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System modelling and performance assessment for naval ship design: An application for an Offshore Patrol Vessel (OPV)

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ABSTRACT: In the proposed paper, a Ship Synthesis Model (SSM) code is presented. It basically consists of a sequence of logically-integrated parametric formulations provided by a statistical analysis derived from existing ships. The code is integrated into a wider numerical architecture, developed by Orizzonte Sistemi Navali S.p.A. and called ASNET (Application System for Naval ship design Evaluation and Testing), which also includes an Operational Evaluation Model (OEM) aiming at evaluating the measure of effectiveness of a certain ship design when different naval tasks have to be complied with. This way, ship design characteristics are linked to operational aspects. A test case concerning an Offshore Patrol Vessel (OPV) is reported as well, in order to assess the capability of the SSM code to evaluate the feasibility of different design configurations, obtained considering different ship requirements.

1 INTRODUCTION

Ship design represents an inherently complex process: this complexity is significantly increased when the particular ship being designed is a naval surface combatant.

The challenge of the ship designer is to engineer a total ship system that fulfils rigorous requirements within certain constraints, such as the laws of nature, the limits of technology and, especially nowadays, limited budgets. Furthermore, most of the times, the traditional design input (ship typology, size, speed) are not given in explicit terms by the Administrations, but with reference to rather different ship capabilities, i.e. patrolling activities, Anti-Surface Warfare (ASuW) operations, Search and Rescue (SAR) support. In fact, what is challenging is to efficiently translate such desired performance into ship technical characteristics and properties.

The traditional method of ship design, concerning both merchant and naval vessels, is essentially a process of making judicious changes to an existing successful ship for which reliable data are available. This so-called "basis ship" is chosen to possess performance characteristics as close as possible to those demanded by the new operational requirements, for a more efficient process. Since the classical calculations of naval architecture consider more the analysis rather than the synthesis entailed by design problem, iteration is involved in seeking those characteristics needed to meet the operational objectives. The well-known Ewans-Buxton-Andrews spiral is popularly used to illustrate this process (Mistree et al. 1990). The reason for iteration resides in the complexity itself of the ship design, which cannot be described by a set of equations to be solved directly. According to this methodology, the ship designer moves through the design process in a sequential series of steps, each dealing with a particular analysis task. After all the steps have been completed, the design is unlikely to be balanced (or even feasible) and typically, a number of iterations are required to arrive at a satisfactory solution.

Clearly, if the design team selects a good basis ship, and if the new requirements do not entail major modifications from it, this is a reliable and rapid method. One obvious shortcoming of the traditional process, then, is that if the designers are presented with operational requirements that differ radically from those of any previous ship in their data bank, they will be unable to choose their basis ship with confidence. Another potential problem is the lack of comprehensive standards. The design team is continually checking specific performance but there is no way of assessing how closely they are approaching an optimum design. Without new integrated tools the exploration of enough cases to be certain all the changes have been done in the best possible way is very difficult. In other words, the experienced designer can be confident of producing a good ship, but cannot admit that this might be the best one (Eames & Drummond 1976).

In any case, even a laborious and expensive process cannot promote the identification of superior solutions, thus limiting innovation at the concept exploration stage. For these reasons, it is generally recognized that the traditional design spiral, even if it represents a valid prescriptive model and may result in satisfactory designs, cannot be seen as the proper model any more to represent the modern ship design process, especially in the field of naval ships (Mistree et al. 1990).

Due to the continuous worldwide contraction of financial resources for naval defence armament, it appears as a crucial point to develop new computational tools able to individuate feasible design solutions in a reasonable time, dealing with the main ship characteristics and their interactions, and at the same time providing also an assessment of the ship configurations in terms of operational capabilities.

In such an exploration phase, a Ship Synthesis Model (SSM) can be seen as an useful and effective tool to be used at an early stage of the ship design process. It is based on the main idea of integrating all parts of the project with the aim of creating an automatic design procedure.

Automation of calculus, since the end of the sixties, has always exerted an impressive attraction on naval architects, due to the impressive amount of calculations required during the activity of ship design. Earliest versions of computational SSM are dated from several decades ago; at their beginning, they were considered able to replace the whole manual design procedure, extremely demanding in terms of manpower and time. They were seen as a booster on the path of the traditional design spiral. But after some years of sincere trust in the innovative tool, they did not take-off as expected.

In recent years, a new interest has risen again toward SSM approach, in line with the renewed growing reliance on computational power currently characterizing the ship design methodology. The need of exploring a significantly large domain of investigation, especially in a preliminary design phase, is contributing to appreciate SSM as a worthy decision-making tool. In fact, a SSM can be a computational device able to evaluate the feasibility of several ship configurations in a preliminary context, in order to permit a wide exploration of a design domain.

Going back to the sixties again, a considerable number of computer-aided ship design tools of this kind have been extensively developed starting from those years.

The US Navy's destroyer model, DD07 and the Center for Naval Analyses Conceptual Design of Ships Model (CODESHIP) are among the first SSM codes that can be found in literature (Reed, 1976). Since the seventies, several other SSM codes for naval applications have been produced within the Department of Ocean Engineering at the Massachusetts Institute of Technology (MIT). Those developed by Reed (1976) and Cassedy (1977) are particularly relevant in literature. More recent studies, for example, are those conducted by Szatkowski (1998), focussed on frigates, Gillespy (2008), who created a tool dedicated to patrol crafts, and Kara (2010), who addressed corvette design.

Another interesting application was presented by Colwell (1988): SHOP5 is a Canadian developed model for monohull frigate and destroyer concept exploration based on NATO frigates with the aim of initializing a new ship design process and performing parametric and comparative studies.

An example of linking operational and ship design synthesis models was presented by Fox (2011), taking into consideration a medium tonnage patrol vessel and a Maritime Interdiction Operation (MIO) mission in a fictional setting.

3D hullform modelling combined with a space-allocation routine has been recently implemented by Van Oers et al. (2010), with the aim of enabling the rapid generation of a large and diverse set of feasible ship configurations suitable to investigate trade-offs between performance and costs.

At present, the Advanced Ship and Submarine Evaluation Tool (ASSET, formerly the Advanced Surface Ship Evaluation Tool), extensively used within the Naval Sea Systems Command (NAVSEA), is one of the most comprehensive and powerful expressions of this kind of computer-aided ship design tools. It was firstly developed in the US in the eighties and since then it has always been improved and updated. It represents a mixture of first principle algorithms as well as regression analysis of US combatant ship data, including the US Coast Guard's WMEC 270 class of ships. Applied in several ship designs for the US Navy, it consists of several interactive modules so as to assess exploration and feasibility studies. Various typologies of vessels are addressed with a dedicated module, e.g. combat ships, amphibious and auxiliary ships, aircraft carriers, SWATH, SES (Kassel et al. 2010). The necessity to have separate codes in relation to the ship typology is intrinsic in the nature of this kind of tool and represents one of its possible limits.

Nowadays, an automated calculus aiming at individuating feasible ship configurations can be exploited better than in the past thanks mainly to the interaction with other codes and to the perspective of an optimization procedure. In other words, a standing alone SSM has a very low value, while it gains its wider utility when linked with other tools, enabling the designer to lead the design decisions toward a better effectiveness of the final ship.

For several reasons, including economic ones, a modern Administration cannot be satisfied with a ship that simply complies with the requirements. It is necessary to investigate the mission effectiveness together with acquisition and life-cycle costs. Therefore the focus has moved from being able to design a ship complying with some requirements to managing to compare different solutions to the problem. Example of optimization techniques applied to a SSM may be found in Shahak (1998) and Meister (1998).

The naval ship is such a complex product that the comparison activity is often very difficult. The most natural and modern framework that seems to be suitable to drive the matter is the formulation of a multi-objective optimization problem.

In this sense an interesting approach can be found in literature in Brown and Salcedo (2003) and several theses developed at Virginia Tech over the years, e.g. Neti (2005), where the problem is faced in terms of OMOE (Overall Measure of Effectiveness) and LCA (Lead Acquisition Costs), intended as objective functions. Others examples are those presented by Corl (2007), who applied multicriterion optimization methods to platform decisions for families of ship variants and Anil (2005), who followed the Parameter Space Investigation technique.

In the proposed paper, a SSM code is presented. It is integrated into a wider numerical architecture, developed by Orizzonte Sistemi Navali S.p.A. and called ASNET (Application System for Naval ship design Evaluation and Testing), which also includes an Operational Evaluation Model (OEM) aiming at evaluating the measure of effectiveness of a certain ship design when different naval tasks are taken into account. This way, ship design characteristics are linked to operational aspects.

A test case is reported as well, in order to assess the capability of the SSM code to evaluate the feasibility of different design configurations, obtained considering different ship requirements. An Off-shore Patrol Vessel (OPV) has been addressed, in line with the recent increasing interest in this particular type of vessel expressed by several international Administrations. In fact, an OPV can be employed with maritime surveillance, fishery protection, SAR and patrolling assignments duties in national and international waters. In general terms, the set of possible operational profiles can be wide and diversified resulting in a large domain of alternative options in terms of ship general characteristics and payload.

In this context, a SSM can represent a suitable tool to carry out trade-off analyses, so as to explore and highlight further possible developments in the design of the selected typology of vessel, setting the trend of future similar projects.

2 THE SHIP SYNTHESIS MODEL

The SSM here presented consists of a sequence of logically-integrated parametric formulations provided by a statistical analysis derived from existing ships, whose main data are organized into external database directly linked to the SSM. The code is developed in a Matlab® environment and it is provided with a very user-friendly Graphical User Interface (GUI).

It is structured into several modules linked together following a logical scheme, which represents a simplified ship design approach corresponding to a single loop of the classical design spiral process. Each loop, i.e. a single SSM run, provides a ship design configuration which is not necessary balanced, as the input data may lead to an unfeasible solution.

The solution feasibility is checked at the end of the procedure through design constrains and performance criteria. The required quantities (for example in terms of space, power, etc...) are compared with the relevant available, i.e. offered, quantities. In particular, if ship weight is greater than displacement, the ship configuration is rejected and the procedure stops. If the check is positive (displacement equal or greater than weight), the remaining modules are processed.

The whole procedure is suitable to possibly be included in an optimization process. The SSM flow chart and its modules subdivision are represented in Figure 1, highlighting the link with the OEM.

The point of departure for the development of the proposed SSM is represented by a modified

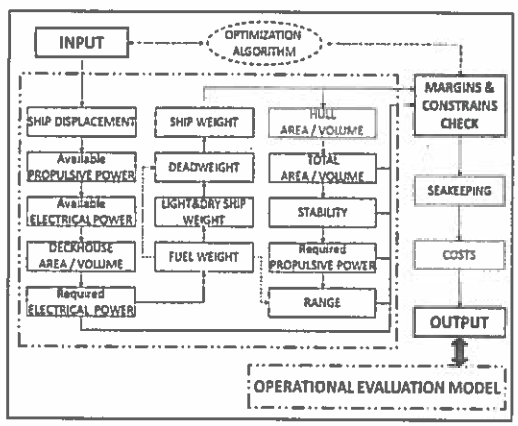

Figure 1. Ship Synthesis Model flow chart and modules subdivision.

version of the axiomatic design model created by Szatkowski (1998), whose Matlab® version can be found in Anil (2005) and which was later reviewed in the framework of a MSc thesis carried out at the University of Genoa (Balossino & Melis 2008) and more recently by Orizzonte Sistemi Navali S.p.A. (Bertolotto et al. 2009, Bonvicini et al. 2012).

In the present paper, a further reviewed and improved version of the code is presented, including new approaches for the assessment of propulsion and energy generation systems (mainly as far as consumptions and physical characteristics are concerned) and seakeeping performance. A re-validation of statistical regressions and formulations, based on the acquisition of new more complete sets of ship data, has been carried out as well.

At present, the code should only be applied to the OPV typology, since the basis ships used in the development of the model have a full-load displacement ranging between 400 and 1700 t, a length between 45 and 80 m and a sustained speed between 21 and 31 kn. At this time, propulsion systems include diesel engines as the only option.

The main required input data include the mission requirements (i.e. sustained and endurance speed, range and endurance) and the main design parameters (length, breadth and draught). Propulsion and generation systems can be selected from the GUI, on the basis of external database. It is possible to choose how many engines to install and how to set their working regime by means of the engine margin. Concerning generation systems, also their redundancy can be set. Payload configuration can be selected from the GUI, linked to another external database including organized set of data regarding armament, ammunitions, control systems, helicopters, RHIBs, UAVs and ROVs. Crew is a required input, but an automatic preliminary estimation is also possible by rule of thumb. Concerning seakeeping analysis and the so-called "added resistance" evaluation, the sea state (or, alternatively, the sea area) can be set from the GUI, as well as the forward speed, the heading angle and a longitudinal position where, in case, assessing vertical accelerations.

With reference to Figure 1, displacement, propulsive and electrical power installed on board (i.e. available) are firstly determined, as these quantities depend exclusively on input data. It must be noticed that the main coefficients of form are set as constants, since the differences among the actual coefficients of the analysed basis ships can be considered negligible.

Estimation of areas and volumes (both the available, i.e. depending on the hull characteristics, and the required quantities), as well as of weights (divided into light weight ship and deadweight), centres of gravity and the required electrical load, is therefore carried out. Each above mentioned quantity is subdivided into secondary elements, according to the NATO Ship Work Breakdown Structure (SWBS), where possible (usually as far as weights or electrical loads are concerned), or to the typical subdivision adopted as common practice. This step is carried out by means of either statistical regressions or parametric formulas.

Concerning the required electrical load estimation, the following operating conditions are considered: harbour, manoeuvre, navigation and war. For each operating condition the total absorbed electrical power is determined and the maximum among them is taken as the maximum functional load. This quantity, divided by the number of running generators, finally provides the required electrical power per generator to be compared with the power of the single installed generator.

Regarding the required fuel estimation, a major modification has been applied with respect to the existing version. In the presented SSM, the evaluation is carried out in two steps with reference to the two different components related to propulsion and electrical generation. The last one is calculated taking into account an average 24 hour electrical load provided by a linear combination of the total absorbed electrical powers corresponding to the four operating conditions considered. Furthermore, in the previous version of the SSM, the Specific Fuel Oil Consumptions (SFOC) of both main engines and diesel generators were fixed values associated with the Maximum Continuous Rating point (MCR). Thus, it was not possible to take into account the actual operating condition in terms of engine consumptions. A new propulsion and electric generation model has been therefore developed (Altosole et al. in prep.), aiming also at evaluating engines physical characteristics by means of statistical regressions.

The minimum intact stability is then assessed, by means of a qualitative parameter related to the metacentric height of the analysed configuration.

The following module concerns the propulsive power prediction. The implemented formulation is based on the Holtrop & Mennen method (Holtrop & Mennen 1982, Holtrop 1985), but a tuning analysis was necessary in order to extend its range of applicability to higher Froude numbers. A first attempt to take into consideration the added resistance has also been made in terms of percentage of resistance increase related to the resistance in calm water provided by the Holtrop & Mennen method modified as above explained. A study proposed by Townsin and Kwon (1983) has been considered and a parametric expression has been developed taking into account a correction factor so as to make the original formula suitable for OPVs (Salio et al. 2013).

Feasibility is finally checked by means of margin functions regarding the percentage balance between the available and required areas, volumes, propulsive power, electrical power and range respectively, in addition to the weight margin function previously calculated.

As an additional capability characterizing the analysed configuration, seakeeping performance assessment is then conducted (Salio et al. 2013). The implemented formulation is based on a semi-analytical approach proposed by Jensen et al. (2004). The method provides the evaluation in the frequency domain of heave, pitch and roll motions, as well as vertical accelerations, considering solely a limited number of parameters (i.e. the ship main dimensions and some dimensionless coefficients of form). This characteristic makes it suitable to be implemented in an automatic procedure such a SSM. In particular, the formulation now implemented in the code consists in a tuned version of the original method, developed in the framework of an MSc thesis carried out at the University of Genoa (Domenicucci & Gualeni 2010) and demonstrated to be suitable for the OPV typology. The method allows different heading angles to be taken into account as well.

A cost evaluation module is also present, although referring only to the platform acquisition cost.

Moreover, it is possible to print a summary report of each obtained ship configuration, including the main output as well as the detailed description of each module results (e.g. secondary weight components or electrical loads).

3 THE CASE STUDY: AN OFFSHORE PATROL VESSEL

In order to assess the robustness of the presented SSM, a sensitivity analysis has been carried out taking into consideration an OPV as a case study. Its main characteristics are reported in Table 1.

The sensitivity of the tool has been tested considering variations in length, speed and range, and setting all the others input parameters as constants. It has to be noticed that variations are carried out one at a time, in order to understand the relationships between a specific parameter and all the other ones, and consequently the ship feasibility.

Table 1. Main characteristics of the OPV under study.

Length-breadth ratio	Breadth-draught ratio	Froude nr	Block coeff.
6.05	3.66	0.55	0.49

It has been decided to keep the payload configuration constant.

In particular, maximum variations of about 15% in length, 25% in sustained speed and 70% in range have been applied. As can be seen, especially as far as the variation in range is concerned, the domain is rather large, but the aim was to force the code until the procedure stops due to the unfeasibility of the solution.

With reference to Figure 2a, b, results in terms of dimensionless total weight (with respect to the original OPV basis ship total weight) are presented as a function of the dimensionless length (with respect to the basis ship length) and of the dimensionless range (with respect to the actual basis ship range). The percentage weight margin function (labelled as ERRWEIGHT) is also reported in order to give an indication of the feasibility domain. As previously explained, a negative weight margin function means that the solution does not comply with the Archimedes' Theorem.

As far as speed variation is concerned (Fig. 2c), dimensionless required propulsive power (with respect to the actual basis ship required power) is shown as a function of the dimensionless speed (with respect to the basis ship speed). In this case, the percentage propulsive power margin function (ERRPOWER) is reported so as to indicate if the installed power, kept fixed, is sufficient (zero or positive ERRPOWER corresponds to a feasible solution).

Results related to the basis ship are represented on each graph with a square marker. Moreover, the domain of unfeasible solutions is highlighted.

The increments in weight due to the increasing length and range, as well as the increment in power due to the more severe design requirement in terms of speed are immediately appreciable. Focussing only on feasible solutions, it can been seen that an increase of about 10% in weight results from a variation in length in the range ±5%, whereas an increment of the same order of magnitude is provided by a much more emphasized modification in terms of range. A variation of about 7% in speed results in an increase of about 20% in propulsive power. It is interesting to notice that the basis ship is rather well optimized in terms of speed and range.

Results seem to be consistent and also represent an interesting source of speculation and discussion for the design team. In fact, such a tool is shown to act as an effective support for performing a trade-off analysis on a new naval unit during the initial concept exploration phase. It provides an indication of the consequences of the variation of a particular parameter, highlighting the corresponding relationships with all the other parameters. Moreover, margin functions allow to define the feasibility domain of the analysed solution.

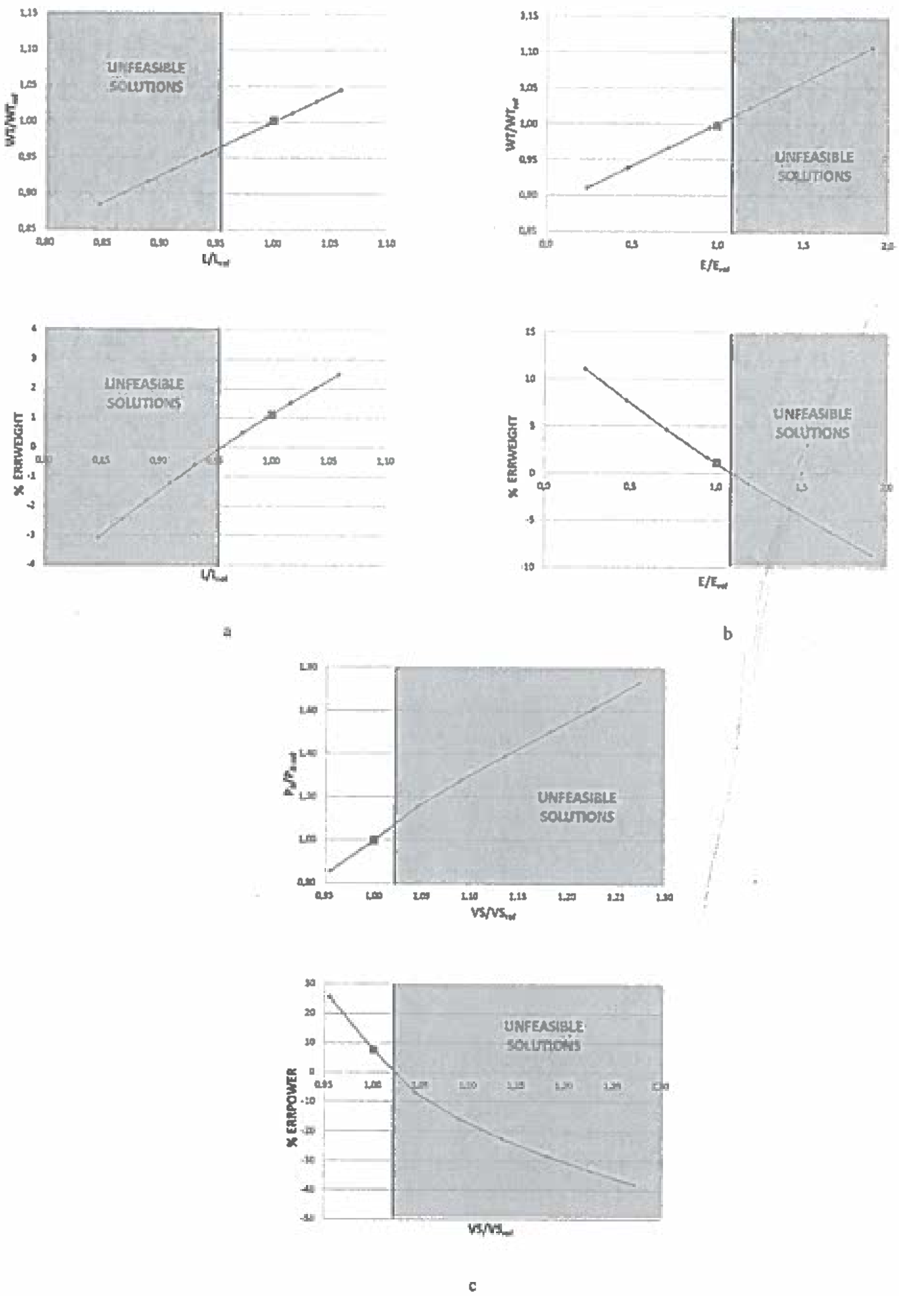

Figure 2. Results of the sensitivity analysis: length variation (a), range variation (b), and speed variation (c). Dimensionless values for weight (WT/WT_{ref}) and propulsive power ($P_B/P_{B\,ref}$) with respect to the basis ship characteristic values are reported, as well as the percentage margin functions related to weight (ERRWEIGHT) and propulsive power (ERRPOWER), all the quantities as a function of dimensionless length, range and speed respectively. The domain of unfeasible solutions is highlighted and the basis ship values are indicated with a square marker.

4 CONCLUSIONS AND FURTHER IMPROVEMENTS

The present paper addresses the development of a SSM to be integrated in a wider computational architecture, including also a tool for the evaluation of the ship operational capabilities.

The proposed study consists in a further validation and improvement of an existing code elaborated by the University of Genoa and Orizzonte Sistemi Navali S.p.A. over the years. The main modifications made have been here presented, concerning new approaches for the assessment of propulsion and energy generation systems (mainly as far as consumptions and physical characteristics are concerned) and seakeeping performance. A first attempt to take into consideration the added resistance has been made as well.

A case study aiming at assessing the robustness of the tool has been reported, taking into account an OPV typology. Results show an adequate sensitivity to variations and highlight some of the advantages of such a tool. Acting as an effective support for performing trade-off analyses, it allows to conduct fast investigation and comparisons among a large number of possible ship alternatives. Moreover, it provides an indication of the consequences of the variation of a particular parameter, highlighting the corresponding relationships with all the other parameters. Finally, margin functions allow to define the feasibility domain of the analysed solution. Such advantages are clearly emphasized thanks to a limited running time and an easy access to output results provided by the GUI.

However, it is considered that the study needs further developments.

First of all, it is thought that a significant improvement could be achieved implementing an automatic routine for the generation of the 3D hull model. Hence, areas, volumes and other hull geometric characteristics could be directly evaluated without using statistical regressions, taking into consideration also the internal space subdivision. Furthermore, the user interface would be more interactive, providing also a visual image of the analysed configuration. Finally, 3D could allow more accurate methods for seakeeping and added resistance analysis to be used and other capabilities, such as signatures or survivability, could be addressed.

Secondly, the range of applicability should be extended, in order to take into account frigates as well. Also more operational capabilities should be considered in order to improve the versatility of the code.

Extending the range of applicability, i.e. the database of the basis ships, would result not only in a re-validation of the existing regressions, but also in a revision analysis, especially as far as propulsion and power prediction are concerned. Further propulsion options are necessary, regarding for example gas turbines so as to be able to assess CODOG/CODAG propulsion solutions. A more accurate model concerning the propulsor should be developed, including both propellers and pump-jets. Furthermore, power prediction should be extended to higher Froude number, taking into consideration alternative predictive methods if necessary.

Finally, more advanced models should be developed concerning crew and costs estimation, since only preliminary formulation are now implemented. Especially cost evaluation represents an important capability in order to complete and fully take advantage of such a tool.

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Design optimization