Learning Aspects of Procedures for Ship Conceptual Design Based on First Principles

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Abstract – **This paper presents the learning process, oriented to undergraduate students in Naval Architecture, of some procedures for the conceptual design of ships based on first principles. Firstly, considering the points of view of the different stakeholders, the design requirements are identified and analyzed, taking into account the relevant physical, economic, technological and social aspects. Based on this information, merits and constraints are established in order to follow a decision making process on the design alternatives. An application example of this learning process in a ship design undergraduate course is described, in which cost and risk are taken as design merits. Certain relations among dimensions and inertias are taken as descriptive parameters of a solution. The bridge between merits and parameters is framed on the following functionalities: cargo capacity, stability, resistance and propulsion, maneuverability, seakeeping, strength. Genetic algorithms are used as a searching process. The scenario of the problem was chosen in accordance with the expectations of the students, being the renewal of the fleet of an oil transportation company. As result, a form of product model is obtained, specifically oriented to conceptual design, which materializes the learning acquired by the students.**

Index Terms – Design based on first principles, parametric design, ship design learning, ship design process.

INTRODUCTION

When the authors began planning the Ship Design course for the students of the 8th semester in Naval Architecture and Ocean Engineering, it was decided that a new learning process would be used. The course would provide the students the opportunity to develop a conceptual ship design in which they would sequentially identify the problem and analyze the relevant information, formulate relationships between design parameters and functional attributes, and consequently acquire a comprehensive discourse about the achieved solution, the principles that model the functionalities, and the searching process. Certainly it would not be a simple task, since there was not enough time to simulate the course development and also because all the past experience in this course had been with the use of Evans' spiral design, apud Andrews [1].

The remainder of this paper is organized as follows. The next section - Ship Design Process - describes two different approaches, namely the point-based and set-based designs. The following section - Models and Principles - presents some models for the estimation of functional attributes of the solutions. Some of these models are mainly based on empirical methods, while others are more oriented to a first principles approach. Nevertheless, the whole frame of the procedures is adequate to the first principles approach, and once the empirical models can be replaced and be analytical ones, the procedures can be adapted accordingly. The following section describes a case study related to the renewal of the fleet of an oil company. The last section presents conclusions about this learning process.

SHIP DESIGN PROCESS

In ship design there are many domain-specific models of the design process, but Evans' design spiral is probably the most well known. This model emphasizes that many design issues interact and must be considered in sequence, in increased detail in each pass around the spiral, until a single design that satisfies all constraints and balances all considerations is reached. This approach is essentially a point-based design, since it leads to a single point in the space design. A disadvantage of this approach, as pointed out by Parsons [2], is that it may not produce a global optimal solution. Nowadays, a different approach, taken from the automotive industry, is being used in the ship conceptual design. It is called set-based design and, as a main feature, it defines broad sets for the parameters' design, in order to allow concurrent design to begin, and keeps open these sets, so that the design teams can see the difference in performance and cost among the different solutions.

The conceptual design process includes the following phases: needs identification, requirements definition; design criteria selection and solutions framework development [3]. Conceptual design influences the largest portion of the life-cycle cost of the product, and thus the use of a set-based design approach is more appropriate to meet an optimal global solution.

In searching for an optimal solution, it is not always possible to make use of traditional prescriptive methods, which are often difficult to evolve to new designs; therefore alternative methods must be tried. In this regard, first principles methods are increasingly used [4], which means that, as far as possible, analytical models are used to relate functional attributes to design parameters. Based on these attributes, merits are built in accordance to the design requirements in order to guide the optimization process.

MODELS AND PRINCIPLES

Weight Estimation and Balance

Weight estimation can be done based on empirical regressions for structure, machinery, outfit and deadweight items other than cargo [5].
An additional approach can be used for estimating how certain parameters such as length, breadth and depth have influence on structural weight. The ship is considered as a longitudinal girder, which has the same length of the ship, being its height is equal to the ship's depth and its width equal to the ship's breadth. For a tanker with double bottom and double sides, one could consider for instance three flanges (for the double bottom and for the deck) and four webs (for both double sides). All the continuous longitudinal material shall be considered as contributing to an equivalent thickness for plating.

The total area of the webs and flanges for the ship modeled as a girder would be:

$$A = 3 \cdot L \cdot B + 4 \cdot L \cdot D \ ,$$

where L is the ship length, B the ship breadth, D the ship height. This area would be roughly proportional to the structural weight of the ship.

The total volume enclosed by the hull girder sides and bottom and deck would be:

$$V = L \cdot B \cdot D \ ,$$

which would be roughly proportional to the cargo volume available.

In the following, only relative increments or decrements of the structural weight and of the girder volume due to relative changes in one of the main dimensions L, B or D will be considered.

Regarding ship length, one has:

$$\frac{\partial A/A}{\partial L/L} = (3 \cdot B + 4 \cdot D)\frac{L}{A} = 1 \ ; \ \frac{\partial V/V}{\partial L/L} = B \cdot D \frac{L}{V} = 1 \ ,$$

showing that volume and area changes are equal to a specific change in length.

Regarding ship breadth, one has:

$$\frac{\partial A/A}{\partial B/B} = (3 \cdot L)\frac{B}{A} = \frac{1}{1 + \frac{4/3}{B/D}} \ ; \ \frac{\partial V/V}{\partial B/B} = L \cdot D \frac{B}{V} = 1$$

For $B/D \cong 1.8$ (as for a tanker, for instance), one has $\frac{\partial A/A}{\partial B/B} \cong 0{,}57$, showing that area change is about 57% of the volume change, for a specific change in breadth.

Regarding ship depth, one has:

$$\frac{\partial A/A}{\partial D/D} = (4 \cdot L)\frac{D}{A} = \frac{1}{\frac{3}{4}\frac{B}{D} + 1} \ ; \ \frac{\partial V/V}{\partial D/D} = L \cdot B \frac{D}{V} = 1$$

Again for $B/D \cong 1.8$, one has $\frac{\partial A/A}{\partial D/D} \cong 0{,}43$, showing that area change is about 43% of the volume change, given a specific change in height.

This type of analysis may give important directions on design changes for adapting multiple compromises in the early stages of the conceptual design. If one needs an increase of volume, for instance, probably the most effective way to obtain it - constraining the analysis to changes in L, B and D – would be changing D, which would imply the least impact on the steel quantity (proportional to area A), and so on.

Weight estimation can be done based on empirical regressions for structure, machinery, outfit and deadweight items other than cargo [5].

Arrangement; Volume Estimation and Balance

Arrangement in the conceptual design is here understood as the definition of dimensions for peak tanks, cargo tanks, cofferdams and machinery space, verifying whether these allocations are compatible with the ship's main dimensions. If not, the main dimensions have to be modified so as to balance the needed and available volumes.

Static Stability

Ship's transverse stability depends upon the metacentric height, which is calculated based on the vertical position of the center of mass and of the center of buoyancy, as well as the metacentric radius.

An analytical model, based on a simplified geometric representation of the ship hull, possibly as a polyedric surface, could be built for the estimation of the position of the buoyancy center and of the metacentric radius. Specifically, the metacentric height is calculated based on the first moment of area of the ship design waterplane. As for the center of mass calculation, the vertical position of the main weight items must be estimated beforehand.

Primary Structure

The main role of any ship structure is to support loads – its own weight, cargoes and sea environment – and deflect as a long flotation beam, generally referred as a hull girder primary structure. Such a hull girder is composed of by several panels, mainly portions of shell plating reinforced by longitudinal stringers and transverse frames, being the last ones responsible to keep the hull girder cross section in its original shape. The hull girder has to support vertical and horizontal bending moments and shear forces. Access to details of the main hull cross section is only available after several design cycles, when the hull forms are detailed. Nevertheless just the ship's lightweight is used in the early stages of ship design. To obtain details of the main hull cross section, it is necessary to have all loads and a first estimate for the necessary longitudinal material distribution for the main hull. At the beginning of the design process, one may use classification societies' rules to obtain the loads, the minimum hull girder bending moment and shear forces and primary minimum safety factor. Then one may use the classical beam theory to deal with a hull girder cross section composed of by plates with equivalent thickness necessary to take into account for the longitudinal reinforcements. Using such methodology, a double hull tanker may be composed of one to six equivalent thicknesses, depending on the detail level adopted at the early design stages. These thicknesses refer to the double bottom, double shell, main deck and longitudinal bulkhead, if present.

Resistance and Propulsion

The mathematical model provides not only an estimation of the hull resistance and engine power demand but also leads to the selection of the propeller engine set for a low-speed Diesel power plant, which is the most common type for tankers.

Although an analytical model could be used to evaluate one component of the hull resistance, namely the wave resistance, Holtrop's formulation [6] is adopted to evaluate the total resistance, since for tankers the frictional resistance is, at least, equal to fifty percent of the total resistance. Holtrop's formulation is based on a statistical analysis of resistance data. A resistance service margin is included to provide the added power required in order to overcome in service the added resistance from hull fouling, waves and wind effects.

Holtrop's models are also used to predict values for wake coefficient and resistance increase (thrust deduction) factor, as well as to provide the relative rotative efficiency.

In order to select propeller alternatives, number of blades, disk area coefficient (expanded blade area ratio) area ratio and pitch-diameter ratio are used as design parameters. The maximum propeller diameter, which usually provides best efficiency, is assumed, but other values can be used as long as engine speed constraints make it necessary. Polynomial representations of dimensionless propeller torque and thrust coefficients for Wageningen B Screw Series propellers [6] are used in order to perform the hull-propeller-engine interaction. Keller's cavitation criterion [6] is used to impose an external cavitation constraint since charts for open water tests do not take it into account.

Essentially, the determination of the best propeller-engine set consists in an optimization problem in which the selected propeller has to produce a thrust equal to the "augmented" ship resistance and a Diesel engine that meets the demand of propeller speed and power. The propeller speed is obtained from the propeller advance coefficient, given by the force equation. The propeller torque coefficient is also obtained from the value of the advance coefficient, combined with the estimate of the relative rotative and transmission efficiencies, to evaluate the required engine power.

Layout diagrams provided by engine builders are used to select feasible engines, with the requirement that the point representing the propeller demand on speed and power lies in the layout diagram. In order to do so a power margin is defined to evaluate the installed power, this corresponding to the specified maximum continuous power.

Maneuverability

Some maneuverability models are based on fundamental principles, but they have some parts or parameters not completely developed or identified, estimated in a way that fit some set of empirical and/or experimental data according to some approximation criteria. These models are usually specific for certain types of ships and maneuvers. [7] and [8] are examples of this approach. Other models rely more extensively on fundamental principles, though with some limitations such as the representation, for instance, linearity. [9] and [10] are examples of this approach.

All these models are quite convenient for application in the early stages of ship design, since the involved parameters are generally some overall dimensions, as well as some shape and functional coefficients of the hull and appendices, which could easily be taken as conceptual design parameters in an optimization search process.

Attributes like those that are considered as interim maneuver criteria by the International Maritime Organization [11] can be evaluated through these methods, for instance:

- Turning ability
- Initial turning ability
- Yaw checking and course keeping ability
- Stopping ability

Additionally to the ship maneuvering in deep unrestricted waters, models for maneuvering in restricted waters and for organizational and human factors, influencing ship navigation and steering, should be considered since the early stages of ship design, due to their potential impacts on ship safety. In fact, as pointed out in [12], "including restricted waterway maneuverability as an important spoke in the ship design spiral would seem a necessary step to enabling proper tradeoffs in vessel design". An approach which considers indirectly maneuverability qualities in restricted waters is addressed in the section "risk evaluation".

Seakeeping

Seakeeping is here restricted to a one degree-of-freedom model of the ship rolling motion. The problem is subdivided in three cases: 1) hull free to roll in previous undisturbed waters; 2) roll motion in regular waves; 3) roll motion in irregular waves. In the first case, there are three terms, namely, the virtual inertia (mass inertia plus added inertia), the damping and the hydrostatic restoration. This problem is typically nonlinear in the damping, which usually is represented by an odd polynomial [13]. As for a linear plus parabolic representation for the damping, the empirical formulation compiled in [14] may be used, with the approach of an equivalent linear representation, in the sense that both representations lead to the same energy dissipation per cycle. As for the restoration term, it can be represented based on the metacentric height. The added mass depends on the geometry of the cross sections and has to be estimated accordingly. This step enables to estimate the roll natural period and decay in previously still waters. In the second case (forced motions under regular waves), the exciting moment is estimated quasi-hydrostatically considering a mean wave slope [15]. This step leads to the response amplitude operator of the ship roll motion. The third case (ship roll in irregular waves) is based on the superposition assumption of the real sea excitation according to [16], leading to the roll significant height.

Cost Evaluation

Cost evaluation may be done based on weight items, such as steel, outfit, deadweight item other than cargo, etc., as well as on power demands. The weight items and power are used in regressions enabling the estimation of acquisition and operational costs.

Risk Evaluation

Risk is here restricted to environmental impacts due to oil spills caused by hull perforation in groundings and collisions.

Ref. [17] considers the powered and drift groundings of ships. The "technique for human error rate prediction" (THERP) is used to predict human error rates based on "possible human task activities and the corresponding error probabilities". It is used in connection with empirical data concerning "human error probabilities" (HEPs) as modified by "performance shaping factors" (PSFs). Fault trees and event trees lead to the identification of system failures and sequences, whose associated probabilities can be assigned using the THERP and statistical data. The system can be further modified to meet the safety requirements concerning grounding probability level.

Collision can be treated in a similar way to powered grounding.

Mean oil outflow can be evaluated, given that collision or grounding occurred, using historical data information about position and penetration of damages. A procedure for oil spill from bunker tanks was proposed to IMO [18]; a similar procedure was used in [19].

In the early stages of design, the definition of double side width and double bottom height is done simultaneously with the definition of the main dimensions of the ship, the lengths of cargo and peak tanks, the length of machinery spaces and cofferdams, etc. Altogether, the ship volumes must be compatible with the allocation of cargo and ship systems; weights and displacement must also be balanced. In this process of volumes and weights balancing, it becomes clear whether or not there is a margin for increasing the double side width and double bottom height, as well as their impact on the mean oil spill.

Optimization process

Considering that a ship a complex product involving many engineering branches, to set up a simple objective to guide the design process is a difficult task. The best hull form will conflict with the requirements for cargo spaces, for example. Usually, the designer has conflicting objectives to satisfy. Before the advent of multi-objective optimization techniques, multi-objective problems were addressed by collapsing all the objectives into a single objective. A classic (i.e., single-objective) optimization algorithm was then used to minimize (or maximize) this collapsed objective. However, one needed to decide a priori as how to prioritize one objective in detriment of others before knowing the resulting alternatives. The key advantage of multi-objective optimization is that it does not require the user to make premature decisions about the ideal trade-off. One approach to handle multi-objective design problems is to employ the concept of Pareto optimality. Pareto optimality was introduced in the late eighteen hundreds by the economist Vilfredo Pareto. A solution is said to be Pareto optimal if there exists no other solution that is better in all attributes. This implies that, in order to achieve a better value in one objective, at least one of the other objectives is going to deteriorate if the solution is Pareto optimal. Thus, the outcome of a Pareto optimization is not one optimal point, but a set of Pareto optimal solutions that visualize the trade-off between the objectives. One of the most used types of algorithms in multi-objective problems is referred as Genetic Algorithms (GAs). GAs have appeared in recent years, and are so called because they try to simulate, and replicate, the mechanisms of natural selection and genetics. They search for the absolute maximum of a function being optimized, (or the group of maxima in the case of multi-objective optimization) by 'mating' designs already assessed, on the basis of probabilities geared to their objective values. GAs, may be specifically tailored to the problem at hand, are simple enough to be easily understood and accepted among the students, and are robust and reliable enough for most purposes. There are several alternative methods for the selection of the designs which will 'mate'. GAs also provide a further mechanism, whose aim is to keep the possibility of diversity in the population of designs in which is modeled: the 'mutation'. It is now recognized that algorithms which belong to the GA's class are among the best ones which lead to effective multi-objective optimization. It is also known that, from an engineering perspective, they are very robust, since they provide the possibility to find a better solution, and hopefully also the maximum extreme, of the function to be optimized. Conversely, for 'classical' methods, their success relies heavily on the proper, and usually far from easy, choice of the initial condition. In other words, genetic algorithms always provide, if not the 'best' solution, a 'good' solution. The claimed drawback of genetic algorithms is their low convergence rate and high computational costs, as a consequence of the excessive number of evaluations needed for the objective-functions and constraints. However, this becomes negligible if the entire design process is viewed, and managed, from an engineering perspective.

CASE STUDY: AN ILLUSTRATIVE EXAMPLE

Context and Motivation

A Brazilian oil company is renewing its ship fleet demanding five different types of ships: gas carriers, product carriers, Panamax, Aframax and Suezmax. The basic ships specification data were available from the company's site and were used as a starting point for the students' design.

The students were enrolled in a one semester course in ship design. The class summed up of about 60 students; 15 groups were formed, each three groups working with the same ship type. The authors were lecturers in this course and each one advised five groups.

In the beginning of the term the students already knew the traditional ship design process based on the spiral model. When the parametric design paradigm was introduced, the students showed some resistance to follow this procedure. This was considered understandable, since in the spiral process, an effective solution is created, meaning that a specific ship is developed, while in the parametric process what is built is a set of attribute estimation models, not enabling the students to visualize specific solutions. Because, in the parametric process, it is possible to consider various set points for design, the specification of each solution remains open until the convergence of the selection procedure.

However, as the students continued working on their projects, they became aware of the strength of the parametric design procedure and finally engaged themselves in it.

Results

Tables I and II present the main dimensions of a couple of final solutions for two types of ships: Handymax Light Products Carrier and Suezmax Crude Oil Carrier.

The requirement for cargo volume for the Handymax was 54000 cubic meters with a mean density of 0.85 tons per cubic meter. For the Suezmax, the requirement was 1050 thousands of barrels with a mean density of 0.94 tons per cubic meter. The minimum service speed was required to be 15 knots.

Group B ship has a smaller block coefficient than Group A ship. Despite the fact that Group B ship has higher values of double bottom height, depth and length, its light weight resulted smaller than that of Group A ship.

Group D ship has also a lighter weight than Group C ship, and this is understandable due to its smaller breadth, despite its larger depth, double bottom height and double side width.

Ships of Groups B and D seem to have a better design than the ships of Groups A and C, respectively, due to the smaller displacement and larger double bottom height and / or double side width. This is though questionable, since different models have been used for the ship attributes estimation, as well as different optimization objective functions and constraints have been assumed.

Nevertheless, all of these models and assumptions about objectives and constraints, as well as the connection of the models and adopted assumptions to reality and the effectiveness of the search process, are explicit and prone to critical assessment by the various groups and advisors. This is a very significant advantage of a more rational oriented design process in respect to a more empirical procedure, being the discussion of the process itself, more than the results, an important part of the learning process.

TABLE I
RESULTS FOR THE HANDYMAX LIGHT PRODUCTS CARRIERS

Group / Parameter	Group A	Group B
Length (m)	183.4	186.1
Breadth (m)	32.2	32.1
Design draught (m)	12.1	12.4
Depth (m)	16.8	17.2
Displacement (ton)	60,232	57,280
Double bottom height (m)	2.0	2.2
Double side width (m)	2.0	2.0
Number of tanks	12	12

TABLE II
RESULTS FOR THE SUEZMAX CRUDE OIL CARRIERS

Group / Parameter	Group C	Group D
Length (m)	264.9	265.9
Breadth (m)	49.6	46.8
Design draught (m)	17.0	17.0
Depth (m)	21.4	26.8
Displacement (ton)	194,600	188,170
Double bottom height (m)	2.3	3.2
Double side width (m)	3.5	4.0
Number of tanks	12	12

Learning aspects

The students were free to choose any computational language and platform to develop their computational design systems. All of them have reached the main purpose and some have mastered their abilities in systems development, arriving at interactive design systems. Others, based on the genetic algorithm basic principles, have got a deep understanding of the metaheuristic, so that they could develop new approaches.

On one hand, with the classical spiral based design, there is more opportunity for the student to go deeper in some ship's systems details. On the other hand, parametric design allows the consideration of a large number of alternatives for design solutions, giving the students a good perception of the influence of each design parameter on the solution attributes.

CONCLUSIONS

For each class of solutions characterized by its typical geometries and technologies, a bridge was built, filling the gap between the merits / constraints and the parameters which describe the solutions of that class. This bridge is in fact an algorithm that, given the descriptive parameters of each solution alternative, enables the calculation of the merits and the enforcement of the constraints. The algorithm is structured on the basis of first principles supplemented by empirical observations, and is applied in a search for the best solution that verifies the applicable constraints.

This learning process enabled the students to: a) become aware of the problem that was being considered, identifying and analyzing the relevant information; b) make use of first principles, as well as empirical data, to conceive classes of solutions to the problem, developing or reinforcing their conceptual understanding regarding the relations between geometric parameters and functional attributes, which lead to the merits; c) acquire an explicative discourse about the achieved solution and how it works, the algorithm and the principles that model functionalities, the process for searching for the best solution, and about the design process itself.

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