w2}{*}MOP2 \qquad (1)$$

In accordance with the objectives of the mission, the following weights have been defined for

Fig. 9. Simulation Evolutive Pattern – Detection USV2



performance measures: w1 = 0.4, w2 = 0.6, values assigned by the operational advisors in the development of this research.

Development of models

For the generation of the different simulation algorithms of the patterns, different considerations are taken into account such as maintaining the same scenario as well as the characteristics of the USVs, and to define a random pattern of movement for the submarine, which means to initiate the simulation by locating the submarine at a random position within the area, random course and previously defined constant velocity.

Each algorithm implemented in Matlab[1], simulates the movement of the USVs according to each pattern, defining the initial position for scanning the area and the course necessary to execute the first route. The pattern is continued and the calculated data is evaluated with each advance in time. The simulation ends in three ways: if the submarine enters the optimal sonar detection range of one of the USVs, if the distance between the two USVs is less than 1 Mile, which means that the whole area was scanned without finding the submarine; valid for Standard, or finally if the USVs end the scanning by leaving the scanning area; Valid for Expanded and Diagonal patterns. In the case of the Evolutive pattern, it ends when the circle has completely closed, which means that the area was already explored and there was no detection.

Seven (7) *.m* (Matlab) files are generated which simulate the movement of the USVs and the submarine for a total of approximately nine thousand nine hundred (9,900) lines of written code, which also allow each one of the factors named in previous subsections to vary.

Fig. 9, displays the exploration area with two USVs (USV1 in magenta and USV 2 in red), performing an Evolutive pattern. Also it is possible to appreciate the trajectory of the submarine (in blue) that is finally detected by the USV1. From this simulation, the time spent by the USV1 is obtained and who detected the submarine. In the event of no detection, the total scanning time of the area is obtained, which means when the two USVs have completed the search within the area.

[1] Interactive environment and high level language for numerical calculation, visualization and programming. [13].

Fig. 10. Triangular distribution for Sonar Range DpS and TAS

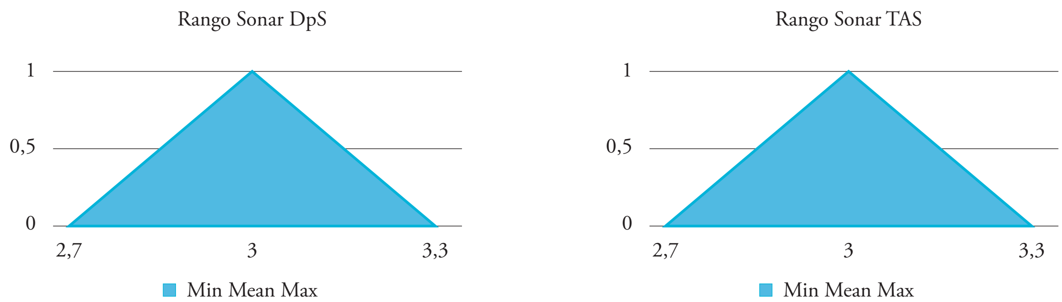


Table 1. Simulation constants

Component	Input	Type	Unit
Scenario	Area [X Y]	Constant	NM
USV 1	Scanning time with Dipping Sonar	Constant	mins
	Dipping Sonar Sonar Range	Average	NM
	Sonar Range TAS	Average	NM
USV 2	Scanning time with Dipping Sonar	Constant	mins
	Dipping Sonar Sonar Range	Average	NM
	Sonar Range TAS	Average	NM
Submarine	Start Position X	Random	[0 – AreaX] NM
	Start Position Y	Random	[0 – AreaY] NM
	Initial Route	Random	[0 – 359.9] °d
	Speed	Constant	Kts

Simulation constraints and restrictions

The parameters that will be present in all the simulation scenarios are defined, which include the constant and random values, see Table 1. For the Dipping Sonar and TAS range inputs, these are values that depend on several factors such as the physical and technical characteristics of the Sonar equipment, the operating environment, the type of target to detect, in addition to others; which means that they are not constant values. The constant value for this input is established by evaluating a triangular probabilistic distribution.

This distribution has the average detection range of the Dipping Sonar and TAS respectively as an input taken from [8][2], and it is evaluated +/- 10% for minimum and maximum values, see Fig. 10. It should be clarified that due to the level of the abstraction with which this model was created, it does not include the detection of the threat using physical formulas that represent the principle of detection.

Taking into account the different levels for each factor in the simulation represented in Table 2, there are factors that present restrictions when they are related to another factor, preventing them from being simulated.

For the USV velocity, the restriction exists only for high scanning speeds, which determines a significant impact on the variation of the detection range and the autonomy of the USV. Also for the type of sonar, a physical model that determines a theory developed for the detection of the submarine is not established within the simulation, which means that a submarine is detected as long as it

[2] Results of research carried out at COTECMAR to determine the best combination of weapons and sensors to be installed in the future Strategic Surface Platforms - SSP of the ARC.

Table 2. Thrusters configuration

Factor	Tipo	Levels			
		Level 1	**Level 2**	**Level 3**	**Level 4**
Speed of the USVs	Continuous	6 Kts	8 Kts	10 Kts	-
Type of the Sonar	Discreet	Dps	TAS	-	-
Number of USVs	Discreet	1 USV	2 USVs	-	-
Search patterns	Discreet	Standard	Expanded	Evolutive	Diagonal
Search start point	Discreet	P1	P2	P3	P4
Seearch start point	Discreet	Vertical	Horizontal		

is within the optimal range of the sonar on board the USV.

Referring to search patterns and the number of USVs in use, new restrictions arise. Each pattern establishes a minimum number of vehicles in the area due to its search principle, which means that to conduct coordinated search patterns, such as Expanded or Diagonal patterns, it is necessary to have at least two USVs.

Model variability

A variability of the model smaller than 1% is established taking into account the compensation between the variation of the MOE response and an acceptable time for the total of the simulations. Different experiments were carried out under an operating point in order to determine the maximum number of repetitions for this model, obtaining results of between 30 seconds and 21 minutes approximately for 100 and 5000 repetitions respectively, representing a relatively low computational cost.

In order to show the variability in the MOE obtained for this point of operation, ten independent simulations were performed for 100, 500, 1000 and 5000 repetitions. Based on these data, they were statistically analyzed, concluding that the number of 5000 simulations was used as the number of simulations, because it does not require a large amount computational resources and offers a standard deviation of less than 1%, providing greater reliability in the simulation results of the model.

Table 3. Number of simulations summary

	MOE			
Experiment	**100**	**500**	**1000**	**5000**
1	0.3679	0.3276	0.2989	0.2812
2	0.3809	0.3299	0.3253	0.2903
3	0.2730	0.3244	0.2696	0.2775
4	0.3464	0.3265	0.2968	0.2739
5	0.3263	0.3231	0.3011	0.2724
6	0.3718	0.2720	0.2839	0.2801
7	0.3854	0.2840	0.3315	0.2868
8	0.3520	0.2977	0.3225	0.2777
9	0.2920	0.2959	0.2997	0.2731
10	0.3712	0.3260	0.2995	0.2903
Simulation time	**0.5 [min]**	**2 [min]**	**5 [min]**	**21 [min]**

Methodology

Different sensitivity analyzes are performed for each of the restrictions described above, using a common operating point and varying the different levels of each factor. These analyzes are performed in order to determine how much the MOE increases or decreases and will serve as a support to determine the most effective operating point. Due to the number of USVs used for the scan, the starting points of the search and the initial direction of the search are not main study variables, and the details from each of these factors are not shown.

- The use of two (2) USVs in the search shows a 20% increase in effectiveness compared to a single USV.
- The scanning starting point that leads to a better effectiveness of the mission differs with respect to the search pattern. P2 and M1 are the most effective for the different patterns.
- The initial direction of the search also differs with respect to the search pattern. For the "Down" start direction a better effectivity performance is observed.

Once the different constraints of the models are identified and analyzed, an experiment design (DOE) is formulated to establish the factors that will influence effectiveness; search patterns, sonar type, and velocity of the USVs, evaluating the impact of each of the variables in achieving the ASW mission.

The DOE is developed taking into account the following parameters:

- For the answers the Probability of detection of the submarines (Pd Sub) is used and also the time to detect a submarine (TD Sub)
- Patterns are used for the factors as a categorical variable for four levels (4) using Standard, Expanded, Evolutive and Diagonal patterns as values, and the Sonar Type for USV1 and USV2 is also used that corresponds to a categorical variable of two levels for towed (TAS) and variable depth (DpS) sonars. Lastly the speed that is taken as continuous variable from 6 kts to 10 kts.

For the development of the DOE and the subsequent analysis, a computational tool called JMP ® is used, which offers graphical and numerical tools that allows the variability of the model to be defined with changes in the input factors, and to observe the impact on the effectiveness in the different simulations. The result of the DOE is the construction of a table with twenty (20) experiments to be developed to later analyze the behavior of each of the responses in relation to the model factors.

In order to continue with the final experiments, the configuration seen in Table 4 and Table 5 of the other parameters of the model is determined using a random point of operation for the variables that have already been reviewed in the previously presented sensitivity analyzes.

Results

After simulating the model for different combinations of sensors, patterns and velocity for both USVs, the results are entered into the JMP tool where a least squares regression model is implemented in order to analyze the behavior of the model outputs. The Effect Screening of the JMP tool is also used to guide the determination of which effects are significant in the model.

In the probability of detection response that the factors with the most influence on the response are sonar type TAS for the USV1 and USV2. In particular, the sonar type infers more than 20% in the variation of this response and another variable is not identified that has a strong influence on this response through the Pareto graph. See Fig. 11.

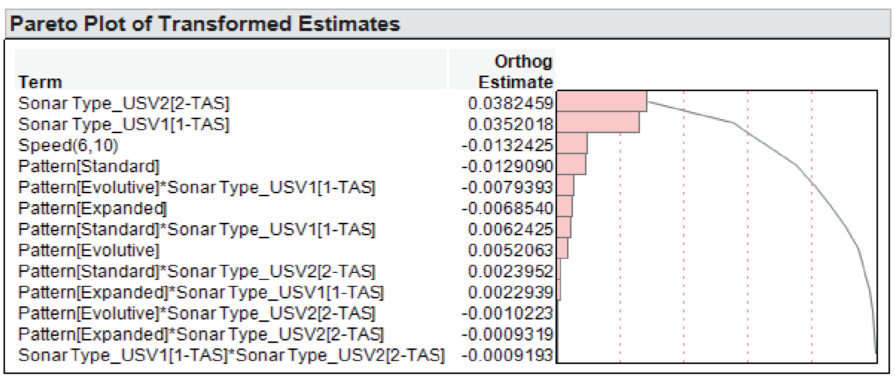
Table 4. Configuration of the operating point

Factors	Amount
Number of USVs	2 USVs
Search Start Point	P3
Search Start Direction	Vertical

Table 5. Simulation constants for the operating point

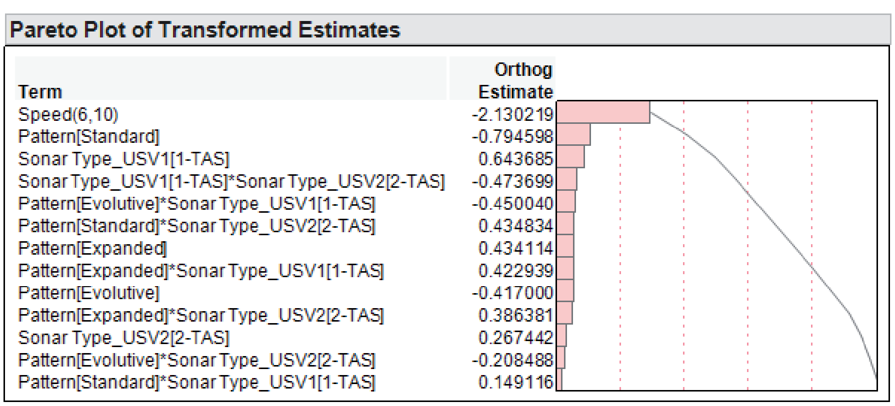
Component	Input	Type	Unit
Scenario	Area [X Y]	Constant	[30 40] NM
USV 1	Sonar Range TAS	Average	3.5 NM
	Sonar Range DpS	Average	2.7 NM
	Scanning time with DpS	Constant	5 min
USV 2	Sonar Range TAS	Average	3 NM
	Sonar Range DpS	Average	2.7 NM
	Scanning time with DpS	Constant	5 min
Submarine	Start Position X	Random	[0 – Area X]
	Start Position Y	Random	[0 – Area Y]
	Initial destination	Random	[0 – 359.9]
	Speed	Constant	6 Kts

Fig 11. Detection Probability Response Time Pareto



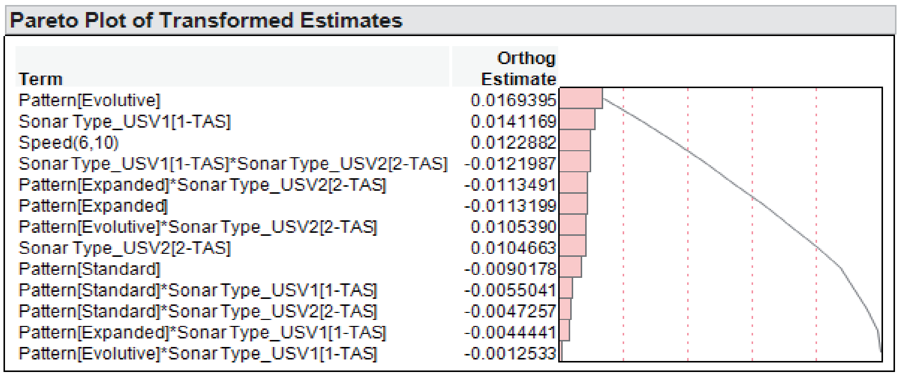
Continuing with the Submarine Detection Time response, it is observed in Fig. 12 that the only factor influencing the variation is speed, with approximately 30%. According to the Pareto graph response, the other factors influence the variability of the detection time of the submarine.

Fig 12. Submarine Detection response time Pareto



Finally we analyze the measure of effectiveness - MOE, which brings together the first two answers in a single metric. It is analyzed by the Pareto graph, in Fig. 13, where it is evidenced that there is no factor that dominates the variability of the model, nevertheless the evolutionary search pattern, the use of TAS sonars and the speed of exploration, are the most influential variables in increasing effectiveness. On the other hand, the Expanded and Standard search pattern have slightly less influence on the output of the model and can be analyzed later with a different analysis. An important detail in the graph is the relationship between the sonar type and the search pattern, representing a minor variation but that should be considered in a more detailed analysis.

Fig 13. Pareto of Measure of Effectiveness Response - MOE



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These graphs allow a quick identification of the most important factors. However, given the relationship between the different inputs and outputs, in the Prediction Profiler graph of the JMP® tool it can be seen how the selection of each factor influences each one of the model responses. See Fig. 14.

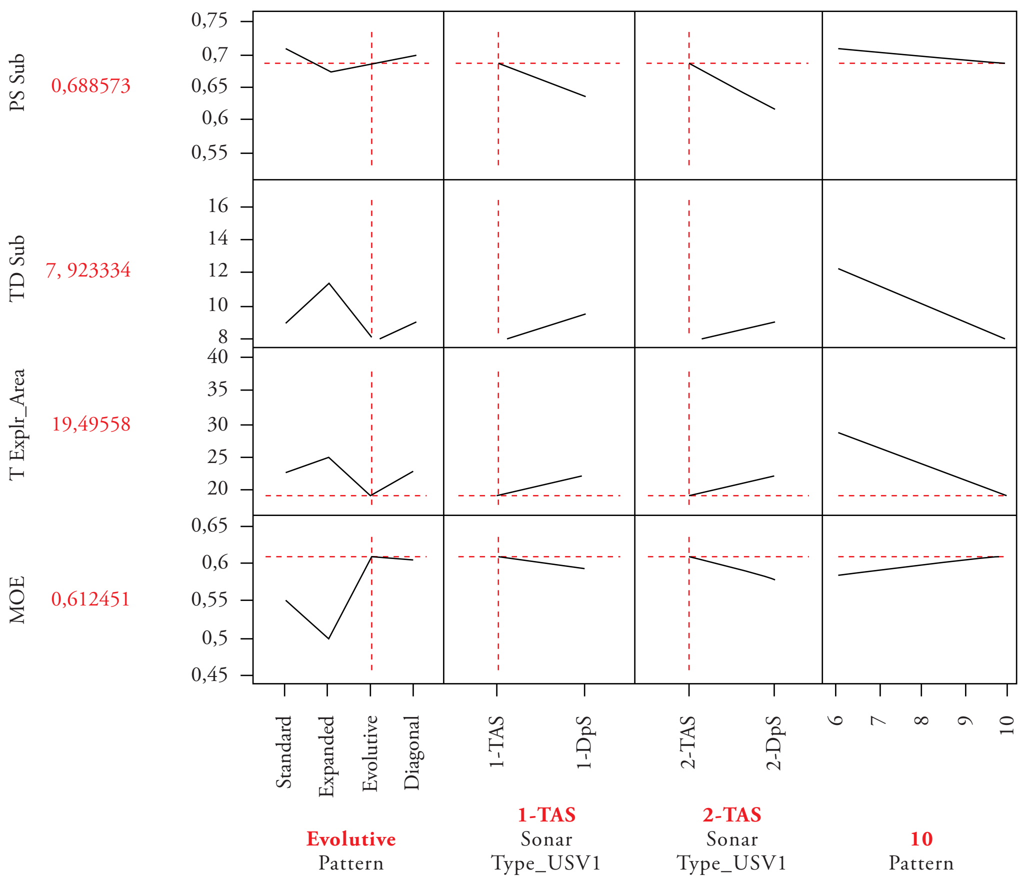
Analyzing in detail the sonar type, it is observed in the graph that the use of Dipping Sonar (DpS), does not generate any positive contribution in the effectiveness. This can happen due to the time that the USV must remain stationary while doing the scanning. In addition the DpS also has less reach than the TAS sonar.

Fig. 14 shows a clear picture of the comparison of the model factors and the measure of effectiveness, with Evolutive as the best search pattern, TAS as the best type of sonar and observing the behavior of the speed that significantly improves MOE up to a maximum value of 10 kts.

Conclusions

The best configurations were obtained for the different factors that affect the ASW using USVs, with the best result being the use of two unmanned vehicles to search for a threat in an area near the coast. It was also determined that the best effectiveness is achieved using a search pattern such as the Evolutive pattern, a towed TAS type sonar and to operate at the maximum possible speed, without degrading sonar performance; 10 Kts was used for the development of this thesis.

Fig 14. Prediction Profiler for MOE



It was determined that performing the search using DpS immersion sonar is less effective than using a towed sonar TAS. This can be due to the way the DpS sonar operates, since the scan is not continuous and it is required to move to different points in the area to perform the search. Also, stopping at a certain time in each scanning point considerably affects the threat detection time.

Carrying out different sensitivity analyzes allows the independent evaluation of each factor in the model to be obtained, simplifying the process by not having to analyze multiple variables of the final result.

Performing the design of experiments with the JMP ® tool allows the complexity of determining the different experiments to be carried out to be reduced. It also allows the number of tests to be optimized, with less time used in the simulation of each simulation condition and fewer computational resources being needed.

On the other hand, adopting the developed evaluation methodology allowed the analysis of the answers to be simplified and by means of complementary analyzes it was possible to verify and detail the results of each simulation.

Thanks

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Calculation of marine air conditioning systems based on energy savings

Cálculo de sistemas de climatización marinos con base en ahorros energéticos

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Abstract

The development of ship propulsion in the areas of Economic Operation, Environmental Protection and Ship Efficiency (Triple E - Economy, Environment, Efficiency) is the comparison standard of the manufacturers of contemporary ships. The standard is based on the application of a more modern design of the diesel engines, the wide use of waste heat and the efficient operation of the ship. In accordance with the Economic Operation, the need to evaluate the design of air conditioning systems has been identified in order to determine the possible savings, which are represented by a decrease in fuel consumption, as a result of: the significant impact of this consumption in the operation of the ship, the current high costs of this energy, the periodic increase in the price of the same, and the international policies for the reduction of emissions to the atmosphere and preservation of the environment. By means of the energy diagnosis of the air conditioning system it is possible to determine the possible opportunities of energy saving during the operation of the ship. The results indicate that the thermal load and the cooling capacity required by the air conditioned spaces have a difference between their maximum and average value of 14%. This justifies the need to use a conditioning system with a variable volume of air supplied to the air conditioned space.

Key words: Thermal load, solar radiation, life cycle cost, marine air conditioning.

Resumen

El desarrollo de la propulsión de los buques en los aspectos de Operación Económica, Protección del Medio Ambiente y Eficiencia de la Propulsión del buque (Triple E- Economy, Environment, Efficiency) constituye el estándar de comparación de los fabricantes de buques contemporáneos. El estándar está basado en la aplicación de un diseño más moderno de los motores (máquinas) diésel, en la utilización amplia del calor de desecho y en la operación eficiente del barco. En correspondencia con la Operación Económica se ha identificado la necesidad de evaluar el diseño de los sistemas de aire acondicionado con el objetivo de determinar los posibles ahorros, que se vean representados en disminución del consumo de combustible, dado por: el significativo impacto de este consumo en la operación del buque, los altos costos de este energético en la actualidad, el incremento periódico en el precio del mismo, y las políticas internacionales para la reducción de emisiones a la atmósfera y preservación del medio ambiente. Mediante el diagnóstico energético del sistema de aire acondicionado se puede determinar las posibles oportunidades de ahorro energético durante la operación de la embarcación. Los resultados indican que, la carga térmica y la capacidad de enfriamiento requerida por los espacios acondicionados tienen una diferencia entre su valor máximo y medio del 14 %. Esto justifica la necesidad de utilizar un sistema de acondicionamiento con volumen variable del aire suministrado al espacio acondicionado.

Palabras claves: Carga térmica, radiación solar, costo de ciclo de vida, climatización marina.

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Introduction

Most of the ships that are built today are based on traditional design concepts. Improvements are observed in simple components such as the engine and the propeller; but this does not apply to the ship as a complete system. Many shipbuilders concentrate and make efforts to improve capacity but, unfortunately, they still consume a lot of fuel unnecessarily.

The shipbuilding industry makes very little effort to reduce operational costs for new vessels or for repaired vessels, as the builder is not responsible for the fuel bill; in general, little time and resources are devoted to monitoring and controlling the use of energy on board ships.

Poor energy knowledge and the absence of a systematic control are the two main barriers to improving energy efficiency in ships. An important tool to overcome this barrier is the conversion of energy flow into monetary flow (money).

On the other hand, the International Maritime Organization (IMO) has established several levels of emissions to the environment. According to IMO, NOx emissions from 2016 should be below 3 g / kWh. CO^2 emissions should be reduced by 30%.

Together with the requirements of the IMO for the protection of the environment, as a result of the increase in the price of crude oil, there has been an increase in the application of technologies and measures that result in fuel savings on ships

The air conditioning systems installed in the frigate units of the Colombian Navy were selected according to the initial cost, with technical capacities similar to those installed in the 1980s when these vessels were acquired, which is why it has technological equipment from 2000 but with energy consumptions similar to those originally installed.

The energy demand for air conditioning systems, for frigate type units, when in operation, on average, is above 40% of total demand. Working to increase energy savings in these systems not only improves fuel economy and economic effectiveness; it also decreases the emission of harmful substances to the environment.

This paper presents the results of applying the energy analysis to the entire air conditioning system. It shows the actual consumption and the potential energy savings that can be achieved during the daily operation of the ship.

Calculation of the thermal load in boats

For the calculation of the thermal load in ships, methodologies have been developed by entities such as the Society of Engineers and Naval Architects of North America (SNAME) who in the technical bulletin T & R 4-16 published the methodology under the name "Calculations for Merchant Ships Heating, Ventilation and Air Conditioning Design" as well as some standards of the International Organization for Standardization (ISO) which will be taken as reference for this paper.

The methodology applied in the energy evaluation of the air conditioning system is summarized below.

The components of the thermal load are as follows:
- Transmission load
- Solar + Transmission Load
- Radiation load through glass
- Lighting Load
- Equipment Load
- Personnel Load
- Infiltration load for port operation

The load components of the system are:
- Fan load (considered as an equipment load)
- Supply duct load
- Load per Return path load
- Outdoor air load

The calculation equations used are shown in Table 1.

Each frigate has an air conditioning system composed of two chiller plants of 457.2 kW (130 TR) each; one in operation and the other as

Table 1. Equations used to calculate the thermal load

TYPE OF LOAD	EQUATION	VARIABLES	DATA SOURCE
WALL AND CEILING TRANSMISION	$q_{ssk} = U \times A \times CLTD_C + (78 - Tr) + (To - 85)]\, f$ $CLTD_C = [(CLTD + LM)\, k$	**CLDT:** Temperature difference for the cooling load according to the group to which the wall belongs. **LM:** Correction according to the latitude of the place and the selected design month. ***K:*** Correction by color.	*ASHRAE.* (1989). Fundamentals Handbook. Atlanta, USA.
GLASS	***Conduction*** $q = U \times A \times CLTD_C$ $CLTD_C = CLTD + (78 - Tr) + (To - 85)$ ***Radiation*** $q = A \times SC \times SHGF \times CLF$	***SC:*** Shading coefficient for glass. ***SHGF :*** Solar Heat Gain Factor in Btu/h*ft² ***CLF:*** Cooling charge factor for glasses.	*ASHRAE.* (1989). Fundamentals Handbook. Atlanta, USA.
ILLUMINATION	$q = 3{,}41 \times W \times CLF \times Ful \times Fsa$	***Ful*** *= W installed / W used = 64/64 = 1* ***Fsa*** *= Special lighting factor depends on the type of luminaire and ballast* ***CLF*** *= Cooling load factor. depends on the number of hours on*	*ASHRAE.* (1989). Fundamentals Handbook. Atlanta, USA.
POWER EQUIPMENT	$q_{motor} = 2545 \times \left(\frac{P}{E_M}\right) \times F_{UM} \times F_{LM}$	***P*** *= The nominal power of the motor in HP.* E_M *= Motor efficiency as a decimal fraction less than 1.0.* F_{UM} *= The usage factor applies when it is known that the motor will be used intermittently for a significant time of not using the total hours of operation.* F_{LM} *= Load factor corresponding to the fraction of the nominal power of the shaft being developed by the equipment under the conditions of the estimated cooling load.*	*ASHRAE.* (1989). Fundamentals Handbook. Atlanta, USA.
MINOR EQUIPMENT	$q_{sensible} = q_{entrada} \times F_U \times F_R$	***FU =*** *Usage factor* ***FR =*** *Radiation factor*	*ASHRAE.* (1989). Fundamentals Handbook. Atlanta, USA.
PEOPLE	$q_{sensible} = G_{sp} \cdot N \cdot CLF$ $q_{latente} = G_{lp} \times N$	G_{sp} **,** G_{lp} **:** Sensible and latent heat gain per person respectively. ***CLF:*** Cooling load factor for people.	*ASHRAE.* (1989). Fundamentals Handbook. Atlanta, USA.
DOORS INFILTRATION	$qs = 1{,}1 \times CFM \times \Delta T$ $ql = 4840 \times CFM \times \Delta W$	ΔT**:** Temperature difference = outer T - inner T. °F ΔW**:** Specific humidity difference in lb water vapor / lb dry air. The values of W are obtained from the psychrometric chart. CFM: Air infiltration or ventilation flow rate. (ft²/min)	*ASHRAE.* (1989). Fundamentals Handbook. Atlanta, USA.

backup, this value corresponds to the hottest time of the day. The cold water is sent to six (6) handling units denominated Z which air-conditioning the residential zones and they have capacity to renew and recirculate the air. The cold water is also sent to one (1) handling unit denominated L and eight (8) handling units denominated U for workshops and warehouses; the L and U type units have recirculation capacity. The thermal load of 457.2 kW was calculated under the following conditions:

Dry Bulb Outside Temperature: 35 C
Wet Bulb Outside Temperature: 27.7 C
Dry Bulb Inside Temperature: 25.5 C
Wet Bulb Inside Temperature: 18.3 C (50% RH)
Temperature of the horizontal sheet exposed to the sun: 63 C
Temperature of vertical blade sheet exposed to the sun: 52 C
Sea Water Temperature: 29.5 C

Calculation of the load of the Air Handling Units (AHU)

The calculation of heat transfer through bulkheads and decks exposed to the sun is performed according to the following formulation,

$$Q = U\,A\,\Delta t \tag{1}$$

where U is the total heat transfer coefficient, A is the area exposed to the sun and Δt is the difference between the surface temperature of the sheet and the indoor temperature of the heated area.

The value of U varies depending on the external material (steel or aluminum), the structural arrangement, the thickness and type of insulation and the interior finish.

The value of the transfer coefficient U for air-air is calculated by means of the equation:

$$U = \frac{1}{\frac{1}{fp} + \frac{1}{C} + \frac{1}{fs}} \tag{2}$$

and for surfrace-air

$$U = \frac{1}{\frac{1}{C} + \frac{1}{fs}} \tag{3}$$

where C is the thermal conductivity of the structure material, fp is the film coefficient of the structural sheet and fp is the film coefficient of the structural reinforcements.

By means of the measurements performed in this investigation, the surface temperatures of the sheets or casings of the ship that are exposed to the solar radiation are obtained. These temperatures vary according to the position of the sun (time of day) as shown in Table 2. These values were measured in Cartagena, with the sheets painted and installed.

Table 2. Temperature variation of the sheets exposed to the sun

TIME	Type		Rh
	Horizontal	Vertical	%
7	29.15	29.60	89%
8	34.73	38.02	84%
9	43.25	41.84	79%
10	47.91	41.65	67%
11	52.80	41.88	70%
12	57.88	41.69	75%
13	62.95	41.50	71%
14	62.63	42.43	59%
15	59.83	44.45	66%
16	50.10	43.97	66%
17	42.70	38.68	66%

Fig. 1 shows the variation of the surface temperature of the ship's deck. Using the data in the above table, the thermal load is recalculated according to the time of day, keeping the thermal loads due to personnel, equipment, lighting, etc. constant. The results are presented in Table 3.

Fig. 1. Variation of surface temperature of the ship's deck

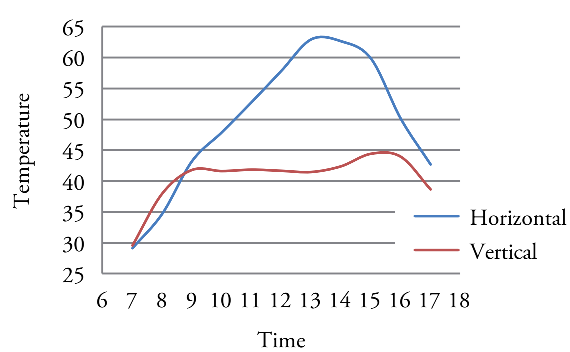
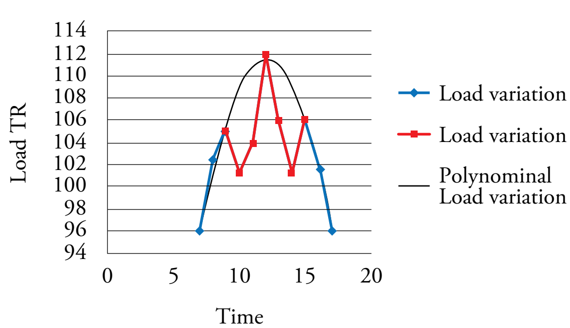


Table 3. Load variation according to the time of day (W)

	TIME										
	7	8	9	10	11	12	13	14	15	16	17
Z1	43.245	47.671	49.544	47.202	49.307	54.867,48	51.204	47.800	50.948	47.211	43.555
Z2	17.760	18.017	18.049	17.797	17.914	18.320,94	17.953	17.665	17.952	17.758	17.570
Z3	49.636	55.227	57.155	54.181	56.163	61.896,39	57.429	53.814	57.782	54.333	50.151
Z4	45.787	50.485	51.946	48.854	50.851	56.792	52.148	48.280	52.158	48.703	45.082
Z6	56.759	62.135	63.627	59.880	62.070	68.825	63.293	58.796	63.410	59.671	55.618
Z8	42.472	45.976	47.943	47.646	48.767	51.377	50.095	49.206	50.404	48.067	45.353
L13	19.845	19.845	19.845	19.845	19.845	19.845	19.845	19.845	19.845	19.845	19.845
U1	2.977	2.977	2.977	2.977	2.977	2.977	2.977	2.977	2.977	2.977	2.977
U2	14.884	14.884	14.884	14.884	14.884	14.884	14.884	14.884	14.884	14.884	14.884
U4	3.969	3.969	3.969	3.969	3.969	3.969	3.969	3.969	3.969	3.969	3.969
U5	2.977	2.977	2.977	2.977	2.977	2.977	2.977	2.977	2.977	2.977	2.977
U7	23.153	23.153	23.153	23.153	23.153	23.153	23.153	23.153	23.153	23.153	23.153
U8	2.977	2.977	2.977	2.977	2.977	2.977	2.977	2.977	2.977	2.977	2.977
U9	4.961	4.961	4.961	4.961	4.961	4.961	4.961	4.961	4.961	4.961	4.961
U10	4.961	4.961	4.961	4.961	4.961	4.961	4.961	4.961	4.961	4.961	4.961
Total (W)	336.364	360.215	368.968	356.264	365.776	392.783	372.825	356.265	373.357	356.447	338.033
Total TR	96	102	105	101	104	112	106	101	106	101	96

From the above table it is evidenced that at midday a maximum cooling capacity is required with 392 kW (112 TR), which is in accordance with the highest temperature of the sheet 60 C. In Fig. 2, the variation of the total thermal load is observed according to the time, in tons of refrigeration (TR).

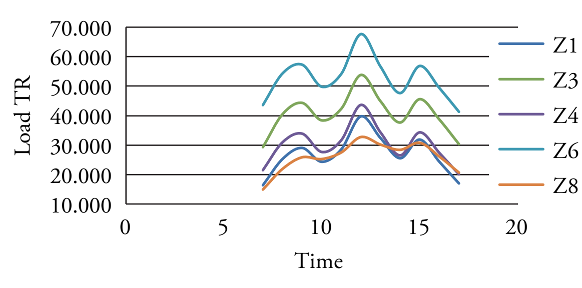
Fig. 2. Load variation by time



$y = -0{,}6204x^2 + 14{,}908x + 21{,}947$
$R^2 = 0{,}9898$

It is observed that the Zs exhibit significant variations in the thermal load, with the exception of Z2. Likewise the *U* and *L* do not present significant variations. For large consumers, the load varies according to Fig. 3

Fig. 3. Load variation for large consumers by time

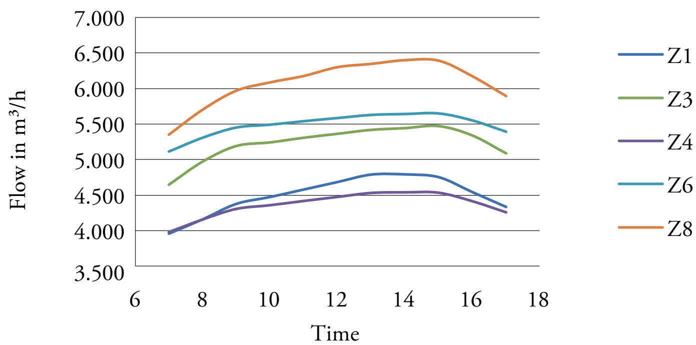


When calculating the air flow rate as a function of the variation of the thermal load, the air flow values for this condition are found, as shown in Table 4 and Fig. 4.

Table 4. Variation of the air flow as a function of the thermal load

	TIME										
AHU	7	8	9	10	11	12	13	14	15	16	17
Z1	3.962	4.163	4.380	4.476	4.581	4.686	4791	4.793	4.755	4.545	4.337
Z3	4.646	4.971	5.190	5.240	5.306	5.361	5416	5.441	5.469	5.337	5.087
Z4	3.984	4.159	4.307	4.359	4.418	4.474	4530	4.539	4.533	4.414	4.260
Z6	5.117	5.311	5.454	5.494	5.543	5.587	5631	5.644	5.652	5.553	5.396
Z8	5.353	5.703	5.970	6.086	6.176	6.300	6346	6.399	6.392	6.173	5.895

Fig. 4. Variation of loads in air-conditioned spaces according to the time



By similarity laws the velocities, powers and discharge pressures of each of the fans and the results shown in Table 5 are calculated for each handler.

Table 5. Behavior of the fans depending on the time of day

Handler Z1				
Time	Q m^3/h	H m	kW	Rpm
7	3.955	0,1758	3,3264	2.889
8	4.198	0,1981	3,9776	3.066
9	4.351	0,2128	4,4295	3.178
10	4.477	0,2254	4,8259	3.270
11	4.599	0,2378	5,2322	3.359
12	4.713	0,2497	5,6297	3.442
13	4.796	0,2586	5,9322	3.503
14	4.820	0,2612	6,0206	3.520
15	4.760	0,2547	5,8001	3.477
16	4.608	0,2388	5,2636	3.366
17	4.382	0,2159	4,5263	3.201

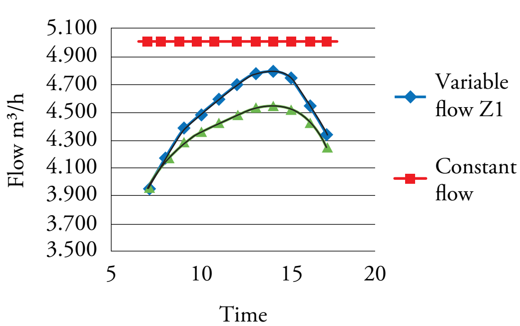
Handler Z4				
Time	Q m^3/h	H m	kW	Rpm
7	3.981	0,1782	3,3925	2.908
8	4.178	0,1962	3,9217	3.052
9	4.290	0,2069	4,2458	3.133
10	4.365	0,2142	4,4727	3.188
11	4.429	0,2205	4,6714	3.235
12	4.489	0,2265	4,8633	3.279
13	4.539	0,2316	5,0278	3.315
14	4.564	0,2342	5,1128	3.334
15	4.546	0,2323	5,0516	3.320
16	4.465	0,2241	4,7868	3.261
17	4.307	0,2086	4,2976	3.146

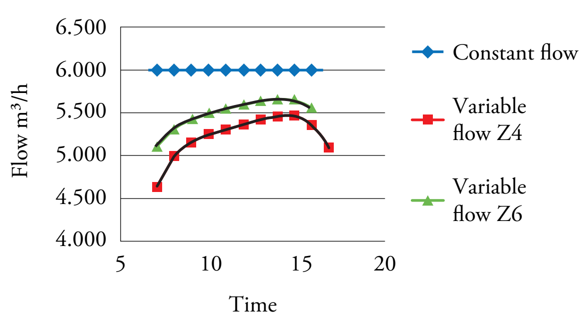
Handler Z3				
Time	Q m³/h	H m	kW	Rpm
7	4.641	0,1755	3,7500	2.960
8	4.986	0,2025	4,6484	3.180
9	5.161	0,2170	5,1568	3.292
10	5.248	0,2244	5,4216	3.347
11	5.300	0,2289	5,5848	3.380
12	5.347	0,2329	5,7343	3.410
13	5.395	0,2372	5,8906	3.441
14	5.430	0,2402	6,0052	3.463
15	5.417	0,2391	5,9624	3.455
16	5.304	0,2292	5,5977	3.383
17	5.023	0,2056	4,7540	3.204

Handler Z6				
Time	Q m³/h	H m	kW	Rpm
7	5.115	0,2132	5,0211	3.263
8	5.321	0,2306	5,6495	3.393
9	5.439	0,2411	6,0366	3.469
10	5.507	0,2471	6,2642	3.512
11	5.551	0,2511	6,4175	3.541
12	5.592	0,2548	6,5590	3.566
13	5.635	0,2587	6,7105	3.594
14	5.670	0,2620	6,8388	3.617
15	5.671	0,2620	6,8409	3.617
16	5.587	0,2543	6,5406	3.563
17	5.343	0,2326	5,7217	3.408

Handler Z8				
Time	Q m³/h	H m	kW	Rpm
7	4.641	0,1228	2,6061	2.576
8	4.986	0,1417	3,2304	2.767
9	5.161	0,1519	3,5838	2.864
10	5.248	0,1570	3,7678	2.913
11	5.300	0,1602	3,8812	2.942
12	5.347	0,1630	3,9851	2.968
13	5.395	0,1660	4,0938	2.994
14	5.430	0,1681	4,1734	3.014
15	5.417	0,1673	4,1436	3.006
16	5.304	0,1604	3,8901	2.944
17	5.023	0,1439	3,3038	2.788

Fig. 5. Flow behavior to ensure comfort at different times, for each handler



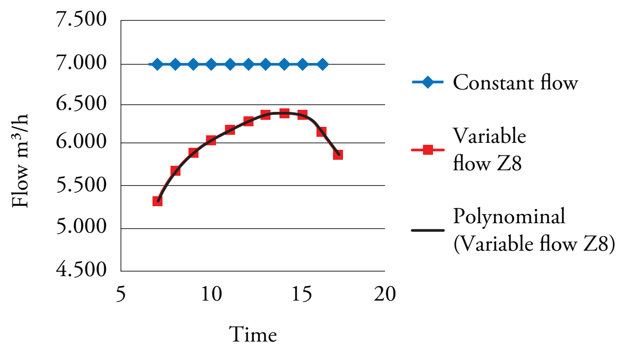


$y = 0{,}0906x^5 - 5{,}7034x^4 + 138{,}63x^3 - 1643{,}6x^2 + 9689{,}6x - 18715$
$R^2 = 0{,}9946$

$y = 0{,}038x^5 - 2{,}6502x^4 + 70{,}573x^3 - 912{,}02x^2 + 5836{,}1x - 10685$
$R^2 = 0{,}996$

$y = -0{,}0255x^5 + 0{,}8788x^4 - 5{,}585x^3 - 115{,}81x^2 + 1803{,}5x - 1600{,}1$
$R^2 = 0{,}9975$

$y = 0{,}0138x^5 - 1{,}7128x^4 + 61{,}595x^3 - 974{,}5x^2 + 7235{,}3x - 15502$
$R^2 = 0{,}997$



$$y = 0{,}05x^5 - 3{,}7366x^4 + 104{,}74x^3 - 1414{,}3x^2 + 9430{,}3x - 19159$$
$$R^2 = 0{,}9962$$

Based on the above results, a system is recommended to vary the airflow of each fan, such as a speed variator for the electric motor and to complement it with variable air flow distribution boxes which operate with sensors that open or close depending on the temperature of each conditioned room, as shown in Fig. 6. An example of the above can be seen in the catalog of the brand TRANE VariTrane TM Products Single Duct/Dual Duct Units VAV-PRC011M-EN

Calculation of the load variation in the chiller feed pump

Taking into account that the thermal load varies according to the time of day, the water flow required by the Z must vary according to this load. Therefore, the calculation is performed by finding the results shown in Table 6 and comparing them with the currently installed pump as shown in Fig. 7. Therefore a system is recommended which varies the water flow of the pump, such as a speed variator for the electric motor.

Electrical power will also vary. This variation is observed in Table 7.

To estimate the energy savings at night, it is assumed that the pump operates the minimum flow calculated on the day, ie at 52.11 m^3/h. Taking into account that the pump operates 100% of the year, current demand is estimated at 84 534 kWh year, with the speed variator, demand is estimated at 31 840 kWh year, saving 52 695 kWh year, which means savings with the proposed system are around 62.3% of current consumption. This variation is shown graphically in Fig. 8.

Fig. 6. Operation of the TRANE variable air volume system

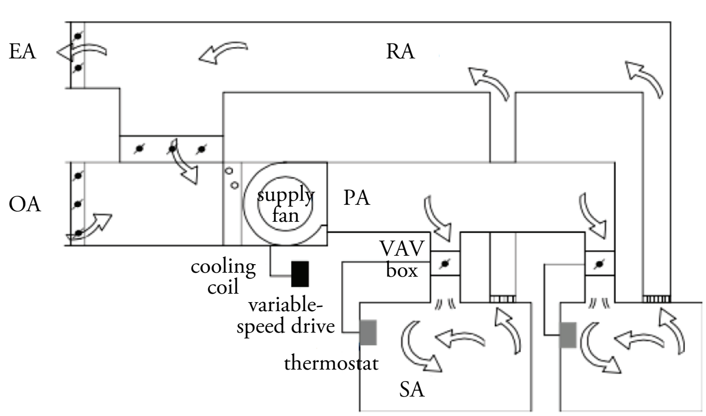
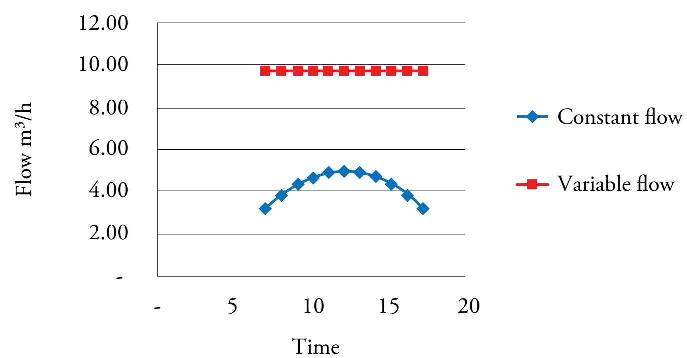


Table 6. Variation of the flow as a function of the time of day

	Time										
	7	8	9	10	11	12	13	14	15	16	17
Q m³/h	52.11	55.15	57.52	59.22	60.24	60.59	60.26	69.26	57.59	55.24	52.22
H m	11.50	12.88	14.01	14.85	15.36	15.54	15.38	14.87	14.04	12.92	11.55
rpm	1205	1276	1330	1370	1393	1401	1394	1371	1332	1278	1208
kW/h	3.15	3.74	4.24	4.63	4.87	4.95	4.87	4.64	4.25	3.75	3.17

Fig. 7. Behavior of the flow according to the time of day

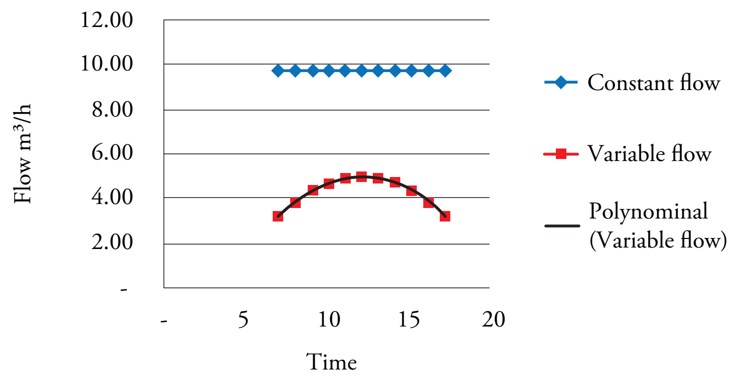


$H = -0{,}337Q^2 + 8{,}0991Q + 11{,}928 \quad R^2 = 0{,}98989$

Table 7. Variation of pump power as a function of time of day

Time	**Current operation**		**Proposed operation with speed variator**		
Time	Q m3/h	kW	Q m3/h	rpm	kW
7	80	9,65	52,11	1.205	3,15
8	80	9,65	55,15	1.276	3,74
9	80	9,65	57,52	1.330	4,24
10	80	9,65	59,22	1.370	4,63
11	80	9,65	60,24	1.393	4,87
12	80	9,65	60,59	1.401	4,95
13	80	9,65	60,26	1.394	4,87
14	80	9,65	59,26	1.371	4,64
15	80	9,65	57,59	1.332	4,25
16	80	9,65	55,24	1.278	3,75
17	80	9,65	52,22	1.208	3,17

Fig. 8. Variation of the power consumed by the pump according to the time of day



$$y = 0{,}0004x^4 - 0{,}0206x^3 + 0{,}2881x^2 - 0{,}968x + 1{,}9744 \qquad R^2 = 1$$

Total electrical consumption in operation of the current and proposed system

Based on the above, it is possible to estimate the total consumption per hour of the day, taking into account the consumption of the compressor, cold water pump and handlers, as shown in Table 8.

These consumptions are related to the variation of the total load due to the solar radiation on the outer sheets of the boat. For the night an average constant demand of 145 kW-h is estimated, as shown in Fig. 9.

Currently the ship has a constant and independent demand of the variation of the load due to the action of the sun; the estimated value of current consumption is equal to constant 174 kW-h. Fig. 10 shows the current consumption comparison curves for the proposed variable energy consumption.

Based on the information in Table 8, consumption is estimated at 3576kWh/day for the complete system with the proposed modifications, assuming that in the hours without solar charge the demand is equal to the lowest with solar load, which means 145.4 kW-hr. Currently, the system consumes 4180 kW-h/day, which is why energy savings of 14.5% are estimated.

Life cycle cost

Based on the above analysis, the life cycle cost of the asset is projected from its acquisition to decommissioning taking into account installation, maintenance and operation to determine the total cost of the asset. Therefore, the life cycle cost of an asset can be calculated by the following equation:

Fig. 9. Variable consumption, depending on the thermal load

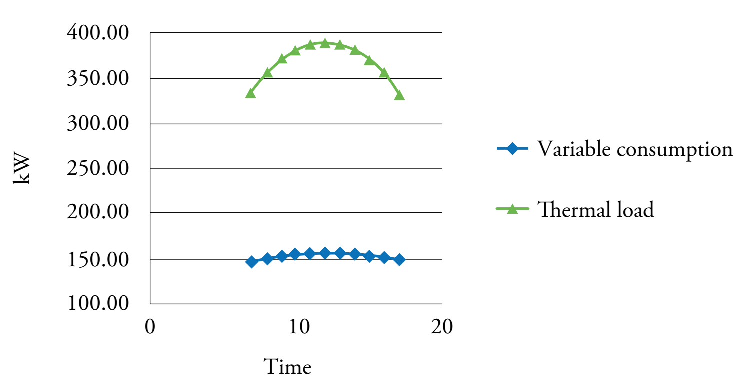


Table 8. Total energy consumption per operation (kW-h)

	TIME										
AHU	7	8	9	10	11	12	13	14	15	16	17
Z1	3.33	3.98	4.43	4.83	5.23	5.63	5.93	6.02	5.80	5.26	4.53
Z2	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
Z3	3.75	4.65	5.16	5.42	5.58	5.73	5.89	6.01	5.96	5.60	4.75
Z4	3.39	3.92	4.25	4.47	4.67	4.86	5.03	5.11	5.05	4.79	4.30
Z6	5.02	5.65	6.04	6.26	6.42	6.56	6.71	6.84	6.84	6.54	5.72
Z8	2.61	3.23	3.58	3.77	3.88	3.99	4.09	4.17	4.14	3.89	3.30
L13	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
U1	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
U2	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55
U4	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
U5	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
U7	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
U8	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
U9	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35
U10	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35
COMP	114.4	114.4	114.4	114.4	114.4	114.4	114.4	114.4	114.4	114.4	114.4
PUMP	3.15	3.74	4.24	4.63	4.87	4.95	4.87	4.64	4.25	3.75	3.17
TOTAL	145.4	149.3	151.8	153.5	154.8	155.9	156.7	156.9	156.2	154.0	149.9

$$L_{CC} = (C_{ic} + C_{in} + C_e + C_o + C_m + C_s + C_{amb} + C_d) \quad (4)$$

Where
C_{ic} = initial cost or equipment purchase cost.
C_{in} = cost of installation and commissioning.
C_e = energy cost.
C_o = operation cost.
C_m = maintenance cost.
C_s = cost due to breakdown time.
C_{amb} = environmental costs.
C_d = withdrawal and final closure

In this case, the useful life of the asset is projected in 20 years and the study is conducted in US dollars under the Net Present Value (NPV) methodology, an increase in the cost of energy and spare parts of 8% per annum, no funding is sought for the additional equipment to be installed, as shown in Table 9.

As shown in Table 9, the proposed option will save 10.17% in 20 years of operation. The distribution of costs is shown in Fig. 11.

Fig. 10. Comparison between the current consumption and the proposed variable consumption

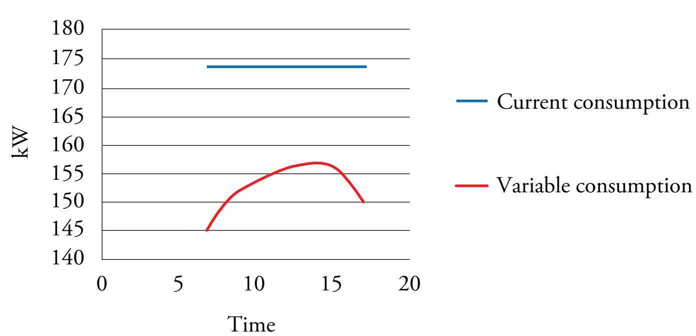
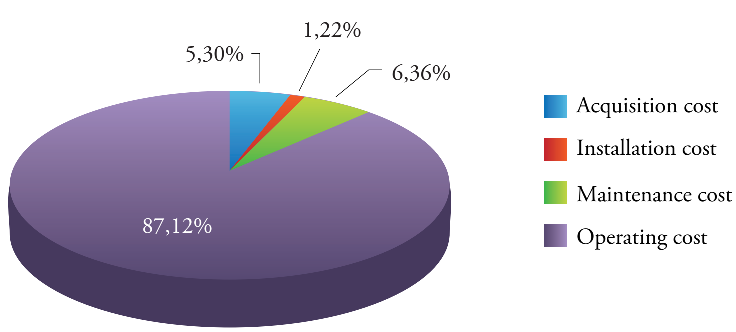


Table 9. Lifecycle cost for the current equipment and the proposed option

	Input Information			
	Components cost per boat	Current system	Proposed system	Unit
0	Acquisition	Unit Cost		
1	Chiller + evaporator + condenser + control	359,488.00	359,488.00	U$
2	Cold water pump	6,116.00	6,116.00	U$
3	Cold water pump speed variator	-	2,935.33	U$
4	Cold water pipe (includes valves and accessories)	33,333.33	50,000.00	U$
5	Condensation water pump	6,116.00	6,116.00	U$
6	speed variator condensation water pump	-	2,935.33	U$
7	Condensation water pipe (includes valves and accessories)	10,000.00	10,000.00	U$
8	AHU (Z1 Z2 Z3 Z4 Z6 Z8)	349,207.00	349,207.00	U$
9	Speed variators AHU	-	10,198.67	U$
	Z1	-	1,931.00	U$
	Z3	-	2,039.33	U$
	Z4	-	1,931.00	U$
	Z6	-	2,039.33	U$
	Z8	-	2,258.00	U$
10	Variable Flow Boxes	-	64,855.00	U$
11	*Total acquisition*	*764,260.33*	*861,851.33*	*U$*
12	Installation			
13	Chiller + evaporator + condenser + control	100,000.00	100,000.00	U$
14	cold water pump	611.60	611.60	U$
15	cold water pump speed variator	-	293.53	U$
16	cold water pipe	3,333.33	5,000.00	U$
17	condensation water pump	611.60	611.60	U$
18	speed variator condensation water pump		293,53	U$
19	water condensation pipe	1,000.00	1,000.00	U$
20	AHU	82.563,00	82,563.00	U$
21	Speed variators AHU	-	1,019.87	U$
22	Variable Flow Boxes	-	6,485.50	U$
23	Total Installation	188,119.53	197,878.63	U$
24	**Total initial investment**	**952,379.87**	**1,059,729.97**	**U$**
25	**Maintenance**	22,927.81	25,855.54	U$/year
26				U$/year
27	**Total maintenance**	22,927.81	25,855.54	U$/year
28	**Energy Costs**			
29	Power Consumption	4,180.00	3.657,00	kW-h/day
30	Days of operation year	346.75	346.75	Days
31	Days of operation with generators	255.41	255.41	Days
32	Days of operation with earth current	91.34	91.34	Days

33	Total Power Consumption	1,449,415.00	1,268,064.75	kW.h/year
34	diesel consumption to produce electricity consumption	1,128.00	984.00	l/d
35	Diesel consumption per year	288,102.48	251,323.44	l/year
36	Diesel cost	1.04	1.04	U$/l
37	Total diesel cost per year	299,626.58	261,376.38	U$/year
38	Current consumption	381,801.20	334.030.38	kW-h/year
39	Actual earth current cost	0.14	0.14	U$/kW-h
40	Total actual earth current cost per year	54,835.56	47,974.56	U$/year
41	**Total Energy Costs**	**354,462.14**	**309,350.93**	**U$/year**
42	**Operating Costs**	-	-	U$/year
43	Cost per breakdown	-	-	U$/year
44	Environmental costs	-	-	U$/year
45	Inflation	0.0677	0.0677	
46	% Fuel increase	0.08	0.08	
47	salvage value	0	0	
48	Total equipment value	764,260	861,851	U$
49	initial investment	764,260	861,851	U$
50	Financing	-	-	U$
51	number of installments	48	48	months
52	financing interest	22	22	% year
53	financing interest	0.018333333	0.018333333	
54	equipment life	20	20	years
55	installment value	-	-	U$
56	total loan	-	-	U$
57	Installation cost	188,119.53	197,878.63	U$
58	Maintenance Costs	916,664.66	1,033,716.69	U$
59	energy costs	16,220,883.81	14,156,506.41	U$
60	TOTAL	18,089,928.34	16,249,953.06	U$
61	Saving		1,839,975.27	U$
62	% saving		10.17	%

Fig. 11. Cost distribution of the proposed option



Environmental impacts

Environmental impacts are measured in accordance with the International Maritime Organization (IMO), which regulates emissions to the environment by marine diesel engines for Nitrogen Oxides (NOx) in g / kWh according to the following equation:

$$NOx = 45{,}0\, n^{0{,}2} \tag{5}$$

Where n is the engine speed equal to or greater than 130 rpm but less than 2,000 rpm. Therefore, NOx emissions generated by generators, which operate at 1800 rpm are estimated at 214 586 Ton over 20 years of equipment life for the current system and 187 377 Ton over 20 years of equipment life for the proposed system, which means avoiding the emission of 26 849 Ton NOx, (12.67%) over 20 years, with the proposed system.

Conclusions

The currently used thermal load calculation methods do not take into account the actual changes in temperature of the outer sheet of the vessels as a function of the time and place of operation, and therefore the result of the calculation will have constant and oversized consumption.

The operating costs of the asset correspond to 87.12% of the total costs in the life cycle, so the savings in operation will have significant impacts on the life cycle cost.

There are opportunities to save on the operation of the fans in the handling units Z and the cold water pump passing from a constant energy consumption to a variable consumption depending on the load, which varies with the time of day.

By integrating the proposed savings measures to the fans, pipes and pumps, savings of 10.17% are estimated in the life cycle of the asset.

Due to fuel savings, the environmental impacts would reduce NOx emissions by 12.6% compared to the current system.

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All articles must contain the following elements that must appear in the same order as follows:

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

Standards

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

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[1] J. K. Author, "Title of thesis," M.S. thesis, Abbrev. Dept., Abbrev. Univ., City of Univ., Abbrev. State, year.

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

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

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

References
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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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