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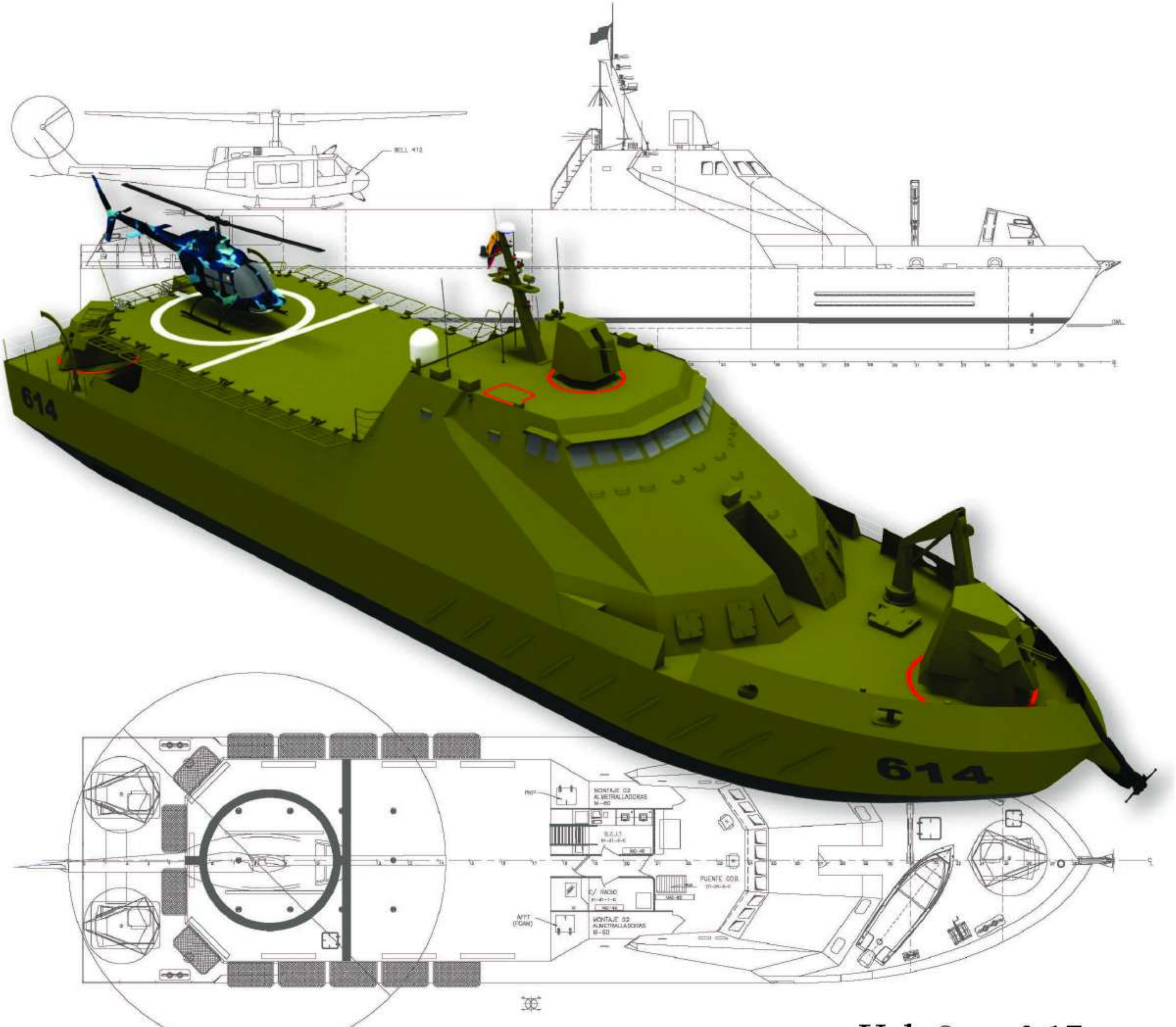

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Ship Science & Technology is a specialized journal in topics related to naval architecture, and naval, marine and ocean engineering. Every six months, the journal publishes scientific papers that constitute an original contribution in the development 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 16th 2015.

As usual, this Ship Science and Technology issue opens up with a set of the best papers presented at the Fourth International Congress of Ship design and naval engineering, held from march 11th to 13th in the Conventions Center of Cartagena City (Colombia), having as principal themes (1) Warship design, (2) Technology solutions for Riverine Industry strengthening and (3) Naval technologies for offshore industry development.

This congress was aimed to position as a biennial event of scientific-technological order that allows knowledge and experience exchanging about innovation, progress and technology development of the industry and maritime sector, being useful as an interface to enable value chain stakeholders interact, define and establish partnerships in order to enhance naval, maritime, riverine and port industries. In this opportunity 63% of the scientific programme were conferences presented by international speakers and the 37% remaining were done by national speakers, besides the schedule was set by four (04) lectures, two (02) VIP conferences, twenty seven (27) scientific papers, eight (08) technical papers, three (03) workshops and one (01) forum, as a result the whole event had 45 academic activities. The attendees of this congress came from Germany, Spain, Panama Brazil, United Kingdom, Belgium, Korea, Ecuador, Netherlands, Colombia, Chile, Peru, Mexico, United states, among others. Considering the above mentioned this edition gathers studies related to naval ship design, cost estimation, dynamics and structure analysis of hull.

Once again we thank to readers and followers of our Ship Science and Technology Journal and also to stakeholders and speakers and attendees of Colombiamar trade show and the International Congress of Ship design and Naval Engineering, for letting continue with the task of giving the tools and scenarios that enable transfer and increase knowledge towards naval engineering, naval architecture, marine engineering and oceanic engineering development, as principal areas to the sea future.

Commander JOSÉ MANUEL GÓMEZ TORRES
Editor of the Ship Science and Technology Journal

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Nota Editorial

Cartagena de Indias, 16 de Julio de 2015.

Como costumbre con este número de la revista Ciencia y Tecnología de Buques abre la serie de publicaciones especiales con los mejores trabajos presentados en el cuarto Congreso Internacional de Diseño e Ingeniería Naval, realizado los días 11, 12 y 13 de marzo de 2015 en el Centro de Convenciones de la Ciudad de Cartagena de Indias, teniendo como temáticas principales (1) Diseño de Buques de Guerra, (2) Soluciones Tecnológicas para el Fortalecimiento de la Industria Fluvial y (3) Tecnologías navales para el desarrollo de la Industria offshore.

El Congreso tuvo como objetivo posicionarse como un evento bienal de orden científico-tecnológico que permite el intercambio de conocimientos y experiencias en innovación, avances y desarrollos tecnológicos de la industria y del sector marítimo, sirviendo de interfaz para que los actores de la cadena de valor interactúen, definan y desarrollen alianzas para el fortalecimiento conjunto de la industria naval, marítima, fluvial y portuaria. En esta oportunidad el 63% del programa científico fueron ponencias de personas extranjeras y el 37% restante por ponencias de personas nacionales, además se estructuró estuvo conformado por (04) cuatro conferencias magistrales, (02) dos conferencias VIP, (27) veintisiete ponencias científicas, (08) ocho ponencias técnicas, (03) Workshops y (01) un foro para un total de 45 actividades académicas. Se contó con asistentes de Alemania, España, Panamá, Brasil, Reino Unido, Bélgica, Corea, Ecuador, Países Bajos, Colombia, Chile, Perú, México, Estados Unidos, entre otros. Partiendo de lo anterior, esta edición se recopila trabajos relacionados con las temáticas de diseño de buques navales, estimación de costos, dinámica y análisis de estructura.

Nuevamente agradecemos al público lector seguidor de nuestra revista Ciencia y Tecnología de Buques como también a los actores y participantes en general de la Feria Colombiamar y del Congreso Internacional de Diseño e Ingeniería Naval por permitir continuar con la tarea de brindar las herramientas y escenarios para transferir e incrementar el conocimiento hacia el desarrollo la ingeniería naval, arquitectura naval, ingeniería marina e ingeniería oceánica, como áreas de interés para el futuro del mar.

Capitán de Fragata JOSÉ MANUEL GÓMEZ TORRES
Editor Revista Ciencia y Tecnología de Buques

Reenactment of a bollard pull test for a double propeller tugboat using computational fluid dynamics

Recreación de la prueba de Tracción a punto fijo de un remolcador de doble propulsor mediante dinámica de fluidos computacional

Adan Vega [1]
David López Martínez [2]

Abstract

Use of CFD simulations is an affordable and trustworthy way of determining a vessel's capacity before its construction. This study focuses in simulating a bollard pull of a specific tugboat and comparing the results with those of the real test to which it was subjected after construction. In compliance with the regulations of the classification societies regarding these types of tests, simulations will be carried out to study the bollard pull tests of a double propeller two boat. The results showed that the mathematical model is suitable for a numerical calculation of the bollard pull tests.

Key words: Bollard pull test, tugboat, power, simulation, modelling, computational fluid dynamics.

Resumen

La utilización de simulaciones CFD es un modo económico y fiable de determinar las capacidades de un buque antes de su construcción. Este estudio está enfocado a simular la prueba de tracción a punto fijo de un remolcador específico y comparar los resultados obtenidos con los de la prueba real a la que fue sometido después de su construcción. Atendiendo a la normativa de las sociedades de clasificación sobre este tipo de pruebas, se realizarán simulaciones para estudiar la prueba de tracción a punto fijo de un remolcador de doble propulsión. Los resultados obtenidos demostraron que el modelo matemático es apto para realizar de forma numérica las pruebas de tracción a punto fijo (bollard pull).

Palabras claves: Prueba de tracción a punto fijo, remolcadores, potencia, simulación, modelado, mecánica de fluidos computacionales

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Introduction

Currently, vessel pull tests are performed using bollard pull tests. Performing these tests requires that the vessel is already built, so that when performing said test compliance with previously established pulling requirements is verified. If the vessel does not comply, going back to the drawing table to make the necessary adjustments to solve the problem is required, which results in additional costs. It is therefore obvious to conclude that developing a methodology that allows verifying the vessel´s pulling capacity during the design stages and thus performing a simulation that can predict the behavior during real bollard pull tests once the vessel is built, would be a very useful tool It is widely known that propeller studies have been done for years using different methods; in most cases it is very difficult to perform a precise analysis, but thanks to advances in information systems this capacity has drastically increased, and is increasing thanks to the use of computational tools in different fields of study, one of them being propeller analysis [1], were the use of simulations using specialized software has become very popular thanks to their versatility that allows to perform study models without the need to physically build them. This results in important financial savings when performing a particular study. Computational fluid dynamics (CFD) is being used in several naval area studies [2], were CFD solution methods have been introduced, such as the Reynolds Averaged Navier-Stokes (known as RANS) [3], which allows for complex solutions of Navier-Stokes equations, in most cases impossible to solve manually.

J. Martinez de la Calle *et al.* (4) developed two methodologies, a numerical and an experimental one, for the study of flow around a marine propeller, performed a flow analysis that presents the non-dimensional characteristic curves or propeller diagram of a marine propeller; obtained both experimentally as well as using numerical simulation techniques. They used a reduced scale propeller model and after developing the methodologies that correspond to both techniques (numerical and experimental) achieved very similar results, indicating the validity of a numerical technique (CFD) as well as the design and flow analysis of a marine propeller.

Isao Funeno (5) used computational fluid dynamics for the hydrodynamic analysis of azimuth propellers, taking into consideration uncompressible viscous fluid, used the SST k-ω turbulence model with wall function. The effect in the flow field of the propeller was taking into consideration introducing centrifugal forces and coriolis forces in a system of coordinates relative to the body's forces using the formulas with Reynolds' averages of the Navier-Stokes equations. From a hydrodynamic point of view, the analysis of azimuth propellers is more complicated than that of conventional propellers given the strong interaction between the propeller and the duct; also, one of the most complicated conditions to analyze is bollard pull. Due to this inconvenience, Kawasaki Heavy Industries (6) has performed water tank tests using small and sophisticated waterproof dynamometers to improve the analysis.

W.H. Lam *et al.*, (7) performed a study using the Reynolds' average of the Navier-Stokes equations (RANS) using computational fluid dynamics to predict water flow through a propeller and compared the turbulence models with the experimental results obtained. The turbulence models used were those of the Boussinesq family, using the standard k-ε model, RNG k-ε, realizable k-ε, standard k-ω, SST k-ω and the Spalart–Allmaras model, subsequently presenting the advantages and inconveniences of one model over another.

Some bollard pull studies have been performed using computational methods (8) but none of them have taken into consideration the pull generated by the set of propeller, duct and interaction with the hull.

The authors have developed a methodology to perform the bollard pull test analysis using computational fluid dynamics which has obtained similar results to those obtained from real environment tests. This article presents the mathematical model that was developed. The results after simulating the hull of a double propeller tugboat are presented and discussed. Finally, a comparison between the numerical results and those obtained using existing equations are compared.

Description of the bollard pull test

Bollard pull tests are performed in order to obtain the static pull that a vessel can attain; during this test, the vessel is grounded so it cannot move over the water and therefore has a forward speed equivalent to zero. A device is used to measure force, which can be a dynamometer, a charge cell or a strain gauge. The pull generated depends greatly on displacement, hull shape, as well as the type of propeller and power. This test is applied to different types of vessel, mainly to measure pull for tugboats, where this condition is quite similar to their operations, such as towing or pulling vessels or floating artifacts at very low speeds.

Mathematical model

Fluid properties

To develop this study, the properties of the fluid used within the computational domain are presented initially, in this case sea water under standard conditions of 20°C, a Newtonian fluid. In the tangential flow of Newtonian fluids, shear strength known in fluid mechanics as viscous stress is governed by the following equation:

$$\tau = \mu \frac{d\theta}{dt} \tag{1}$$

where μ is dynamic viscosity, and $\frac{d\theta}{dt}$ is the stress yield.

Fundamental fluid equations

The equations that describe the behavior of any fluid are those of continuity and amount of movement. During this investigation the assumption of an isothermal fluid will be made since temperature changes are very small. This constant temperature consideration eliminates the need to implement an additional variable, temperature, which is the reason why the differential equation of energy conservation is not introduced. The fundamental equation originates any fluid analysis and is the continuity equation resulting from:

$$\frac{D\rho}{Dt} + \nabla \bullet (\rho \vec{V}) = 0 \tag{2}$$

where:

$$\frac{D\rho}{Dt} = \frac{\partial \rho}{\partial t} + u\frac{\partial \rho}{\partial x} + v\frac{\partial \rho}{\partial y} + w\frac{\partial \rho}{\partial z} \tag{3}$$

$$\nabla \bullet (\vec{V}) = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \tag{4}$$

The continuity equation describes mass conservation within a control volume. This case study the fluid is treated as uncompressible and thus the continuity equation is simplified as follows:

$$\nabla \bullet (\vec{V}) = 0 \tag{5}$$

The second important equation in this analysis is the amount of movement equation defined by:

$$\frac{D(\rho \vec{V})}{Dt} = \nabla \bullet \bar{\sigma} + \rho \vec{g} \tag{6}$$

where:

$$\frac{DV}{Dt} = \frac{\partial \vec{V}}{\partial t} + u\frac{\partial \vec{V}}{\partial x} + v\frac{\partial \vec{V}}{\partial y} + w\frac{\partial \vec{V}}{\partial z} \tag{7}$$

The amount of movement equation does not sole the fluid mechanics issues since it is not mathematically solvable. This is due to the fact that it needs to express stress yield $\bar{\sigma}$ in terms of primary variables, that is, density, pressure and speed. In order to achieve an analytical solution to the so called constitutive equations are introduced which allow expressing stress yield as a function of speed and pressure, as follows:

$$\begin{gathered} \sigma_{ij} = -p\delta_{ij} + \tau_{ij} \\ \tau_{ij} = 2\mu D_{ij} - \frac{2}{3}\mu \nabla \bullet (\vec{V})\delta_{ij} \begin{bmatrix} \tau_{xx} & \tau_{yz} & \tau_{zx} \\ \tau_{xy} & \tau_{yy} & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & \tau_{zz} \end{bmatrix} \end{gathered} \tag{8}$$

where:

$$D_{ij} = \frac{1}{2}\left(\frac{\partial v_i}{\partial j} + \frac{\partial v_j}{\partial i}\right) \tag{9}$$

is the viscous stress yield and

$$\sigma_{ij} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{10}$$

component is known as Kronecker delta. This way, the constitutive equation for Newtonian fluids is simplified as follows.

$$\sigma_{ij} = -p\delta_{ij} + \mu\left(\frac{\partial v_i}{\partial j} + \frac{\partial v_j}{\partial i} - \frac{2}{3}\nabla \bullet (\vec{V})\delta_{ij}\right) \tag{11}$$

After replacing the constitutive equation, the Navier-Stokes equations are obtained, which represent the basis for fluid mechanics:

$$\begin{aligned}
\frac{D(\rho u)}{Dt} &= -\frac{\partial p}{dx} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \\
&\quad + \frac{\mu}{3}\frac{\partial}{\partial x}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right) + \rho g_x \\
\frac{D(\rho v)}{Dt} &= -\frac{\partial p}{dy} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) \\
&\quad + \frac{\mu}{3}\frac{\partial}{\partial y}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right) + \rho g_y \\
\frac{D(\rho w)}{Dt} &= -\frac{\partial p}{dz} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) \\
&\quad + \frac{\mu}{3}\frac{\partial}{\partial z}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right) + \rho g_z
\end{aligned} \tag{12}$$

For uncompressible fluids the Navier-Stokes equations are simplified to:

$$\begin{aligned}
\frac{\rho D(u)}{Dt} &= -\frac{\partial p}{dx} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) + \rho g_x \\
\frac{\rho D(v)}{Dt} &= -\frac{\partial p}{dx} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) + \rho g_y \\
\frac{\rho D(w)}{Dt} &= -\frac{\partial p}{dx} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) + \rho g_z
\end{aligned} \tag{13}$$

The analytical solution of the Navier-Stokes equations results almost impossible for vessel and propeller flow. There are several mathematical models that allows simplifying phenomena such as viscosity and turbulence. One of the most commonly used models are the Averaged Navier-Stokes (RANS). This method takes the variables and divides them in two components; the mean or average component, and the fluctuation component, as shown in the following equation:

$$u_i = \bar{u}_i + u'_i \tag{13}$$

Where: $\bar{u}_i$ is the mean component and u'_i is the fluctuation component.

This model adds the Navier-Stokes equations in a term known as Reynolds stress; thanks to this term it is possible to achieve a numerical solution applying a turbulence model. The following equation shows the solution, better known as Averaged Navier-Stokes equations:

$$\begin{aligned}
\frac{\rho D(u)}{Dt} &= -\frac{\partial p}{dx} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \\
&\quad + \rho g_x - \rho\left((\overline{u'u'})_x + (\overline{u'v'})_y + (\overline{u'w'})_z\right) \\
\frac{\rho D(v)}{Dt} &= -\frac{\partial p}{dy} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) \\
&\quad + \rho g_y - \rho\left((\overline{v'u'})_x + (\overline{v'v'})_y + (\overline{v'w'})_z\right) \\
\frac{\rho D(w)}{Dt} &= \frac{-\partial p}{dy} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) \\
&\quad + \rho g_y - \rho\left((\overline{w'u'})_x + (\overline{w'v'})_y + (\overline{w'w'})_z\right)
\end{aligned} \tag{14}$$

Curve of characteristic coefficients of propellers s

Fig. 1 shows a typical open water diagram. These diagrams describe the specificities and characteristics of propellers for a variety of advances, rotation speeds, fluid density and propeller diameters. The diagrams present defined lines for the propeller pass relation (P/D); these lines are applicable to various propeller diameters as long as the same geometric shape is kept, defined by the characteristic curve that also works for any other fluid. When using the pull and torque coefficients defined in these diagrams, the propeller diameter and fluid density of the operation medium must be determined. Then, when the advance and rotation speed is established the advance coefficient is obtained (J); then a vertical line is drawn from the advance coefficient that intercepts the pass relation curve Kt for the thrust coefficient and Kq for the torque coefficient; once these operations are performed the thrust as well as the theoretical torque generated by the propeller are found. Below are the equations describing the open waters diagrams:

Advance Coefficient:

$$J = \frac{V_a}{nD} \tag{15}$$

where V_a is the advance speed, which is equal to zero in the Bollard Pull condition, therefore in our case study $J = 0$ thrust coefficient:

$$K_T = \frac{T}{\rho n^2 D^4} \tag{16}$$

where T is thrust force. For the case of propellers with ducts the thrust coefficient is the sum of the thrust coefficient of the propeller and the thrust coefficient of the duct. In K_T is equal to 0.525.

Torque coefficient:

$$K_Q = \frac{Q}{\rho n^2 D^5} \tag{17}$$

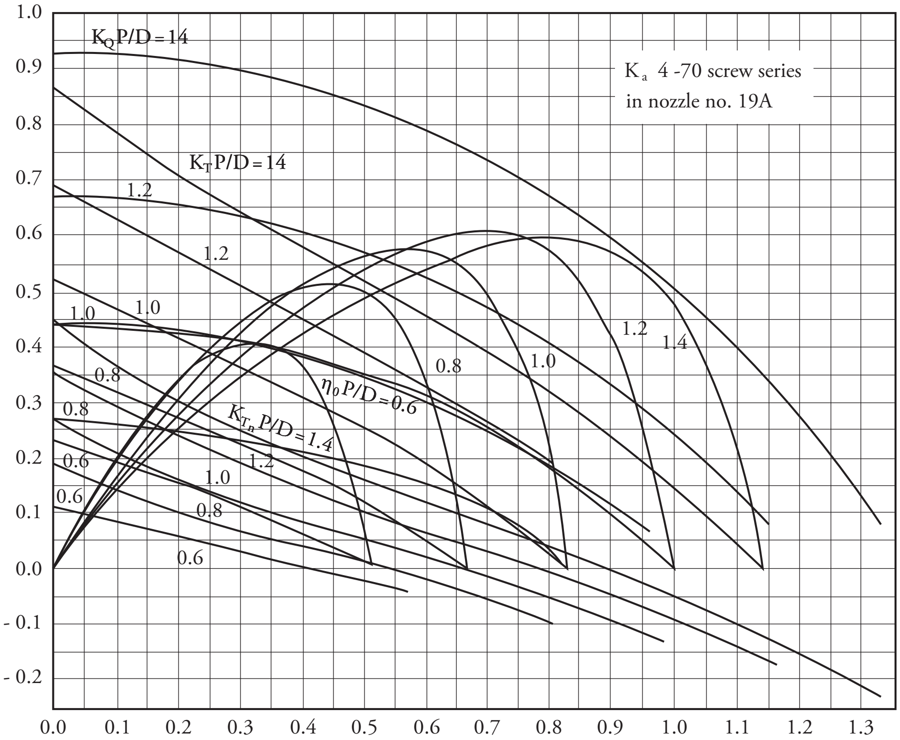
where Q is the propeller torque in our case K_Q equals 0.044.

Simulation of bollard pull test using CFD

Generation of the tridimensional hull model

The first step in performing the bollard pull test is developing the tridimensional hull model of the vessel. The Rhinoceros 3D software was chosen for this effect. It is a software tool for 3D modelling, based on NURBS surfaces that allows including a file of the bitmap as a basis for drawing the water

Fig. 1. Diagram of thrust coefficients, torque coefficients and propeller efficiencies Ka 4-70 with 19A ducts [9].



lines, frames and other shapes of the tugboat's hull. Fig. 2 shows the different sections of the shape for the tugboat selected for the study. After a series of operations, the 3D model was transformed into a mathematical model of finite elements that can be used in the ANSYS software, which we used for our simulations. The tridimensional hull model and its annexes are shown in Fig. 3.

Fig. 2. Sections of hull shapes.

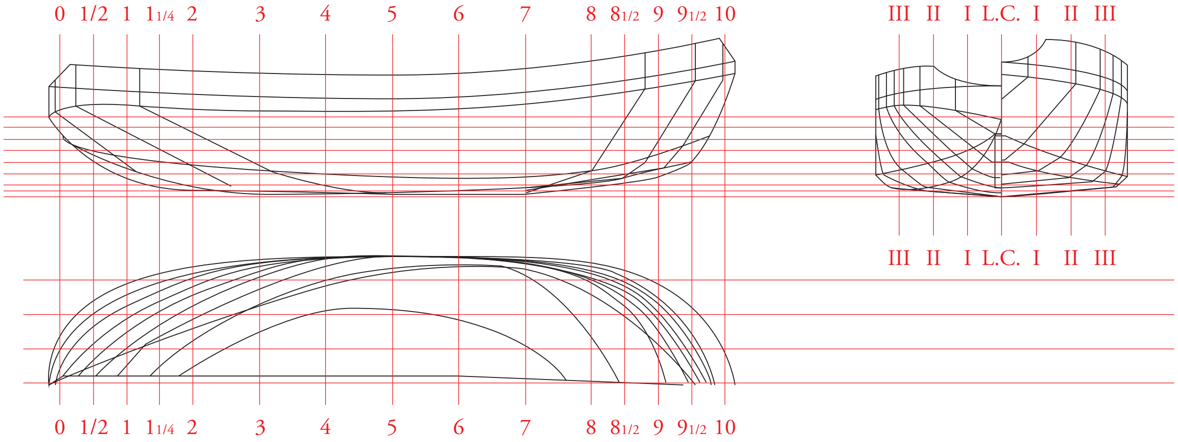
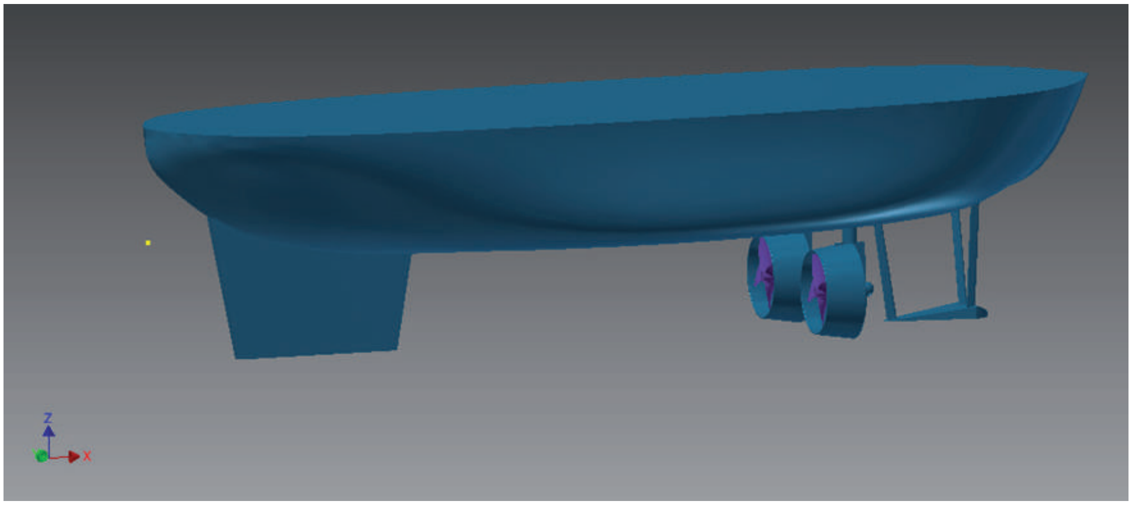


Fig. 3. Tridimensional model of the hull used in the simulation.



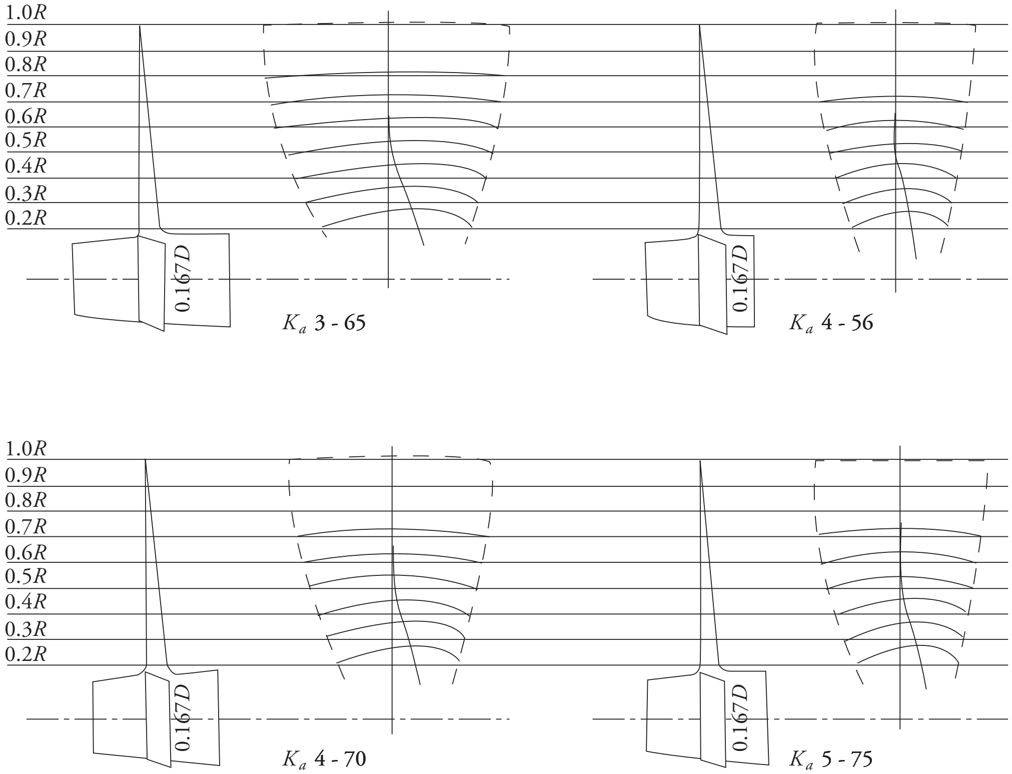
Selection of propulsion system

In our case the selected tugboat uses a double propulsion system where one of the propellers will be dextrogyre. The shape of the blades is obtained from the manufacturer and belongs to the Ka series [5], as shown in Fig. 4.

Meshing of the finite elements model

An unstructured tetrahedral meshing was used in the Patch Independent mode, which initially creates the mesh in the domain surfaces and then the boundaries, opposite to the Patch Conforming mode which first

Fig. 4. Shape of propeller blades series [5].



ρ = uniform

creates the boundaries and then the surfaces. The asymmetry known as skewness is reduced in this way while at the same time the quality of the meshing is increased. The area with the greatest asymmetry is the propeller area due to its complex geometry; a meshing of asymmetry of less than 0.75 is recommended to obtain acceptable meshing and achieve a realistic simulation; in our case, a maximum asymmetry of 0.6948 was obtained in the computational domain. Fig. 5 shows details of the model's meshing and its main components.

Fig. 5. Meshing of the model of the tugboat: a) duct and propeller set, b) propeller.

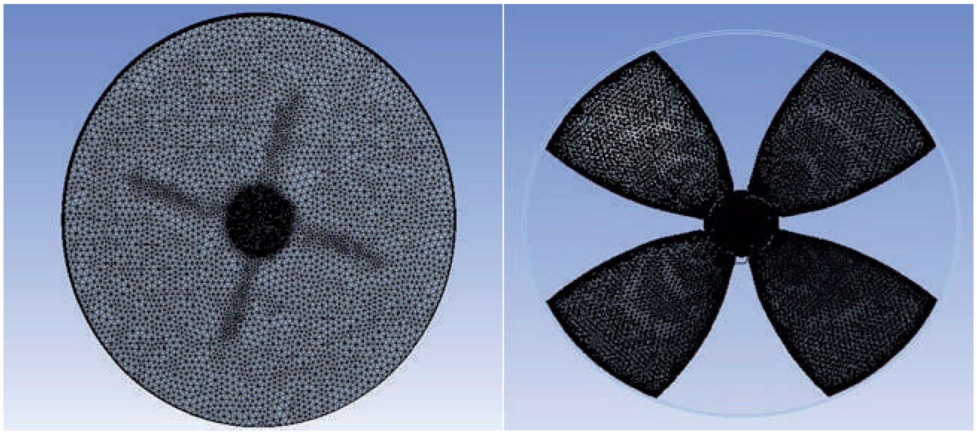
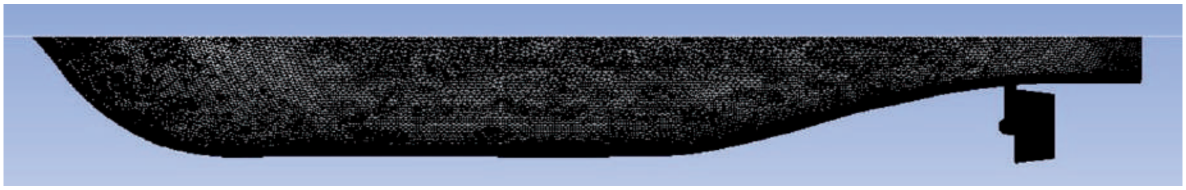


Fig. 5. c) Hull, duct and propeller set.



Boundary conditions

Development of computational fluid dynamics simulations requires establishment of boundary condition for the domain. These have been selected to achieve an environment that is closest to the real environment, achieving an appropriate ratio between the fluids and the vessel's components. The boundary conditions represent a fundamental aspect to develop the Navier-Stokes equations, fulfill the continuity equation and achieve convergence of the simulation. For this analysis the following boundary conditions were used: (1) boundary condition for the water surface: established as symmetry given that the surface is not a real wall and therefore there are no viscous stresses on it; also there is no convective fluid through the plane of symmetry since there is no mass transport over this surface, which is why the normal velocity component is equal to zero. There is also no diffuse fluid on this surface, so the normal gradients of the flow variables are also equal to zero. (2) Boundary condition for the entire vessel: a no slip wall boundary condition was selected. This means that the fluid movement does not fully stop at the surface and achieves a speed of zero in relation to it. A fluid in direct contact with a solid sticks to the surface due to viscous stress. The fluid property that affects the no slip condition is viscosity. Therefore, for these no slip surfaces $V.\ n = 0$. Where V is the fluid speed in relation to the surface and n is a normal unit vector of the surface. (3). The sea bottom boundary condition: the boundary condition established at the sea bottom is also a no slip condition, this boundary is close to a flat wall. This condition was selected since the sea bottom is a real surface and is therefore subjected to viscous stress. (4) Domain limits boundary condition: the boundary condition established for the sides, the front and back of the computation al domain is the pressure *outlet* = 0 condition. At first sight establishing this condition might seem as a mistake, but the Ansys Fluent software redefines pressure in terms of modified pressure including the hydrostatic effects as follows: Modified pressure: $P'=P-\rho_o\vec{g}.\vec{r}$ where P is conventional pressure, ρ_o is constant reference density $\vec{g}$ is the gravity vector and $\vec{r}$ is the position vector. Conventional hydrostatic pressure for a fluid is equal to $P=\rho\vec{g}.\vec{r}$ where ρ is equal to the fluid density. Therefore, in the case of an uncompressible fluid which is the assumption for the $\rho=\rho_o$, simulations and a hydrostatic pressure condition may be established: Pressure Outlet: $P'= 0$.

Results of the simulation

Figs. 6 and 7 show examples of the results obtained after simulating the bollard pull test in the selected tugboat. As shown, the pressure as well as the viscous stress that cause water movement around the propellers and the duct can be reproduced.

Result validation

Fig. 8 (see page 18) shows a comparison between the torque obtained using simulation and that obtained using theoretical analysis for the different propeller duct combinations. As shown in the figures, the difference between the numerical and theoretical results is small, and it can therefore it can be ensured that the model developed is appropriate for simulation of bollard pull tests for tugboats.

Conclusions

This article has successfully proven an analysis

Fig. 6. Pressure outlet: Suction side (left), Pressure side (right).

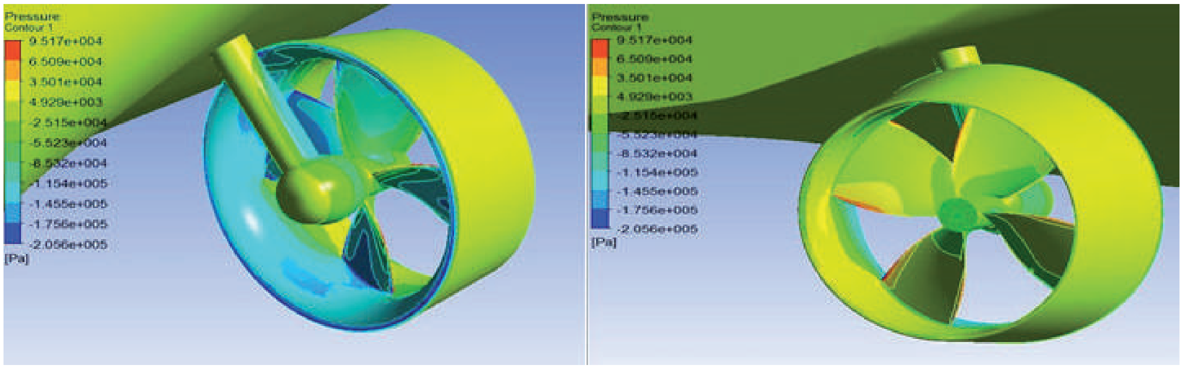
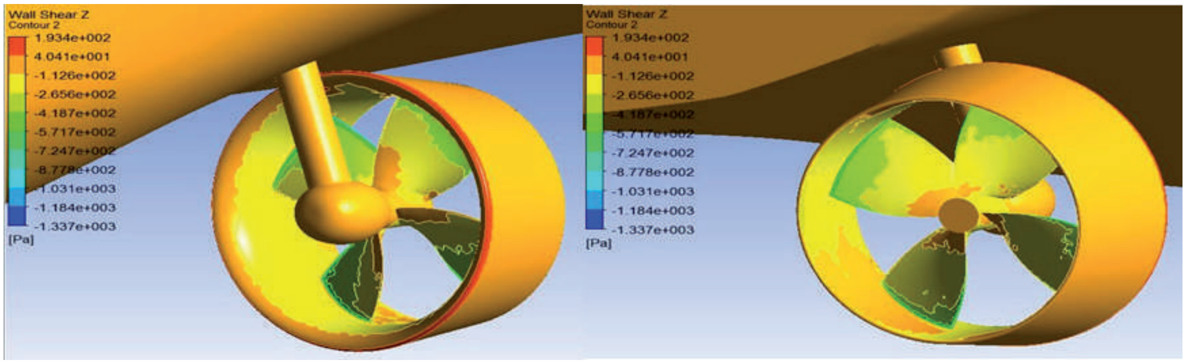


Fig. 7. Viscous pressure outlet: Suction side (left), Pressure side (right).



methodology to simulate bollard pull tests for vessels, taking into account the propeller-duct set and its interaction with the hull. The methodology's efficacy was proven through validation of the simulation results to the expected theoretical response. The code was developed using the results of the finite volumes of Ansys Fluent, which achieved replication of bollard pull tests that are similar to the real ones. We may conclude that using this mathematical model the bollard pull test may be reproduced successfully during the design process, thus saving time and money and preventing future complications once the vessel is built.

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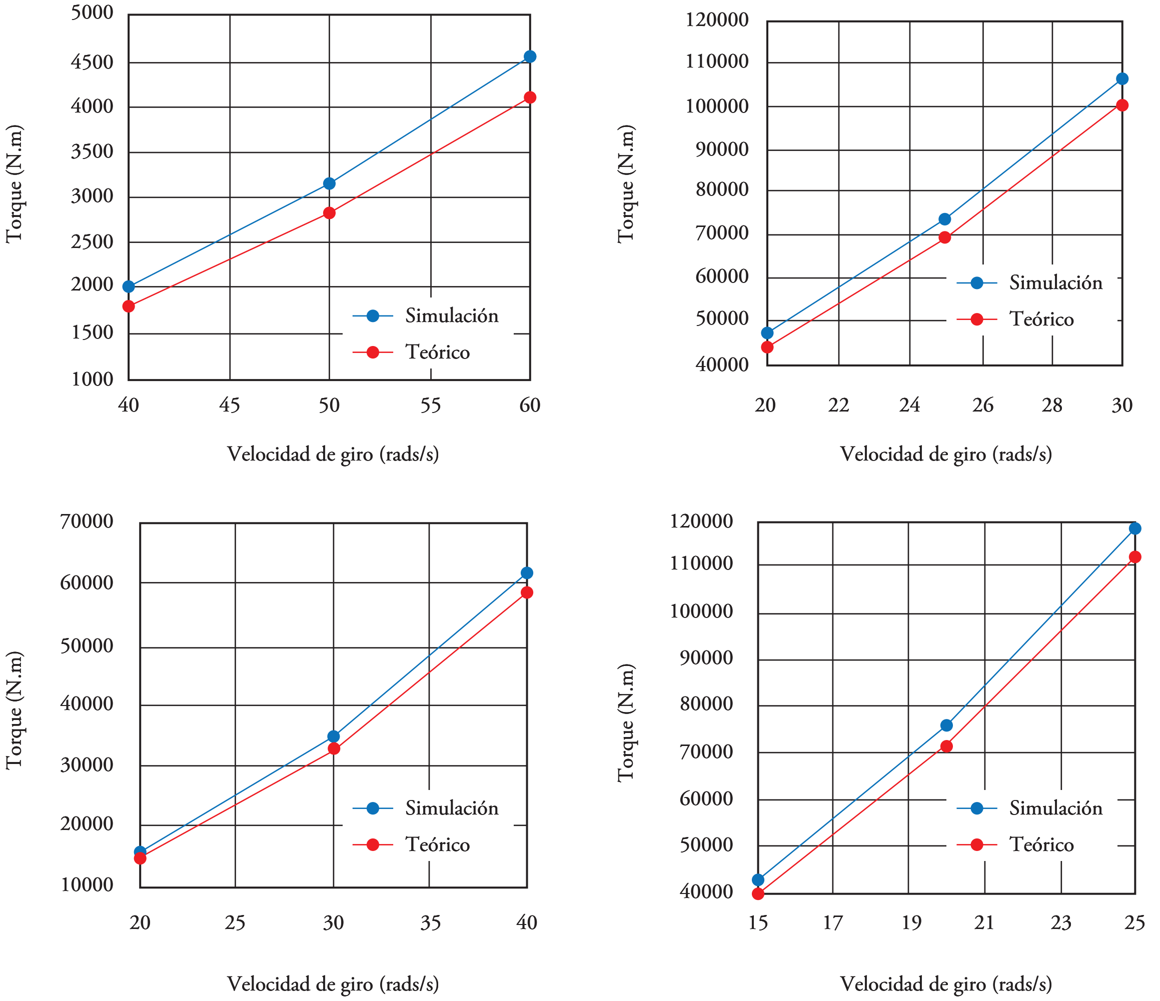
Fig. 8. Torque for propeller-duct configuration of a) 1 meter, b) 1.5 meters, c) 2 meters, d) 2.5 meters



Designing for the Gap: The space between the OPV and the Frigate

Diseño para la brecha: El espacio entre la OPV y la Fragata

Andy C. Kimber [1]

Abstract

One of the enduring struggles for the warship designer has been the design of the affordable warship; a ship that offers useful military capability at a fixed and ideally lower price than a pure frigate or destroyer type. BMT has been investigating this design space, through the creation of a patrol ship design called the "Venator 110", using a variety of tools to measure performance rapidly. A capability modelling tool has been developed to rapidly compare how different designs achieve military roles and how modular systems may be used to enhance a platform. Investigations have also focused on exploring methods of achieving pragmatic enhancements to survivability. These draw on the company's experience in developing naval and auxiliary ships which use a mix of naval and commercial equipment and practises to "tailor" survivability. Finally, design solutions that offer maximum flexibility have been incorporated within the design to explore their practicality.

Key words: Capability, Survivability, Modularity, Affordability.

Resumen

Una de las luchas duraderas para el diseñador de buques de Guerra ha sido el diseño asequible de una embarcación de estas características; un buque que ofrezca capacidad militar útil en un ajustado e idealmente más bajo precio que una fragata o una fragata tipo destructor. BMT ha estado investigando este espacio de diseño, a través de la creación del diseño de un patrullero llamado "Venator 110", usando una variedad de herramientas para medir desempeño rápidamente. Una herramienta de modelado de capacidades ha sido desarrollada para comparar rápidamente cómo diferentes diseños logran los roles militares y cómo los sistemas modulares pueden ser usados para mejorar una plataforma. También las investigaciones han sido enfocadas en la exploración de métodos de mejora para la supervivencia. Estos se basan en la experiencia de la compañía en el desarrollo de embarcaciones navales y auxiliares, las cuales usan una mezcla de equipos navales y comerciales, y prácticas para "ajustar" la supervivencia. Finalmente, las soluciones de diseño que ofrecen una máxima flexibilidad han sido incorporadas dentro del diseño para explorar su practicidad.

Palabras claves: Capacidad, supervivencia, modularidad y asequibilidad.

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Introduction

One of the enduring struggles for the warship designer has been the design of the affordable warship – a ship that offers useful military capability but at a fixed and ideally much lower price than a true frigate or destroyer type. Historically many navies have adopted this type of vessel, for example the Royal Navy's Type 14 or Type 21 frigates. However, this type of vessel seems to have become less fashionable since the later part of the last century, with many navies choosing to dispose of these vessels although in favour of smaller numbers of high end warships.

Looking forward, with many navies focused on delivering maritime security rather than posturing, and continued world economic constraints, ship designers and builders are again turning to the affordable patrol vessel as an alternative to the frigate. BMT has been investigating this design space, through the creation of a patrol ship / patrol frigate design called the "Venator 110". As part of this project paper, BMT has developed a capability modelling process to compare how different designs achieve a defined set of military roles and how modular systems may be used to enhance a platform.

Within this paper, this work will be summarised, including a description of the capability assessment tool, methods of achieving pragmatic enhancements to survivability and the impacts of designing warships for flexibility and modular systems.

The Affordability versus Capability Argument

The key to affordable design is to understand what the true requirements are, in what environment they are to be conducted, and to prevent requirements creep occurring through more capability being added than strictly necessary. The designer needs to keep a close eye on the design being spiralled upwards in the enthusiasm to procure the best possible solution; but he must also be open to the opportunity to achieve extra value where cost in not significantly affected.

It is also true that the "design space" is not uniform and designs do not necessarily grow in proportion to requirements. Rather, it consists of cliff edges and plateaus where the designer can find themselves "on the wrong side" of a step change or where additional capability can be added for modest cost because of the solution adopted. This non-linear characteristic of the ship design process is explored further in Reference [1]. Such a process may not be considered appropriate in all situations and as Reference [1] suggests there is no single process able to capture all ship designs.

This implies that requirements definition and design development are parallel activities, each being traded towards the goal of an affordable solution. For a warship, there are a range of expectations of capability and often a difficulty to pin down the exact capability need and therein conduct a robust trade; for example if a ship is to be flexible, to what ends? The wide range of

Fig. 1. BMT Venator 110 - Patrol Ship (left) and Venator 90 Reconfigurable Minor Combatant (Right)

interpretations is illustrated at Reference [2]. Hence, for the Venator 110 concept the team set out to consider the following:

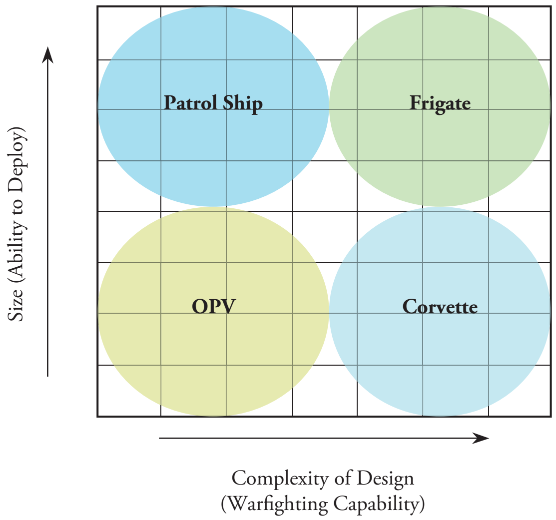
What, in a defined framework, is the vessel expected to do?

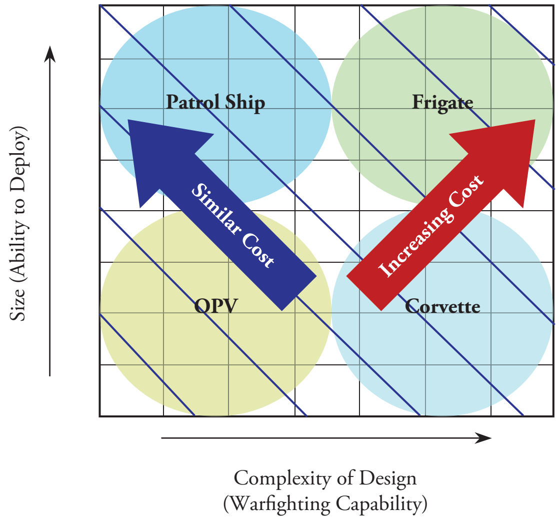
- What coherent steps in military fit should be considered?
- What level of survivability is consistent with the above?
- What is the range of flexibility expected and how can this be achieved in a design which is still affordable and buildable?

For small navy combatants, the typical vessel types are expressed as frigates, corvettes or OPV's. The former is typically an ocean going complex combatant and the latter a simple off-shore vessel. The Author would contend that a corvette represents a complex but short endurance vessel, whilst a patrol ship would offer longer endurance but be a simpler platform [1]. Fig. 2 illustrates this visually. However, these terms do not represent clear boundaries, although when applying in the context of military tasking and threats they are also not necessarily a continuum; there may be gaps where no useful capability exists. The variation of cost will in general occur in a diagonal across the diagram as shown; from bottom left to top right represents increasing cost (or fewer platforms for a budget) whilst top left to bottom right represents a line of common cost (or class size) but represents a different sort of delivered capability (trading size / flexibility for warfighting effect / survivability).

For the purposes of the capability model described in this paper, the problem has been addressed by adopting and then tailoring the latest UK Maritime Doctrine, Reference [3], which clearly and concisely identifies a range of Military Tasks. The approach taken in the development of the Venator 110 Patrol Ship was to set the requirements against the Maritime Security Roles, whilst being able to flex to achieve the International Engagement Role (not requiring concurrent operations and allowing for mission specific fits) and to deliver the maximum Warfighting Role possible from the platform without increasing size, complexity and platform cost (Fig. 3). With this level of understanding, it was also possible to set survivability objectives, including identifying and recording likely threats.

Fig. 2. Relative Performance for Combatant Types.





Using Capability Modelling as a Design Tool

A key enabler to trading cost and capability is the ability to "measure" the capability delivered by a design. It is important that such measurements can

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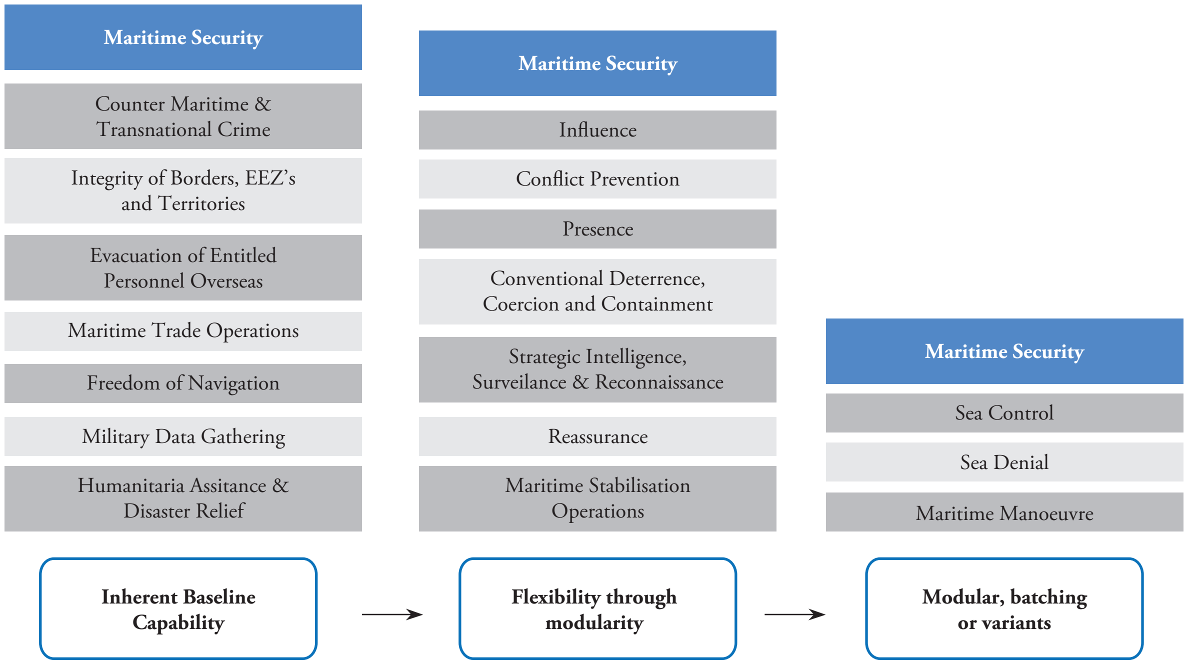
[1] In developing the Venator 110 concept, the term "Patrol Ship" has been used to refer to a ship with similar roles to an OPV but with a blue water or global reach; the term "Patrol Frigate" is used for a more capable version of the same platform, but still less capable than a tradition frigate.

Fig. 3. Patrol Ship Roles.



be traced to the original capability requirements; in this respect the model needs to reflect not only the performance of an individual weapon or sensor system but how each contributes to the roles the ship will perform. The model also needs to be rapid and straight forward to interpret, as complex models involving scenario modelling often take too long to produce results for the design to test the "what if?" questions throughout the design's concept development.

In the design development of BMT's Venator 110, a parallel research task was conducted to create and explore the use of a capability modelling tool. The objective of this tool, undergoing continuous development by BMT, is to provide a method which allows the rapid comparison of the capability delivered by design alternatives. The key aspect here is to undertake the comparison in terms of delivered capability rather than performance or systems selected. The tool used is based on a relational database, which provides a means to create a path that traces from the systems provided within the design to the overall capability delivered. Key to this is the recognition that this is a many to many relationship; capability is delivered by combinations of systems (even multi-layered in some cases) whilst a system may contribute to a range of capabilities.

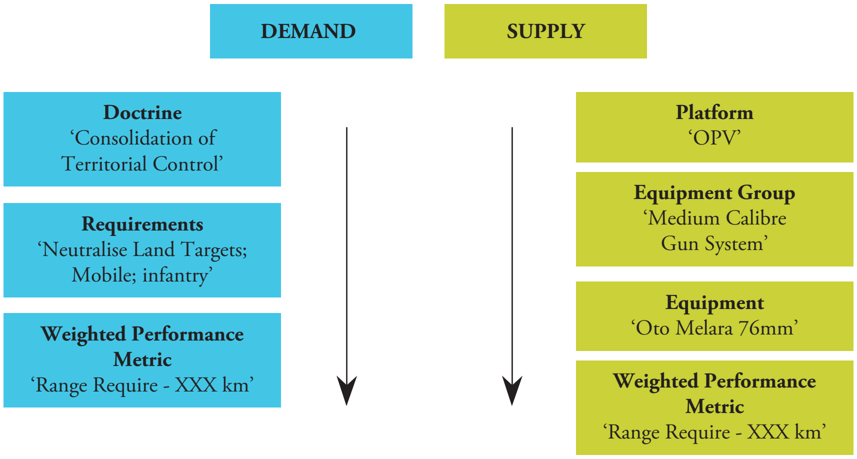
Hence, a capability assessment tool has been developed that allows the mapping of platform capability against a variety of comparators, including Doctrine and Key User Requirements. The objective is to provide a comprehensive and easily understood picture of how a platform's physical design combined with technical system selection is able to meet key national operational requirements, or otherwise. This methodology allows comparison of the overall capability against the chosen requirements to enable platform comparison. The comparison process can be used in a variety of ways to assess system choices, the implications of specific design changes, or the ability of a platform with chosen capability to meet national requirements.

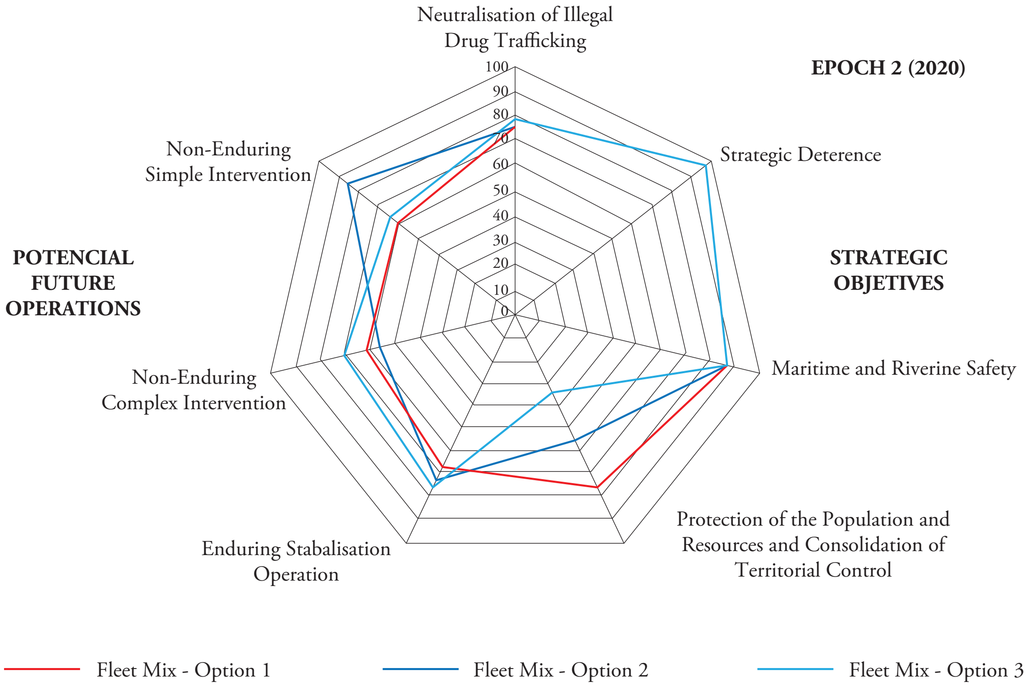
The capability assessment tool has been developed to enable a clear mapping to be carried out between the demand and supply functions for maritime platforms and the relationships between these are shown at Fig. 4. This tool can be used to assess and understand the capability decisions associated with maritime platform design. The assessment is tailored to suit the specific requirements of each platform type under consideration. This means that the platform comparisons are conducted on a like for like capability basis.

Fig. 4 shows the basic structure of the capability tool. The demand side starts with Doctrine, moving to subsidiary requirements. These requirements within the capability tool were previously developed from British Maritime Doctrine and have produced a detailed structure, consisting in excess of 1,800 comprehensive capability taxonomy statements that cover the maritime capability domain. These requirements are tempered and changed where necessary to reflect the requirements of the particular nation for which the analysis is performed. These requirements are weighted based on their importance in fulfilling the overarching Doctrine. Metrics are defined against the requirements, which represent measurable performance parameters to be achieved.

The supply side of the tool starts at the platform level, moving through a system or group of equipments to an individual item of equipment or platform characteristic. A number of different types

Fig. 4. Capability Tool Basic Structure.





of equipment or characteristics contribute to fulfil the requirement. For example under the Armada de la República de Colombia policy statement, Reference[4], 'Consolidation of Territorial Control' the requirement to 'neutralise land targets; Mobile; Infantry' is included. The requirement for 'search, detect and track surface targets', 'identify surface targets' and 'determine intent of surface targets' are also included (amongst others) to capture all of the contributory factors necessary to fulfil the policy.

The metrics assigned to the demand requirements can then be directly linked to the metrics supplied by the selected equipment. The example shown in Fig. 4 (76mm Medium Calibre Gun System) is but one performance metric between one item of equipment and one requirement. Outside of this example shown, the 76mm capability is measured by a number of metrics beyond a simple range analysis. Prior to the final capability diagrams being generated there are a significant number of such weighted performance metrics considered within the tool, to provide a comprehensive view of capability.

The output for each platform variant is plotted as a solid line on the Radar Plot to allow direct capability comparison on a like for like basis, and a representative version of this plot can be seen at the base of Fig. 4. Each axis should be considered separately; a discrete value when comparing platform types. For example, a platform score cannot be directly compared against a score on a different axis for the same platform, but can be compared with another score on the same axis for a different platform, facilitating a direct comparison between platform options.

Survivability

Many ship designers will recognise survivability as a cost driver and many studies have been conducted to identify "affordable" survivability. A fundamental part of providing cost effective survivability is to understand the threats and to ensure that the design presents a balanced solution, such that the correct measures are included to protect against the threats in the environment associated with the tasks that the ship is designed to conduct.

Survivability is a multi-layered capability that enshrines the operational doctrine, equipment and system specification, material design and the operational procedures adopted. Creating a design solution that successfully achieves the right level of survivability requires consideration of all these aspects in a balanced and coherent way. Having a clear understanding of the requirement for survivability is critical for developing both a robust and cost effective approach. There are two elements to defining the approach to survivability:

- The level of capability to be maintained, which defines the aspects of the ship which require protection;
- The threat level, which determines the level of protection to be provided.

As a simplification, an approach taken for a frigate could be to define the worst case threats likely to be encountered and to define the set of capabilities to be maintained (for example, propulsion and key combat systems). This defines the set of equipments and systems requiring protection, the remaining non-critical systems needing no protection. In the case of an OPV, survivability over and above safety considerations under normal operating conditions is paid little attention as these are not considered warships. Often the design is based on the application of (commercial) classification society rule sets to ensure crew and vessels safety in a non-threatening environment. Neither approach offers significant cost scaling, rather a binary decision to provide protection or not.

However, as OPV like vessels are increasingly seen as force multipliers to supplement warships in limited threat environments and indeed warships are more cost constrained and capability traded, there is a need to consider a more layered approach to ship vulnerability. In defining the threat and capability to be maintained, there may be a case for a scaled approach in which the capability maintained is graduated against increasing threats. This becomes a risk based consideration.

Prescribing proven (military) equipment and systems to achieve vulnerability protection across many systems reduces the risk of vessel loss but adds cost. As the decision is taken to relax the extent of system capabilities retained post damage, or adopting good practise guidance with more commercial approaches rather than specifying tested and proven military equipment, then risk is increased but cost reduced. Ultimately the correct balance point becomes where affordability is achieved with acceptable risk levels for loss of capability during the perceived range of missions.

As a minimum, the vessel needs to offer safety and protection to the crew for all scenarios. In principle, a starting assumption may be that an OPV-like warship may spend much of its time in a maritime security environment in which there is no or limited military threat. The threat may be characterised as man-portable, low technology weapons of short range (e.g. hand weapons, machine guns or rockets). In this situation, the platform is likely to be operating as an independent unit and therefore minimum loss of capability will be preferable. When the same platform is operating at a higher threat level, it will be in operations beyond maritime security and therefore may be assumed as a supporting unit to other more capable units. As a supporting unit, the level of capability to be maintained could be much reduced, perhaps to float / crew safety and potentially only a limited move capability.

This approach allows both 'capability to be maintained', and 'threat' to be considered and traded for each system to achieve a cost effective policy against the appropriate combinations, as demonstrated in Table 1. It should be noted this is not the same as the disposable warship concept, which suggests warships are produced cheaply such that more vessels balance the greater risk of loss in high threat environments (as envisaged for example by the "Streetfighter" concept, Reference [5]). Here, the argument is that warfighting is primarily delivered by the vessels designed for the purpose whilst a vessel such as the patrol frigate is a supporting asset and therefore the loss of its capability should not represent a significant risk to force level mission success.

Table 1. Proposed Levels of Survivability for Patrol Ship

	Low Threat Environment	**Higher Threat Environment**
Float	Retain full capability	Maintain Float for safety of crew (e.g. to allow ordered abandonment if necessary)
Move	Retain full capability or partial capability (e.g. 50% power and propulsion)	Either no move or limited propulsion to maintain steerage / safe navigation
Fight	Retain full capability or self-defence as minimum	No capability maintained

Another useful approach to explore is the adoption of classification society rules that offer appropriate levels of vulnerability protection. Although not intended to achieve warship survivability objectives, the use of classification society rules offer a degree of certainty (as they are articulated rules that will not change during design and construction). It would allow use of some commercial practises and equipment suppliers, and many shipyards are familiar with their application and approval against class rules. The wider application of classification society rules and the advantages are discussed in Reference [6].

Whilst adoption of class rules may not mitigate all potential risks, combining classification society rules with project specific guidance to tailor the class notations can result in acceptable performance whilst retaining many "commercial" practises, effectively as "owner's requirements" would for commercial vessels. This guidance may take the form of prohibiting specific materials in the design of systems or specification of equipments, such as those of a brittle nature (e.g. cast iron) or which are likely to result in dangerous fragments (e.g. glass).

The design of the structure may adopt commercial practises and structural profile sections[2]. Enhanced performance may be achieved under weapon damage through careful attention to

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[2] Such as Off-set Bulb Profiles (OBP) instead of traditional "T" sections.

structural details, avoiding those known to have poor resilience to the effect of weapon damage. Again this can be achieved through project specific structural policies and guidance (i.e. avoiding stress concentrations, sharp corners, the use of gussets to spread loads).

Many classification societies have redundant power and propulsion notations (such as the LR PMSR or DNV RPS notations). Adoption of a redundant power and propulsion notation for a patrol ship would ensure that the potential failure leading to loss of the move function (and hence loss of mission) could be reduced to a negligible level. As some of the notations also specify separation of power and propulsion into independent machinery rooms, some degree of protection is afforded to loss of a machinery room due to flood or fire as a result of either accidental or weapon damage.

An example of how this philosophy is applied is the arrangement of the power and propulsion solution. The following approaches could be applied to a ship to offer increasing levels of protection from attack:

- Single engine room and generator room but redundant equipment to class society notation, offering redundancy to equipment failure but no redundancy for compartment loss;
- Separate engine rooms with power and propulsion arranged in each to class society notation, offering redundancy if one compartment suffers flood or fire but with no redundancy if the adjoining bulkhead is breached, e.g. by fragments;
- Separated engine rooms with a protected bulkhead between as an owners enhancement to a class society notation, offering redundancy if one compartment suffers flood or fire and with limited capability to maintain redundancy against fragments and small arms;
- Separated engine rooms with at least one compartment separation as typically adopted for a frigate, offering redundancy against flood, fire and weapons damage to a level consistent with the separation achieved.

The separation of engines rooms offers survivability improvements as illustrated in Reference [7]. However, such arrangements have a significant impact on the design and become a size driver as the engine rooms are forced further towards the ends of the hull and the uptake arrangements require separate funnels. It is therefore important to understand if the improvement in survivability is actually justified by the capability need.

For the Venator 110, given the survivability intent described in Table 1, providing redundancy for power and propulsion as a result of fire or flood in one engine room would offer significant operational advantage, as it would provide for a graceful loss of capability in the event of an accident. Some degree of protection for the separating bulkhead would also mitigate fragment or small arms causing loss of adjacent engines rooms. However, the design impact of separating the engine rooms by another space would outweigh the advantage as it would only enhance vessel survivability against larger threats, which was not a stated design objective. In the smaller Venator 90 design, the separation of the engines is not practical and in this case the solution reverts to the next level, offering redundancy in equipment but not in the arrangement. However, an auxiliary drive may prove attractive in offering a limited level of redundancy.

Modularity as an Enabler

The incorporation of “modularity”, or perhaps more correctly “flexibility” into designs seeks to address a number of objectives as described below (Reference [8] also provides further discussion on modularity):

- Reduce acquisition and through life costs by allowing one ship class to address multiple roles;
- Reduce acquisition and through life costs by allowing one ship to perform the role of several legacy platforms;
- Reduce acquisition costs by simplifying the integration interface between ship and equipment;
- Reduce through life costs by allowing future capability / technology insertion;

However, these perceived advantages must be traded against the cost of incorporating modularity, which includes the cost of developing and purchasing modules; the increased platform size to accommodate modules; and the cost of storing and maintaining modules when not deployed on vessels.

In fact, modularity can be achieved at a variety of levels with differing impacts on platform design and cost, for example from Reference [9]:

- Construction modularity – use of modules to simplify construction interfaces and integration;
- Configuration modularity (e.g. MEKO®-class ships) – use of modularity to allow different configurations to be adopted within one design;
- Mission modularity (e.g. Stanflex series of vessels) – the use of modules to allow one ship to change its capability between missions;
- Battle (network) modularity – the use of modularity to allow one ship to reconfigure elements to adapt capability during a mission.

Table 2 attempts to show the relationship between these objectives and the approach taken to modularity. A further variation in the theme of modularity that is emerging in more recent designs is how modularity is incorporated into the design. Two approaches have been adopted:

- Flexible space able to accommodate a range of different "modules", equipment and other items (for example, as applied to the USN LCS, UK Type 26 and Danish Absalom Class);
- Specific module spaces allocated around the ship for installing different "types" of module (for example the Danish Stanflex).

The former approach is being increasingly adopted in modern designs as it would appear to offer the most flexible Mission Modularity solution. A large "garage" area, often capable of embarking multiple ISO TEU containers gives the ultimate flexibility; if the capability can be accommodated within then the ship may carry it. However, such "garages" have significant design impacts. Some of these are discussed at Reference [10] and they are generally associated with the large volume required (containers are not a space efficient approach to providing capability) and the subsequent impact on ship size and structural configuration. These impacts are significant enough to warrant the designer to consider if this is really the most cost effective means of delivering the required flexibility.

Table 2. Potential Cost Savings for different approached to Modularity.

	Construction modularity	**Configuration modularity**	**Mission modularity**	**Battle (network) modularity**
Reduce Individual Ship Acquisition Cost	Yes	Yes (reduces design and non-recurring costs across classes)	No, likely to increase individual ship cost as greater size required	No, likely to increase individual ship cost due to greater complexity
Reduce Number of Classes	No	Yes, one class may perform multiple legacy class roles	Yes, one class may perform multiple legacy class roles	Yes, one class may perform multiple legacy class roles
Reduce Number of Ships	No	No, as reconfiguration is still generally fixed for each ship	Yes, provided that the roles are not concurrent	Yes, provided the roles can be reconfigured at sea
Reduce Through Life Modification Costs	Likely to be limited	Yes, as equipments may still be switched	Yes, as equipments may still be switched	Limited as this level does not suggest significant equipment change

Table 3. Characteristics for Modular Capabilities.

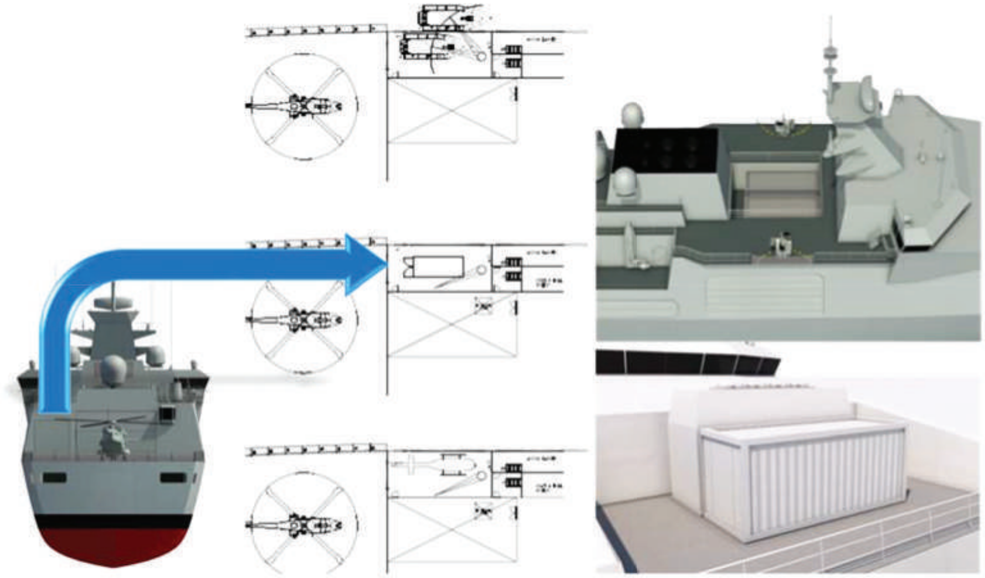
Modular Capability	Characteristic
Enhance warfighting capability – additional launchers,	Requires upper deck space and sufficient structural clearance for munitions
Enhanced command and control capabilities (potential for control of off-board vehicles, enhanced electronic warfare or increased planning facilities)	Enclosed space with suitable hotel support, ideally located for ease of access from other "command" spaces
Additional off-board vehicles	Enclosed space but external to hotel environment to offer protection to vehicles, with access to flight deck or overboard to deploy
Additional stores – for increased endurance or humanitarian operations	Ideally open deck for ease of embarkation with sufficient space to access or move stores to other areas

When conducting the development of the Venator 110 concept, the adopted approach was to consider how a number of "modules" could be provided which require different characteristics. Based on the defined roles (as illustrated in Fig. 3) it was concluded that the capabilities could be provided in a modular form, with corresponding characteristics as illustrated in Table 3.

This approach results in a vessel with a number of defined flexible areas, each capable of embarking one or two modules, as an alternative to a single large garage area. This requires a compromise in terms of overall flexibility (now limited by the size of each flexible space) but allows the spaces to be more integrated within the design. The final design solution adopted incorporates three flexible spaces, as illustrated in Fig. 5:

1. Forward, open to the topside and suitable for containers or weapon modules;
2. Midships, suitable for containers which could plug into the aft end of the forward superstructure which contains the command spaces;
3. Aft and adjacent to the hangar, to allow for an additional boat, unmanned vehicles or additional stores.

Fig. 5. Venator 110 Flexible Spaces (as described above: Mid-ships [2], top right; Forward [1], bottom right; Aft [3], left).



Conclusions

The design of small surface combatants have in recent years led to a range of different vessel configurations, varying not only in size but in capability and flexibility. This has led to more vessels being designed outside of the traditional frigate or OPV design envelopes. Matching the target vessel cost, achieved capability and ability to survive in the intended threat environment will lead to the increased use of capability and survivability modelling to ensure that the platform designs are capable of delivering against the navy's requirements. This modelling is becoming necessary as the vessel designs fall outside of the prescribed norms and standards for the traditional vessel types and confidence in the designs robustness requires greater testing at early design stages.

In addition to the cost and capability debate, the increased need for flexibility and the perceived use of modularity to achieve cost savings will lead to complex debates over the correct design solution. Modularity is used to express a range of solutions to different objectives and the designer will need to truly understand the objective to ensure the correct selection of a modular solution.

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Cost estimation and cost risk analysis in early design stages of naval projects

Estimación de costos y análisis de riesgos de costos en primeras etapas del diseño de proyectos navales

Michael Rudius [1]

Abstract

During the design and engineering process for naval projects a comprehensive cost management is required. The overall aim is to ensure the financial feasibility throughout the project with a low financial risk. Cost management combines acquisition costs and in-service costs in order to obtain life cycle costs. In this context methods for cost estimation have to be adapted to the phase of the planning process of a naval vessel. This paper introduces challenges and solutions for the cost estimation in general and describes MTG´s cost estimation approach for conceptual and preliminary designs. Additionally the utilization of cost risk analyses in order to ensure a reliable budget planning and the identification of cost risk drivers will be described.

Key words: Cost Estimation, Cost Risk Analysis, Design and Engineering, VORGES, Risk Minimization, Budget Planning, Program Acquisition Cost, Life Cycle Cost.

Resumen

Durante el proceso de diseño e ingeniería de proyectos navales se requiere un manejo integral de los costos. Esto tiene por objeto garantizar la viabilidad financiera a lo largo del proyecto con un bajo riesgo financiero. Esta gestión de costos combina los costos de adquisición y costos durante el servicio con el fin de obtener los costos del ciclo de vida. En este contexto, los métodos para la estimación de costos tienen que ser adaptados a la fase del proceso de planificación de un buque de guerra. Este documento presenta retos y soluciones para la estimación de costos en general y describe la forma en que MTG ha abordado la estimación de costos para los diseños conceptuales y preliminares. Además, la utilización del análisis de riesgo en costos a fin de asegurar una planificación presupuestaria fiable y se describirá la identificación de factores de riesgo en costos.

Palabras claves: Estimación de costos, análisis de riesgo de costos, diseño e ingeniería, VORGES, minimización del riesgo, planeación de presupuesto, programa costo de adquisición, costo del ciclo de vida.

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Introduction

An inherent requirement of every naval project is a timely and economical meeting of the customer's demand. This implies a nearly exhaustive planning process. Especially in early design phases – and in mid-term planning - risk minimization is emphasized. At the same time the technical and economic feasibility of the procurement plans is paramount.

Reliable cost estimates are necessary for the government to support funding decisions and budget planning. They are also useful for the project management to avoid budget overruns and its consequences (e.g. performance cutbacks, missed time schedules and increased funding), assessing competing solutions and evaluate tenders and select the most efficient solution. Especially in early design phases cost estimation is extraordinarily challenging because:

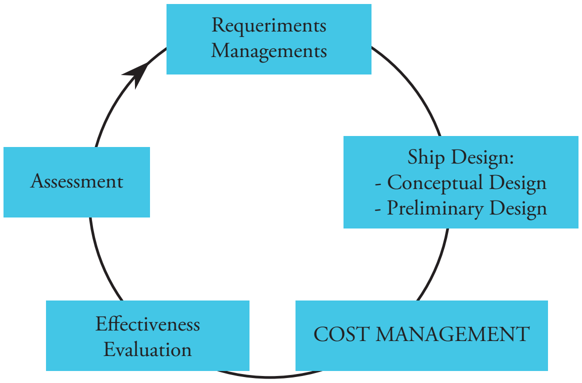
- detailed and meaningful data regarding the technical design is sparse at this point of time;
- an arguable basis for a comparison of the considered systems is mostly not given (due to technological leaps, e.g.);
- cost data for systems under development are not available, i. e. they are not specified finally;
- estimation of in-service costs is very ambitious for systems which are not introduced into the Navy yet, so historical data for maintenance and repair is not available.

Cost estimations are required to be as precise and reliable as possible which necessitates trustful relationships to suppliers and a lot of experience in the field of cost estimation and planning. Ideally cost estimations are supported by a comprehensive database filled with technical and cost data for naval technology.

Determining cost estimations, based on technical solutions developed in-house, are the main tasks of MTG Marinetechnik GmbH (MTG) in the course of this process. These activities create the foundation in order to provide information and data for phase documents needed during the planning process. This expertise is used by MTG to support the public contracting authority in planning phases and during operation of nearly every project of the German Navy since 1966.

MTG has organized its internal process and work steps in a process model called VORGES (Vorgehensmodell Gesamtentwurf Schiff, comprehensive model for total ship system engineering). This model allows the generation of feasible and affordable solutions based on the customer's requirements in comparatively short time. Fig. 1 shows the process steps whereas especially ship design and cost estimation are of particular significance. Ship design and cost estimation are interdependent. In the majority of planning processes ship design forms the basis for cost estimation (design-to-requirements). Occasionally a ship design has to comply with a given upper cost limit (design-to-budget). In these cases the portion of fulfilled requirements has also to be determined. Both designs are optimization processes characterized by repeating design loops aiming at an optimal and low-risk solution.

Fig. 1. VORGES cycle [1].



See [1] for any further details concerning the process model VORGES. The rest of this paper focusses on the third step cost management which comprises cost estimation and cost risk analysis. In general terms cost management is the process of collecting and analyzing historical and up-to-date data and applying quantitative models, tools and databases to forecast future costs of a project. Cost management helps to translate functional requirements into budget requirements and determine a realistic view of a probable cost outcome which forms the basis for executing the project itself.

During the early stages of the design process several conceptual and preliminary designs have to be generated in a short period of time. Those designs need to be comparable in order to support decision making processes. Requesting prices of potential equipment for the designs implies two problems:

1. Oftentimes internal compliance regulations will not allow suppliers to provide budgetary prices to potential customers without a tender process. Not finalized specifications at the time of the cost request will lead to budget prices that might be fare away from specifications at the time of the tender. This implies the danger that budget prices will be used during the contract negotiations. Also the technical and financial information given by a supplier might be used for the tender documentation and will therefore be given to potential other suppliers, which is undoubtedly not in their sole interest.
2. The process of gathering trustworthy cost data is time-consuming and administratively challenging.

MTG as an independent consultant on the other hand is not a potential customer and can therefore request prices to build up a technical and cost database that also can be used for other designs and the sole purpose of generating comparable designs in a relatively short period of time.

Cost Estimation

Basics

A cost estimate of prospective warships is the most probable total of individual cost elements based on a work breakdown structure (to identify all cost elements), technical parameters (to define the ship to be estimated) and several rates (e.g. labour rates, overheads).

In this context cost estimation is the systematic elaboration of costs based on available data in order to determine the most probable total system costs at the time of estimation. Systematic means a comprehensible, reproducible and widely objective method is used which can be applied to any naval shipbuilding project. Obviously estimations can only rely on data which is available at that moment. Therefore cost estimations always relate to a particular point of time. Regarding that usually a lot of assumptions have to be met – which can change in the course of the project – it is unavoidable to document not only results but especially assumptions and inputs carefully.

Acquisition Costs

Estimating acquisition costs is traditionally the main task of a specialized cost estimation team. This section gives a brief introduction to commonly applied cost estimation methods and the cost estimating process at MTG. Acquisition cost estimations are conducted from a shipyard's perspective.

a) Estimation Methods

Glancing at the literature one finds multiple estimation techniques which may be summarised as follows [9]:

- Expert opinions
- Analogies
- Parametrical approaches
- Engineering Build Up

Expert opinions may serve as a rough order of magnitude (ROM) if very little information is available and quick statements are required. An "expert" may be an experienced member of the cost estimating team itself or a vendor of a system willing to provide cost information. Asking the vendor directly is advantageous because numbers are typically available but oftentimes it is difficult to understand what is included in the communicated costs.

Using analogies means to perform cost estimation with comparable systems as a basis for the system in question. Analogous estimates always need subjective and elusive adjustments to meet the characteristics of the estimated system. Further downside of analogies is that they rely on a single data point and that it is sometimes hard to identify comparable systems at all. In many cases analogies are the only way to estimate generic systems or prototypes characterised by little definition.

Parametric cost estimation means estimating with mathematical equations which are found in standard software tools or are better based on proprietary models [10]. Parametric equations relate the dependant variable cost to one or more independent cost-driving variables (which may be amongst others: technical parameters, performance characteristics or costs of other elements). The resulting function is a so-called Cost Estimating Relationship (CER). One of the strengths of CERs is that they are an excellent tool for performing rapid sensitivity analysis ("what if"-questions). Oftentimes collecting sufficient appropriate data to generate CERs is difficult and time consuming. Parametric estimation plays an important role at MTG so the idea is picked up again in part (b) of this section.

Engineering build up is a "bottom-up"-approach as it combines single estimates of each cost driving element at a very detailed level into the overall estimate. Usually each cost element causes material and labour costs (e.g. manufacturing the hull, system integration and installation) which have to be estimated separately. If little data is available this approach is similar to expert opinions. Engineering build up is an intuitive and easily arguable approach but it is costly and the many times demanded "what if"-questions are hard to answer in short time.

b) Cost Estimating Process at MTG

The cost estimating process at MTG is organised in the following 7 steps:

1. Start-up of project
2. Define work breakdown structure (WBS)
3. Choose Estimation Model
4. Generate cost estimate
5. Review and validate estimate
6. Perform cost risk analysis
7. Document and present estimate

Step 1 serves as an initiation of the estimation process in order to understand the project's objectives and its requirements. Technical, programmatic and cost data are collected. Prevalently it is required to adjust the data to account for inflation, learning and quantity. Furthermore the acquisition strategy (competition, consortium) has to be gathered. Typical sources of data are: cost proposals of vendors, historical databases, governmental agencies (the customer), experts and open source (Internet, Jane's). Additionally necessary assumptions are identified in this step. Amongst other things assumptions are made for inflation rates, hourly wage rates and overheads

The start-up is followed by the definition of the WBS elements in step 2. A WBS is a decomposition of the ship in smaller components or rather functional technical groups like hull structure, propulsion plant, electric plant and so on. A commonly used WBS is the Expanded Ship Work Breakdown Structure (ESWBS) which is promulgated by NAVSEA [11]. The level of decomposition depends on the current stage of the project and the required detail of the results. Obviously the more is known about the project, the more can be detailed in WBS.

The selection of the estimation model in step 3 also depends on the current phase of the project. In order to estimate acquisition cost, a ship design is divided into platform and payloads. To put it simple, platform comprises systems and components needed by the ship to participate in maritime transport. On the other hand payloads are necessary to fulfil the military tasks (e. g. weapons, sensors as well as RAS-equipment and cranes). The methods for estimating costs of platform and payloads differ considerably. Platform costs are estimated by means of a parametric approach, i.e. costs for a specific component (e.g. main engine) are estimated indirectly via a parameter (e.g. power of main engine). The resulting curves called cost estimating relationships (CER) are described below. This method is not applicable for payload estimation because the costs of a payload are typically not dominated by one parameter. Therefore cost estimation of payloads requires intensive cooperation with the suppliers of systems. Expert opinions and analogies are required if contact to the supplier does not lead to plausible results in short time.

Nonrecurring costs are being estimated by means of empirical formulas which are derived from realized projects and include amongst others:

- Software costs
- Logistic support (initial spares, tools and training equipment)
- Documentation
- Detailed design
- Management
- Initial training.

It is without a doubt that there are lot of valuable software tools for cost management available on the market. The tools are used frequently on industry and government side. Therefore MTG has repeatedly tested different applications. According to MTG's experience the following statements can be made:

- Tools including a cost database can produce results in a very short time. Probably these results are trustworthy for the majority of the users.
- These tools are expensive and therefore cannot be applied economically in small- or medium-sized companies.
- The delivered databases contain projects from different nations and even different industries. Usually naval projects are rare. It is at least debatable whether projects from other nations/industries can be transferred without difficulty.
- These tools oftentimes require input data which is not available at very early project stages.
- Tools without a database necessitate to build up an own database in order to calibrate the calculations.
- MTG has not found a tool which could be used without customization regarding MTG's design process.

Based on these findings combined with the longstanding experience using cost estimation tools MTG has decided about 10 years ago to develop in-house tools which are highly flexible and may be adapted precisely to the VORGES process. The VORGES database is a main tool in the methodology and contains technical, cost and risk data which is necessary in order to conduct cost estimations. Therefore MTG's cost tools have a bidirectional connection to the VORGES database in order to load input data and save results. The database is subject to continuous development which requires immediate modifications of the tools which are not possible with commercial software.

MTG uses two models, one for the very early rough, conceptual design phase (SCEM) and one for the preliminary design phase (GELIMAKO). Both of them are proprietary models which are represented in in-house software tools as no COTS software is available for this kind of estimation task. Both tools apply a combination of the above mentioned methods. The main method of SCEM is parametric estimation with CERs. The data points which were collected in the course of time are connected via polynomial or cubic spline interpolation. Parametric estimation is used for platform cost elements like hull, propulsion and electric plant. Accordingly independent variables like volume of hull, power of main engines, number and kind of propellers, power of electric plant are used. It's not easy to generate CERs for payloads so expert opinions and analogies are used. Engineering costs for construction, management, proofs and so on are estimated via empirically found formulas. Typical parameters in these formulas are number of yards, number of ships, installation costs of payloads etc. SCEM is usually used for ROM-estimates and "what if"-questions.
On the other hand GELIMAKO is a method which uses engineering build up. This implies much more detailed knowledge about the project and the ship. Therefore GELIMAKO also incorporates different currencies, individual inflation per cost element and price adjustment clauses. Bottom-up is simpler regarding the calculation itself but it requires a much higher effort in researching suitable data.

Costs are estimated on per component basis whereas a typical frigate-sized project is made up of several thousand cost elements.

If all necessary data are collected and entered into the software running the model generates the cost estimate at the push of a button. This always goes along with a review and validation of the estimate in step 5. Reviewing means to cross check the overall estimate with historical projects to see if the results are plausible. Implausible results lead to a revision of all input data and one or more re-runs of estimation.

The final result of the acquisition costs estimation comprises of the following elements:

- Acquisition costs of platform and payloads
- Nonrecurring costs
- Contingencies
- Taxes

In-Service Costs

Next to the acquisition cost estimation the in-service costs are the main cost driver during the lifecycle of a naval vessel and are therefore required to elaborate life-cycle-costs. MTG´s studies in collaboration with the German government have shown that personnel costs (crew), maintenance costs and costs for petrol, oil and lubricants dominate the in-service costs of a naval ship.

The annual consumption of petrol, oil and lubricants is estimated based on ship's operating profile, characteristics of main engines and electrical plants as well as environmental conditions. This is mainly a technical task. Combining the results with actual and forecasted prices for petrol and oil allows deriving the annual costs or the ship's in-service time. Forecasting of price changes is unavoidable in cost estimation. This applies to all categories of in-service costs therefore MTG's approach at the end of this section.

Personnel costs are another major factor. MTG considers costs for crew members. Consideration of personnel costs is becoming increasingly important as salaries typically rise more than defense budget. As the systems aboard the ship become more and more sophisticated highly qualified personnel is needed. Therefore each government has to make efforts to ensure that enough qualified personnel is available in order to operate the ship. One prerequisite for this is an adequate payment. Therefore estimation of personnel costs is a valuable resource for a comprehensive planning of future crews.

The number of crew members and its structure is required to estimate personnel costs. Additionally plausible assumptions concerning distribution of military ranks, age and sex are needed. These data is usually based on each Navy's experience or statistical authorities. MTG's calculations then consider basic salaries, accruals for the future (if relevant), additional personnel costs and benefits. These data are available to the public in Germany. If the numbers and the structure of the crew are given (or assumed) a reliable cost estimation is possible. Finally, personnel costs can be rather seen as a bottom-up calculation than estimation.

The technical concept of the ship class as well as administrative rules and operating profiles create the foundation for cost estimation of preventive and corrective maintenance costs. Historical data of the naval ships already in service is combined with expert knowledge in order to perform rough cost estimations. MTG as an independent service supplier has remarkable advantages in data acquisition over competitors. On the one hand data of the navy arsenals which is not available to the market can be incorporated in the estimations. On the other hand suppliers are cooperative as they may find their systems integrated in MTG's designs. Estimation of maintenance costs is the most challenging task in in-service cost estimations. This is mainly due to the following facts:

- Only large suppliers (e.g. for engines, weapons) focus on in-service costs. Even if this data is available the rest of the ship may be neglected in no case. This requires assumptions to be made.
- Historical data of ships already in service is often difficult to transfer to current systems due to technological changes.

MTG estimates these costs on per component basis using a statistical approach. The cost estimation database contains up-to-date numbers for equipment and military payloads which have been maintained in German yards. These data will be used to forecast preventive and corrective maintenance costs for the future ships. It shall be noted that the following approach allows forecasting the costs for any component, i.e. the component investigated has not to be installed aboard a German Navy ship.

1. Compilation of all available costs for planned and corrective maintenance ($c_{maint}=c_{maint,p}+c_{maint,c}$) on a per component basis
2. Compilation of acquisition costs (c_{aqc}) and weights (*wgt*) for these components.
3. Statistical test of the assumption: $c_{maint}=f(c_{aqc})$
4. Statistical test of the assumption: $c_{maint}=f(wgt)$
5. Statistical test of the assumption: $c_{maint}=f(c_{aqc},wgt)$
6. Calculation of the coefficient of determination R^2 for each assumption.

Linear regression methods are used to estimate a straight line for assumptions 3 and 4 leading to an equation of the type:

$$y = \propto + \beta x \tag{1}$$

where:
y = forecast of maintenance costs per year
x = acquisition costs (step 4) ; weight (step 5)
$\propto$, β = coefficients estimated by regression.

Multiple linear regression methods will be applied in order to investigate step 5:

$$y = \propto + \beta x_1 + \gamma x_2 \tag{2}$$

where:
y = forecast of maintenance costs per year
x_1 = acquisition costs
x_2 = weight
$\propto$, β , γ = coefficients estimated by regression.

The assumption yielding in the highest R^2 will be used to forecast the maintenance costs of the component under investigation. It is recommended to use this approach only if $R^2 >.65$. This allows forecasting the maintenance costs for any component with known or estimated acquisition costs and/or weights. If $R^2 <.65$ for all three assumptions maintenance costs are estimated as a percentage of acquisition costs based on experience. This is on the one hand not the best way but one the other hand a simple and fast method to achieve numbers at all. Additionally the assumption

$$c_{maint} = f\,(c_{aqc}) \tag{3}$$

mostly leads to the highest R^2 according to MTG's experience.

Usually in-service costs are estimated for comparing different designs in all ship program acquisition phases and even during the operational phase of a naval vessel. This requires an approved instrument which also considers acquisition costs in order to achieve an overall picture of the life-cycle costs. The next section describes MTG's approach.

Economic Feasibility Studies

Combining the results of acquisition and in-service costs is recommended when comparative analyses are conducted. In many countries financial regulations obligate the Ministry of Defense to comply with the cost-effectiveness principle. This principle implies cost-minimization i.e. procuring only those goods which are absolutely necessary for closing operational capability gaps. Economic feasibility studies are aimed at finding the most economical solution for a planned procurement.

Oftentimes administrative rules prescribe that economic feasibility studies have to be conducted executed in any governmental procurement having direct budgetary impact. Besides that these studies have to be carried out in advance, during and after a procurement project to allow for an efficiency review.

In Germany any major investment project requires the net present value (NPV) method to be applied. NPV is commonly used for budgeting to analyse the profitability of an investment or project. Despite the fact that a naval project is not a classical investment in order to earn financial profits (naval projects do not generate financial revenues) and in absence of better methods NPV can be applied in this context. Compared to the simple and static methods which sum up the annual payments this is a capital budgeting method which considers the moments of cash flows in order to calculate the time value of money. The NPV is the sum of all present values of cash outflows discounted to a fixed point of time.

$$c_0 = -a + \sum_{t=1}^{T} \frac{e_t - a_t}{(1+i)^t} + L(1+i)^{-t} \qquad (4)$$

where:
C_0 : net present value
$-a$: initial investment
e_t : cash inflow in period t
a_t : cash outflow in period t
i : discount rate
L : decommissioning / sale

This allows an objective comparison of life-cycle costs of alternative designs to the greatest possible extent in very early design stages.

Fig. 2. Comparison of alternative designs using NPV.

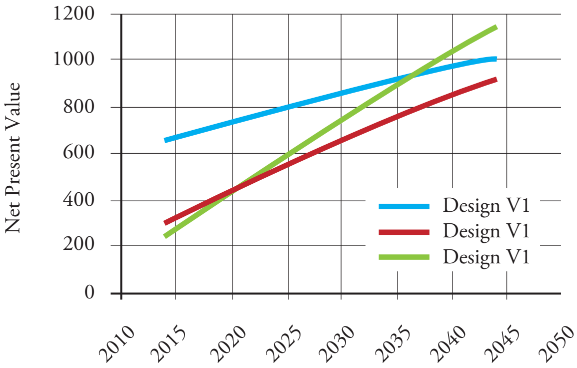
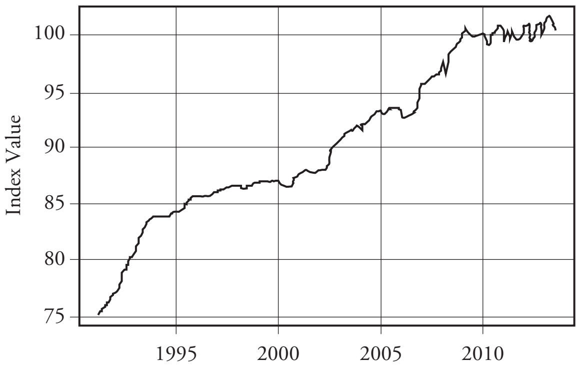


Fig. 2 shows a comparison of military ships which solely induce cash outflows (but no inflows). Compared to the typical presentation of net present values the sign has been changed in order to achieve positive values. This means lower net present values are more economic. In this case it is interesting to compare designs V1 and V3. V1 has significant higher acquisition costs than V3 but is less expensive during the operational phase which leads to a lower NPV beginning in the year 2037.

Price Escalation

Another important aspect - especially when estimating in-service costs - is to respect price escalation. This is mainly due to the quite long in-service times of naval ships (probably more than 30 years) and the obvious change of prices in such a long period. Besides applying a simple percentage change per year MTG generally uses a sophisticated approach which is based on time series analysis. Time series analysis may be used in many different fields of applications which led to a great amount of literature. Analysis of time series is a complex field of applied economic research and a full coverage of this topic is beyond the scope of this paper. Therefore MTG's approach is explained here in short terms only (see [2] for a detailed description and further references).

Fig. 3. Exemplary price index.



In broad terms a time series is a set of observations y_i of an indicator Y at uniform time intervals. MTG uses price indices as basis for the cost forecasts.

Fig. 3 shows a typical time series which represents any exemplary material price index (Y = exemplary consumer price index, y_i = index value observed in i):

This approach requires the user to find suitable price indices to be forecast by means of escalator clauses. It therefore is assumed that a nation has some kind of statistical office or census bureau in order to search for suitable price indices.

Given this, forecasting of prices is based on the following main steps:

1. Identify suitable price indices for cost categories to be forecast (e.g. oil price index for changes in petrol and oil prices).
2. Analyse and forecast price indices.
3. Build escalator clauses for each field to be forecast (usually personnel costs, maintenance costs and petrol/oil costs).

In order to analyse and forecast prices the following classes of methods are commonly used ([8]):

1. Simple: average, naive, random walk
2. Sophisticated: decomposition, exponential smoothing, ARIMA processes.

The choice of the method is heavily dependent on the price index to be analysed. Error measures help to identify the most suitable method for each use case.

The above mentioned escalator clause (step 3) can be written in general terms as follows:

$$P_{t+n} = P_t \left[\propto + \left(\sum_{i=1}^{m} \beta_i \frac{M_{i_{t+n}}}{M_{i_t}} \right) + \left(\sum_{j=1}^{l} \gamma_j \frac{L_{j_{t+n}}}{L_{j_t}} \right) \right] \tag{5}$$

where:
P_t : price at *t*
P_{t+n} : price at *t+n*
$\propto$: percentage of price not to be escalated
Mi_t : price index of *i*-th material *M* at *t*
Mi_{t+n} : price index of *i*-th material *M* at *t+n*
β_i : weight factor of *i*-th material
Lj_t : price index of *j*-th labour input *L* at *t*
Lj_{t+n} : price index of *j*-th labour input *L* at *t+n*
γ_j : weight factor of *j*-th labour input

and:

$$\sum \beta_i + \sum \gamma_j = 1 \tag{6}$$

The degree of detail, i.e. the number of material and labour indices is up to the user requirements and finally depending on available time and data. It is recommended to search for labour and material indices reflecting the underlying work breakdown structure of the project. This probably allows distinguishing between mechanics, electronics, software, energy and different labour types.

MTG has developed escalator clauses for the main in-service cost categories (see section (3)) which are typically applied in life-cycle cost estimations of conceptual and preliminary designs.

Applicability of MTG's Cost Estimation Approaches in other nations

In order to transfer the methods of acquisition cost estimation to other countries it is definitely worth to think about productivity as the average labour rates differ significantly between countries.

Productivity may be used to measure performance of yards and it is simply defined as the amount of output achieved for a given amount of input. In this context input is primarily material and manpower (labour).

In order to incorporate productivity at least two approaches are conceivable:

1. Use economic indicators like gross domestic product (GDP) per employee or GDP per hour worked
2. Use yard indicators which are specific to the considered yards. This may be a steel labor rate (hours needed to work with 1 ton of steel) or hours needed to produce 1 ton of ship, e.g.

Economic indicators are available to the public for almost every country but obviously this leads to a macroeconomic level of analysis. Individual yard indicators would probably lead to more meaningful results are often difficult to determine.

The above mentioned approaches to estimate petrol and personnel costs can be transferred without difficulty. Of course data concerning operational profiles and crew structures/salaries have to be adjusted to the respective country/navy. Transferring methods to estimate maintenance costs requires an intensive discussion due to strong dependence on national procedures.

Price escalation methods can also applied in other nations. Of course, German price indices must be replaced by local ones. If, for whatever reason, this is impossible macroeconomic values like consumer price index (CPI) or producer price index (PPI) may be analyzed and forecasted for reasons of simplicity.

Cost Risk Analysis

Basics

Cost estimation especially in early project phases requires a multitude of assumptions which in addition are often prone to changes in the project's progress. Given this, it becomes apparent that cost estimations inevitably contain various uncertainties, e.g. in way of cost estimation methods itself, in time schedules, economic terms and conditions, as well as changes to requirements just to name a few. This means: The singular outcome of a conventional estimation just produces one of the possible cost results. This implies the need for a model which allows to quantify these uncertainties and hence to assess the inherent cost risks of the project. A cost risk analysis (CRA) is a powerful instrument which provides the project management with the possibility to achieve a better transparency in cost estimation and with it the probability to adhere to the limits of a given budget.

A CRA enables the user of the model to quantify uncertainties and hence to identify the cost risks of a project. The magnitude of uncertainty around an estimate is valuable information for the decision maker. Much more detailed information on a variety of topics – that cannot be assessed with a conventional estimation – can be obtained by means of a CRA, including but not limited to the following:

- Cost margins and confidence intervals;
- Probability of exceeding the budget by a certain amount;
- Identification of cost elements that chiefly contribute to the project uncertainties ("risk drivers", e.g. technology with a low technology readiness level (TRL)).

These results allow the project manager to plan budgets and to derive measures for risk reduction on a quantitative and objective basis.

The remainder of this chapter is organised as follows. Section (2) defines essential terms for the further understanding of the paper. Additionally typical sources of uncertainty are mentioned. In Section (3) exemplary probability distributions are introduced as an idea in order to model uncertainty. Furthermore the impact of correlation on a cost estimate's risk result is examined. Two commonly applied risk simulation methods, Monte Carlo and Latin Hypercube Sampling, are described briefly in section (4). Running the simulation leads to several results which are shown and interpreted in section (5). Section (6) illustrates a concept to "buy" additional certainty for the project. The chapter closes with the most important conclusions in section (7).

Risk and Uncertainty

c) Definitions

It is important to distinguish between the terms risk and uncertainty. Glancing at the literature a lot of different definitions of the term risk can be found dependent on the contemplated field of activity. In the context of CRA the following definitions are commonly accepted [3]:

- Risk: A chance of loss or injury. Risk is the probability a given budget will be exceeded.
- Uncertainty: Is the indefiniteness about the outcome of a situation. The uncertainty of a cost estimate is modelled as a basis for estimating the risk associated with a specific budget.

Given this, a CRA is a process of quantifying the uncertainties associated with the cost model [3]. As a conclusion one might find that CRA should better be called cost uncertainty analysis as uncertainties are analysed and not risks. In fact this is also a term in use.

d) Sources of Uncertainty

Firstly, the sources of uncertainty depend on the cost model. Generally speaking almost every input variable in the model might be considered as uncertain. However, the more uncertain inputs, the more effort is required for performing CRA.

The following bullets categorise typical sources of uncertainty in 4 groups (the list is not exhaustive) [4]:

- Economic: inflation rates, wages, overheads;
- Technical: New/not introduced technologies, obsolescence;
- Programmatic: Changes in requirements, changes in quantity, uncertainty about budget;
- Estimating: Estimating methods itself, learning curve assumptions.

Usually acts of God, strikes and bankruptcy are neglected as it is nearly impossible to model the associated uncertainties.

Modelling Uncertainty

a) Overview

It was quite easy to identify sources of uncertainty in the last section but it is definitely more complicated to model uncertainty quantitatively as an input to CRA. First of all there are at least two general ways of simulating uncertainty: Inputs-based and outputs-based. Using outputs-based simulation the analyst applies uncertainty directly to the results of the cost model (the estimated costs). This paper will focus on inputs-based simulation which means that uncertainty is modelled by means of statistical distributions that have to be assigned to each uncertain input. Regarding this, one of the main tasks of the analyst is to find suitable distributions and to specify its shape. In the sense of a recap the main characteristics and terms of probability distributions which are necessary for CRA are given in the next sub-section.

b) Probability Distributions

A probability distribution function (PDF) describes the likelihood of all possible outcomes in a given situation. These outcomes, with values that change from trial to trial are called random variables. $P(X=x)$ is used to indicate the probability that a random variable X takes a certain value x. It is necessary to differentiate between discrete and continuous random variables. A discrete random variable can only take a finite number of possible values x [5]. Running through the set of possible values X the probability always adds to one:

$$\sum_x P(X=x) = 1 \tag{7}$$

Values which are not included in set of possible values of X always have probability zero.

On the contrary a variable is said to be continuous if it can take an infinite number of values in a given interval. In this case it is not allowed to just sum up the singular probabilities; instead an integral over the function $f(x)$ (which models the behaviour of X) is needed:

$$\int_{-\infty}^{\infty} f(x)\,dx = 1 \tag{8}$$

A further characteristic (which is used later in this paper) of continuous functions is that the probability that X falls into specified interval $[\alpha, \beta]$ is given by:

$$P(\alpha \le x \le \beta) = \int_{\alpha}^{\beta} f(x)\,dx \tag{9}$$

In the context of CRA discrete functions might be used, for example, to model uncertainties of input variables like number of ships or number of involved yards. In contrast to this continuous functions can be applied to model uncertainties of variables like weight or power.

Another important concept which is helpful in this regard is the so-called cumulative distribution function (CDF). A CDF states the probability that X takes a value less or equal to u. That is, if $f(x)$ is the PDF of X then

$$F(u) = \int_{-\infty}^{u} f(x)\,dx \tag{10}$$

can be found as the CDF. To put it simply, a CDF is the integral over a PDF up to a certain value

u. Often it is not easy to integrate the PDFs but luckily the CDFs can be found in the relevant literature for commonly applied distributions.

c) Finding Suitable Shapes

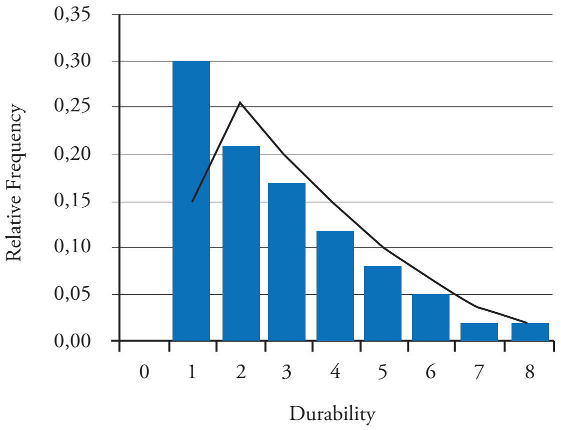
As stated above, finding adequate distribution shapes to model the uncertainty under investigation is a comprehensive task. In general there are three different approaches to select a distribution:

- Use historical data to fit the distribution;
- Distribution is suggested by underlying physics;
- Choose simple distribution with arguable limits.

Most of the times the first approach is not applicable as enough historical data is not available in naval shipbuilding. The second option might be used if sufficient data points are not on hand but the analyst has a reasonable feeling to shape a distribution. The third one is a kind of last resort as a consequence of a significant lack of data [4].

For example a triangle distribution can be considered as simple in that sense. A triangle distribution is defined by only three values: Lower bound, most likely and higher bound. Actually triangle distributions are favoured by analysts because the point estimate can be entered as most likely value. In addition to that the analyst often has a feeling for lower and upper bound values based on his experience.

Fig. 4. Application of Log-Normal distribution.



Just to give another example, one can imagine the durability of some kind of assembly as an input in the underlying cost model. Possibly historical data of that assembly is available which is shown in Fig. 4. Looking at the graph it becomes obvious that a log-normal distribution probably fits the data points.

Of course, there are lots of further distributions defined in the literature. It is recommended to constrain the selection of distributions to the following ones in the context of CRA [3]:

- Normal (quite easy to use but symmetrical shape is sometimes unrealistic)
- Log-Normal (always > 0, positively skewed)
- Triangle (easy to use, understand and communicate)
- Uniform (use if very little is known, every value has the same likelihood)
- Weibull (popular because of remarkable diversity of possible shapes)

d) Example: CER Uncertainty

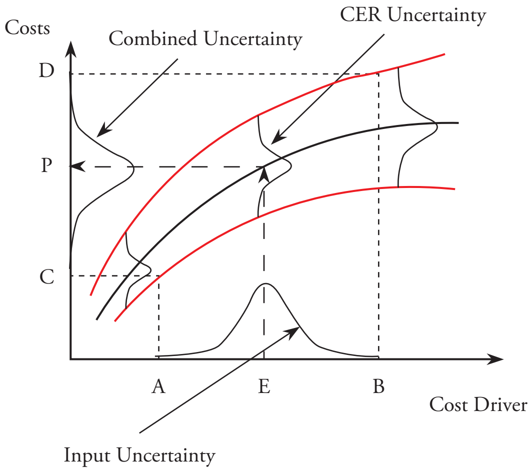
A very popular tool for conducting cost estimations are Cost Estimation Relationships (CER) which are mostly based on parametric equations. CERs relate the dependant variable cost to one or more independent cost-driving variables (which may be amongst others: technical parameters, performance characteristics or costs of other elements). The data points which were collected in the course of time may be connected for example by regression analysis, polynomials or cubic spline interpolation to obtain a mathematical function.

To give another illustrative example, consider the power of a diesel engine as its main cost driver for the sake of simplicity. Furthermore a positive correlation of cost with power is assumed. This might lead to a CER depicted by the middle line in Fig. 5.

Disregarding the uncertainty would result in the estimated costs P for the engine based on the input E (power). In reality this CER holds twofold uncertainty:

- The necessary power might change so it is not certain, especially in very early design stages;

Fig. 5. CER Uncertainty.



- The position of the CER itself may vary in an area which is indicated by the dotted lines which act as lower and upper bound.

Both uncertainties have to be represented by a suitable distribution. The example in Fig. 5 uses normal distributions for both uncertainties.

If input uncertainty is considered the input power may vary in the interval [A, B]. The probabilities of each possible value within A and B are described by the corresponding normal distribution. Finally, adding the uncertainty in the position of the CER results in the combined uncertainty which is illustrated by the possible values in the interval [C, D] for the engine costs.

e) Correlation

Usually a lot of CERs are utilised to estimate the singular components of a ship. If two (or more) CERs rely on the same parameter (imagine the power of diesel engine is also used to estimate costs for exhaust pipes) they are correlated. A change in the power value leads to a change in both cost estimates. This is called implicit or functional correlation as it is introduced through the cost model itself. In this case no further correlation needs to (but can) be considered [3].

On the other hand there are often situations in which cost elements are "tied together" by other means (explicit correlation). For example, this would be the case if two (or more) components are made from the same material and the material price is uncertain. In the majority of these cases the relationship is not perfect but varies from time to time [6]. Explicit correlation also arises if uncertainty is applied to outputs. Obviously no functional correlation is present in that case.

Correlation has an impact on the spread of the resulting distribution: the higher the correlation, the wider the spread

Without accounting for correlation, adding multiple distributions will result in too low variances of the final PDF which makes it artificially too narrow. This fact can easily be demonstrated mathematically. Let σ_i and σ_j be the standard deviations of the i-th and the j-th cost element, respectively. Additionally, the total cost variance σ^2 expresses the spread. Using ρ_{ij} as correlation coefficient for elements i and j gives:

$$\sigma^2 = \sum_{i=1} \sigma_j^2 + 2\sum_{j=2}\sum_{i=1}^{j-1} \rho_{ij}\,\sigma_i\sigma_j \tag{11}$$

Omitting correlation, i.e. letting $\rho_{ij} = 0$ implies the last addend to become zero and therefore a smaller total variance.

Knowing all this, the analyst now faces the problem to apply correlation by a certain amount, i.e. it is required to find reasonable values for ρ_{ij}. "Measuring" this kind of correlation is an important task and, especially if several hundred cost elements are used (which is quite common), another real challenge in CRA. In the absence of better data it is even recommended to enter a "default" correlation coefficient for each combination of cost elements. This issue is complex and beyond the scope of this paper. Please see [3] and [6] for further details.

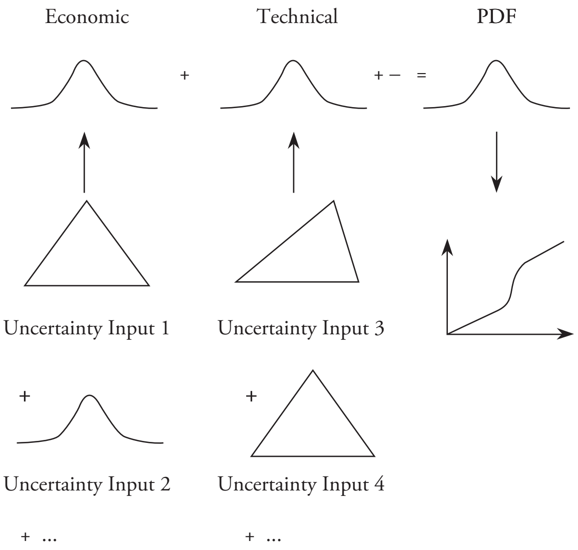
Monte Carlo Simulation Method

Assuming that suitable distributions are found for all uncertain input variables the analyst's next task is to start simulation in order to estimate the distribution of the total results.

Monte Carlo is a stochastic simulation method relying on a large number of random experiments. This methodology is used to estimate the probability of certain outcomes by running multiple trials using random variables. Determining π by dropping needles on a floor is probably the most-cited application of this method in the last 70 years. This shows that Monte Carlo is a manifold approach which can be applied in various fields of interest.

Coming back to CRA the general workflow of Monte Carlo is illustrated in Fig. 6 (based on [4]):

Fig. 6. Application of Log-Normal distribution.



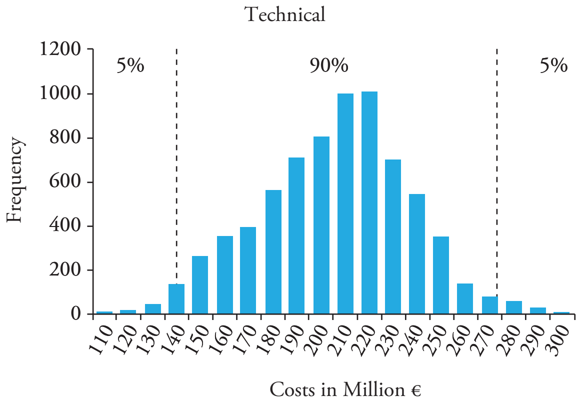
In this example four uncertain input variables (economical, technical) are shown in which the uncertainty is modelled by triangle and normal distributions (the '…' shall illustrate that there are usually a lot more uncertain variables). For each trial run a point is selected randomly based on the corresponding distribution. Doing this for all input variables leads to a first point estimate. After repeating this for thousands of trial runs finally a PDF is shaped. As a consequence of the central limit theorem the mean of a large number of random variables is normally distributed which is also shown in Fig. 3. Finally a CDF can be derived (its interpretation is given in section 5).

Results

a) Total Cost Histogram

Fig. 7 displays an exemplary histogram which is the first result of CRA. This distribution was shaped based on about 7,000 iterations. The diagram shows the ship's estimated costs on the abscissa and the respective frequency categorised in 20 intervals (bins).

Fig. 7. Final Cost Distribution.



As already illustrated in Fig. 3 it can be seen clearly that the results approximate a normal distribution.

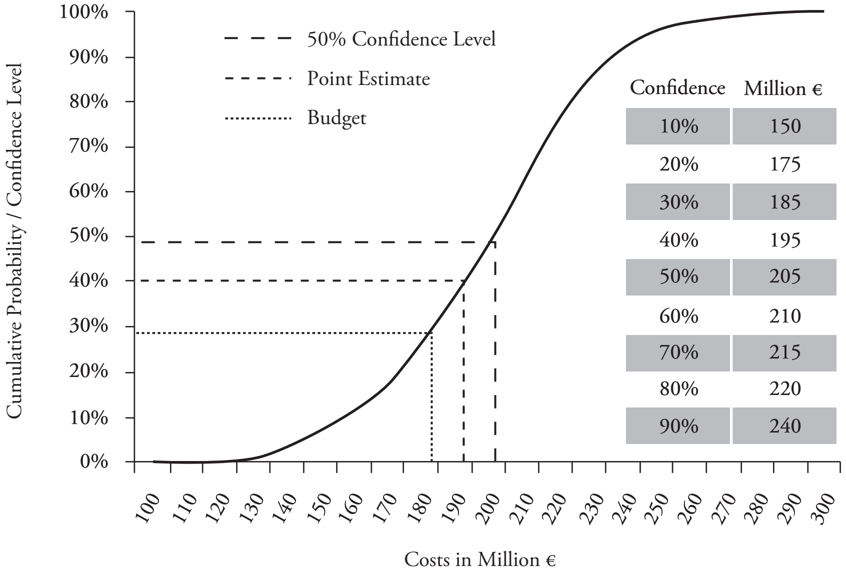
A couple of results may be derived from that distribution. First of all it can be stated that the total cost range which is indicated by leftmost and rightmost result. Furthermore the analyst can identify the 90%-range, i.e. there is a 90% probability that the costs fall within that range. Of course, other statistical values like mean or median can be computed easily.

b) S-Curve

What every analyst wants to know is the probability of overrunning the point estimate or a specified budget. Such interpretations can be made best using the CDF or S-Curve which is – as stated in section 3.2 – the integrated PDF. An exemplary S-Curve is shown in Fig. 8.

Besides the S-Curve itself there are three markers in the figure. All of them can be interpreted in the same way. Using the project's budget as an example the graph shows that there is a 30% probability

Fig. 8. S-Curve.



Confidence	Million €
10%	150
20%	175
30%	185
40%	195
50%	205
60%	210
70%	215
80%	220
90%	240

of being on budget, so there is a 70% chance of overrunning it. Additionally, the table presents the percentiles and its respective cost values which also may be interpreted in this way.

c) Risk Drivers

Cost risk drivers are those distributions that produce the highest variability in the risk adjusted cost estimate. Usually the coefficient of variation (CV) is used to identify the risk drivers. CV is a ratio or percentage that divides the standard deviation of a distribution by its mean. This value is accepted as a metric which characterises the spread of the CDF. A higher CV denotes a wider spread of the S-Curve and therefore a higher risk in the component under investigation.

It is important to understand that this is idea can only serve as an indication for risk rather than as an exact computation. Bearing this in mind, it is recommended that the analyst focusses on the top five or ten risk drivers and considers their risk equally.

Above described results supports the project managers decision making process in the following perspective:

- objective and transparent budget planning
- definition and initiation measures to reduce financial risks
- higher confidence in the cost estimation results (usually conventional cost estimates underestimates real project costs).

Modelling Uncertainty

At this stage the analyst knows how to model uncertainty and how to assess the results of CRA. At least the project management is interested in ways to "buy" additional certainty for project. In general there are two ways of gaining certainty. The first one focusses on the reduction of risk to increase confidence (e.g. using proving technologies instead of new ones or investing in risk reduction efforts). The second possibility is to make use of additional funding in order to reduce uncertainty. Regarding the S-Curve (Fig. 5) the main steps to determine an amount of funds needed to raise confidence are [3]:

- Calculate point estimate
- Calculate CDF by simulation
- Choose a desired confidence level
- Use S-Curve to obtain an value on the abscissa based on chosen confidence level

- Compute the amount of funds as the difference between chosen confidence level and point estimate.

Summary

Naval vessels are technically complex and sophisticated systems. Therefore one of the core issues concerning the planning of a naval ship is to identify requirements and translate them to technical solutions. Another important aspect for any project manager is that the technical solutions are affordable in line with the budget or given cost limitations. Therefore MTG has developed a cost management procedure in order to take up the challenge of estimating costs and cost risks for naval projects in very early design stages enabling governmental decision making processes and budgetary planning. Accordingly this paper has introduced cost estimation and cost risk analysis in general terms and also summarized MTG's approaches.

It should be noted that cost estimation is challenging and difficult especially in early project stages. Cost estimating requires a lot of experience, valuable contacts to industrial suppliers and governmental facilities, comprehensive databases and supporting software tools.

Another key finding of this paper is that every cost estimation model is prone to uncertainty by nature. This is why MTG has established a process for cost risk analysis which is a valuable concept to advance an existing cost estimation process and achieve higher transparency when dealing with cost estimates.

In the course of MTG′s cost estimating process the acquisition costs, in-service costs and cost risk analysis will be elaborated in order to ensure low risk and financial feasibility throughout the planning, acquisition and operational phase of naval vessels.

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SWATH- A new concept for the Safety and Security at Sea

SWATH-Un nuevo concepto para la Seguridad y Protección en el mar

Fritz Grannemann [1]

Abstract

SWATH means Small Waterplane Area Twin Hull and is guarantor for excellent sea keeping behaviour. The basis of this ship type was born in the 1960's and 70's when semi-submersible vessels were introduced to the offshore market. Naval architects developed these vessels further and it was used as navy test craft, pilot tender, yachts, passenger boats etc.

The German Shipyard Abeking & Rasmussen has more than 100 year of experience in innovative ships and designs. Since 1999 more than 20 SWATH vessels like pilot tender, pilot station vessel, explorer yacht, wind park maintenance tender, offshore patrol vessels and a hydrographical research vessel were built.

This paper should give an insight to the SWATH technology and the implementation in the market. Different applications and ideas will be shown. Whatever you need - a navy ship, a workboat, a multi-purpose platform a ferry or a yacht – there are many possibilities.

Key words: Small Waterplane Area Twin Hull, seakeeping, platforms, ship design.

Resumen

SWATH significa Small Waterplane Area Twin Hull (Cascos Dobles con Pequeña Área de Flotación) embarcación que garantiza un excelente comportamiento marinero. El fundamento de este tipo de buque nació en los años 1960 y 70, cuando se introdujeron en el mercado offshore las plataformas semisumergibles. Desde entonces los arquitectos navales de Abeking & Rasmusen han desarrollado más y nuevos diseños que han sido utilizados como embarcaciones de prueba para la marina armada, transporte de pilotos, yates, barcos de pasajeros, etc.

El astillero alemán Abeking & Rasmussen tiene más de 100 años de experiencia en construcción de barcos y de llevar a cabo diseños innovadores. A partir de 1999, Abeking & Rasmussen ha contruído más de 20 embarcaciones tipo SWATH para servicios tales como transporte de pilotos, buque-estación de pilotos, yate explorador, embarcaciones para el mantenimiento de parques eólicos en costa afuera, buques de patrulla en alta mar y un barco de investigación hidrográfica.

Esta presentación dará una visión de la tecnología SWATH y sus aplicaciones en el mercado. Se mostrarán sus diferentes aplicaciones e ideas. Lo que Usted necesite - un buque para la Armada, un barco de trabajo, una plataforma multiusos, un ferry o un yate – contamos con muchas y diversas opciones.

Palabras claves: Cascos Dobles con Pequeña Área de Flotación, comportamiento en el mar, plataformas, diseño de embarcaciones

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Introduction

The seakeeping capability of conventional ships depends mostly on their size and displacement. Naval architects usually optimize seakeeping behavior by well chosen main dimensions and refined hull lines.

Depending on sea state, a vessel is exposed to alternating accelerations, rolling and pitching motions. The difficulty is not to design a vessel strong enough to withstand those environmental forces, but exposing sailors operating the vessel to these adverse conditions over a longer period of time.

Various stabilization systems have been developed to reduce rolling and pitching, some with remarkable results, but all of these systems have their limits as they cannot push beyond the limit set by physics.

By mastering a unique design, which focuses on minimizing the waterplane area of the vessel, A&R succeeded in reducing roll, pitch and accelerations in bad weather conditions to a comfortable level, even for non-sailors.

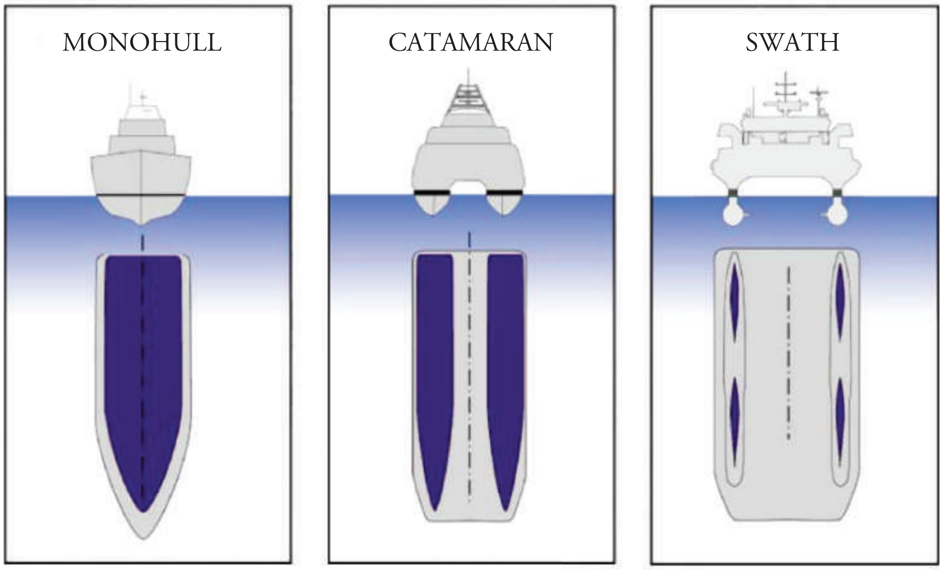
Since 1999 SWATH@A&R®-vessels are in daily service in the German Bight providing pilots a safe and stable platform with exceptional seakeeping capabilities. Over the years other applications were explored, designed and built and by today more than 20 SWATH vessels have been delivered.

This paper presents an overview of semi-submersible technology at the state-of-the-art for twin hull vessels and the special features developed by A&R.

What makes a SWATH a SWATH?

The buoyancy of a SWATH is provided by fully submerged, torpedo-like bodies, which are connected by single or twin struts to the upper platform. The cross-section at waterline level is minimized and thus lowering the hydrostatic restoration forces at design draft. The resulting wave induced motions in the vertical plane are reduced about one quarter of those of comparable monohulls. Fig. 1 shows a comparison of waterline areas for different hull configurations. The buoyancy of a SWATH is provided by fully submerged, torpedo-like bodies, which are connected by single or twin struts to the upper platform. The cross-section at waterline level is minimized and thus lowering the hydrostatic restoration forces at design draft. The resulting wave induced motions in the vertical plane are reduced about one quarter of those of comparable monohulls. Fig. 1 shows

Fig. 1. Comparison of different waterline areas.



a comparison of waterline areas for different hull configurations.

Using the precise wording of the German War Weapon Control Law, a SWATH is a craft with reduced waterplane area (A_{WL}) relative to its displaced volume (∇), specifically:

$$A_{WL} < 2 \cdot \nabla^{2/3} \tag{1}$$

Two design justifications for reducing the waterplane area are:

- to reduce the wave-making resistance
- to reduce sea-induced ship motions

The original intention for the design of SWATH vessels was probably to develop unconventional fast crafts by reduction of wave-making resistance. A&R concentrated on the reduction of sea-induced ship motions to improve seaworthiness, crew effectiveness and vessel availability in bad weather conditions.

A SWATH@A&R® is by definition a fast displacement vessel. It is designed for operation at speeds up to a Froude number of 0.75, without slamming. These are speeds higher than those of frigates, refrigerated carrierers or corvettes, when related to ship length.

Semi-submersibles can be classified by the number of displacement bodies in each configuration. Table 2 divides SWATH configurations into design configurations.

The evolution of SWATH design from first generation to third increases the complexity of the development process because of the increasingly complicated interactions of the displaced bodies. The analysis of hydrodynamic and structural factors, including the optimization of resistance, becomes more difficult, increasing the required qualifications for naval architects during design development.

The greater the number of displacement bodies in a SWATH design, the greater the potential for meeting specific design requirements. At the same time, increased complexity of the design procedure adds to the sensitivity of the design to construction inaccuracies, expressed as excess weight or inadequate hull structure.

Generation I SWATH: single strut

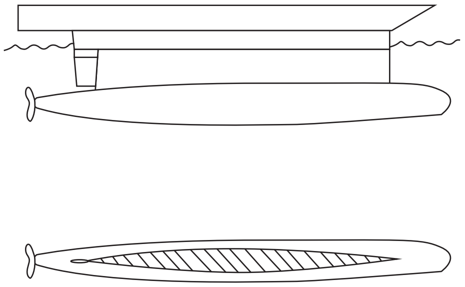
Advantages:
- good accessibility to spaces in lower hulls
- good transverse strength
- simple construction
- significantly reduced ship motions compared to monohulls and catamarans

Disadvantages:
- dissimilar transverse and longitudinal stability
- hydrodynamic efficiency (resistance and seakeeping) limited by layout
- sensitive to speed dependent trim moments (Munk moments)

Table 1.SWATH generations.

Type	**Configuration modularity Mission modularity**		**Status**
Monohull	1 Hull	1	proven
Catamaran	2 Hulls	2	proven
Generation I SWATH (single strut)	2 Struts 2 Torpedos	4	proven
Generation II SWATH (twin strut)	4 Struts 2 Torpedos	6	proven
Generation III SWATH (SLICE)	4 Struts 4 Torpedos	8	experimental
Generation IV SWATH (single strut, single hull) (SWASH)	1 Strut 1 Torpedo	2	experimental

Fig. 2. Generation I SWATH
2 x 2 buoyancy hulls, usually streamlined, single struts and relative large waterplane area.



Generation II SWATH: twin strut

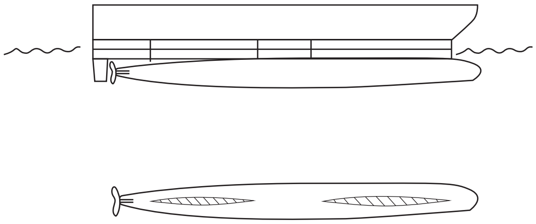
Advantages:

- more options for hull form shape to optimize resistance
- longitudinal stability can be matched to transverse for optimal seakeeping compared to Generation I SWATH (single strut)
- higher speed with stability in smooth water or a seaway
- compared with Generation I SWATH (single strut) further reduction of ship motion
- more sensitive reaction of ride control action, even stability longitudinally is increased

Disadvantages:

- limited accessibility to lower hull spaces („bottle necks“ in the struts for maintenance, ventilation, manholes, emergency exits)
- increased requirements to an optimized hull structure

Fig. 3. Generation II SWATH
2 x 3 buoyancy hulls, with optimized hull form and minimized waterplane area. The different buoyancy parts (twin strut and longer hull) interact depending on form, length and width.



SWATH vs. Monohull

Human beings which are permanently exposed to sea response motions (i.e. alternating accelerations) suffer from lack of concentration, exhaustion and seasickness. Even if experienced sailors get accustomed to motions of a vessel, it only prolongs the period of time when exhaustion and fatigue occurs.

In order to keep crew and passengers fairly comfortable and enable them to perform their main duties, limits have been defined, e.g. by the U.S. Navy or by ISO for the permanent allowable accelerations on board of seagoing vessels.

Following limits are widely accepted:

- Crew and passenger comfort: 0,2 g
- Operating limit experienced Crew: 0,4 g

Fig. 4 shows a comparison between vertical accelerations onboard a 33 m A&R built DeepVee Monohull and a slightly smaller 25 m SWATH@A&R® Pilot Tender. Measurements were conducted at various speeds in head seas of approximately 2 m and 3 m significant wave height respectively which corresponds to about sea state 5.

To stay within the “Crew Limit” of 4 m/s^2, the maximum speed of the DeepVee vessel needs to be reduced to 16 and 20 knots depending on sea state.

In comparison, the 25m SWATH@A&R® Pilot Tender maintains its top speed of 20 knots even without exceeding the “Crew Comfort” limit of 2 m/s^2.

SWATH@AR Design Features

General Design Concepts

A&R has until today developed and built four different groups of SWATH vessels defined mainly by length and deadweight capacity. Each group is characterized by the same underwater body hull form, strut configuration, platform design and hull structure. Given the constraints for weight and centers of gravities, almost any other change to the designs are practicable which has been successfully proven by A&R in several cases (Table 2).

Propulsion Concepts

Both diesel-electric and diesel-mechanic propulsion concepts are available for all SWATH@AR® vessels. Depending on the main task of the vessel, the most suitable concept with regards to operational and economical requirements is installed.

The contrast between both propulsion concepts is noticeable, especially for the smaller 25 m SWATH. Two diesel-generators are installed within the platform above water level providing power for electric motors which are installed within the displacement bodies below water level. Each of the electric motors drive fixed pitch propellers through reduction gearboxes

Fig. 4. Comparison of vertical accelerations.

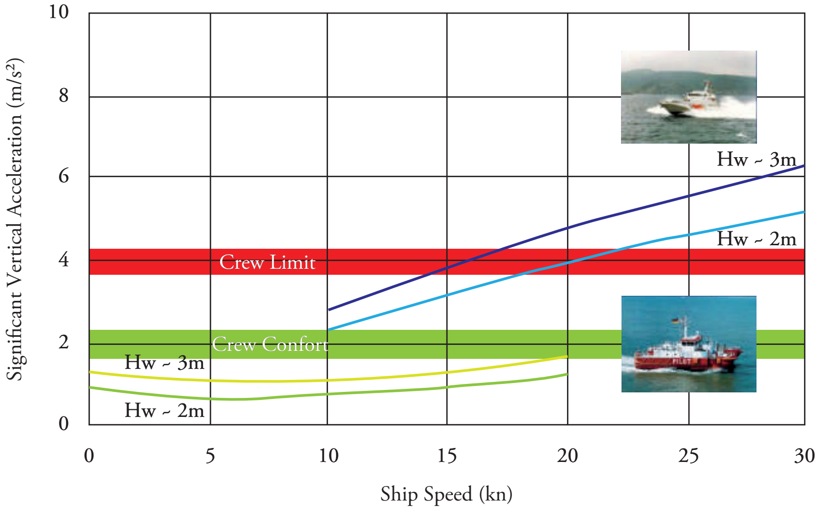


Table 2. Different applications of SWATH@AR®.

Group	Configuration modularity Mission modularity	Status
25 m SWATH	Pilot Tender	built
	Hydrographic Research Vessel	built
	PV - Patrol Vessel	built
	MCMV - Mine Countermeasures Vessel	experimental
	USV - Unmanned Surface Vehicle	project
	Wind Farm Crew and Maintenance Vessel	built
40 m SWATH	Explorer Super Yacht	built
	Crew Supply Vessel	project
	Research Vessel	project
50 m SWATH	Pilot Station Ship	Built
	Wind Farm Maintenance and Hotel Vessel	project
60 m SWATH	Pilot Station Ship	built
	Wind Farm Maintenance and Hotel Vessel	project
	SIGINT Vessel (SIGnal INTelligence)	project
	Research Vessel	project

enabling speeds up to 20 knots. A&R succeeded in implementing a diesel-mechanic propulsion where propulsion diesels are installed within the displacement bodies below water level driving controllable pitch propellers through reduction gearboxes enabling even higher speeds up to 21.4 knots.

Advantages of the diesel-mechanic propulsion are:

- added space within the platform which can be utilized for extra cabins or other purposes
- low noise and vibration levels since exciters are installed below water level remote from personnel onboard

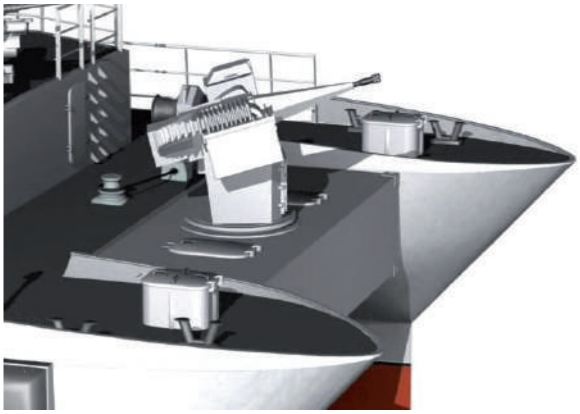
General Design Concepts

A multi-purpose tool contains a variety of elements in one basis. The different tasks can be fulfilled by "switching" from one to the other element. By the nature of such a tool, the integration of the different elements requires compromises with regard to handling the tool and the integration of other elements. Some bulked variants of the well known Swiss Army Knife represent best whereto multi-purpose might lead. A modular tool consists of one common basis which can be supplemented by modules for a dedicated task. By exchanging the modules the tool can be configured for various different tasks and at the same time each configuration represents a dedicated tool. A socket wrench set is the best example for such a modular tool. Dedicated, single tasked vessels are hardly affordable in an era of shrinking budgets while the mission variety is increasing, which is the case especially for navies and authorities. With decreasing number of hulls within most fleets, modular or multi-purpose "tools" are considered to be the solution for executing all required naval tasks.

A&R responded to these requirements by implementing a containerized solution to its 25 m SWATH. One module with the size of a standard ISO 20ft. container can be stored in front of the superstructure in-between the stems (Figs. 5 and 6).

Fig. 5. 20' container storage for modules.

Fig. 6. Example of a gun module.

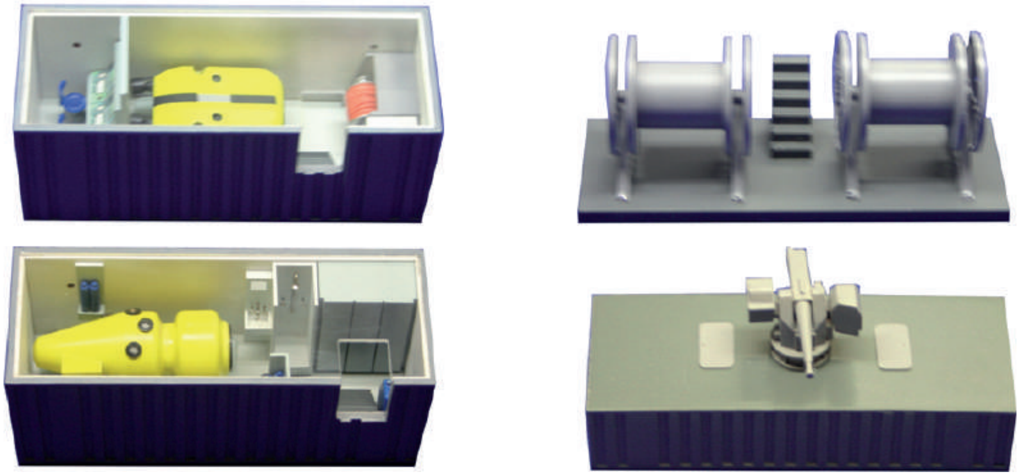


The gun module fitted with a medium calibre gun contains all subsystems necessary for operation of the gun, including ammunition. Only electric voltage (440V) will be supplied, target data will be transmitted by a data bus. Due to this limited interface requirement, the gun module can also be used on other units and even onshore.

Under condition of a compatible target assignment format, modules can be used by army units as well, e.g. for camp protection tasks. This brings the advantages of modular ship design into a "joint" account.

Instead of the gun module, other modules are possible for secondary tasks. The interfaces remain the same, i.e. only electric voltage, connection to the ship's data bus plus seawater and possibly freshwater. These interfaces will be available on almost every other craft of opportunity thus broadening the basis of using

Fig. 7. ROV module, oil spill response module, diving chamber module and gun module.



the modules other than installed on board of the 25 m SWATH.

A module equipped with sonar ROV will enable MCM operations, such as e.g. route survey. Even a hyper baric diving chamber and breathing air compressor might be fitted for diving operations. The stable SWATH makes a perfect platform for diving operations. Access to the water is conveniently given by a hydraulic lift on the starboard side which reaches from main deck level well below the water surface.

Other modules might contain equipment for oil pollution control or hydrographic research equipment. Further applications can be developed as long as it is within the geometrical dimensions and the maximum weight. This allows cost effective future upgrades and enhancements of secondary missions.

Redundancy

Depending on the requirements and operational profile of a vessel, different redundancy levels for propulsion and ship's service system can be achieved with a SWATH. In any case two independent compartments comprising both lower hulls including two identical propulsion systems (one in each hull) are available. Given this compartmentation, gensets, auxiliary systems and electric panels need to be located in separate and independent engine rooms within the superstructure to achieve extra safety and redundancy effects. This can be achieved with small structural changes within the platform and of course with duplication of systems as required by redundancy class. An additional benefit is the large spatial distance between both propulsion trains providing additional safety.

SWATH@A&R® in Service

25 m SWATH@A&R® Pilot Tender Mk I

Fig. 8. A&R Pilot Tenders MK I.

Length o.a: 25.65 m
Displacement: 129.0 t
Breath o.a.: 14.25 m
Speed: 18 kts
Draught: 2.70 m
Class: GL

In close cooperation with the Elbe Pilot Association Abeking & Rasmussen developed technical systems tailored to the boarding procedure required, such as

- fendering system
- quick ballast system
- boarding aids

Until today each of the vessels has accumulated more than 15.000 operating hours in regular all day/all weather pilot operation.

This longtime operating since 1999 experience of SWATH vessels in a tough workboat application gives Abeking & Rasmussen a good insight into the structural and mechanical stresses of such a vessel and as such is a valuable design feedback.

50 m SWATH@A&R® Pilot Station Ship

Fig. 9. 50 m A&R Pilot Station Ship.

Length o.a: 49.90 m
Displacement: 1,480.0 t
Breath o.a.: 22.55 m
Speed: 14.2 kts
Draught: 5.90 m
Class: GL

Since commissioning in 2000 the "ELBE" has been in continuous operation in the North Sea off Cuxhaven. She is just undergoing her second class docking and has not been in a shipyard since the class docking before.

The "ELBE" stays at sea all year round acting as a hotel ship for the off-duty Elbe Pilots. She is off station for about 12 hours when she calls Cuxhaven every 14 days for replenishment and crew change.

During approx. 40.000 operating hours which were accumulated by the "ELBE" until today a lot of operational experience in supporting the SWATH Pilot Tenders was gained. This resulted in some important improvements with regard to SWATH Pilot Tender operation and replenishment at sea.

25m SWATH@A&R® MCMV Demonstrator

Fig. 10. A&R MCMV Demonstrator.

Length o.a: 26.15 m
Displacement: 132.9 t
Breath o.a.: 14.25 m
Speed: 16 kts
Draught: 3.20 m
Class: GL

In 2002 the German MoD placed an order for the development of a remote operated Mine hunting System. Apart from the sonar system the sea keeping performance of the platform was a key issue. A calm and stable platform with good maneuverability is required to enhance the sonar performance. Therefore the choice was made for the SWATH@A&R® technology.

40m SWATH@A&R® Motor Yacht

Fig. 11. 40 m A&R SWATH Motor Yacht.

Length o.a: 40.50 m
Displacement: 597.0 t
Breath o.a.: 17.80 m
Speed: 14 kts
Draught: 4.10 m
Class: GL/MCA

In 2006 Abeking & Rasmussen secured the first order for a SWATH Motor Yacht for worldwide operation. This was the first SWATH-type Mega yacht of the world. It accommodates one yacht tender and a landing deck for a 2.5 t helicopter.

All demanding contractual requirements for sea keeping parameter, speed and comfort were even exceeded. Her seaworthiness equals the much larger 50m SWATH@A&R® Pilot Station Ship

60 m SWATH@A&R® Pilot Station Ship

Fig. 12. 60 m A&R Pilot Station Ship.

Length o.a: 60.40 m
Displacement: 1,800.0 t
Breath o.a.: 24.60 m
Speed: 12.5 kts
Draught: 6.0 m
Class: GL

In 2007 the German Ministry of Transport ordered two larger variants of the existing Station Ship to serve the increasing traffic in the German North Sea to/from the ports and the Kiel Canal.

The new ships include all improvements based on the 7 years of experience with the existing ships.

25 m SWATH@A&R® Windpark Tender

Fig. 13. A&R Windpark Tender.

Length o.a: 26.10 m
Displacement: 132.9 t
Breath o.a.: 13.00 m
Speed: 18 kts
Draught: 2.70 m
Class: GL

In March 2008 the BARD group ordered the 25m SWATH@A&R® platform as service vessel for their offshore wind farm under construction in the North Sea. To achieve a high availability of the wind energy converters it is mandatory to be able to transfer service personnel to the offshore structures even in high seas. Consequently the SWATH technology was chosen.

The 25 m SWATH@A&R® Windpark Tender is equipped with a special bow fender for additional damping, allowing direct boarding of the offshore structure and a dedicated diesel-electric propulsion for highest maneuverability at zero speed.

25 m SWATH@A&R® Patrol Boat

Fig. 14. A&R Patrol Boat.

Length o.a: 25.80 m
Displacement: 132.9 t
Breath o.a.: 14.25 m
Speed: 20 kts
Draught: 2.70 m
Class: GL

In 2008 the Latvian Navy placed an order for five 25m SWATH@A&R® Patrol Boats based on the design of the 25m Pilot Tender. The decision was explicitly made to benefit from the well proven seaworthiness of the compact vessels. A crew of eight can remain at sea for one week to fulfill patrol and surveillance tasks, SAR missions and to participate in international assignments.

The new vessels features a modular mission bay at the fore ship. By fitting appropriate mission modules, such as a medium caliber gun or mine hunting equipment, the capabilities of the vessels can be flexibly enhanced to suit the actually assigned task.

Infrared Signature Analysis of Surface Ships

Análisis de la firma infrarroja en buques de superficie

Stefany del P. Marrugo Llorente [1]
Vladimir Díaz Charris [2]
José M. Gómez Torres [3]

Abstract

The process of analyzing IR signature of a vessel is described in this document, which was developed using the ShipIR/NTCS software. As important aspect of the process, highlighting the pre-processing stages of the geometry under study and characterization of the environment. This document contains the results obtained for different background conditions, varying the type of sensor used, their distances and height measuring speed vessel under study and the time of day.

Key words: Infrared (IR) signature, MWIR, LWIR, IRSS, ShipIR.

Resumen

El documento describe el proceso de análisis de firma IR de un buque, el cual fue desarrollado empleando el software ShipIR/NTCS. Como aspecto importante del proceso, se destacan las fases de pre-procesamiento de la geometría bajo estudio y caracterización del entorno. El documento contiene los resultados obtenidos para condiciones de fondo distintas, variando el tipo de sensor empleado, sus distancias y alturas de medición, velocidad del buque bajo estudio y el momento del día.

Palabras claves: Firma Infrarroja (IR), MWIR, LWIR, IRSS, ShipIR.

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Introduction

The integral design of any naval superstructure must consider two basic factors that allow the increasing of survivability in the specific operating environment: reduced vulnerability and low detectability.

This implies "design platforms that distort as few as possible the environment in which they operate, increasing in that way, the difficulty for detection, classification and acquisition by enemy weapons. Similarly, designs must be designed to minimize the effects of damage caused by the impact of enemy weapons" (*Sierra & Vilchez*).

As is known, all objects within our range, due to they are at a temperature above 0° K, emit thermal energy in the IR region of the electromagnetic spectrum. This radiation source may be employed for detection and monitoring by a gun provided with infrared sensors.

The spectrum of emitted or reflected energy of a ship or the way to modify certain physical parameters of the environment, are characteristic of each unit, so that is the reason why we talk of signatures. IR signature is the one associated with the electromagnetic radiation emitted in the infrared wavelength range.

The goal of this paper is to describe the methodology for obtaining and analyzing IR signature of a ship, showing the tools and procedures that were used, as well as design recommendations to be considered during the early design stages of a vessel, in order to reduce IR signature.

IR Signature basic concepts

Sierra & Vilchez [1] stated that "for an object can be detected, must be distinguished from the surrounding environment. Therefore, the principles on which the reduction IR signature are based, consist on the reduction of the temperature differences between the surfaces of the vessel and the environment and reduction of the temperature of the exhaust gases", that is why is essential to identify the sources of IR radiation on ships, in order to find mechanisms to reduce it.

In general, the IR signature of a vessel consists of two components: those generated internally and those that are generated externally.

Internally, the main sources of generation include the heat emitted by engines and other equipment, engine exhaust gases and air ventilation systems; however, most internal IR source comes from the main machinery on board, especially from electric motors and generators.

Externally, IR signature is the result of absorptions and/or reflections on the ships surfaces, of the radiation received from their environment. The main sources of radiation in the environment are: the sun, the sky radiation and the sea.

For an effective IR signature reduction of a ship it must be considered both, internal and external sources.

General Design Concepts

The IR signature management has become very important for modern warships. In fact, now a day it is essential to use sophisticated computational design tools that allow designers to handle ships IR characteristics of a ship, before its construction.

The purpose of such simulators is to predict, analytically, ship IR signature and evaluate how vulnerable to an enemy IR detection could be, through a wide range of operating and sea conditions.

Some of the existing simulation tools, for modeling and evaluation of ships IR signature are: ShipIR/NTCS, RadThermIR and OSMOSIS.

Simulators use specifications

Input specifications are all parameters that affect platform susceptibility against threats, including:

- Background: Geography, date and time, weather.

- Platform: Size and shape, materials and coatings, propulsion and auxiliary equipment, deck and deck maneuvering equipment.
- Threats: Bandwidth (MWIR, LWIR), spatial resolution (scanner, image management, etc.), sensitivity (noise detector, confusion.).

The above are inputs for tools like NTCS, used to perform analysis, incorporating the 3D model of the platform, the realistic effects of sea and sky, multiple reflections from the surface, atmospheric attenuation and chimney emissions.

In general, the use of computational models allows sensitivity studies that would be extremely expensive to do through experiments or that are not possible due to logistical reasons. Some of the research topics that can be analyzed using such tools are:

- The effect of the sun's position in the surface temperatures of the ship.
- Estimate the ship’s signature from any location of the observer.
- Identify hot spots contributions to the detection susceptibility.
- Objectively compare the effectiveness of different options of IR suppression in identical operating conditions.

IR Signature Suppression (IRSS) techniques

The most modern ships in the world include mechanism of IRSS to reduce ship’s susceptibility against missiles guided by IR sensors. The recent year’s trend of new ship’s development programs shows more systematic and comprehensive designs that are more approximated to IRSS, those designs include studies to analyze the susceptibility of the ship and the cost-benefit analysis of designs, which means that new ships are being designed with low signatures and increased survivability.

Below deck IRSS

To eliminate or minimize the severity of hull’s hot sections and sides of the chimney, is required to make use of basic thermal design. Compartments must be vented enough, in order to maintain temperatures below the 50° C inside the compartment. Any compartment or chimney space that could be heated above room temperature will require thermal insulation applied into all external bulkheads.

Apply a 25 mm (1") fiber glass insulation can reduce external surface temperature to an acceptable temperature contrast. As a guideline, surfaces of the hull that are heated from inside should not exceed a contrast temperature of ±5°C.

Other compartments around the ship that may have different ambient temperature, must be considered. Negatively contrasted surfaces resulting from fans, air conditioning in electronic assemblies, for example, must be avoided too.

It is possible to use different IR suppression levels, which are mainly applied to the engine exhaust system and ships surface.

There are four suppression levels for the engines exhaust:

- No suppression
- Visible metal cooling to + 30°C ambient
- Metal cooling + chimneys cooling up to 250°C
- Metal cooling + chimneys cooling up to 150°C

Fig. 1 (pag.60) shows a number of systems currently in use for IRSS.

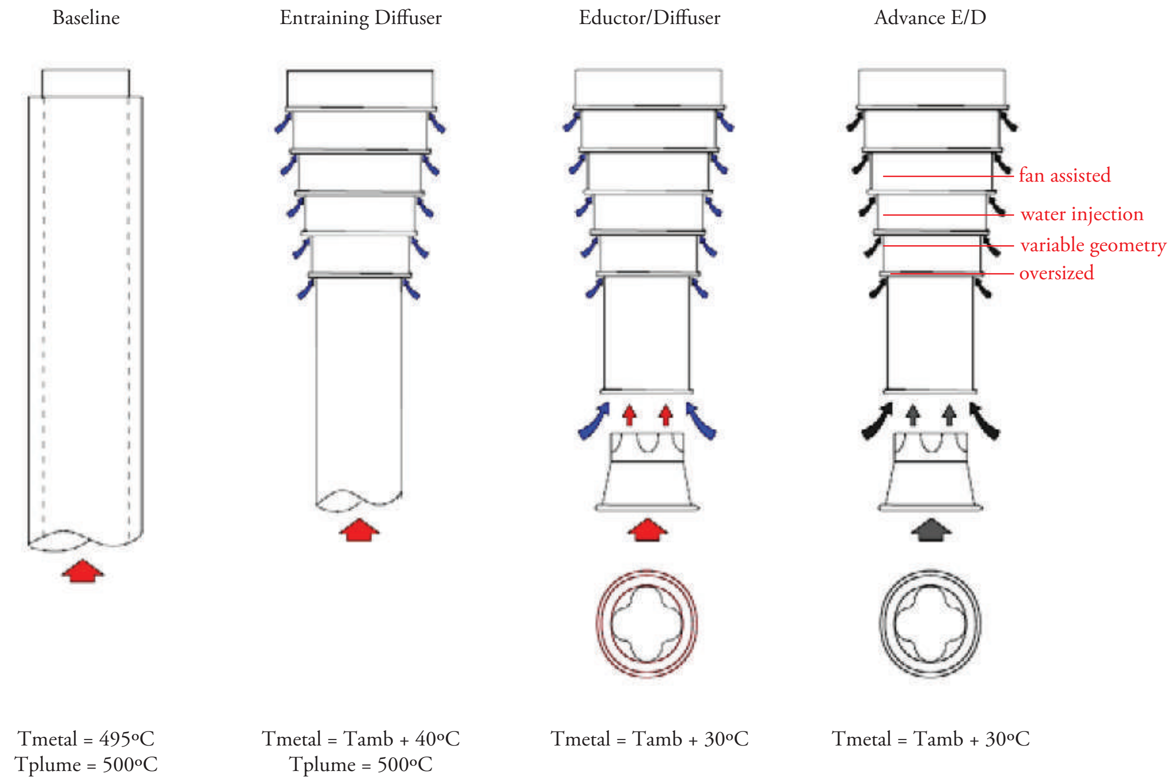
These systems incorporate a layer of air cooling and exhausts. For some systems, the irrigated water is used to reduce the chimneys temperature.

IRSS en la superficie de la plataforma

The platform surface signature is due to the heating by the sun and heat loss from the interior spaces.

The solution for the heat losses is to use internal insulation and ventilation, while for the sun heating the solution is to use water cooling and low solar absorption paints.

Fig. 1.IRSS systems for engines.



Special paints

According to Vaitekunas, Thompson and Birk [3], the selection of special paints is a very complex issue and there is no single correct answer. There will always be a balance between the best solution for sunny conditions versus the best solution for the conditions at night or cloudy days.

For example, under sunny conditions, the hull paint must:

1. Not to absorb solar radiation below 3 micron wavelength (i.e., low emissivity with short wavelength)
2. Absorb all radiation above 3 microns (i.e., high emissivity of medium and long wave).

This type of spectral painting is available but it is expensive and its effectiveness can be drastically reduced by surface contaminants such as rust, dirt, etc.

Under overcast conditions, it would be desirable to have low emission paints. In this case, the ship would emit less and reflects the environment. Note that the low emission gradually tend towards greater emission due to factors such as the accumulation of salt, engine exhaust, soot and dirt.

Water Shower

Authors of [3] stated that this suppression technique involves the active cooling of the hot parts of the surface of the ship with seawater.

It is necessary to be careful of not to cool so much the surfaces of the ship. A high negative contrast imposes an effective target to modern browsers. By using a feedback system, water shower could be activated and/or deactivated according to the needed, keeping the surface of the ship at a constant temperature of low contrast.

Cloud of water mist

About this particular, experts [3] indicate that a thick cloud of water mist is sprayed onto the ship, hiding the ship from the point of view of IR seekers. There are not data about the efficacy of this type of system as an IR countermeasure. However, if this system is handled properly, it can improve the performance of other countermeasures such as decoys.

Some problems of a water mist system are the darkening of optical sensors on board, and the accumulation of salt at spray nozzles and over the entire surface of the ship.

Uses of any of these three methods as hull IRSS do not eliminate the requirement of proper insulation and ventilation design and use of suppression techniques for main machinery.

IR signature analysis of a platform

The aim of this section is to identify how the IR signature of a surface platform type Fassmer OPV-80 and the way how this varies depending on changes in their environment. The software used for analysis is ShipIR / NTCS.

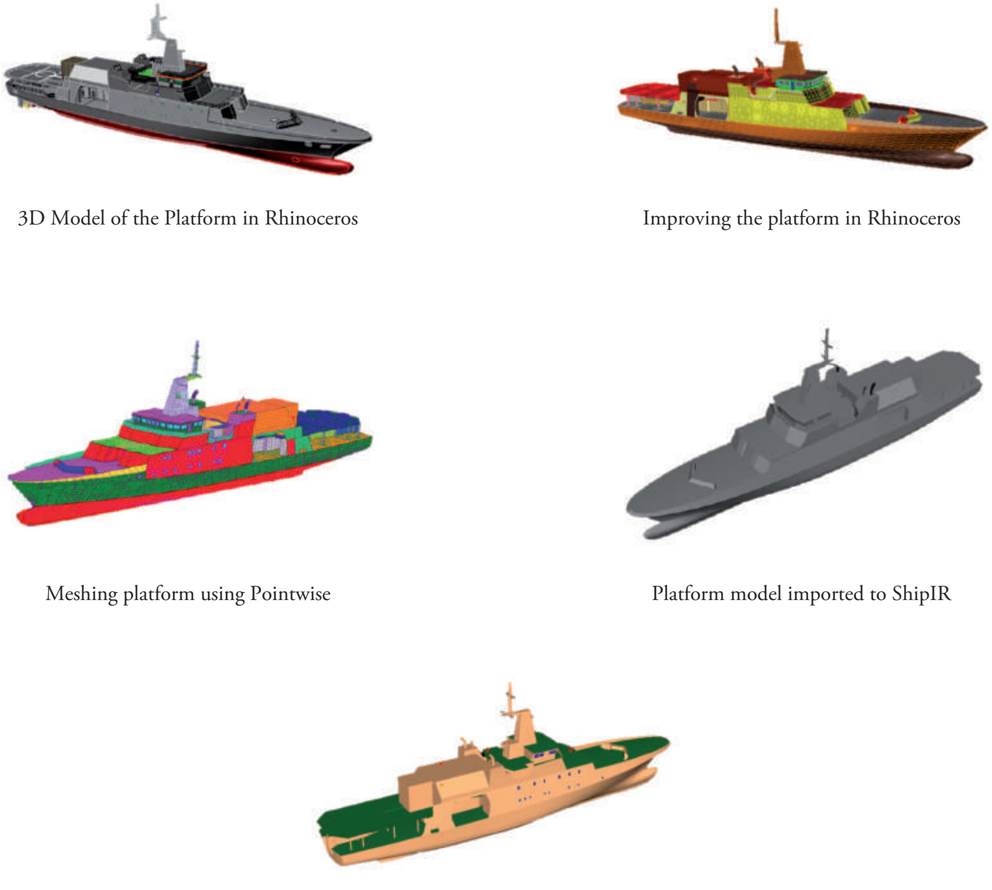
Platform

Requires initially have the geometry of the vessel, in this case, was available in the software Rhinoceros. It is necessary to model the hull and superstructure, as well as flares, windows or other openings that may exist airflow / gases.

Fig. 2, presents a table with the procedure for pre-processing of geometry under study.

The development platform is also made in Rhinoceros. Further, is necessary to use the Pointwise (commercial tool meshing) software, in order to make an appropriate meshing for IR 3D surface model analysis.

Fig. 2.Geometry Pre-processing of the platform under stude.



3D Model of the Platform in Rhinoceros

Improving the platform in Rhinoceros

Meshing platform using Pointwise

Platform model imported to ShipIR

Last Model. Includes assigning materials to surfaces.

Then the 3D model of the platform is displayed by Model View Editor (MVE) of ShipIR / NTCS software, which is possible to assign the characteristics of materials to surfaces.

Machinery

For a ship IR analysis, it is not necessary to model the 3D geometry of the main machinery, but it is important to understand fundamental aspects of them for assignment thermal characteristics to the surfaces of the vessel. This information is essential to characterize the conditions of exhaust required as inputs to the thermal model of IR signature, as well, is required to verify which is the power consumption in operating condition of the vessel, in order to know what equipment will being used in each case.

For this study, was taken into account the operating condition representing higher power consumption (ie, the worst condition) and simulations were performed.

Fig. 3 presents a model of the exhaust pipes on the ship under study.

Optical Properties

Was used a coating (paint) for much of the surface of the vessel type gray Admiral. It is important to know the characteristics and optical properties of this type of coating, since it will depend the IR signature variation of the vessel under study. This type of paint is used, because it is fully characterized and is not necessary to make additional field studies to determine their properties.

The company W.R. Davis Engineering Ltd, who advised the developers of this work, provided information of optical properties of the coating used. The detail of each is explained in [4]. In general, it is determined solar coating as absorptivity α_s=0.65 and thermal emissivity is ε_T=0.94.

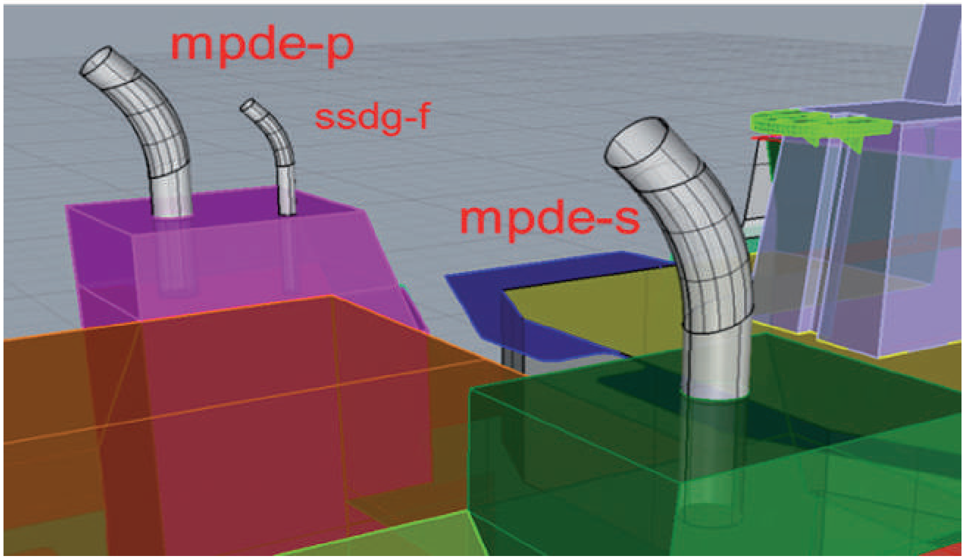
Environmental Data

The right set of data describing the climatic conditions of the Colombian maritime zone for use infrared analysis of the unit under study is defined.

The data used is provide from the buoy # 42058 of US National Oceanic and Atmospheric Administration (NOAA).[1]

The buoy is located 15° N 75° W. It has historical data from 2006 to the present (36,759 points) and provides plane and graphical information to room

Fig. 3. Exhaust pipe model.



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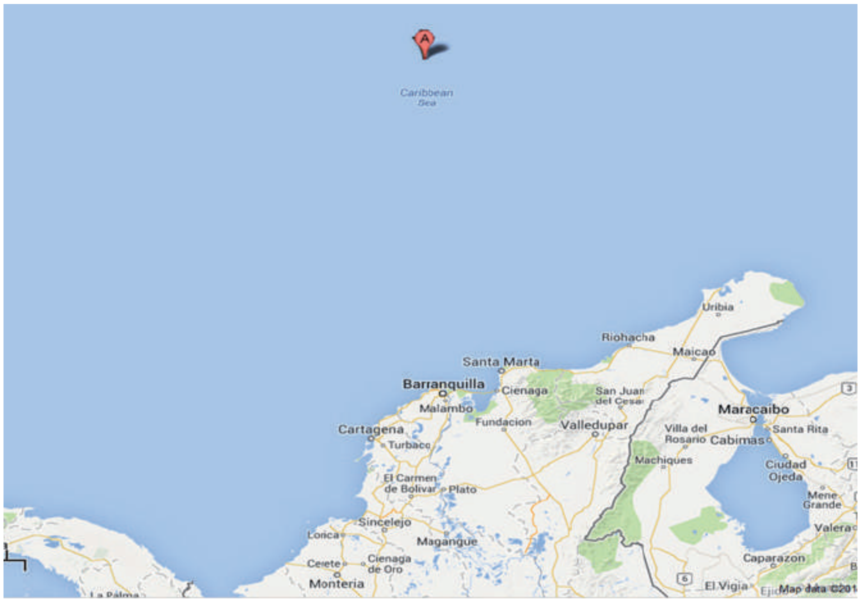
[1] Available in http://www.ndbc.noaa.gov/maps/West_Caribbean.shtml.

Fig. 4. Geographic location of the selected Buoy.



temperature, sea temperature, relative humidity, wind speed and direction at each point. Spatial location is shown in Fig. 4. Twenty (20) scenarios (dates and weather conditions) were selected to evaluate the performance of the OPV - IR signature. Table 1 presents a list of scenarios used.

Table 1. Entornos Colombianos resultantes: (a) Condiciones climáticas, (b) fechas y horarios.

Point	Location	Wd (°)	Ws (m/s)	W24 (m/s)	Tsea (°C)	Tair (°C)	RH (%)
1	Caribbean	118	9.1	7.4	28.8	27.2	81
2	Caribbean	196	2.9	8.5	27.6	23.6	89
3	Caribbean	70	8.3	10.3	25.4	26.1	74
4	Caribbean	95	9.5	9.3	27.2	28.9	71
5	Caribbean	89	10.8	8.5	28	28.1	85
6	Caribbean	43	1.8	5.5	27.3	25.9	77
7	Caribbean	80	7.1	8.1	27	26.6	78
8	Caribbean	106	4.0	4.2	27.7	26.9	76
9	Caribbean	92	4.6	4.3	29.5	28.5	79
10	Caribbean	59	6.1	7.6	28.5	28	83
11	Caribbean	85	7.8	9.9	26.4	26.7	80
12	Caribbean	72	8.9	7.8	27.2	27	79
13	Caribbean	32	5.3	5.8	27	26.5	76
14	Caribbean	68	12.5	11.9	27.4	27.3	80
15	Caribbean	78	12.8	11.7	26.9	26.5	74
16	Caribbean	73	11.4	10.2	27.1	27.1	79
17	Caribbean	75	8.7	7.8	26.1	26.2	77
18	Caribbean	86	10.9	12.4	26.6	26.9	75
19	Caribbean	65	7.7	8.0	28.1	27.6	69
20	Caribbean	87	8.4	8.3	26.5	26.3	78

Date / Time					
Point	Year	Month	Day	Hour	Min
1	2011	8	29	9	50
2	2008	5	29	17	50
3	2009	2	3	14	50
4	2007	3	7	18	0
5	2011	5	30	9	50
6	2007	3	27	10	0
7	2007	4	5	10	0
8	2012	4	12	17	50
9	2008	9	1	4	50
10	2008	8	14	23	50
11	2012	4	1	17	50
12	2012	5	1	3	50
13	2012	4	8	23	50
14	2007	4	1	20	0
15	2012	4	16	15	50
16	2012	4	28	2	50
17	2012	2	10	4	50
18	2009	1	11	16	50
19	2011	12	6	1	50
20	2012	4	4	9	

Results

Simulations in ShipIR / NTCS tool were made to the following conditions:

- Twenty (20) environments
- Two (2) speed vessel (12 Kts, 18 Kts)
- Two (2) times of the day θ_{sun}=30°,noche
- Two (2) operating bands sensor (LW, MW)
- Two (2) heights for sensors (10 m, 300 m)
- Two (2) distances at which is located in sensor (1 Km, 10 Km)

After the simulation process in ShipIR / NTCS tool 640 resulting files were obtained. For each of them is possible to analyze the OPV - IR signature, under conditions that were set.

In order to make a filter in the process, the scenarios presented IR signatures low, average and high (10%, 50% and 90%) were analyzed. For platform in these six (6) scenarios, polar graphs showing IR signature, low speed conditions, time of day, type of sensor and height thereof, mentioned at the beginning were developed. In all polar graphs, the bow of the ship is to 0°.

Fig. 5 shows the IR signature of the vessel under study to the following conditions:

- Six (6) environments
- Two (2) speed vessel (12 Kts, 18 Kts)
- Time of day (θ_{sun}=30°)
- One sensor operating band (LW)
- One height sensor (10 m)
- One distance sensor location (1 Km)

Fig. 6 shows the IR signature of the vessel under study to the following conditions:

- Six (6) environments
- Two (2) speed vessel (12 Kts, 18 Kts)
- Time of day (θ_{sun}=30°)
- One sensor operating band (MW)
- One height sensor (10 m)
- One distance sensor location (1 Km)

The peak observed on the horizontal axis of the polar graph in Fig. 6, is due to a radiation intensity contrast (CRI) negative.

It is important to clarify that only negative CRI occur within the band "solar glare" (near the solar azimuth). The image next to the polar graph shows the flash that causes this CRI. Generally this negative contrast is characterized by long spikes on

Fig. 5. Contrasts radiation intensity conditions: Lw-010M (θ_sun = 30 °, 1km).

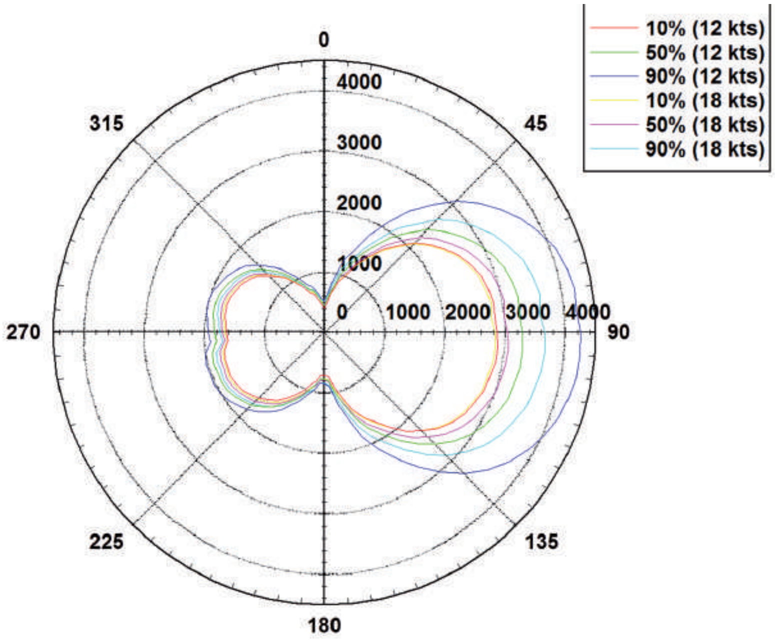
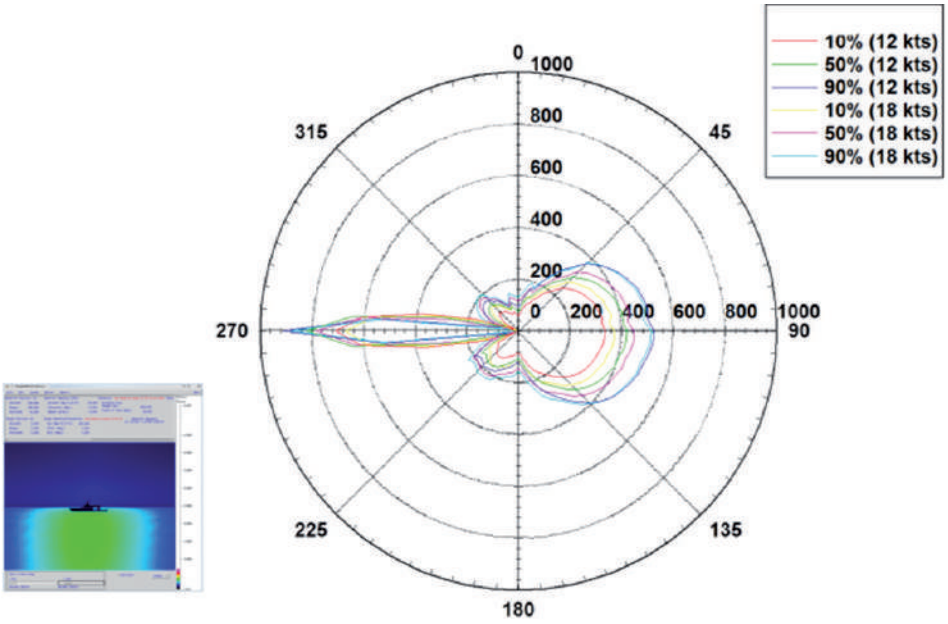


Fig. 6. Contrasts radiation intensity conditions: Mw-010M (θ_sun = 30 °, 1km).



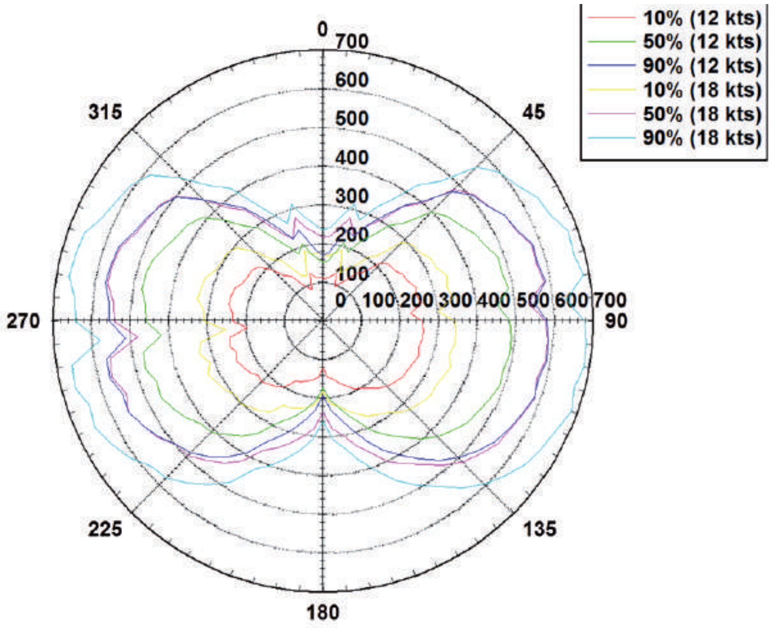
the polar graph, to 270 from the bow of the ship.

Fig. 7 shows the IR signature of the vessel under study to the following conditions:

- Six (6) environments
- Two (2) speed vessel (12 Kts, 18 Kts)
- Time of day (night)
- One sensor operating band (LW)
- One height sensor (10 m)
- One distance sensor location (1 Km)

Fig. 8 shows the IR signature of the vessel under study to the following conditions:

Fig. 7. Contrasts radiation intensity conditions: Lw-010M (night, 1 Km).



- Six (6) environments
- Two (2) speed vessel (12 Kts, 18 Kts)
- Time of day (night)
- One sensor operating band (MW)
- One height sensor (10 m)
- One distance sensor location (1 Km)

Conclusions

It was possible to show in the case of the unit under study, in daylight, positive contrasts (due to the exhaust pipes) and negative (surface without sun exposure) can coexist on the same scenario and reflected in some specified scenarios for IR signature modeled.

"Corridors brightness" seen in half-wave sensors, are always negative. This because the background is always warmer than the ship, for reasons such as: Solar dispersion in the atmosphere (the sky) and the reflected sunlight on the surface of the ocean (sea). This is usually more common when the shadow side of the ship is evaluated (during the day).

The signatures for night, they are often negative contrast. Surface temperatures are always lower than the air temperature (overnight) due to: the cold sky radiation (cooling) air convection (heat).

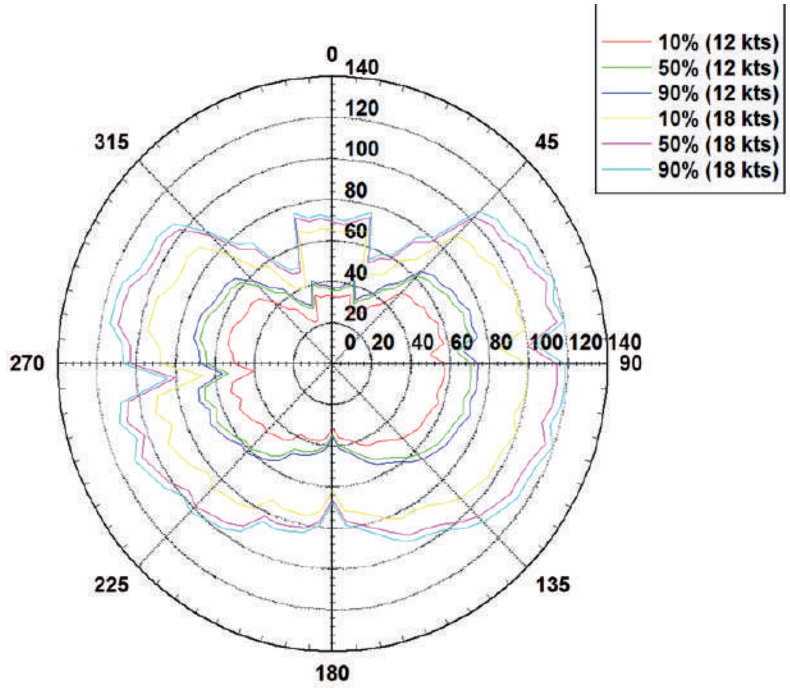
Low CRI not mean that it will also be under the detection range, since in the case of detection, the sensor is narrower in the area of analysis (engagable with one pixel), while the CRI surface discussed in general.

A great reduction in the detection ranges (stern / bow) with sensors in low and medium-wave located 300 meters indicates detection sensitivity due to the size of the target (i.e., the projected area of the ship).

The detection ranges (no sun) in LWIR are almost constant, with a small increase in the sides of port / starboard (due to hot chimneys) and considerably lower than those obtained during the day (without heating from the sun).

The ranges of detection (no sun) in MWIR have much larger oscillations, directly proportional to engine power (speed), with little or no reduction (compared to the day) - this indicates that the

Fig. 8. Contrasts radiation intensity conditions: Mw-010M (night, 1 Km).



exhaust stacks (hot steel) are largely responsible for detection.

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Development of Fire Fighting & Damage Control automation that enables future crew reduction

Desarrollo de automatización de control de daños y contraincendios que permite la futura reducción de la tripulación.

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Abstract

The Holland-class Patrol Vessels of the Royal Netherlands Navy has been designed to conduct world-wide operations with a low level of violence. Minimization of the exploitation costs has been translated in a frigate size vessel design to be manned by a crew of 50. In particular, the support of Battle Damage Repair required serious development as today's solutions are based upon having a much larger crew. Adoption of modern fire-fighting techniques such as ship-wide deployment of automated water-mist systems and extensive use of center-fed hose reels appeared to be essential steps to cope with lower manning levels. However, that is not enough as there are other internal battle aspects that (today) require significant manpower such as information gathering to obtain the desired situational awareness of the current state of the damage, and complex engineering tasks to mitigate the damages and the management of the necessary resources. For this reason, this paper discusses the approach and development of four (4) platform management system Damage Surveillance and Control (DSAC) applications as an example how future internal battles can be supported to achieve a higher quality (less human errors) of battle damage control, by means of a better situational awareness and a significant reduction of the workload during Battle Damage Repair.

Key words: Battle Damage Repair, Damage Surveillance & Control (DSAC), Fire Fighting & Damage Control (FFDC).

Resumen

Los buques patrulleros holandeses de la marina de los Países Bajos han sido diseñados para conducir operaciones a nivel mundial con un bajo nivel de violencia. Minimización de la explotación de los costos ha sido llevada al tamaño de las fragatas, las cuales son diseñadas para llevar una tripulación de 50 personas. En particular, el apoyo a la reparación de daños en batalla requiere un importante desarrollo dado que las soluciones actuales son con base en mantener un mayor número de tripulación. La adopción de técnicas contraincendios modernas tales como la implementación en la toda la embarcación de sistemas de agua nebulizada de manera automática y el uso extensivo de carretes de mangueras centro-alimentadas, parecen ser pasos esenciales para enfrentar bajos niveles de dotación. Sin embargo, esto no es suficiente mientras que se encuentren otros aspectos internos de batalla un significante esfuerzo de recurso humano, entre los que se destaca la consolidación de la información para obtener la situación actual de los daños ocurridos, así como las complejas tareas de ingeniería para mitigar los daños y la gestión de los recursos. Por esta razón, éste estudio discute el alcance, desarrollo y aplicaciones de cuatro (04) sistemas de gestión de la plataforma para vigilancia y control de daños (DSAC), tomando como ejemplo como futuras batallas pueden ser apoyadas para alcanzar una mayor calidad (disminución de errores humanos) de control de daños, por medio de un mejor conocimiento de la situación y una reducción significativa de la carga laboral durante la reparación de daños en batalla.

Palabras claves: Reparación daños en batalla, Vigilancia y control de daños, contraincendios y control de daños.

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Introduction

Integrated Platform Management Systems

Contemporary Integrated Platform Management Systems (IPMS) provide the promise of reduced manning and increased operational capabilities. However, in the design of modern Human Machine or Graphical User Interface (HMI, GUI) human factors are frequently underrepresented.

Common HMI is based on a representation of the platform installations with simplified process and instrumentation diagrams (P&ID) and corresponding alarm & event handling (Alarm Table). These so called 'mimics' only contains a limited 'functional' representation of the arrangement of components in a specific platform system. Within a mimic, components are represented by a symbol, with dynamic fields for values and control items. Interaction with other systems normally is limited to conditional relations (inhibits) which are programmed in the core of the software.

To be able to safeguard the ship, the operator has to have a profound overview, or situational awareness of the complete system and interaction with other platform components and systems (propagation of failures). Although the amount of I/O steadily increases, not all devices of each system are equipped with sensors and actuators and available I/O data usually is not correlated to provide with a comprehensive situational overview of the platform systems. For operators of IPMS systems, this means that a lot of knowledge and experience is necessary to operate the entire platform from the IPMS, which results in high cognitive loads, especially in case of failure or damage.

Another universal trend is that the system complexity of equipment is growing continuously and a growing number of platform installations are equipped with own 'automation' or CPU's with many I/O and Build In Test (BIT). Frequently, this diagnostic data is directly distributed through the network which causes overflow for operators and hardware. A high automation and integration level is required to support reduced manning and maximize the diagnostic support functions of the IPMS.

As IPMS systems become increasingly complex, negligence of human factors will automatically lead to systems that are more difficult to use, more problematic for training and less effective.
In addition, knowledge of the system will decrease rapidly and the operators will adapt with regard to the system deficiency with 'workarounds'.

Future IPMS require Human Machine Interfaces (HMI) for IPMS must assist the users optimally, with information at the right time at the right place required to operate, manage and maintain the technical installations, and in different States of Readiness. In such a task oriented IPMS, processing and visualization information needs to be adapted to tasks, roles and events, i.e. the information shall be matched to given functions or personnel levels (manager, operator, maintainer) of the platform system.

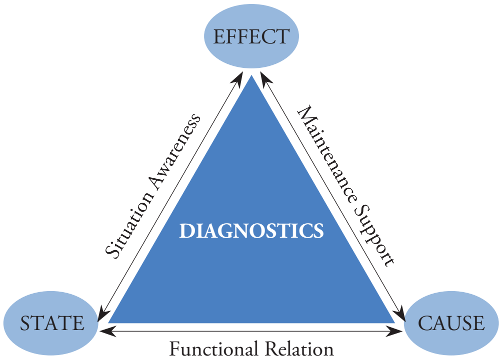
The level of integration and automation of individual components has a direct influence on the allocation of (maintenance) functions or tasks that can be performed by humans, hardware or software. According to RNLN, the diagnostic support function of the (integral) Platform Management System can be divided into three basic elements, namely:

- 'State Function', or availability of hardware and software components of the system or functional chain;
- 'Effect Function' which relates to disturbances of capabilities in the functional chain;
- 'Cause Function' for fault location and maintenance support.

This model is now being applied throughout all of RNLN new building and modernization projects and as a result, a more structured approach towards Human Factors and allocation of tasks to automated systems to reduce the workload and, subsequently, the size of the crew.

This is reflected in the approach of the (development of) automation systems for the Holland-class patrol vessels, particularly the Damage Surveillance and Control systems.

Fig. 1.



Holland Class PV Concept

In the operational concept of the newly build Patrol Vessels for the Royal Netherlands Navy (RNLN), the objective was to realize an unmanned Ship's Control centre. In the "Progamma van eisen voor het realiseren van een onbemande Technische Central", RNLN focused on the functions and tasks of the Automation System and appointing those to designated personnel, including authorizations, inhibits and individual man machine interfaces, such as workstations, mobile devices and communication equipment. This resulted in an advanced IPMS system with Flexible Function Allocation, which supports the crew in the operation (control and monitoring) of the platform systems.

Apart from the reduction of the workload during normal operation of the vessel, much emphasis was laid on the Damage Control Tasks, as historically these have a significant influence on the size of the complement not only for the marine engineering department, but also for the weapons and operational departments. Therefore, the main potential and resulting measures to reduce the (engineering) crew were considered two-fold, first to have an unmanned ship's control center and secondly to have a combined Command Bridge to direct all operations, including Battle Damage Repair. In addition, several automated fire-fighting systems were installed including a high pressure water mist system for machinery spaces and cabins. To determine how Battle Damage Repair management can be improved and supported using automation, and reduce the total complement, a workload analysis including task allocation was performed.

Theoretical Framework: Workload Analysis

Platform management processes particularly focus on operational capabilities while maintaining the safety of systems and crew. Even under normal operational circumstances this is a challenge for the complement of the 'Holland' Class Patrol vessels, but becomes paramount in the event of damage. In this case, the primary goal of the management is to create an overall Situation Awareness for correct decision making. This requires a very complex and layered organization and information model that is able to identify, assess and respond to a great variety of events that can occur. For the technical departments, platform management is directed towards the availability of operational capabilities, decomposed to the correct functioning of operators, maintainers, installations and components.

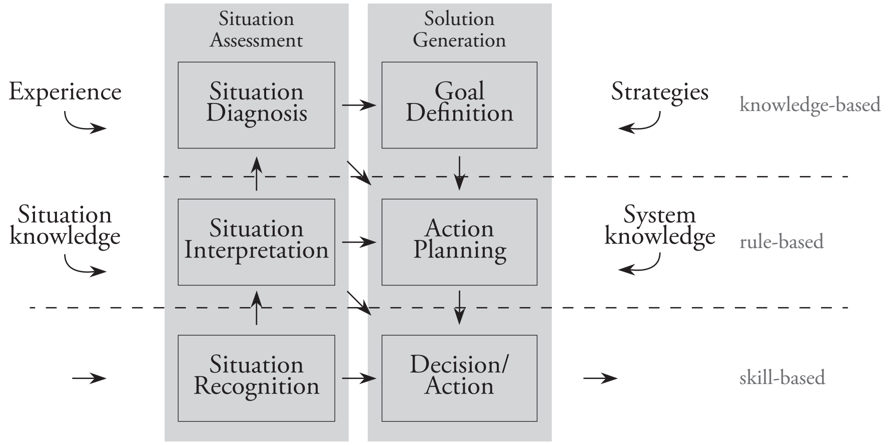
As a result, the technical departments' main objective is to provide with diagnostic information, i.e. Situational Awareness as well as operation and maintenance of the subordinate systems and installations. This requires in-depth knowledge of the platform systems and their interrelationships and implies that for all levels within the organization the goals (Command Aim) are known and projected on solving complex system problems.

Human Centered Approach

According to Rasmussen (5) information processing and decision making on board ships can be assigned based on three different levels (shown in the model below):

- *Skill-based (or natural) behavior:* predetermined signals are physically and automatically interrelated directly with one

Fig. 2.



or more actions to be performed (nature/ common sense).

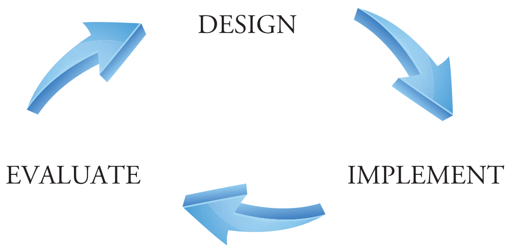
- *Rule-based (or procedural) behavior:* situations are interpreted according to general rules for a certain situation.
- *Knowledge-based behavior:* if there are no rules present, in e.g. a new situation, one will assess the situation by calling experiences and by building correlations between information triggers.

In the development of IPMS systems, like Imtech, most manufacturers only apply technical frameworks to make sure that the technical requirements will be met. As a result, human-related requirements are not involved at all. Absence of knowledge on intended operational processes on board is the main cause why the actual users are not happy with the delivered system, complaining that their tasks are not supported by the actual system.

For the development of the Battle Damage Repair support functions, a more Human Centered Approach was chosen to specify requirements and develop solutions for the DSAC support applications. The chosen approach actually fits the standard DIN EN ISO 13407 standard on human-centered design processes for interactive systems. The method calls can be summarized with the following model, and implies the following realization:

- Investigative research on intended workflow or work Description (tasks, decisions etc)
- Visualize the intended context of users and systems (objects, people, locations, communication and relations with other objects etc)
- Discussions with the intended users to document equirements and expectations.
- Evaluate interim ideas and concepts of the to be delivered system by any means of prototyping (e.g. screen shots, diagrams, material prototypes etc) and adapt the solution according to the results of these evaluations
- Evaluate the delivered system once it has been in operation for a number of months.

Fig. 3.



In 2010, the Royal Netherlands Navy and Imtech Marine & Offshore formed a Fire Fighting and Damage Control (FFDC) workgroup to address this problem and aforementioned approach to develop the necessary applications to support Battle Damage Repair.

For the initial contract, a number of requirements were formulated and agreed upon, resulting in a scope of work decomposed in multiple phases, including prototyping of the generated solutions against the 'improved' workflows or procedures. Evidently, the Royal Netherlands Navy concentrated on general starting points and (changing) tasks and procedures not only for the Holland Class Patrol Vessels but towards BDR in general while Imtech concentrated on the requirements and design of the necessary tooling and Platform Management Systems (IPMS) applications.

Situational Awareness and Performance Shaping Factors

The Performance Shaping Factors (PSF) as occurring in a BDR situation may lead to critical situations caused by human failures. One of the most important PSF is Situational Awareness.

Situational Awareness can be defined as the human percipience of the condition of an environment within an operational process. Situational Awareness has three (3) levels:

1. Perception, the cognition of the situation;
2. Comprehension, interpretation of the recognized situation;
3. Projection, estimation of the consequences of the situation.

Ideally, decisions are taken based on these three pillars, resulting in a changed environment in which new situational awareness is being established. Evidently, this process is iterative and will take place for every situation/incident within the Battle Damage Repair process, which is shown in the following picture. The quality of the model depends on other PSF, such as availability and presentation of information, communication but also experience of the individual.

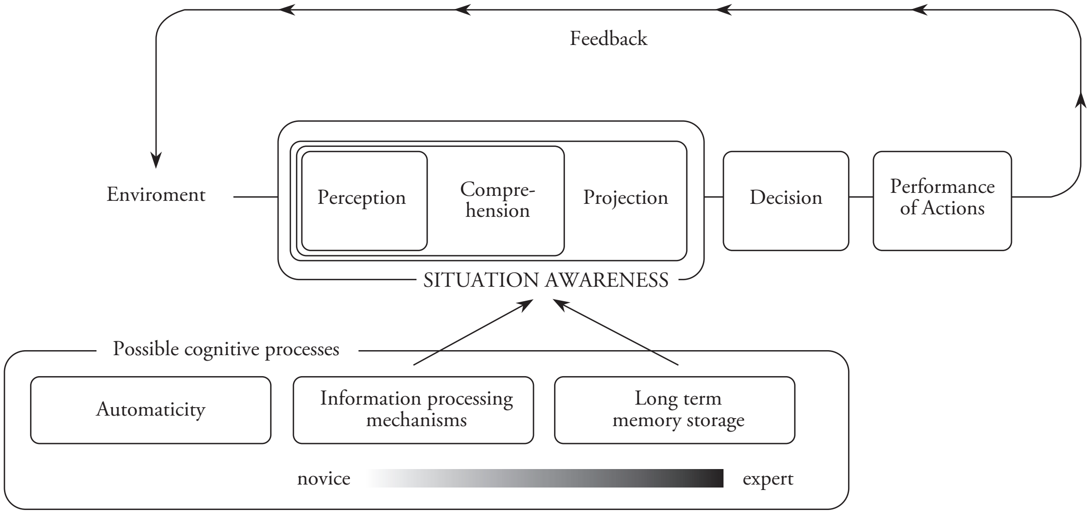
Another way of decision making is called 'automaticy', or an automated (conditioned) response. Although a certain level of experience or routine can increase the quality of decision making, automaticity is not the desired response on situational awareness and might result in human error.

Elimination of the occurrence of this effect can be realized by optimizing the Man Machine Interface, which was tested during the prototyping sessions and during the evaluation after delivery.

Workflow analysis approach

For gaining the actual deeper insights on the operational workflow of our IPMS-users, a workflow analysis was conducted according to the so-called GIVS-method. How this GIVS method works will be explained later in this paragraph. The research questions for this type of research were as follows:

Fig. 4. Situational Awareness Model.



- Which specific tasks can be distinguished per employee during a battle damage repair process?
- What specific information is needed to carry out each of these specific tasks?
- How do they gain this information? By consulting colleagues/ looking up the IPMS, using artefacts/relying on their own experience?
- When does decision making occur? What kind of information is used to make the decision and what are the consequences?
- In what parts of their workflow do they have to compose/update/revert to situation awareness (external/internal battle) in mental models? What kinds of information do they use to do so?
- What problems do occur during a procedure? When do they occur and what are possible causes and/or consequences?

To gain insights in the deeper layers of their workflow the the GIVS-method is applied, or better known as Generative Interview Visually Supported. GIVS is a common interview tool, to reveal the aspects as named in the research questions. By doing so, each of their personal tactics can be revealed in a one on one interview-like session.

Internal Battle / Battle Damage Repair

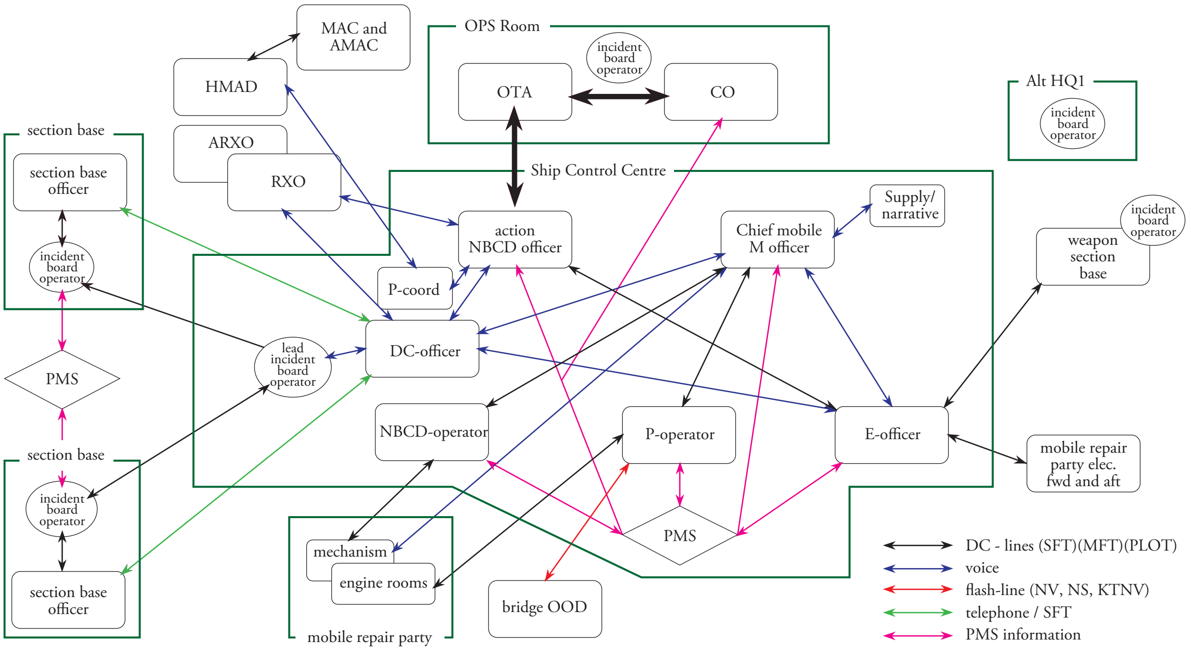
In order to understand the task analysis first the state 1 Battle Damage Repair (BDR) organization of a typical frigate that was analyzed is presented in below Fig. 5.

The BDR Organization picture illustrates the extent of manpower and information flow involved in managing the ‘Internal Battle’; the collective term for all activities to recover the maximum possible war fighting capability that supports the command aim after having suffered serious damage.

The purpose of the detailed task analysis described in this paper is to identify the tasks performed by the management team in the BDR organization that can be automated.

The Damage Control (DC) officer is in charge of this process. He directs the section base officers who manage the fire-fighting teams in their section, each covering half the ship. In the traditional situation the DC-officer and the section base officers share a number of tasks.

Fig. 4. Battle Damage Repair Organization.



Well trained section base officers will perform most of these tasks autonomously but they have to check their actions with the DC-officer and make sure the information is provided to him. For this reason the tasks the DC-officer and section base officers perform are presented in one column in the task analysis. Incident board operators support the DC-officer and section base officers. They keep the incident board up to date and communicate information to all other incident board operators, 6 in total. In the traditional situation two IPMS operators support the DC-officer, one operating systems and one executing electrical isolation under supervision of the Electrical (E) officer (DCO-L). However, they also perform tasks for the Mechanical (M) and Weapons-officer. The tasks the operators perform are presented in one column of the task analysis.

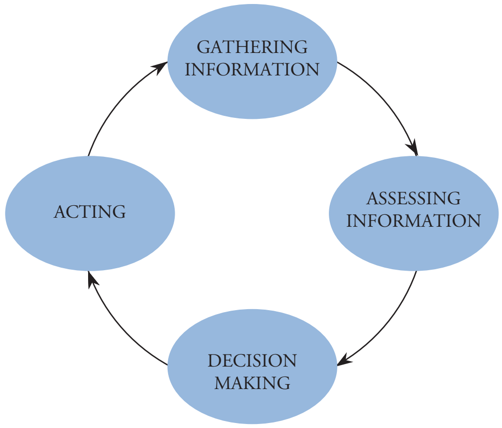
Patrol Vessel Battle Damage Repair Task Analysis

The purpose of a task analysis in this context is to identify the main drivers of the BDR organization. The scope is limited to the Platform Management System and thus the Damage Control and Marine Engineering Repair organization. It does not take into account the Combat Management System; the analysis excludes the Weapon Engineering repair organization. Of course, further integration of both organizations and corresponding management systems would be a significant improvement and will be a challenging subject for a future (integration) paper.

A rough Subject Matter Expert assessment describes the percentage of time BDR management spends on generic tasks. These tasks are subdivided in:

1. Gathering information (through communication and plotting),
2. Assessing information (to obtain situational awareness),
3. Decision making, and
4. Acting.

Fig. 6. BDR Activity Cycle



As illustrated in the above Fig. 6, these actions are performed in a continuous cycle, in accordance with the Situational Awareness Model of the previous chapter.

The task analysis was performed by a working group of Royal Netherland Naval officers, which all performed the role of DC-officer in their career, supported by an automation expert. The authors were part of this working group. The results of the task analysis are presented below.

Author's comment:
To incorporate Human Factors in the design of a new system it is necessary to identify, analyze and describe all functions that the system will perform, to be able to allocate functions or tasks to a person or technology. In the case of a ship's platform systems, this often exceeds the boundaries of the automation that is installed to actually control and monitor the installations. For an interdisciplinary or integral Platform Management approach, it is necessary to understand function allocation strategies.

A good example of flexible allocation is the auto-pilot in an aircraft or on a vessel, where highly trained and experienced operators can decide allocation of (sub)tasks to a highly complex control system.

Also, Operational Readiness functions have to be maintained and managed with Platform

Management Processes or Operating Procedures. By nature, these procedures / protocols are interdisciplinary and require a multi-level organization to manage, operate and maintain both Platform and Weapon systems. In order to achieve this, Operational Readiness Functions (Operation & Maintenance) have to be projected/mapped on actual Platform/Weapon interdependencies on an installation/component level, i.e. Functional Chains.

At this moment, these functions are neither integrated nor allocated in a (superordinate) automation system and therefore these complex tasks are left to the operators. In particular during live or exercise environment or scenarios this results in high cognitive and communicative loads.

Furthermore, the nature of these interdisciplinary tasks and functions like Battle Damage Control and Sewaco Support unavoidably leads to high cognitive and communicative loads.

Task Analysis of Battle Damage Repair

The task analysis results show that the fire-fighting management process includes numerous task performed by the DC-officer and section base officers, most taking place within the first 5 minutes after fire detection. Many of the tasks and corresponding actions directly affect the situational awareness, and are, by nature, iterative resulting in high communicative workload. Correct functioning of the BDR organization is further complicated as a result of the different locations in the ship and verbal communication doctrines.

The introduction of FFDC IEIB on the OPV provides a shared information space and reduces the required communication. This can potentially reduce the amount of plotters.

However the mere quantity of tasks the section base officer and DC-officer need to perform in the first 5 minutes after an incident remains large. Therefore, it was also investigated what tasks of the fire-fighting organization can be automated in order to support manning reduction.

In order to understand the results of the task analysis first the generic tasks and how these are performed are described. Subsequently an estimate is given of the time spent on these tasks by the BDR team.

Gathering information, narrative

The information on the extent of damage after a hit of the ship by external projectiles is gathered by executing a physical 'blanket search' by the crew of the ship while in parallel the IPMS generates alarms that indicate potential problems.

With the 'blanket search', every single compartment is physically checked by teams of two crew members that subsequently vocally report the damage through the BDR organization following the communication lines illustrated in the BDR Organization. This means information on the damage is communicated to the SCC and ultimately the NBCD Officer over 3 to 5 levels.

Damage related to leakages and fires is first gathered in the section base by the Section Base Officer (SBO) and plotted on the incident board by the section base plotter there. Subsequently, this information is verbally communicated to all other stations, including the SCC, through the plotter over a DC communication line. At these stations this information is plotted again on the incident board. Therefore, the quality of the information on the incident board strongly depends on the quality of communication that takes place under stress. It is clear that the information on the incident boards often is out of date, incomplete and inaccurate, even if the information is available at the section base. It's also evident that this communication and plotting process is very manpower intensive. Fortunately the information on the SCC incident board is available for the whole SCC team.

Damage related to mechanical and electrical systems is communicated to the Mechanical and Electrical Officer respectively. These officers gather this information on their personal state board and subsequently report their top priorities to the NBCD Officer and other team members that need to know. Again, the gathering of information is manpower intensive. The information on the incident boards is often inconsistent, of a low quality and not available for the whole SCC team. Plotters and messengers spend 100% of their time on gathering and presenting information, the managers in the SCC an estimated 50% of their time, the SBO's around 40% or their time as they have their individual plotters and a single hierarchical structure and the operators in the SCC around 20% of their time as their primary task is operating the ships systems through the IPMS. The numbers are presented in the table below.

Assessing information

All the managers in the SCC and in the section base need to assess the incoming information to obtain situational awareness. Although not always consistent and often inaccurate the DC incident boards provide a good means to obtain situational awareness on DC incidents for all managers in the SCC. The availability of technical systems, although often indirectly available in the Platform Management System.´(IPMS) is not presented in any way to the management, other than scrolling through the enormous amount of MIMIC presentations in the IPMS. Therefore every team member acts on the information he or she has available for him- or herself on the personal state board. It needs no explanation that the situational awareness of the team is not consistent and often inaccurate. In order to overcome this operators and managers maintain handwritten lists of system availability that are stuck to the SCC wall to release information for the whole team.

The managers in the BDR organization on average spend 30% of their time on assessing information, as presented in below Table 1.

Decision Making

Because information is not presented in a structured way and because information has to be gathered from multiple sources that do not communicate related information simultaneously, only very limited time is available for decision making. What makes it even more challenging is that often decisions are requested from the lower hierarchical levels but the information required to take the right decisions is not readily available. This has two effects: The quality of the decisions is not optimal and the time spent on decision making is very limited: estimated between 10 and 30% of the

Table 1. BDR Task Analysis.

	Gather information (comm's and plot)	**Assess information: situacional awareness**	**Decision making**	**Acting: repetitive operator sequence**
NBCD Officer	50%	30%	20%	
Damage control officer	50%	30%	20%	
Survivality operator	20%		10%	70%
Plotter DCO	100%			
Plotter SBO FWD	100%			
Plotter SBO AFT	100%			
SBO FWD	40%	30%	30%	
SBO AFT	40%	30%	30%	
Messenger FWD	100%			
Messenger AFT	100%			
Mechanical Officer	50%	30%	20%	
Mobility Operator	20%		10%	70%
Electrical Officer	50%	330%	20%	
Electrical Operator	20%		10%	70%
TOTALS 14	**840%**	**180%**	**170%**	**210%**
Overall percentage	**70%**	**13%**	**12%**	**15%**

available time. Again these numbers are presented in the table.

Acting

Acting comprises:

1. Execution of operator sequences determined in the analysis and
2. Deployment of Battle Damage Repair teams (to fight fires, stop leakages and repair systems).

The execution of operator sequences under stress often causes errors and takes the focus away from sufficient communication and maintaining situational awareness. Therefore SCC officers are all supported by an operator. The execution of repetitive operator sequences requires significant manpower and the high workload of the operator causes operator errors. The operators are executing operator sequences (that can be automated) 70% of their time spending their remaining time on communicating their actions to the SCC officers.

The deployment of Battle Damage Repair teams takes the reverse route of the information on the incidents. Due to the overload of communication lines often the deployment of these teams is delayed as officers are awaiting confirmation of their priorities and thus where to send the limited amount of resources. The time spent on ordering the deployment of Battle Damage Repair teams is included in the tasks decision making and communication (gathering of information taking place in both directions).

Conclusions of task analysis

To build up the desired awareness of the overall damage situation the management of the Damage Control Organization spends approximately 50% of her time on communication. Communication between the scene of an incident and the Ships Control Centre may take place over as many as 5 levels. This is time consuming and still can result in an incomplete picture. The Damage Control Organization requires a system that achieves significant reductions in the amount of communication and related workload and provides a consistent situational awareness across the BDR organization.

In order to make the right decisions, the technical management in the Ships Control Centre (the NBCD officer, the mechanical officer and the electrical officer) requires a good overall awareness of the situation. On today's ships, these officers rely for 80% of their information on communication even though the information on the status of all technical systems is available in the IPMS. The technical management in the SCC requires a system that provides a clear, commonly accessible, overall picture of the technical systems and their status in relation to the Command Aim.

The operators in the Ships Control Centre experience a high workload. This is partly caused by the time required for repetitive operator sequences and high communication and cognitive loads. A system is required that automates repetitive sequences and assists the operator in analyzing the effect of alarms, can reduce the workload and increase the effectiveness of the operator.

Design of Task Oriented Based FFDC Applications

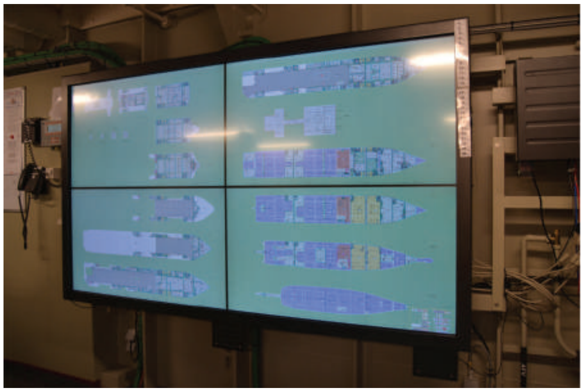
Interactive Electronic Incident Board

One of the first objectives of the FFDC Workgroup was to re-design the electronic plotting aids. This resulted in an Interactive Electronic Incident Board that combines a conventional plotter screen with a distributed FFDC automation and Multi-Touch displays. This feature also allows presentation of other applications, such as CCTV, which provides immediate access to visual information about the scene of the incident directly on the IEIB displays.

This FFDC application ensures that entered information is distributed to all electronic incident boards and workstations across the ship, ensuring the available information is consistent across the ship. This also includes interfacing with ships' automation system with information of fire detectors, doors, hatches, etc.

This FFDC application ensures that entered information is distributed to all electronic incident

Fig. 7. JSS Interactive Electronic Incident Board.



boards and workstations across the ship, ensuring the available information is consistent across the ship. This also includes interfacing with ships' automation system with information of fire detectors, doors, hatches, etc.

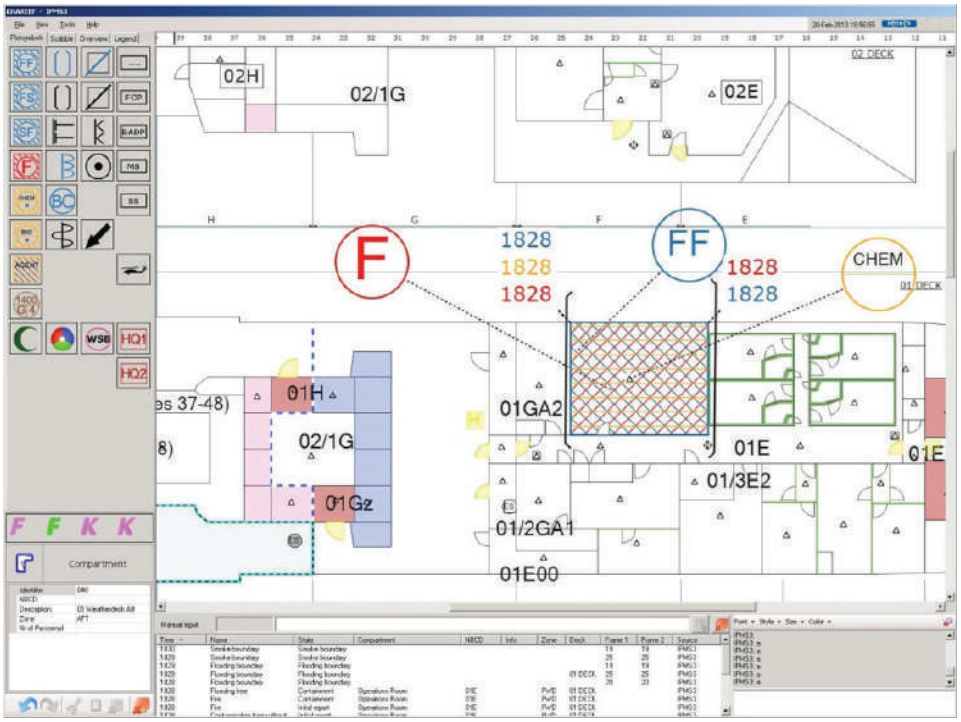
From every FFDC position it is possible to plot symbols like fire, boundary cooling and smoke boundaries, either through mouse and keyboard, or via multi-touch displays. Every type of symbol has its own specific properties and stages. The plot symbols are electronic version of the symbols defined in the Royal Netherlands Navy standard KN 15750. This makes it easy for personnel on board to switch from the conventional incident board (where the plotter draws the symbols by hand) to the FFDC HMI.

Selecting a plot symbol from the library and dragging it into a compartment is a user-friendly approach for placing a symbol on a desired spot. Subsequently, the state and time of the symbol becomes automatically available on all FFDC stations. In the FFDC HMI all kinds of features have been implemented to meet requirements for optimal control of the application, particularly under stress conditions. In the FFDC overview screen it is possible to present all kinds of important information for BDR. The FFDC HMI stores this information in layers. It is important that at any given time only the relevant and required information is presented; other information layers can be hidden.

Examples of information layers are:

1. A and B-type fire wall layer;
2. Citadel information layer;

Fig. 8. Interactive Electronic Display Mimic.



3. Safety and fire equipment layer;
4. Hazardous equipment layer.

A free scribble option of the FFDC HMI gives the operator the possibility to draw (and share) lines (e.g. attack and evaluation routes) and to place texts in the Deck view window of the FFDC plotter screen.

The IEIB was specifically designed and tested to increase situational awareness while at the same time reduce communication.

Wireless Hand-Held Devices

A second application that resulted from the working group are the Hand Held devices, or PDA's that are deployed on the Holland Class PV. Engineers can use PDA's to display the status of the systems when operating the equipment, during planned maintenance and in case of incidents. As a result, the Ship's Control Center can be unmanned, while duty personnel are 'online' and have access to the designated systems anywhere on the vessel.

For Battle Damage Repair the integration of wireless connected handheld devices can be used to optimize local tasks/actions and increase situational awareness. For example, the handhelds allows team leaders to directly enter information from the scene of the incident into the FFDC system, while the FFDC system ensures that information is shared almost instantaneously and can make plotters redundant.

Battle Damage Repair Procedure Application

A system to program and execute BDR procedures is under development that can automate repetitive sequences and assist the operator in analyzing the effect of alarms, thus reducing workload and increasing the effectiveness of the operator.

In general, it is not too difficult to automate functions and sequences, a feature which is already incorporated in Imtech Platform Management System (IPMS).

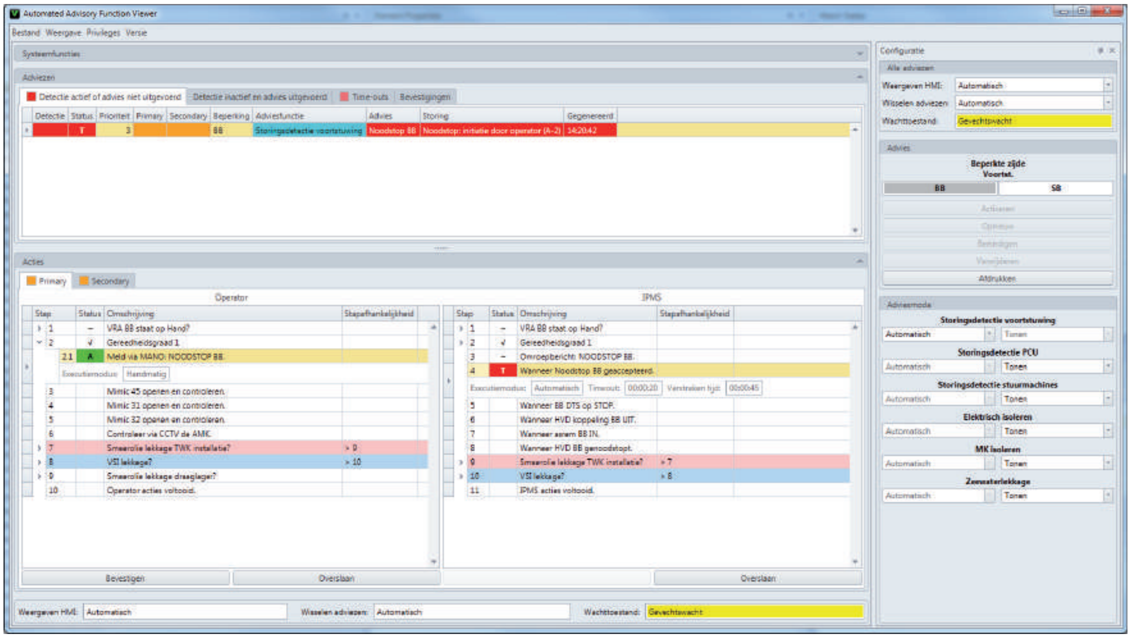
Fig. 9.

However, as mentioned in chapter 2, automaticity also has drawbacks and BDR automated sequences have to be specified way in advance when the software is configured or hard coded. This is particularly the case for sequences that depend on the various conditions or sensor information. This causes another serious drawback as the definition of procedures depends heavily on experience which is obtained over the life cycle of a ship.

This insight initiated the requirement of the Royal Netherlands Navy for an Advice Builder, an application that enables designers as well as operators to assemble procedures during the engineering phase and during the time that the ship is in service. The Imtech IPMS used on modern ships of the Royal Netherlands Navy already includes 'Apps' that allow external systems to give commands to virtually any ship system that is monitored and controlled by the IPMS. That enabled the workgroup to acquire a better understanding of the real requirements. This resulted in an application comprising four parts:

1. a Procedure Module in the IPMS filled with the available procedures;
2. a dedicated HMI interface to the operator;
3. 'App' within the IPMS responsible for executing the triggers and steps;
4. an Advice Builder to be used for configuration of the procedures.

Fig. 10. BDR Procedure mimic.



Detectie	Status	Prioriteit	Primary	Secondary	Beperking	Adviesfunctie	Advies	Storing	Gegenereerd
	T	3			BB	Storingsdetectie voortstuwing	Noodstop BB	Noodstop: initiatie door operator (A-2)	14:20:42

Operator

Stap	Status	Omschrijving	Stapafhankelijkheid
1	–	VRA BB staat op Hand?	
2	√	Gereedheidsgraad 1	
2.1	A	Meld via MANO: NOODSTOP BB.	
		Executiemodus: Handmatig	
3		Mimic 45 openen en controleren.	
4		Mimic 31 openen en controleren.	
5		Mimic 32 openen en controleren.	
6		Controleer via CCTV de AMK.	
7		Smeerolie lekkage TWK installatie?	> 9
8		VSI lekkage?	> 10
9		Smeerolie lekkage draaglager?	
10		Operator acties voltooid.	

IPMS

Stap	Status	Omschrijving	Stapafhankelijkheid
1	–	VRA BB staat op Hand?	
2	√	Gereedheidsgraad 1	
3	–	Omroepbericht: NOODSTOP BB.	
4	T	Wanneer Noodstop BB geaccepteerd.	
		Executiemodus: Automatisch Timeout: 00:00:20 Verstreken tijd: 00:00:45	
5		Wanneer BB DTS op STOP.	
6		Wanneer HVD koppeling BB UIT.	
7		Wanneer asrem BB IN.	
8		Wanneer HVD BB genoodstopt.	
9		Smeerolie lekkage TWK installatie?	> 7
10		VSI lekkage?	> 8
11		IPMS acties voltooid.	

Weergeven HMI: Automatisch
Wisselen adviezen: Automatisch
Wachttoestand: Gevechtswacht

Beperkte zijde
Voortst.
BB SB

Storingsdetectie voortstuwing: Automatisch / Tonen
Storingsdetectie PCU: Automatisch / Tonen
Storingsdetectie stuurmachines: Automatisch / Tonen
Elektrisch isoleren: Automatisch / Tonen
MK isoleren: Automatisch / Tonen
Zeewaterlekkage: Automatisch / Tonen

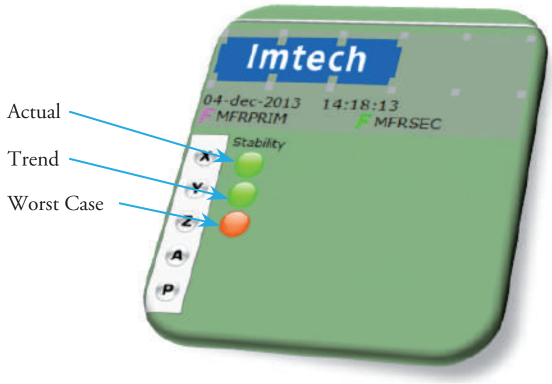
The Procedure Module resembles a database filled with procedures that have been designed, and subsequently tested, on shore-based facilities. The 'App' within the IPMS will start a specific Procedure once the pre-defined condition of that Procedure is met. There are 3 types of procedures

1. Alarm procedures are procedures initiated by the activation of an alarm. These procedures are often used to handle problems of platform systems;
2. Engine Room Emergency Measures are procedures relevant to the safe navigation of the ship. These can be initiated by an alarm or from a comparison of in the IPMS available plaform signals;
3. Killcards are procedures which can be selected by an operator via a drop-down list box in the IPMS mimic. The Killcards are sorted by section, deck, position and type of killcard (Fire, Energy, Flooding).

Procedures are presented in a dedicated IPMS Procedure Mimic. In mode Auto, the procedure 'App' will carry out the procedural steps. In modes Semi-Auto and Manual, the procedure App will wait upon operator acceptance. Each step implies executing a command and waiting upon start conditions for the next step. Below Fig. 10 shows the HMI of the IPMS Procedure Module. The 10 buttons on the left side of the procedure mimic depict the active procedures and the type of the procedures. The color of the buttons indicates the status of the procedures: Green for active and Red for a failure of a procedure.

Stability Management System (currently under development)

Fig. 11. Stability Status Application



The stability management system shows the ship stability in the event of an incident. Normally this will only be the tank levels for they have a major impact on the ships stability. But there are more events that can cause ship instability on board, of any kind of vessel. One of this causes are leakages, whether they are internal leakages (oil leakage, defective pipes, water used for fire extinguishing, etc) or external leakages (collision or impact damage) they can play a crucial part in maintaining the ships stability.

Within the Interactive Electronic Incident Board it is possible to set leakage plot symbols on the general arrangement containing information about the kind of leakage (oil, water, etc.) and a list of all the known water levels related with the leakage.

Together with the water levels, this information will be automatically processed by a ships stability application which calculates the impact on the ships stability. As a result, the IEIB will show the user three stability states each with three severity indicators:

- *Green* - No danger for ships stability, no further action needed.
- *Orange* - Possible danger for ships stability, further action desired.
- *Red* - Ship stability is in grave danger, instant action needed.

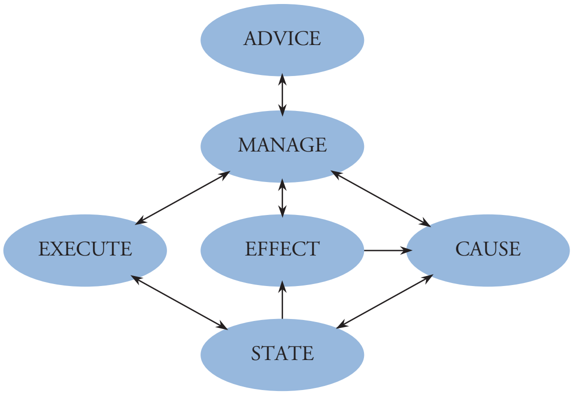
The Stability Management System gives the crew a comprehensive status of the current stability and where it might lead to if no counter actions will be made. And because it is all integrated, the crew will only have to update the IEIB which saves time feeding the system with stability information.

Future Developments

Operational Maintenance Support Model

As a baseline for future integration of multiple technical disciplines and maintenance tasks, the RLNL developed an enhanced Battle Damage Repair Activity Cycle or 'Operational Maintenance Support Model', including following discrete elements and tasks:

Fig. 12.



1. **State:** Operational State of the System and it's components as indicated through the automation system or manually identified and documented.
2. **Effect:** Availability of the Function translated to other Systems and Capabilities.
3. **Cause:** Troubleshooting by means of Diagnostics (BITE) or through the experience and training of the crew.
4. **Execute:** Measures (Procedures) to correct malfunctioning equipment
5. **Manage:** Reduce the impact of malfunctioning and maintain the desired Capabilities.
6. **Advice:** Interaction between operational objectives and Capabilities of the vessel.

As the State of discrete elements like technical systems and components form the foundation for this model, the information available within the automation systems (I/O, BITE messages) are paramount.

To predict the effect of one discrete element, operational requirements and platform capabilities must be decomposed or projected on the configuration of all participants that contribute to a particular function. This so called 'Functional Chain Analysis', has already been utilized in the diagnostic features of RNLN Combat Management Systems, however they exclude platform systems.

For future Frigate projects of the RNLN, this method will be applied to support maintenance and crew reductions by means of automation.

Platform/Weapon Integration

The CMS support systems typically consist of three important functions.

1. Power Generation
2. Electrical Distribution
3. Heating, Ventilation & Cooling (chilled water)

For the Holland Class PV, the functional dependency between platform and CMS was not integrated in the automation systems. However, to achieve the Operational Requirements with a reduced complement, the RNLN decided to develop a Command Bridge comprising of Navigation Bridge, CIC and SCC. Battle Damage Repair can also be directed from the Engineering Office, depending on the operational scenario.

However, as mentioned earlier, for the future Frigate project, platform and CMS (automation) systems will be integrated using a generic data-bus system and diagnostic data elements including applications to process this information according the Operational Maintenance Support Model.

Fig. 13. Command Bridge.

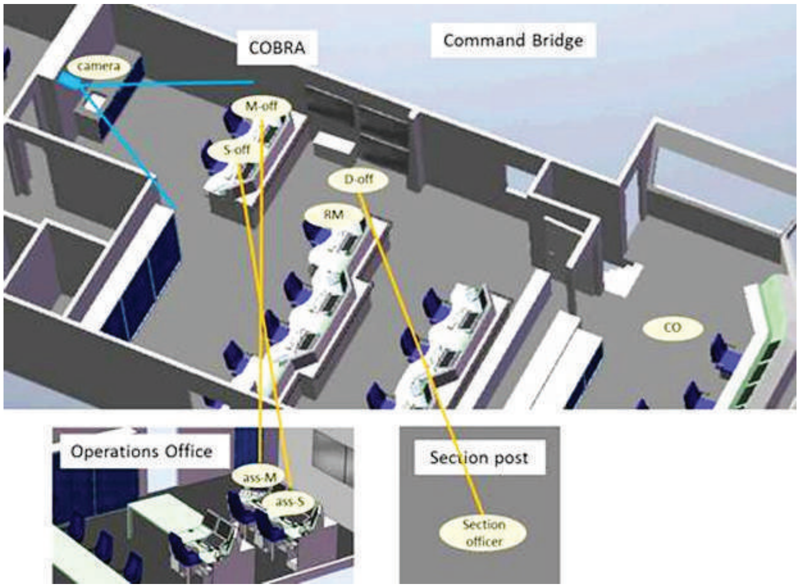
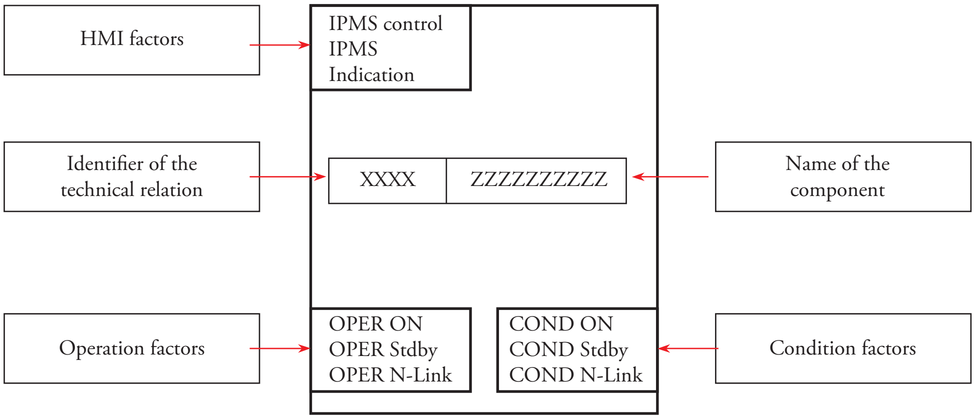


Fig. 14. Generic Data Element.



Distributed Intelligent Networked Control Systems

On board Royal Netherlands Navy ships many complex platform support systems exist such as cooling systems, electrical systems, and fire extinguishing systems. The complexity of these systems is hard to manage for the personnel, especially in case of emergency when reaction times have to be short. The problem is made worse by the decreasing availability of highly qualified personnel over the last decade. Both problems are reason for the Defence Materiel

Organization (DMO) to create control systems that can autonomously restore the functionality of the platform support systems in case of (battle) damage, taking into account the ever changing and uncertain status of these platform support systems.

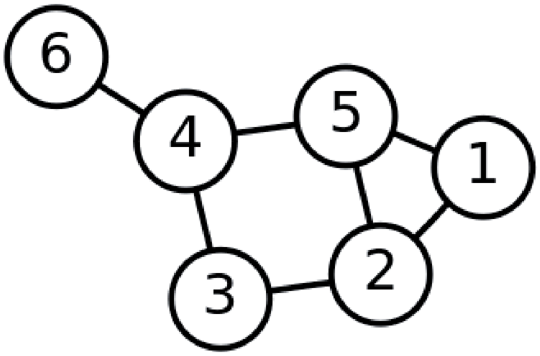
The approach is to create intelligent components such as chillers, pumps, valves, sensors, and end users, and to give these intelligent components human-like reasoning. In real life, the human operator will always follow three steps when dealing with a damaged system, irrespective of the physical nature of that system: (1) isolating the damaged part from the rest of the system to prevent further damage; (2) finding new supply paths to the end users of the system so as to restore the system's functionality; and (3) supplying the end users with the correct amount of what they need (e.g., cooling, electricity). In a research project performed by TNO, intelligent agents were created with three levels of intelligence that contain these steps. These agents communicate with each other through a shared network. If part of the control system is lost, the remaining agents are still able to communicate with each other and control the part they have access to.

The DINCS engine or algorithm is based on a 'Graph' representation, similar to contemporary navigation systems, which is decomposed in following elements/definitions:

- Platform system comprises of:
    - − Platform Devices (Pumps, Valves, Generators)
    - − Connections (pipes, cables, ducts)
- Mathematically represented as Graph by:
    - − Edges
    - − Nodes
- Properties of Edges / Nodes:
    - − One-direction
    - − Cost (usage of resources, wear and tear (running hours))
    - − Capacity
    - − Priority
- Mathematics provided algorithms for:
    - − Shortest path
    - − Maximum flow
    - − Minimum cost

The DINCS prototype is currently implemented for the fire mains system of RNLN LPD Rotterdam, as part of an upgrade of the (Imtech) automation system.

Fig. 15. DINCS mathematical model.



Conclusion

Operator Load analysis are paramount in the development of future Automation Systems, in particular Damage Surveillance And Control systems. The development of applications must incorporate operational management as well as functional interrelationships between platform systems. As a result application of technological advances can only be realized in close cooperation with intended users and designers. For the Patrol Vessel of the RNLN this was realized by a joint project team, task- and workload analiyisis supported by a rapid prototyping development model.

This working method not only proved very effective but also unveiled substantial potential for future developments, which RNLN will implement successively.

Acknowledgements

This paper contains a logical compilation of earlier studies performed by Imtech and personnel of the Netherlands' Defense Material Organization. Although major authors have been listed, the proceedings described in this document, surely could not have been established without the commitment of the FFDC workgroup members, the project teams and many other people who have contributed to the fundamental research.

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Structural Analysis of an Aluminum Multihull

Análisis estructural de un Multicasco de aluminio

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Claudio Troncoso[4]

Abstract

Structural analysis of a multihull is relatively complex since the connecting structure introduces additional stress than those typical of a monohull. The aluminum trimaran presented in this work was designed within the framework of the research project "Conceptual Design of a High-performance Vessel for Passenger Transport in Chile's Austral Zone". The trimaran was structurally measured using the regulations of classification societies *Germanischer Lloyd, Det Norske Veritas* y *Lloyd´s Register*. For the scantlings obtained with each regulation a Finite Element Model was created and the structural analysis for the slamming and splitting moment events was made. The results were analyzed and the stress concentration zones were determined to compare them with admissible stresses and conclude whether the structural sizing adequately and safely responds to the design stresses.

Key words: Multihull, structural analysis, finite elements.

Resumen

El análisis estructural de un multicasco es relativamente complejo debido a que la estructura de unión entre los cascos introduce esfuerzos adicionales a los típicos de un monocasco. El trimarán de aluminio presentado en este trabajo fue diseñado en el marco del proyecto de investigación "Diseño Conceptual de Embarcación de Alto Desempeño para el Transporte de Pasajeros en la Zona Austral de Chile". El trimarán se dimensionó estructuralmente usando los reglamentos de las sociedades de clasificación Germanischer Lloyd, Det Norske Veritas y Lloyd´s Register. Para el escantillonado obtenido con cada reglamento se creó un Modelo de Elementos Finitos y el análisis estructural se llevó a cabo para los eventos de *slamming* y *splitting moment*. Se analizaron los resultados y se determinaron las zonas de concentración de esfuerzos para compararlos con los esfuerzos admisibles y concluir si el dimensionamiento estructural responde en forma adecuada y segura a las cargas de diseño.

Palabras claves: Multicasco, análisis estructural, elementos finitos.

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Introduction

Structural analysis using the Finite Elements Method is a tool for structural design of vessels, that allows verifying if the structural sizing complies with the established acceptance criteria and to determine points of stress concentration, according to the admissible loads hypothesis in the analysis.

The purpose of this work is to analyze the structural response of a multihull vessel, designed in aluminum, by constructing a Finite Elements Tridimensional Model, for each structural sizing calculated using the regulations of the classification houses "Germanischer Lloyd" (GL), "Det Norske Veritas" (DNV) y "Lloyd´s Register" (LR). The results obtained for each of the models are compared with the established acceptance criteria for each classifiers. Recently, using the finite elements method, Morris (1991) and Ojeda *et al.* (2004) performed different structural analyses to multihull vessels were they identified the stresses and deformations of the structure; using the same method, Paik and Hughes (2006) and Blanchard and Chunhua (2007) analyzed the different cargo conditions established by different classification houses were they highlight the Slamming load in the Crest Landing and Hollow Landing moments and the Splitting Moment.

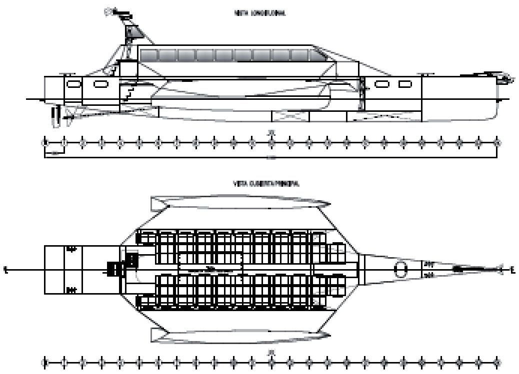
Table 1. Main Trimaran Characteristics.

Characteristics	Dimensions
Waterline length	24,00 m
Lateral hull length	9,48 m
Maximum beam	7,91 m
Main hull beam	2,60 m
Lateral hull beam	0,72 m
Depth	2,30 m
Distance between hulls	3,50 m
Design draft	1,20 m
Block coefficient	0,387
Displacement	31,6 Ton
Design speed	30 Kn
Propulsive power	800 kW

Vessel Characteristics

The vessel being analyzed is a Wave Piercing multihull trimaran defined by Tampier (2013) as the "design that offers the best set of good sea keeping capacities, transversal stability, ease of distribution and the least power requirement". The main characteristics of this ship are shown in Table 1., the same way presented in the general assembly of the ship in Fig. 1.

Fig. 1. General Trimaran Design.



Source: Tampier (2013)

Cargo Conditions

According to Cheng and Mayoss (2007) for small and medium vessels, the main criteria governing structural design are local stresses. Theses types of stresses are produced by those events that make a vessel's structure be in the most unfavorable condition during the navigation period. However, considering that the vessel being analyzed is multihull some global events must also be evaluated, as follows:

Slamming event of the hull

This occurs when the vessel suffers a severe impact against the water as a result of a pitch and heave movement at advancing speed. This is a strong and intense impact that generates large hull pressures; this event is one of the most common causes for structural damage of the hull.

GL classification houses establishes that slamming pressure acts between 0,5L y 0,8L; and calculates it using the following equations:

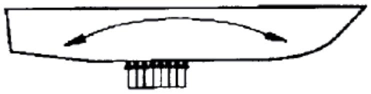
$$P_{sl} = 70 \cdot \frac{\Delta}{S_r} \cdot K_1 \cdot K_2 \cdot K_3 \cdot a_{cg} (kN/m^2) \qquad (1)$$

Where:

Δ: displacement, in tons. $\cdot \frac{\Delta}{T}$
S_r: reference area, n m^2 and equal to: $S_r = 0,7$
K_1: longitudinal hull impact factor; 1 para 0,5≤x/L≤0,8
K_2: impact area factor; equal to 0,5. $K_3 = \frac{(70 - a_d)}{(70 - a_{dCG})}$
K_3: Deadrise angle factor; equal to: ; a_{dCG}, this is the deadrise angle of the LCG (Longitudinal Center of Gravity) and a_d, the deadrise angle at the area of calculation.
a_{CG}: Vertical design acceleration at the LCG.(m/s^2)

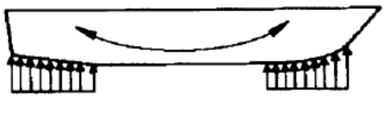
The DNV classification houses analyzes the slamming event experienced by a vessel during navigation during two moments; the moment of crest landing (CL) (Fig.2), happens when the vessel lands on the crest of the wave, this pressure acts upon the reference area placing this area at the LCG. The Hollow landing (HL) moment occurs when the vessel falls upon the hollow of the wave (Fig. 3); likewise, this pressure acts upon the reference area which is divided between the bow and the stern in this case. The mentioned reference area (AR) is found using equation (2).

Fig. 2. Moment of Crest landing.



Source: Ojeda et al. (2004)

Fig. 3. Moment of Hollow landing.



Source: Ojeda et al. (2004)

$$A_R = k\Delta \left(\frac{1 + 0,2 \, \frac{a_{cg}}{g_0}}{T} \right) \qquad (2)$$

Where

A_R: reference area (m^2)
$k = 0,7$
Δ: displacement in tons
T: design breadth (m)
g_0: acceleration of gravity (m/s^2)
a_{cg}: vertical design acceleration acting upon the center of gravity (m/s^2)

The slamming pressure that acts upon the previously mentioned reference areas is found using equation (3):

$$P_{sl} = 1,3 \, k_l \left(\frac{\Delta}{nA} \right)^{0,3} T_o^{\,0,7} \; \frac{50 - \beta_x}{50 - \beta_{cg}} \, a_{cg} \qquad (3)$$

where:

P_{sl}: slamming pressure on the hull (kN/m^2)
K_l: longitudinal distribution factor
n: number of hulls
A: design area for the considered element (m^2)
T_o: breadth in L/2 (m)
Δ: displacement (Ton)
β_x : deadrise angle of the transversal section to consider (minimum 10° maximum 30°)
β_{cg}: deadrise angle at the center of gravity (minimum 10° maximum 30°)
a_{cg}: vertical acceleration of design (m/s^2)

The LR classification houses establishes that the slamming pressure is exerted by the hull between 0.8L and L of the main hull and stabilizers is given by equation (4):

$$IP_{bi} = f_{bi} \left(19 - 2720 \left(\frac{T_x}{L_{wl}} \right)^2 \right) \sqrt{(L_{wl} V_{sp})} \qquad (4)$$

Where:

IP_{bi}: slamming pressure at the hull (kN/m^2)
f_{bi}: impact factor at the hull, equal to 0,18
T_x: design breadth (m)
V_{sp}: service speed or 2/3 of maximum speed. (knots)

Slamming event at the connection deck

This event occurs due to pitch and heave at the vessel´s advance speed, which produces a strong impact on the water against the connection deck of the lateral hulls of the main hull. This phenomenon is magnified by the funneling effect produced between the lateral and main hulls.

The GL classification houses established that slamming pressure on the connection deck will occur when the distance between the bottom of this deck and the design water line is less than $z_{wd} = 0{,}05L$; likewise this pressure acts between 0,8L and L. (Equation 5)

$$P_{sl} = 3 \cdot K_2 \cdot K_{WD} \cdot V_x \cdot V_{SL} \cdot \left(1 - 0{,}85\left(\frac{H_A}{H_s}\right)\right)(kN/m^2) \tag{5}$$

where:

V_{sl}: relative impact speed, equal to: $V_{sl} = \left(\frac{4H_s}{\sqrt{L}}\right) + 1$(knots)
H_S: significant height of wave (m)
K_{WD}: impact factor of the connection deck; 1 for x/L≥0,8
V_x: vessel speed (knots)
H_A: distance between the design water line and the connection deck (m).

The DNV classifier house establishes that the slamming pressure on the connection deck is found using equation (6)

$$P_{sl} = 2{,}6k_t\left(\frac{\Delta}{A}\right)^3 a_{cg}\left(1 - \frac{H_C}{H_L}\right) \tag{6}$$

where:

P_{sl}: slamming pressure at connection deck (kN/m^2)
Δ: displacements (Ton)
A: design area for the considered element (m^2)
a_{cg}: design vertical acceleration (m/s^2)
H_C: minimum vertical distance between the buoyancy line up to the connection deck (m)
H_L: height margin necessary from the buoyancy line up to the connection deck to prevent slamming; . $H_L = 0{,}22l\,(K_c - \frac{0{,}8}{1000}L)$ (m)
K_c: height margin factor, $K_c=3$

For the LR classification houses the slamming pressure upon the connection deck is exerted between 0.8L and L of the mentioned structure and is given by equation (7):

$$IP_{wi} = f_{imp}\, k_f\, V_R\, V_{sp}\left(1 - \frac{G_A}{1{,}29H}\right) \tag{7}$$

where:

IP_{wi}: slamming pressure over the connection deck (kN/m^2)
f_{imp}: impact factor equal to 1/3
k_f: longitudinal distribution factor, equal to 2
V_R: relative vessel speed at the moment of impact, is equal $V_R = \frac{8H}{\sqrt{L_{wl}}}$ (knots)
G_A: distance between the connection deck and the design water line (m)
H: significant wave height, equal to 4.

Also, for the model to adequately represent reality, the hydrostatic pressure exerted by the sea over the hull of the vessel was considered. The effects of inertia forces due to vertical acceleration were also taken into consideration. Table 2 shows the pressure according to each classification houses. It should be mentioned that slamming pressure for the DNV classification houses is less because of design acceleration, calculated with this regulation, is less than the one calculated with other regulations, as well as the maximum admissible stress, which is less with this regulation.

Table 2. Slamming load over the hull and connection deck.

Model	Slamming Hull	Slamming Connection Deck
GL	74,25 kN/m^2	91,16 kN/m^2
DNV	61,51 kN/m^2	55,86 kN/m^2
LR	70,80 kN/m^2	138,13 kN/m^2

Splitting moment or lateral hull separation moment

This event occurs when due to the force of the waves, the lateral hulls are pressured to move closer or further away from the main hull, giving rise to structural tensions on the connection deck. To simulate this event, the classification houses establish that a force must be applied that generates the value of the transversal flexion moment, which can also be generated applying pressure to the lateral hulls that generate the calculated moment.

The GL classification houses establishes that the transversal flexion moment is found using equation (8):

$$M_{bt} = \frac{\Delta \cdot b \cdot a_{cg} \cdot g}{5} \tag{8}$$

where:

M_{bt}: moment of transversal flexion (kNm)
b: transversal distance, in meters, between the central lines of both hulls
g: acceleration of gravity, 9,81 m/s^2.
a_{cg}: vertical design acceleration at the LCG. (m/s^2)

The DNV classification houses establishes that the transversal flexion moment for a multihull is found using equation (9):

$$M_s = M_{S0} + f_y (z - 0{,}5T) \tag{9}$$

where

Ms: moment of transversal flexion (kNm)
MS_0: moment of transversal flexion in calm waters, $MS_0 = 4{,}91\Delta(y_b - 0{,}4B^{0{,}4})(kNm)$.
Y_b: distance between the central line of the central hull to the lateral hull (m)
B: Maximum beam(m)
f_y: separation force at the submerged area

$$f_y = 3{,}25\left(1 + 0{,}0172\,\frac{V}{\sqrt{L}}\right)\Big)\, L^{1.05}\, T^{1.3}\,(\,0{,}5B_{wl})^{0.146}$$

$$\left[1 - \frac{L_{BMAX}}{L} + \Big(\frac{L_{BMAX}}{L}\left(\frac{B_{MAX}}{B_{wl}}\right)^{2.1}\right] H_1\,(kN)$$

H_1: significant wave height (m)
B_{wl}: maximum beam at the water line (m)
B_{MAX}: maximum beam (m)
L_{BMAX}: length at maximum beam (m)
z: distance between the base line of the connection deck (m)
T: draft (m)

The LR classification house establishes that for a trimaran type vessel, analyzing two moments of hull separation, during hogging (M_{sph}) which is when the lateral hulls tend to come together with the central hull due to wave action and sagging (M_{sps}) that is when the lateral hulls tend to drift away form the main one; they are found using the following equations; Fig. 4 shows an illustration of both moments.

$$M_{sph} = 9{,}81 f_{serv}\, \Delta_{sh}\, (1 + a_z)\left(y_{sh} - \frac{B_{mh}}{2}\right) \tag{10}$$

$$M_{sps} = 9{,}81 f_{serv}\, \frac{(\Delta - 2\Delta_{sh})}{2}\, a_z\, (y_{sh} - y_o) \tag{11}$$

where

M_{sph}: moment of separation during hogging (kNm)
M_{sps}: moment of separation during sagging (kNm)
Δ_{sh} : displacement of lateral hull (Ton)
y_{sh} : distance between the center line of the central hull and the lateral hull (m)
y_o : distance between the center line of the main hull and the connection between the lateral hull and the connection deck (m)

Table 3 shows the results obtained for the moment of transversal flexion and the pressure exerted over each model.

Fig. 4. Splitting moment during hogging and sagging.

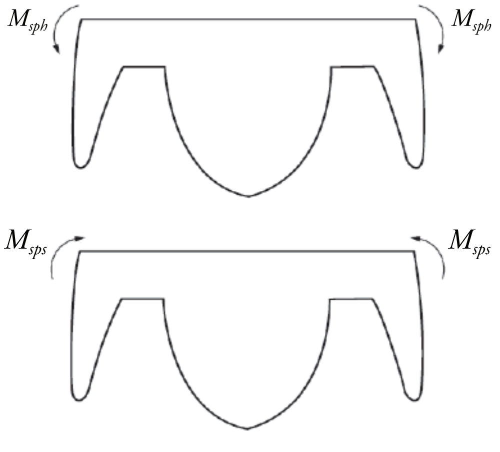


Table 3. Moment of transversal flexion and exerted pressure during the Splitting Moment.

Model	Flexion moment kNm	Pressure kN/m²
GL	1906,0	44,47
DNV	1130,6	26,66
LR– hogging	1101,2	25,56
LR – slagging	1527,0	35,46

Other boundary conditions

As a boundary condition, the inertia relief condition was established, which acts leaving a model of the free body considering the inertia of the movements that may be produced on the model and allowing the applied loads to act over it without the restriction generated by other types of restrictions. This tool calculates any load unbalance and applies inertia forces along the model with the purpose of obtaining equilibrium, Morris (1991).

Scantling of the Vessel

Scantling of the vessel was done using the classification regulations of *"Germanischer Lloyd"*, *"Det Norske Veritas"* and *"Lloyd´s Register"*. Each of the scantlings is specified on Table 4.

Finite Elements Model

Using the Rhinoceros software, a 3D model of the hull was constructed and the scantling structure calculated with each classification house, since although the geometry of the hull is the same, there are difference both in the planking thickness as well as in the size of the reinforcements. Then, each of the 3D models was imported into the ANSYS structural analysis software. For the material, the mechanical properties of 5083 aluminums were assigned, with a density of 2770 Kg/m^3, elasticity module 7,1x10^{10} Pa and Poisson coefficient 0,33.

Meshing

Four types of meshing were done in order to compare the results obtained with each model as far as thee percentage and change trends of the results, and thus optimizing the use of the existing computational resources and verifying the meshing sensibility. Initially a thick meshing is made without advanced refinement functions, quick element transition and medium softness. The next meshing corresponds to a medium

Table 4. Structural Sizing.

Structural Element	GL	DNV	LR
Keel	T 150*100*10	T 150*100*10	T 150*100*20
Bottom longitudinal	FB 90*8.0	FB 90*10.0	FB 90*9.0
Side longitudinal	FB 75*8.0	FB 75*6.0	FB 65*6.0
Deck longitudinal	FB 50*6.0	FB 65*7.0	FB 65*6.0
Connection deck longitudinal	FB 75*10.0	FB 90*9.0	FB 120*10.0
Bulkhead	FB 50*6.0	FB 50*6.0	FB 50*6.0
Collision bulkhead	FB 65*6.0	FB 60*8.0	FB 60*8.0
Superstructure	FB 50*6.0	FB 65*8.0	FB 65*8.0
Hull	8mm	8 mm	6 mm
Side	8mm	8 mm	6 mm
Deck	6mm	6 mm	6 mm
Connection deck	8mm	8 mm	8 mm
Collision bulkhead	8mm	6 mm	6 mm
Bulkhead	6mm	6 mm	6 mm

quality meshing, without advanced refinement function, slow transition between the elements and high softness. After this, there is a medium high level meshing, with advanced refinement functions, increasing the amount of elements found in proximity with other parts and/or contact regions, medium relevance level and high softness. Finally, there is a fine meshing with advance refinement meshing, increasing the amount of elements found in proximity with other parts and/or regions of contact, increasing the amount of elements in the curvatures, medium level of relevance and high softness. The elements used are "SHELL 181", in each refinement it was verified that the elements complied with the aspect relation necessary for the element to continue behaving as a "Shell" element. Table 5 shows the amount of elements used in each meshing by the model, and Figs. 5 and 6 show the trimaran with thick meshing and fine meshing, respectively.

Table 5. Moment of transversal flexion and exerted pressure during the Splitting Moment.

Meshing quality	MODEL	ELEMENTS
Thick	Model GL	68504
	Model DNV	69461
	Model LR	69542
Medium	Model GL	87486
	Model DNV	89559
	Model LR	89161
Medium High	Model GL	212096
	Model DNV	213145
	Model LR	202531
Fine	Model GL	218342
	Model DNV	213480
	Model LR	205444

Fig. 5. Trimaran Thick Meshing.

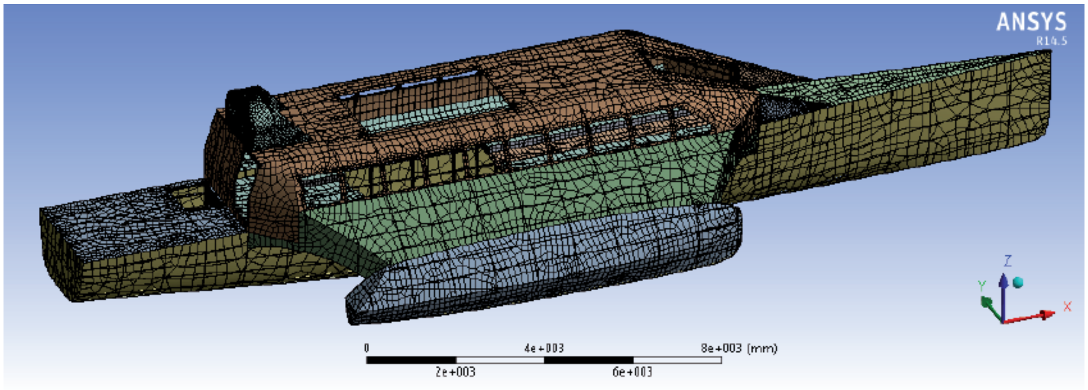
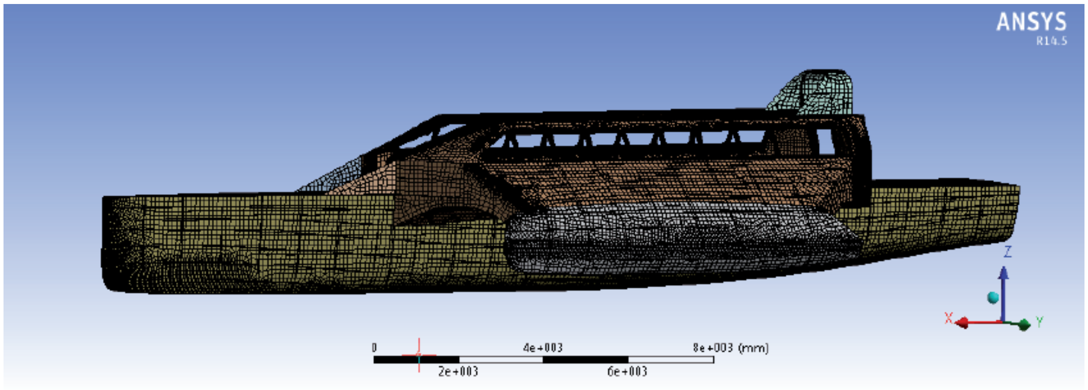


Fig. 6. Trimaran Thin Meshing.



Structural Analysis

The structural analysis of the models evaluated the slamming and splitting moment loads, thus comparing the results obtained with different meshing and finally verifying if the results obtained comply with the minimum acceptance criteria established by each classification house.

Slamming event simulation results

When simulating the slamming event for each constructed model and taking into account the disposition of the loads explained in the previous section, the results shown in Table 6 are obtained. In order to verify the mesh sensibility and define the meshing that best represents the structural response of the vessel upon the action of different loads, and proceeded to compare the results obtained for each meshing. It was observed that the stress and deformation increase as the meshing becomes finer, for the scantling model with the GL classification house, the between the thicker meshing and finer meshing the maximum stress increased by 15.1% and deformation increased 16.6%. The model of the DNV classification house for crest landing the difference between the stress with thick meshing and the stress with fine meshing is 2.73% while the deformation difference for the same meshing is 33.4%; for the hollow landing moment, the stress increase between the thicker meshing and the finer meshing is 13.3% and deformation increased 31.4%. For the scantling model with the LR classification house, maximum stress between the thicker and finer meshing increased by 11.48% and deformation increased 18.63%. Table 7 presents a comparison between the percentage of change as the quality of the meshing improves, the analysis performed to the results presented in this table may conclude that the model that best represents the structural response of the vessel is the medium-high meshing, taking into account that the percentage of change with this meshing and the finer meshing is less than 5% in the models analyzed in each classification house, however when having the necessary computational resources we decided to use the fine meshing as base

Table 6. Stress and deformation obtained during Slamming event.

Model	Meshing type	Equivalent maximum stress (MPa)	Maximum deformation (mm)
GL	Thick meshing	83,33	6,26
	Medium meshing	87,36	6,56
	Medium high meshing	98,24	7,49
	Fine Meshing	98,25	7,51
DNV Crest Landing	Thick Meshing	48,41	1,79
	Medium Meshing	48,85	1,87
	Medium high meshing	49,30	2,64
	Fine Meshing	49,77	2,69
DNV Hollow Landing	Thick Meshing	50,217	1.86
	Medium Meshing	52,650	1,95
	Medium high meshing	56,372	2,70
	Fine Meshing	57,922	2,71
LR	Thick Meshing	94,11	7,60
	Medium Meshing	96,20	9,31
	Medium high meshing	105,96	9,34
	Fine Meshing	106,32	9,35

meshing to compare the results obtained for the finer meshing, with the acceptance criteria issued by each classification house. Figs. 7 to 10 show the results obtained for Fine Meshing.

Table 7. Sensibility analysis for meshing, Slamming event.

Model	**Meshing to compare**	**Stress change percentage**	**Deformation change percentage**
GL	Thick - Medium	4,6%	4,5%
	Medium – Medium High	11%	12%
	Medium High - Fine	0,01%	0,6%
DNV - Crest Landing	Thick - Medium	1%	4,2%
	Medium – Medium High	1%	29,1%
	Medium High - Fine	0,9%	1,8%
DNV- Hollow Landing	Thick - Medium	4,6%	4,6%
	Medium – Medium High	6,6%	27,4%
	Medium High - Fine	2,6%	0,07%
LR	Thick - medium	2,1%	18,2%
	Medio - Medio alto	9,2%	0,3%
	Medium High - Fine	0,3%	0,1%

Fig. 7. Slamming - GL.

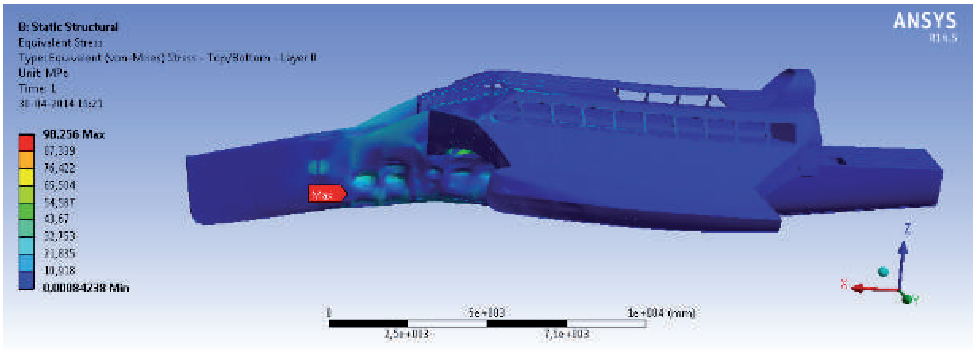


Fig. 8. Slamming DNV “Crest Landing”.

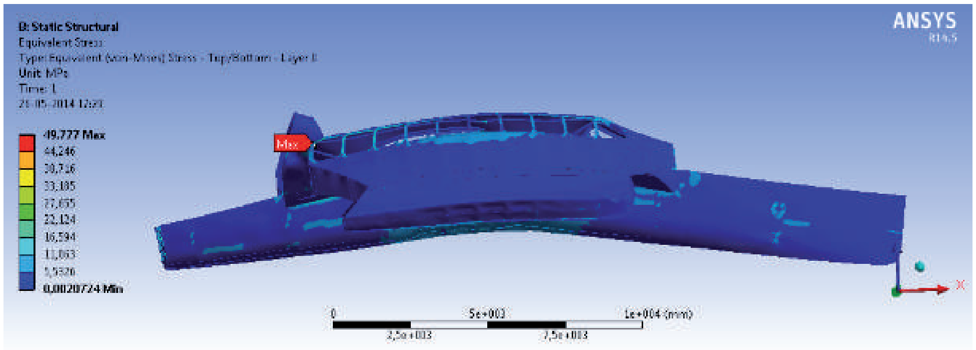


Fig. 9. Slamming DNV "Hollow Landing".

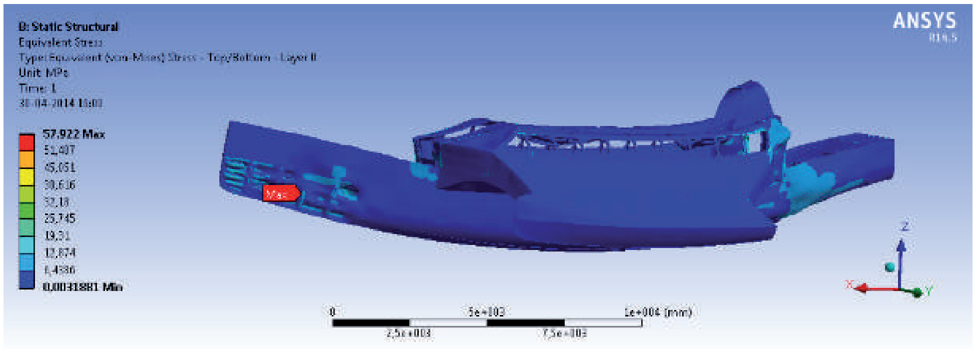
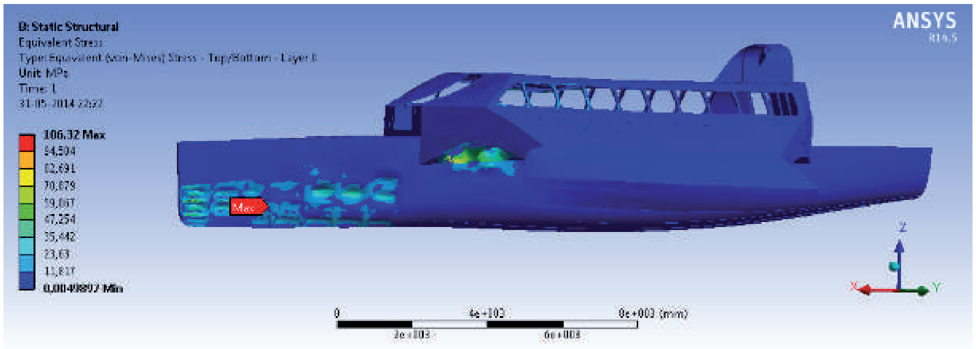


Fig. 10. Slamming LR



Simulation Results Splitting Moment event

For the simulation of the splitting moment event for each model built, the dispositions of the loads explained in the previous section were used and the results presented in Table 8 were obtained.

Between Figs. 11 and 14 the results obtained for Fine Meshing are shown.

Acceptance Criteria

Acceptance criteria for GL classification house

For vessels built on aluminum and designed using GL regulations, the maximum equivalent stress must not exceed the permissible stress $\sigma \leq 110{,}46 MPa$. When comparing the results obtained for the sized model with this classification house with the acceptance criteria, the maximum equivalent stress for the Slamming event *g* (98,25 *MPa*) and the *Splitting moment* (80,1 *MPa*) event is less than the maximum permissible event.

Acceptance criteria for DNV classification house

The DNV classification house established the acceptance criteria for the equivalent stress obtained in each simulation must be less than $\sigma_e \leq 85{,}68$ *MPa*; when comparing the results obtained with the acceptance criteria, the maximum equivalent

Table 8. Stress and deformation obtained during Splitting Moment event.

Model	Maximum equivalent stress (MPa)	Maximum deformations (mm)
GL	80,10	4,7
DNV	47,84	2,87
LR – Sagging	76,08	4,44
LR – Hogging	55,47	3,2

Fig. 11. Splitting Moment GL.

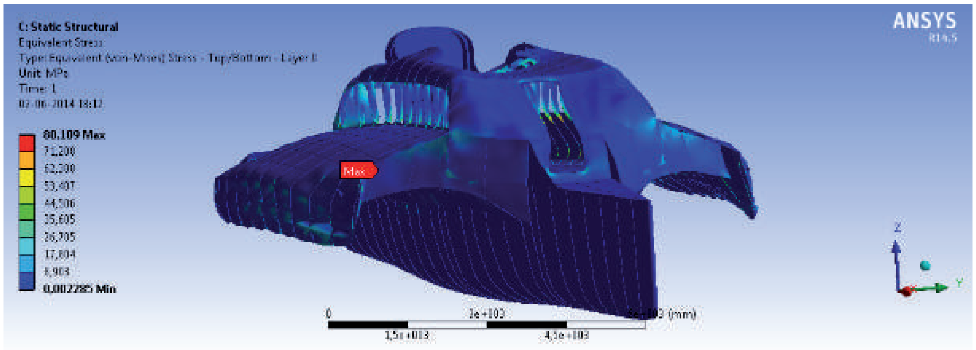


Fig. 12. Splitting Moment DNV.

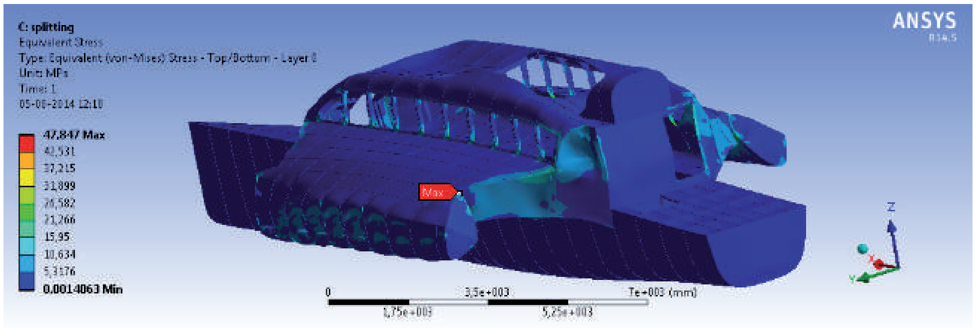


Fig. 13. Splitting Moment LR – Sagging.

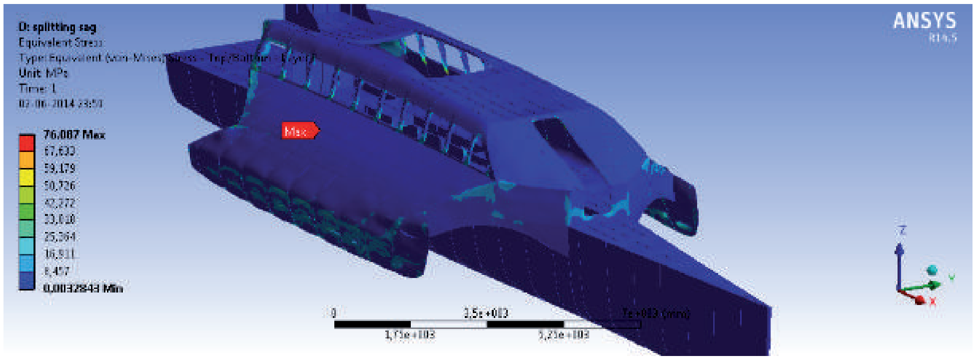
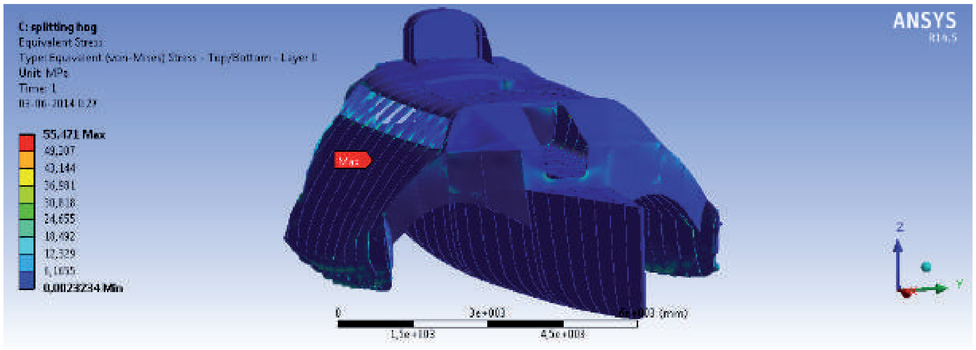


Fig. 14. Splitting Moment LR – Hogging.



stress for the slamming event (57,92 *MPa*) and the *splitting moment event* (47,84 *MPa*) is less than the maximum permissible stress.

Acceptance criteria for LR classification house

The acceptance criteria for this classification house says that the equivalent Von Mises stress obtained for the vessel during each simulation, must be less than $\sigma_{vm} \leq 112{,}5\ MPa$; comparing the results obtained for each sized model with this classification house with the acceptance criteria, it is observed that for the maximum equivalent stress obtained for the *Slamming* event (106,32 *MPa*) and for the *Splitting moment* event (76,87 *MPa*) is less than the maximum permissible effort.

Analysis of Results

Analyzing the results obtained and making a comparison with the acceptance criteria the maximum equivalent stress for the vessel during the slamming event is between 5% and 32% below the acceptance criteria and for the Splitting Moment event between 23% and 44%, below the acceptance criteria as shown on Table 9.

These results show that when sizing a vessel using the regulations of a classification house ensures that subjecting the structure of the vessel to different events or load conditions, they do not exceed the permissible stresses for each classification house. Also, when comparing the stresses obtained with fluency of Aluminum 5083 under the welding conditions described by Paik and Hughes (2006), the margin of safety is broader.

Conclusions

The structural analysis of the initial model showed that performing the scantling with the classification house, the maximum obtained stress is below the admissible stress for each classification house between 5% and 32%, depending on the house used, which allows for a relative safety margin in the material.

The finite elements method allows not only to verify not to exceed admissible stresses, but can also identify high stress efforts, which may be diminished with the adequate structural optimization processes, modifying the structural design geometry for example, and that not necessarily can increase scantling in general.

Although the analyzed vessel was a minor vessel, its multihull configuration is affected by different loads than those of the monohull. For this reason, for an exhaustive structural analysis not only the most unfavorable condition must be taken into account, in this case the slamming pressure, but also other conditions that request the structure in a different way must be assessed as well as possible stress combinations due to loads acting simultaneously.

Table 9. Comparison between permissible stress vs. obtained stress.

Classification House	**Germanischer Lloyd**	**Det Norske Veritas**	**Lloyd´s Register**
σ permissible (MPa)	110,46	85,68	112,5
σ maximum obtained Slamming (MPa)	98,25	57,922	105,96
σ maximum obtained Splitting (MPa)	80,1	47,84	76,08
σ maximum obtained Transversal Torsional (MPa)	84,45	70,04	92,60
% Slamming	11,05	32,39	5,81
% Splitting	42.51	44,16	23,37

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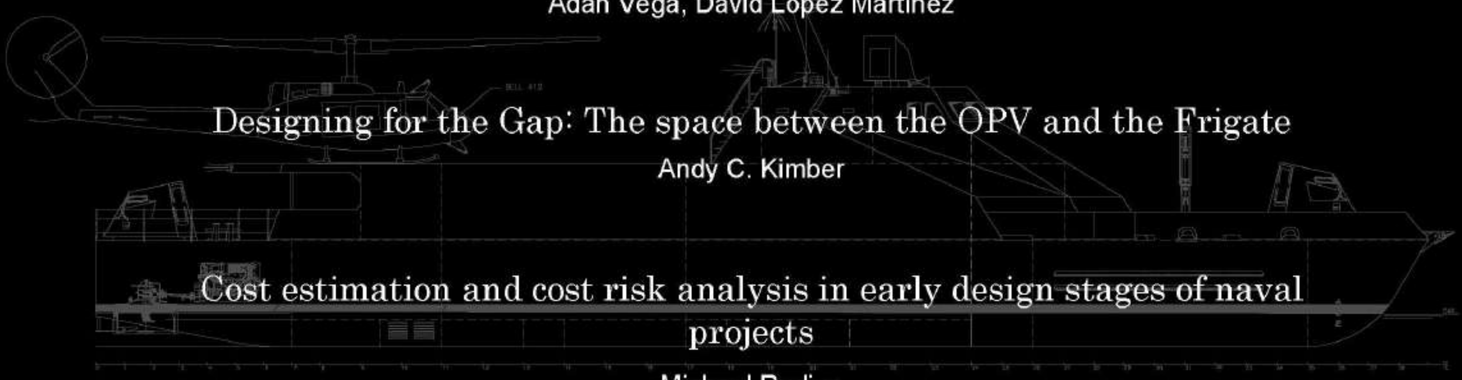

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Michael Rudius

SWATH- A new concept for the Safety and Security at Sea

Fritz Grannemann

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Stefany del P. Marrugo Llorente, Vladimir Díaz Charris, José M. Gómez Torres

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Rinze Geertsma, Nine Badon Ghijben, Erik Middeldorp, Robin de Ruiter

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