The role of virtual prototyping in the early-stage design of a research vessel for the Mediterranean Sea

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ABSTRACT: Research has always been the fundamental tool for the human technological and social progress. Often, it is necessary to perform studies in places that can be reached only with ships specifically designed and built. However, from a careful analysis of the available data about existing research vessels in Europe, it appears that their average age is very high, making the work of scientists very difficult. Thus, considering a new generation research ship, new ship design methodologies and tools are required. The present work, recognizing many similarities with naval ships, proposes the application of an integrated ship design approach. Consequently, modular design principles and tools for virtual prototyping were applied. Moreover, these methodological choices were further justified by the adoption of the newest propulsion and energy generation/storage systems.

1 INTRODUCTION

Research vessels are often the only mean to conduct research campaigns at sea or in remote locations. Research vessels can be classified according to their mission (instrumentation carried onboard, laboratories, etc.) and according to their class. It is possible to distinguish between ships devoted to hydrographic research, oceanographic research, fisheries research, naval research (mines, submarines detection), polar research, oil exploration. These categories are not mutually exclusive, thus, often research vessels are multi-role. It means that are equipped or can be reconfigured to carry out different missions. Considering vessel size, four different classes can be identified: the Global, Ocean, Regional and Local (IWG-F 2007, EurOcean 2021). Reference particulars for each class are provided in Table 1 along with the number of research vessels active in European fleets.

Table 1. Classification of research ships and number of vessels in the European fleet.

Class	Length	Scientists	Endurance	Range	N
	m	-	days	nm	-
Global	> 65	30-35	50	13,500	71
Ocean	55-65	20-25	40	10,000	28
Regional	35-55	15-20	30	8,000	49
Local	< 35	< 15	20	5,000	159

It is worth noticing that the average age of the European research ships is quite high: about 25 years (EurOcean 2021). Hence, many of the vessels are approaching the end of their operative life and should be replaced. Moreover, focusing on the Mediterranean sea, large research ships (Global, Ocean class) are lacking compared to the Atlantic coast and the North Sea. Besides, the advances in technology and research are redefining the requirements for research vessels. In particular, a low environmental footprint to assure the execution of multiple missions in any scenario is required along with improved flexibility (EMB 2019). They must be able to support campaigns in particularly fragile marine ecosystems, without significantly interfering with the experimental measurements. Therefore, the need is to have ships with very low emissions (air pollution, sea pollution and noise). Research ships have very high operating costs, thus a new construction could be cheaper than a technological update of an existing one. All these considerations have driven to consider the construction of a large multi-role research ship, based in Venice and operating mainly in the Mediterranean Sea to be shared by several Italian bodies.

Multi-role research vessels can be considered among the most complex ships to build because they must operate with minimal disturbance of the surrounding environment (Kunz-Pirrung 2008, Capasso et al. 2016). Having the possibility of conceiving a new-generation ship, authors decided to use this project also as a testbed to validate new ship design methodologies and tools. Specifically, recognizing many similarities with naval ships, it was decided to use an integrated ship design approach (Bucci et al. 2021). Consequently, modular design principles (Bertram 2005, Erikstad 2019) and tools for virtual prototyping (Lindner & Bronsart 2017, Major et al. 2021) were applied. Moreover, these methodological choices were further justified by the adoption of the newest propulsion and energy generation/storage systems. In this work, the early-stage design of a multi-role research ship for the Mediterranean Sea is presented focusing on the energy generation system. Starting from the identification of the appropriate rule framework, the modular design application and the alternative fuels to lower the vessel's carbon footprint are presented. Then, after the definition of the CONcept of OPerationS (CONOPS), the main characteristics of the vessel have been defined. Moreover, structures and main systems have been modelled in a 3D parametric environment defining the ship's virtual prototype.

2 INNOVATIONS IN RESEARCH SHIP DESIGN

In the present section, the most important innovation that affects the design of a modern research ship are presented. Starting from the rule framework that heavily affects the ship layout, then two other important aspects to be considered in outlining the virtual prototype are introduced. First, the application of the modular design is discussed to improve the flexibility of the ship, ease construction, reconfiguration and retrofit. Then, the application of alternative fuels such as LNG, ammonia, hydrogen is presented to reduce the environmental footprint of the ship. In this regard, focus has been made on the innovation readiness of the propulsion plant.

2.1 *Rule framework*

In the design of a research vessel, the rule framework shall be considered since the early stages to define a feasible layout of the ship. Aiming at designing a large research ship fuelled with LNG and ready for fuel switch, several special regulations shall be considered and applied.

A research vessel, depending on the mission has to carry and accommodate all the personnel due to research activities, which is added to the crew devoted to navigation and ship maintenance. Hence, the Special Purpose Ship (SPS) code can be considered as a reference regulatory framework (IMO 2008). In the SPS code, besides the standard categories (crew and passengers) a third halfway one is defined: "special personnel", which consider all persons carried on board in connection with the special purpose of that ship or because of special work being carried out aboard that ship. For the research vessel, special personnel includes researchers and technicians. If their number exceeds twelve persons, the SPS code shall be applied instead of rules for cargo ships. The improved knowledge of the ship and safety training required for special personnel enables to relax the design requirements compared with the passenger ships ones. In detail, for ships having a length lower than 100 m, the intact stability code requirements can be waived and for ships carrying less than 240 persons the SOLAS requirements for cargo ships can be applied considering special personnel as crew and disregarding Safe Return to Port regulations. Nevertheless, some special requirements relating to fire-fighting and other equipment differing from cargo rules are embedded in SPS code.

Besides, a ship using LNG as fuel shall comply with the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF) issued by IMO in 2015 (IMO 2015). The code comprises mandatory requirements for the design, installation, control and maintenance of systems, equipment and machinery using low-flashpoint fuels (such as LNG). The code covers all the areas requiring special attention such as fuel storage, engine room, etc. The application of the IGF code has a strong impact on the ship general arrangement. The fuel storage shall be placed at a minimum distance from the hull shell and protected by a double side and double bottom (Fig 1). If fuel storage is neighbouring the engine room a 900 mm cofferdam at engine room bulkhead is required for self-supporting tanks without secondary barrier, whereas for membrane tanks a complete cofferdam around them is required.

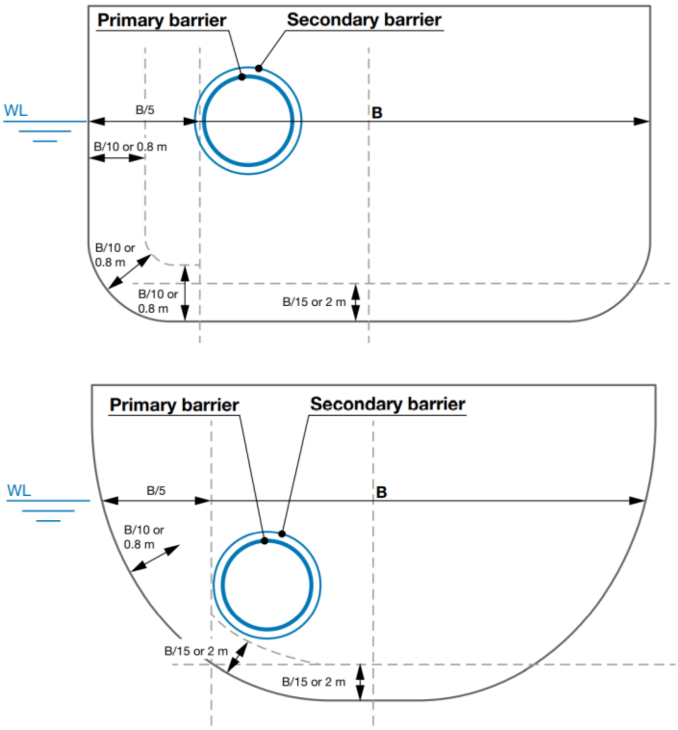

Figure 1. Minimum distances of fuel storage from hull shell according to IGF code.

Finally, special considerations regarding the International Convention for the Prevention of Pollution from Ships (MARPOL) are necessary (IMO 2019). In Annex VI of the MARPOL, the emissions limits are stated, defining several Emission Control Areas (ECA) where tighter requirements shall be applied. Currently, the Mediterranean Sea (principal envisaged operative scenario of the studied research vessel) is not classified as ECA. However, its inclusion is under discussion and often a research ship is required to operate in fragile or protected environments. Hence, it is of the utmost importance to reduce as far as possible its environmental footprint. This justifies the application of LNG as fuel or other alternative fuels to make at least the ship compliant with the ECA requirements.

2.2 *Modular Design*

The modular design concept has been introduced for the design and construction of naval ships (Drewry & Jons1975, Doerry & Koenig 2017) but has then been extended to other types of vessels such as cruise vessels (Ahola et al. 2015), support vessels (Choi et al. 2018), etc. The main scope of modular design is both a faster and cheaper construction/retrofit of the ship and improved flexibility in the ship operative profile.

As opposed to integral architectures where multiple modules concur to one functionality of a product, the modularity concept aims to reduce the interconnections by splitting a system into several functionally independent components. It means that a single module is devoted to a single functionality and multiple modules can be combined to obtain the final product. In modular design, interfaces (i.e. connections between modules) are of the utmost importance. The global system or structure shall be broken down into modules identifying the key interfaces which are usually implemented according to the industry standards.

The second key concept in modular design is the flexibility that allows going beyond the fixed boundaries and interfaces typical of the modularity. Flexibility allows to rapidly reconfigure the vessel to fulfil a specific objective/mission acting on a limited area of the ship. Typical examples are the usage of mobile structures within a watertight compartment (Braidotti et al. 2020) or reserve space for the installation of different modules/equipment (Doerry 2012, Greco & Serpagli 2018) to obtain different configurations for one vessel. Usually, standard connections to power, cooling, communications and ventilation can be made available for a flexible installation.

It is possible to identify three main different types of modular design, although the classification boundaries are not always clearly defined. In detail:

- *Common Modules*: they can be used to decompose the structure and systems of multiple ships of the same or different classes. Blocks or pre-engineered elements can be built even outside the shipyard and there just assembled leading to a more straightforward construction process and cost reduction. A typical example of this kind of modularity is represented by the cabins in a large passenger vessel. This kind of modularisation can be applied to the accommodations of a research vessel, too.
- *Modular Installations*: these are self-standing modules connected to the rest of the vessel by means of standard interfaces (plug-and-play). Thus, modular installations can be easily replaced during the ship operative life minimising the retrofit costs. An example is represented by Vertical Launching Systems on naval ships. In the design of a research vessel, modular installations can be developed for the main fixed equipment susceptible to fast obsolescence (e.g. sensors) to ease its replacement.
- *Containers*: containers are by definition modular cargo. They have standard dimensions and maximum weight so they can be easily handled, transported ad stored onboard and onshore. Arranging part of the payload in containerised modules can improve significantly the flexibility of a vessel. By connecting them to standard interfaces, the profile of a ship can be changed to fit a specific mission without carrying onboard unnecessary equipment (with space and weight savings). For instance, a container with an ROV can be carried when submarine activities are planned. Fitting a modular area for mission-specific containers can be a viable solution to improve the flexibility of a multi-role research vessel.

When dealing with modular design, the application of virtual prototyping software and 3D models can be very useful to visualise the system/structure components and study their interfaces (Chaves et al. 2015, Pérez Fernández & Peter Cosma 2019). In the design of a research ship, these concepts can play a key role. Such a kind of vessel shall be capable to carry out different operations driving to a complex operative profile. To best fit the ship CONOPS, flexibility can substantially improve the overall ship performance and her adjustment capacity. Besides, considering the fast evolution of technical equipment and the long operative life of a ship it is hard to foresee future needs of marine research and environmental protection. Hence, modularity can play a key role to ease the replacement of obsolete instrumentation, auxiliaries, polluting energy generation systems, etc.

2.3 *Innovation readiness*

As mentioned, often research vessels operate in protected or fragile environments. Hence, the reduction of pollutant emissions, noise emissions and the wave pattern is extremely important to extend as far as possible the area of operations. In this context, the application of alternative fuels other than Low-Sulphur Heavy Fuel Oil (LSHFO) and Marine Gas Oil (MGO) can make the ship compliant with current rules and ready for future more strict requirements. Actually, IMO posed the challenging objective of reaching a 50% reduction of carbon dioxide (CO_2) emissions from shipping within 2050.

Nowadays, after the introduction of 4 ad 2 stroke dual-fuel engines and considering the growth of bunkering facilities, the application of LNG as fuel is becoming a very good option. Dual-fuel engines can use both traditional fuels and LNG assuring high flexibility and lower emissions. LNG is the most eco-friendly hydrocarbon leading to a 25% reduction of CO_2 emissions compared to MGO while reducing also the emissions of nitrogen and sulphur oxides and particular matter (Lindstad et al. 2020). The main disadvantage related to the adoption of LNG is the cryogenic temperature: to maintain the liquid phase at the atmospheric pressure it is required a temperature of about –160°C. Hence, LNG shall be stored in dedicated cryogenic tanks installed according to the IGF code requirements. Besides, LNG has a lower energy density compared to traditional fuels (Fig. 2) requiring about 2 times the volume keeping the range constant. Considering the containment system accommodation, the volume is further increased reaching about 2.75 times the one of comparable traditional fuel tanks.

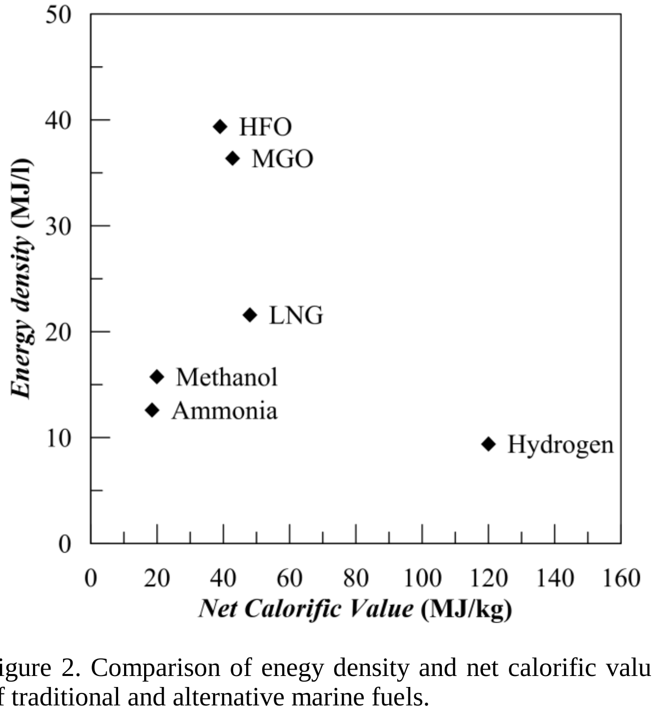

Figure 2. Comparison of enegy density and net calorific value of traditional and alternative marine fuels.

Another alternative maritime fuel that has been recently investigated especially for short routes is liquid hydrogen. Hydrogen can be used in fuel cells or combustion engines and completely zeros on-site CO_2 emissions. However, most of the disadvantages of LNG are magnified: hydrogen is liquid at about –253°C and has a lower energy density than LNG (Fig. 2). Moreover, hydrogen is not available in nature and shall be produced. Currently, about 95% of hydrogen is produced from hydrocarbons so it is not truly carbon neutral as the one produced from renewable sources. In the latter case, it is currently expensive and avalible in small quantities. Finally, hydrogen might imply additional costs for safety equipment and mitigation measures required by its extremely low temperature and high flammability.

Recently, ammonia has been also considered a promising maritime fuel contributing to decarbonisation. It is less flammable than hydrogen, has a higher energy density and can be stored at a relatively high temperature (–35°C). It can be used in both combustion engines and fuel cells, although these technologies have not reached yet a high maturity. Ammonia can be synthesized from hydrogen and nitrogen, hence, to assure zero emissions shall be produced using renewable energy sources. Currently, green ammonia is available in very small quantities and is very expensive compared to traditional fuels. Moreover, unlike natural gas and hydrogen, it is toxic and, unlike traditional fuel oils, it is soluble in seawater (making a fuel spill dangerous for the marine ecosystem).

Finally, another alternative can be considered to meet the IMO decarbonisation targets: methanol. It is liquid at room temperature, soluble in water and biodegradable. Again it can be produced from hydrocarbons (mostly natural gas and coal) or using renewable energy from CO_2 or hydrogen. Methanol price is comparable with traditional fuel oils and can be already used in both 2 and 4 stroke engines. Currently, its widespread application is hindered by the low energy density and the limited availability of bunkering facilities.

Considering the maturity of technologies and the lacking of bunkering facilities, the application of dual-fuel engines powered by LNG or MGO is considered the best choice to assure immediately the operation of a research vessel in the Mediterranean Sea while complying with the current requirements on emissions in ECAs. However, considering the fast development of alternative fuels technologies (new combustion engines, scale-up of fuel cells), the ship should be designed to be ready for the application/integration of alternative fuels. To this end, the modular design paradigms shall be extensively applied in the design of the propulsion system. To reduce the effort of a retrofit, a series hybrid-electric propulsion system can be applied. With this configuration, the propulsors and main electric engines can be driven with any source of power. Hence, in the case of a fuel switch, only the engine room, the fuel storage and handling systems might be affected. Regarding the engine room, it is expected that the combustion engines can be upgraded to burn hydrogen, ammonia or methanol. Alternatively, if the generators and related auxiliaries are arranged in modules, they might be easily replaced with fuel cells using LNG, hydrogen or ammonia, possibly in a mixed configuration. Regarding the storage system, it shall be composed of multiple independent tanks to assure redundancy and to make possible a future combination of different fuels. Furthermore, materials and systems shall be ready for the alternative fuels, e.g. stainless steel tanks can be used instead of nickel alloy (ready for ammonia) or insulations shall be designed for the most demanding alternative (liquid hydrogen temperatures and flammability). However, it shall be bared in mind that any replacement of LNG with other fuels keeping constant the storage system capacity implies a reduction ship range (for hydrogen case it will be about half of the original one).

3 CASE STUDY

In the present section, the modular design is applied to a Mediterranean research vessel. First, the CONOPS has been defined with the support of the Italian Institute of Oceanography and Experimental Geophysics (OGS). Then, the initial design of the ship is presented, focusing on the propulsion system design and accommodation and the definition of its virtual prototype in a parametric software environment.

3.1 *Concept of operations*

The project was born from the need to dispose of a large research vessel dedicated to Mediterranean missions by several Italian bodies. At the base of the project, there is the idea to combine several features, to arrange a ship capable of meeting different needs, thus reducing the total manning costs. The ship will have a size comparable to a Global class research vessel but will be adapted to the specific geographical context. Analysing the existing fleet, a design speed of 12 kn and a maximum speed of 14 kn have been chosen in line with the class. Considering that the vessel is designed to operate mainly in the Mediterranean sea, a 3500 nm range has been deemed sufficient although it is quite limited for a vessel having dimensions comparable with existing Global class research ships.

The ship must be equipped with every space and equipment necessary for a multi-role unit: dry lab, wet lab, aft crane for launching the equipment, refrigerated rooms for containing the collected samples. In addition, the following requirements have been identified:

- *Educational*: an exhibition area shall be arranged for public exhibits when the ship will be moored in Venice or other cities. This constraint requires a space free of bulky equipment. Taking advantage of the principles of modularity, it is also necessary to provide for the use of this space during navigation. In addition, a conference room is planned for possible lectures and seminars to be held both in port and during missions.
- *Transport capacity*: the ship must be equipped with a touch and go heliport, for emergencies and fast transport of people or goods (e.g. archaeological finds or samples requiring immediate treatment). Onboard there must be also two service tenders for the transport of goods and people or the support to research operations in places unreachable by a Global class vessel.
- *Humanitarian Capabilities*: It must be possible to use the ship to provide humanitarian aid in case of natural disasters. To this end, a hospital area of greater capacity than the average global unit must be provided. This area will also house a fixed hyperbaric chamber to provide first aid to divers in the event of an emergency during diving operations.

3.2 *Preliminary design of propulsion system*

Based on the CONOPS, the main dimensions of the ship has been defined as per Table 2. The length has been kept under 100 m in order to apply the simplified requirements according to SPS code. The draught has been limited to fit the foreseen berth of the vessel (San Basilio, Venice) and ease the access to the Venice Lagoon and restricted waters in general. Then, hull forms, transom and bulbous bow have been designed to fit the design speed of 12 kn.

Table 2. Research ship main characteristics.

Length overall	L_{OA}	90 m
Length at waterline	L_{WL}	87.56 m
Breadth	B	19 m
Draught	T	6 m
Depth	D	10 m
Displacement	Δ	5,641 t
Block coefficient	C_B	0.349
Prismatic coefficient	C_P	0.359
Design speed	V	12 kn
Maximum speed	V_{MAX}	14 kn
Frame spacing		0.8 m
Crew		29
Special personnell		45
Range (at 12 kn)		3,500 nm

As mentioned, a hybrid-electric series propulsion power has been chosen. The ship is equipped with two azimuting thrusters with ducted propellers that combined with a bow thruster enables the ship to perform dynamic positioning. The application of a series configuration guarantees the possibility of a flexible fuel switch. Furthermore, considering that at the service speed the brake power is about 1500 kW (including 10% sea margin), the series configuration is appropriate (Vicenzutti 2020), having a comparable electric load required by other users (about 2000 kW). In the basic configuration (ready for fuel switch) the electric generation is performed by four dual-fuel gensets (1420 kW each). To cover the whole 3500 nm range with LNG, 300 m^3 are required. Hence, three type C stainless steel tanks have been fitted in a dedicated compartment with double sides, having a 100 m^3 capacity each.

In order to increase the flexibility of the ship, possible future configurations for powering the generators using the previously introduced fuels have been considered. Concerning ammonia, the fuel switch should be very easy thanks to the similar characteristics between ammonia and natural gas. Once the technologies and regulations for ammonia will be available, dual-fuel engines shall be upgraded to cope with ammonia, keeping the previously installed tanks. Considering a fuel switch to liquid hydrogen, the tank shall be replaced since current ones are not suitable for lower temperatures related to liquid hydrogen. Currently, all the technologies to use methanol as fuel are available on the market. However, considering the Mediterranean sea, the LNG supply chain and bunkering facilities are already in development. Moreover, even if methanol bunkering will be available in the future, a switch towards carbon-free fuels such as hydrogen or ammonia should be preferred.

3.3 *Virtual Prototype*

The vessel has been modelled in a commercial 3D parametric environment in order to build a virtual prototype. It has been used to obtain a fast assessment of structural, equipment and consumables wights as well as to graphically check the interference among structural modules, main machinery and equipment. In Figures 3 and 4 the structural model complying with RINA rules and the capacity plan of the virtual prototype are reported, respectively.

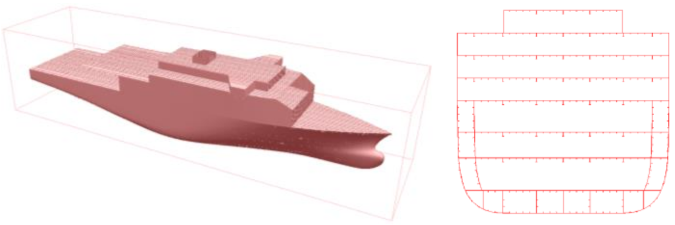

Figure 3. Structural model and midship section of the research ship.

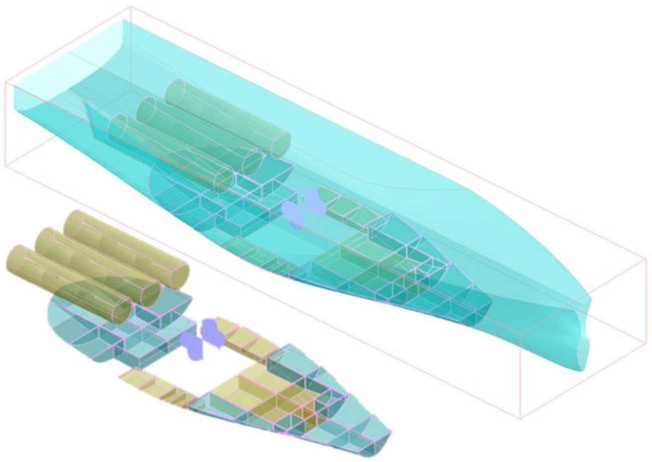

Figure 4. Capacity plan of the research ship.

Furthermore, the virtual prototype has been used as a source of information for all the initial technical calculations (such as the assessment of stability, structural strength, dynamic positioning, seakeeping, etc.) and to elaborate the main technical drawings. For instance, in Figures 3 and 5 the midship section and the general arrangement of the vessel, respectively are provided.

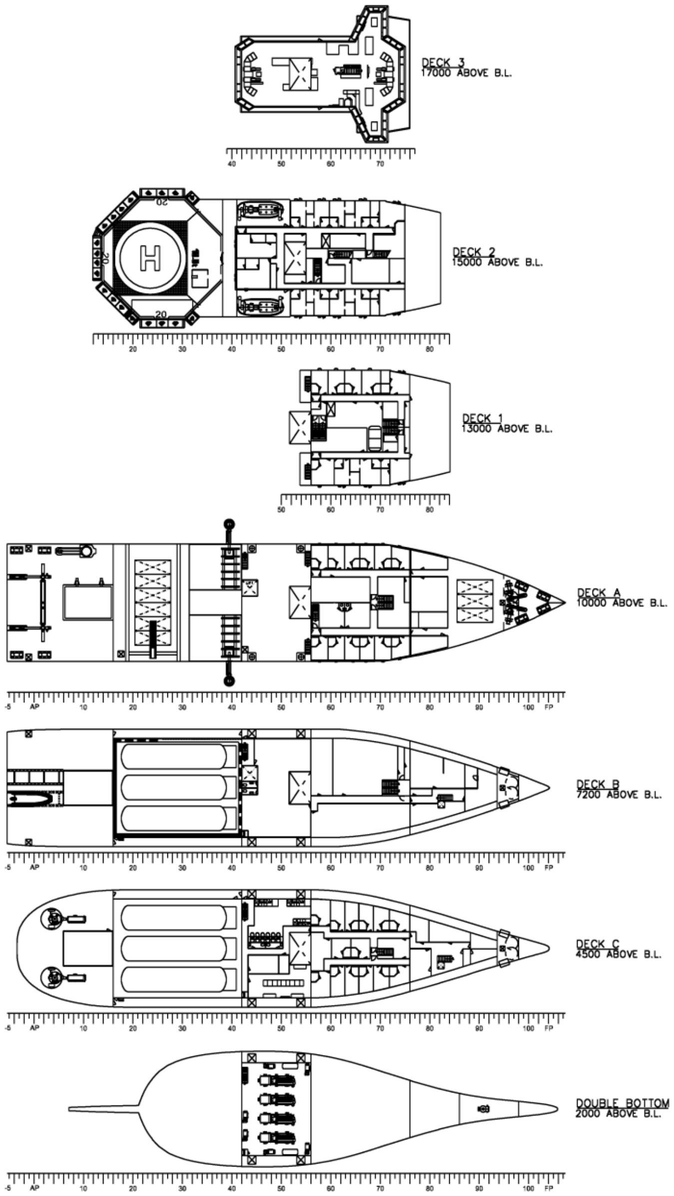

Figure 5. General Arrangement of the multirole research ship.

Focusing on the general arrangement, it is worth noticing some peculiarities of the vessel. At the extreme stern, two 45 deg slipways for launching tenders have been placed between the rooms where main propulsion engines and azimuting thrusters' steering gears are fitted. On the main deck at the stern, a 320 m^2 open area is equipped with a 12 t A-frame for lunching heavy instrumentation or for net towing and a 10 t multipurpose crane. Then, beneath the helideck, there is a modular space equipped with an overhead crane for the handling and stowage of up to six 20 ft containers. The containers can carry the special equipment or facilities required for a specific mission, allowing a fast reconfiguration of the vessel. This area, as well as the 200 m^2 cargo space located amidship, can be also used for temporary exhibitions as the vessel is moored. Between the modular area and the cargo one, a baltic room is fitted to each side of the ship for launching instrumentation through telescopic booms. The boundaries of these spaces are mounted on tracks and removable to allow a complete reconfiguration if required. All the accommodations and laboratories are fitted in the forepart of the ship, including a wide conference room spanning over two decks in the front of the superstructure and a 70 m^2 health treatment area located on the first superstructure deck. All the accommodations have been designed considering the introduction of common modules such as cabins, restrooms and offices. Finally, to ease a future fuel switch, the machinery (main engines and their auxiliaries) has been designed following the modular installations logic as well as main deck equipment and sensors.

4 CONCLUSIONS

The present work applied modern tools for virtual prototyping to develop the initial design of a new research vessel for the Mediterranean Sea. Virtual prototyping has been proved to well support the application of modular design principles. Modularity and flexibility allowed to best fulfil the CONOPS requirements and to assure a fast reconfiguration of a multi-role research vessel. Such characteristics might lead to significant savings in time and costs maximising the benefits of a vessel shared among multiple users with different needs.

Furthermore, the application of modular design has been proved capable to support a future fuel switch towards carbon-free fuels such as hydrogen and ammonia. Today LNG has been deemed the best choice for the Mediterranean area. Nevertheless, the fuel tanks and the modular arrangement of the propulsion system might ease future improvements as the rule framework and technologies will be sufficiently mature and bunkering facilities will be available in the region.

It shall be bared in mind, that the application of LNG as marine fuel had a strong impact on the general arrangement of the ship. The fuel tanks shall be installed according to international rules and are more space-consuming compared with traditional liquid fuel tanks. Moreover, considering the energy density of alternative fuels, they will require more space to keep the range constant or, with a constant geometry, will affect the range of the vessel. Further stuydy is still advisable about this issue.

Finally, the present work addressed the technical feasibility of the research vessel only. Considering that the ship should be based in Venice city centre, attention shall be given to the visual issues. Hence, architects/designers shall be involved to draw a more pleasant topside, without affecting the operational capability of the ship. Besides, considering the fragile environment of the Venice Lagoon, additional work is required for the detailed design of the electric distribution system and its interaction with the shore electric grid in order to prevent local pollution when the ship is berthed.

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