Holistic Ship Design Optimization: Merchant and Naval Ships

Optimización del diseño holístico de buques: Embarcaciones Mercantes y Navales

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Abstract

The present paper provides a brief introduction to a *holistic* approach to ship design optimization, defines the generic ship design optimization problem, and demonstrates its solution by using advanced optimization techniques for the computer-aided generation, exploration, and selection of optimal designs. It discusses proposed methods on the basis of some typical ship design optimization problems of cargo and naval ships related to multiple objectives, leading to improved and partly innovative design features with respect to ships' economy, cargo carrying capacity, safety, survivability, comfort, required powering, environmental protection, or combat strength, as applicable.

Key words: holistic ship design, parametric design, multi-criteria optimization, naval ships.

Resumen

Este documento brinda una breve introducción a un enfoque *holístico* a la optimización del diseño de embarcaciones, define el problema genérico de la optimización del diseño de embarcaciones y demuestra su solución mediante el uso de técnicas avanzadas de optimización asistidas por computador para la generación, exploración y selección de diseños óptimos. Discute los métodos propuestos sobre la base de algunos problemas típicos de optimización de diseño de embarcación de buques de carga y navales relacionados a los objetivos múltiples, conllevando a características de diseño mejoradas y parcialmente innovadoras con respecto a la economía de la embarcación, capacidad de carga, seguridad, supervivencia, comodidad, potencia requerida, protección ambiental o fortaleza de combate, como sea aplicable.

Palabras claves: diseño holístico de buques, diseño paramétrico, optimización de múltiples criterios, buques navales.

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Introduction

Ships are built to cover needs of society through the provision of specific services. These services may be on a commercial or non-commercial basis; whereas, in the first case (commercial ships) the objective is to generate profit for the ship owner, the latter case is related to a public service of some kind, the cost of which is generally assumed by a governmental authority. The main bulk of commercial ships are cargo ships, which carry all types of cargo (solid and liquid cargo or passengers) and provide in fact the largest (by volume of cargo and transport distance, [ton-miles]) worldwide transportation work, compared to other modes of transport.

The design of ships is a complex endeavor requiring the successful coordination of many disciplines, of both technical and non-technical nature, and of individual experts to arrive at valuable design solutions. Inherently coupled with the design process is design optimization, namely the selection of the best solution out of many feasible ones on the basis of a criterion, or rather a set of criteria. Such evaluation criteria are the shipbuilding cost or the required freight rate for merchant ships or more complex ones that include, besides economy, ship performance in terms of safety, comfort, survivability in intact and damage condition and environmental friendliness. A systemic approach to ship design may consider the ship as a complex system integrating a variety of subsystems and their components, e.g., for merchant ships subsystems for cargo storage and handling, energy/power generation and ship propulsion, accommodation of crew/passengers and ship navigation, whereas for naval ships combat systems are added.

Considering that ship design should actually address the whole ship's life cycle, it may be split into various stages that are traditionally composed of the concept/preliminary design, the contractual and detailed design, the ship construction/fabrication process, and ship operation for an economic life and scrapping/recycling. It is evident that an optimal ship is the outcome of a *holistic* optimization of the entire, above defined, ship system over its whole life cycle. But even the simplest component of the above-defined optimization problem, namely the 1st loop (conceptual/preliminary design), is complex enough to be simplified (*reduced*) in practice. Inherent to ship design optimization are the conflicting requirements resulting from the design constraints and optimization criteria (merit or objective functions), reflecting the competing interests of the various ship design stake holders (ship-owner, shipbuilder, cargo owner and cargo forwarder, flag and class authorities, etc.).

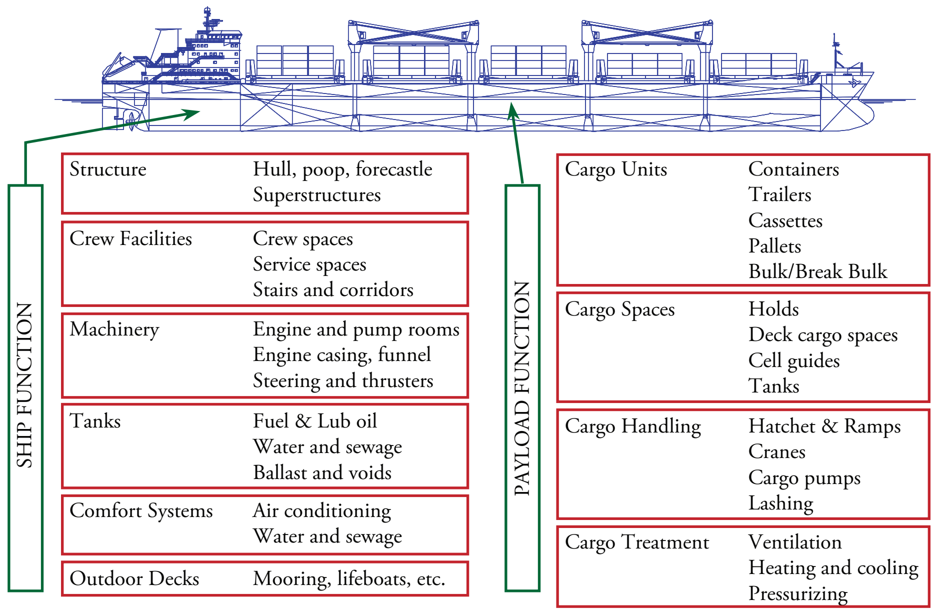
The present paper provides a brief introduction to a *holistic* approach to ship design optimization, defines the generic ship design optimization problem, and demonstrates its solution by use of advanced optimization techniques for the computer-aided generation, exploration, and selection of optimal designs. It discusses proposed methods on the basis of some typical ship design problems of cargo and naval ships related to optimizations with multiple objectives and leading to improved and partly innovative design features with respect to ship economy, cargo carrying capacity, safety, survivability, comfort, required powering, environmental protection or combat strength (naval ships), as applicable.

Holistic Ship Design Optimization

Inherently coupled with the design process is design optimization, namely the selection of the best solution out of many feasible ones on the basis of a criterion, or rather a set of criteria. A systemic approach to ship design may consider the ship as a complex system, integrating a variety of subsystems and their components, e.g., subsystems for cargo storage and handling, energy/power generation and ship propulsion, accommodation of crew/passengers, and ship navigation. They are all serving well-defined ship functions.

Ship functions may be divided into two main categories, namely *payload* functions and *inherent* ship functions.For example, for Ro-Ro passenger ships, the payload functions are all those related to the provision of public and private accommodation spaces for the passengers and spaces/handling and access equipment for the cargo (Ro-Ro decks, ramps, ventilation, etc.); inherent ship functions

Fig. 1. Payload and Ship functions of Cargo Ships (Levander, 2003)



are those related to the transport of passengers and cargo safely from port to port with certain speed, namely the ship as a system, consisting of ship's hull (main and superstructure), facilities of crew, navigation control (bridge), machinery, tanks (fuel and lubrication oil, water and sewage, ballast and voids), comfort systems (air conditioning, water and sewage, electrical), mooring and life-saving equipment, etc. (Fig. 1).

Independently, considering that ship design should actually address the whole ship's life cycle, it may be split into various stages that are traditionally composed of the concept/preliminary design, the contractual and detailed design, the ship construction/fabrication process, and ship operation for an economic life and scrapping/recycling. It is evident that the optimal ship with respect to her whole life cycle is the outcome of a *holistic*[1] optimization of the entire, above defined ship system for its life-cycle. It is noted that mathematically, every constituent of the above defined life-cycle ship system forms evidently itself a complex nonlinear optimization problem for the design variables, with a variety of constraints and criteria/objective functions to be jointly optimized. Even the simplest component of the ship design process, namely the 1st loop (conceptual/preliminary design), is complex enough to be simplified (reduced[2]) in practice. Also, inherent to ship design optimization are the conflicting requirements resulting from the design constraints and optimization criteria (merit or objective functions), reflecting the interests of the various ship design stake holders: ship owners/operators, ship builders, classification society/coast guard, regulators, insurers, cargo owners/forwarders, port operators etc.

Assuming a specific set of requirements (usually the *shipowner's requirements for merchant ships* or *mission statement for naval ships*), a ship needs to be optimized for lowest construction cost, for highest operational efficiency or lowest Required Freight Rate (RFR), for highest safety and comfort of passengers/crew, for satisfactory protection of cargo and the ship herself as hardware and last but not least, for minimum environmental impact, particularly for oil carriers with respect to marine pollution in case of accidents and for high-speed vessels with respect to generated wave wash. Recently, even aspects of ship engine emissions

[1] Principle of holism according to Aristotle (*Metaphysics*): "The whole is more than the sum of the parts"

[2] Principle of *reductionism* may be seen as the opposite of *holism*, implying that a complex system can be approached by *reduction* to its fundamental parts. However, *holism* and *reductionism* should be regarded as complementary approaches, as they are both needed to satisfactorily address complex systems in practice.

and air pollution need to be considered (see current discussions about the Energy Efficiency Design Index (EEDI), International Maritime Organization-MEPC, 2008). Many of these requirements are clearly conflicting and a decision regarding the optimal ship design needs to be rationally made.

To make things more complex but coming closer to reality, even the specification of a set of design requirements with respect to ship type, cargo capacity, speed, range, etc. is complex enough to require another optimization procedure that satisfactorily considers the interests of all shareholders of the ship as an industrial product and service vehicle of international markets or others. Actually, the initial set of ship design requirements is the outcome of a compromise of intensive discussions between highly experienced decision makers, mainly on the shipbuilder's side and end users who attempt to articulate their desires and tradeoffs they are willing to allow. A way to undertake and rationally consolidate this kind of discussion has been advanced by the EU-funded project LOGBASED (*Brett et al., 2006*).

Since the mid 60s with the advance of computer hard- and software more and more parts of the design process were taken over by computers, particularly the heavy algorithmic and drafting elements of ship design. Simultaneously, the first computer-aided preliminary design software systems were introduced, dealing with the mathematical parametric exploration of the design space on the basis of empirical/simplified ship models for specific ship types or the optimization of design variables for specific economic criteria by gradient based search techniques. With the further and faster advance of computer hard- and software tools, along with their integration into powerful hard- and software design systems, the time has come to look ahead in ship design optimization in a *holistic* way, namely by addressing and optimizing several and gradually all aspects of ship life (or all elements of the entire ship life-cycle system), at least the stages of design, construction and operation; within a *holistic* ship design optimization we should herein also understand exhaustive multi-objective and multi-constrained ship design optimization procedures even for individual stages of ship life (e.g., conceptual design) with *least reduction* of the entire real problem (*Nowacki, 2009, Andrews et al., 2009, Papanikolaou et al., 2009a, and Papanikolaou, 2009b*).

The use of Genetic Algorithms (GA), combined with gradient-based search techniques in micro-scale exploration and with a utility functions technique for the design evaluation, is advanced in the present paper as a generic-type optimization technique to generate and identify optimized designs through effective exploration of the large-scale, nonlinear design space and a multitude of evaluation criteria. Several applications of this generic, multi-objective ship design optimization approach by using the design software platform of the Ship Design Laboratory of NTUA, integrating well-established naval architectural and optimization software packages with various application methods and software tools, as necessary to evaluate stability, resistance, seakeeping, structural integrity, etc., may be found in the listed references. The following examples, deduced from past projects of NTUA-SDL, may be highlighted.

- Hydrodynamic hull form optimization of high-speed, twin-hull vessels (*Papanikolaou, 1991, Papanikolaou et al., 1996*).
- Hull form optimization of high-speed mono- and twin-hull vessels for least wave resistance and wave wash (*EU project FLOWMART, Zaraphonitis and Papanikolaou, 2003*).
- Multi-objective optimization of naval ships (Boulougouris and Papanikolaou, 2004).
- Hull form optimization of a wave piercing, high-speed, mono-hull vessel for least resistance and best seakeeping (*EU project VRSHIP-ROPAX2000, Boulougouris and Papanikolaou, 2006*).
- Parametric design and multi-objective optimization of conventional and high-speed ROPAX ships (*Zaraphonitis and Papanikolaou, 2003, Skoupas et al., 2009*).
- Risk-based ship design (see a series of examples of application by various research teams, *Papanikolaou* (ed), 2009c).
- Logistics-based optimization of ship design (*Gkohari and Papanikolaou, 2010*).

- Multi-objective tanker optimization (*Papanikolaou et al., 2010*).

The Generic Ship Design Optimization Problem

Within a *holistic* ship design optimization, we should herein mathematically understand exhaustive multi-objective and multi-constrained optimization procedures with *least reduction* of the entire real design problem. The generic ship design optimization problem and its basic elements may be defined as follows (Fig. 2).

- **Optimisation Criteria (Merit Functions, Goals):** This refers to a list of mathematically defined performance/efficiency indicators that may be eventually reduced to an economic criterion, namely the profit of the initial investment. Independently, there may be optimization criteria (merit functions or goals) that may be formulated without direct reference to economic indicators, see, e.g., optimization studies for a specific X ship function, like ship performance in calm water and in seaways, ship safety, ship strength including fatigue, etc. The ship design optimization criteria are generally complex nonlinear functions of the design parameters (vector of design variables) and are often defined by algorithmic routines in a computer-aided design procedure. According to Levander (2003), the most important performance indicators for cargo vessels are summarized in Fig. 3.
- **Constraints:** It mainly refers to a list of mathematically defined criteria (in the form of mathematical inequalities or equalities) resulting from regulatory frameworks pertaining to safety (for ships, mainly the international SOLAS and MARPOL regulations). This list may be extended by a second set of criteria characterized by uncertainty with respect to their actual values and being determined by the market conditions (demand and supply data for merchant ships), by the cost of major materials (for ships: cost of steel, fuel, workmanship), by the anticipated financial conditions (cost of money, interest rates), and other case-specific constraints. It should be noted that the latter set of criteria is often regarded as a set of input data with uncertainty to the optimization problem and may be assessed on the basis of probabilistic assessment models.
- **Design Parameters:** It refers to a list of parameters (vector of design variables)

Fig. 2. Generic Ship Design Optimization Problem

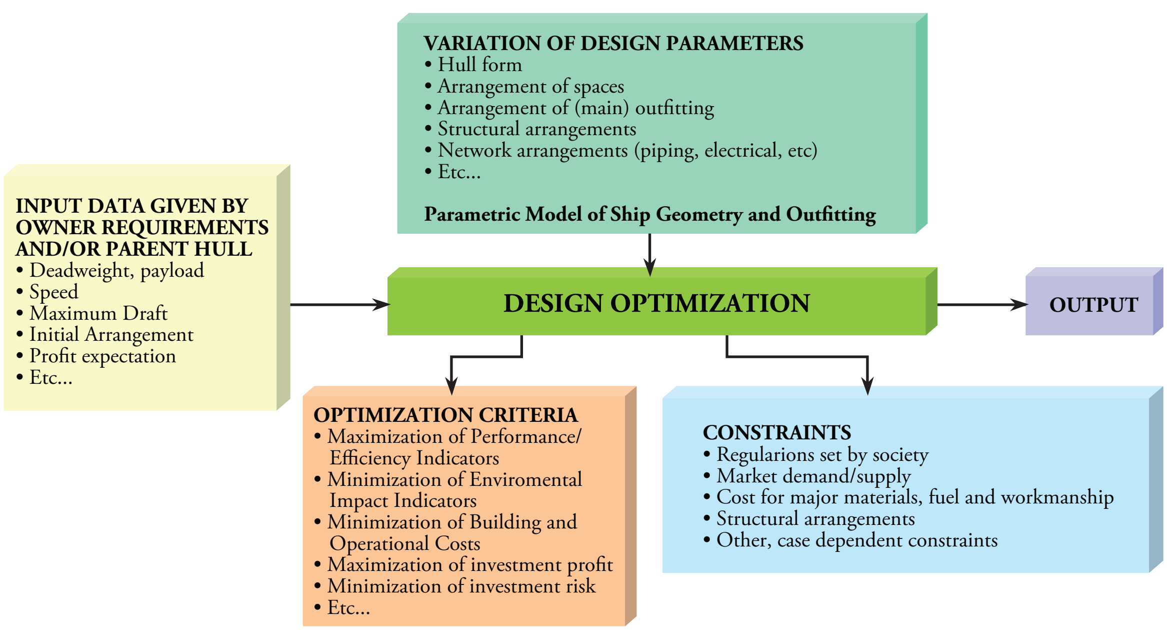


Fig. 3. Key Performance Indicators for Cargo Ships (Levander, 2003)

IMPACT AREA	TECHNOLOGY DRIVERS	GOALS	INDICATOR
Construction	Design Concept Standard Solutions Modular Construction Supplier Networking	Construction Efficiency	Building cost [$ / Payload unit]
Payload Functions	Payload Capacity Speed & Power Cargo Units Cargo Handling	Transport Capacity	Money making potential [RFR]
Ship Functions	Hull Form Propulsion Solution Fuel Type & Consumption Heat Recovery	Propulsion Efficiency	Bunker cost [$ / year]
	Navigation Machinery Operation Docking & Mooring	Automation	Crew cost [$ / year]
	Planned Maintenance Preventive Maintenance Condition Monitoring	Reliability	Keep schedule Time saving
	Fire prevention Grounding prevention Collision prevention	Safety	Casualties Insurance cost Repair & replacement cost
Social Values	Smoke & Emissions Waste, Sewage, Ballast Wake & Noise Recycling & Scrapping	Enviromental Friendliness	Health risk Enviroment fees & fines Disposal cost

characterizing the design under optimization; for ship design, this includes the ship's main dimensions, unless specified by the ship owner's requirements (length, beam, side depth, draft) and may be extended to include the ship's hull form, arrangement of spaces and of (main) outfitting, of (main) structural elements and of (main) networking elements (piping, electrical, etc), depending on the availability of topological-geometry models relating the ship's design parameters to a generic ship model to be optimized.

- **Input Data:** This initially includes the traditional owner's specifications/ requirements, which for a merchant ship are the required cargo capacity (deadweight and payload), service speed, range, etc., and may be complemented by a variety of further data affecting ship design and its economic life, like financial data (profit expectations, interest rates), market conditions (demand and supply data), costs for major materials (steel and fuel), etc. The input data set may include, besides numerals of quantities, more general type of knowledge data, like drawings (of ship general arrangements) and qualitative information that needs to be properly translated for inclusion in a computer-aided optimization procedure.
- **Output:** It includes the entire set of design parameters (vector of design variables) for which the specified optimization criteria/merit functions obtain mathematically extreme values (minima or maxima); for multi-criteria optimization problems, optimal design solutions are on the so-called Pareto front and may be selected on the basis of tradeoffs by the decision maker/designer. For the exploration and final selection of Pareto design solutions, a variety of strategies and techniques may be employed.

In mathematical terms, the multi-objective optimization problem may be formulated as:

$$\min\ [\mu_1(x), \mu_2(x), \ldots, \mu_n(x)]^T, \quad \text{subject to } g(x) \leq 0 \text{ and } h(x) = 0 \text{ and } x_l \leq x \leq x_u \tag{1}$$

where μ_i is the *i*-th objective function, *g* and *h* are a set of inequality and equality constraints, respectively, and *x* is the vector of optimization or vector of design variables. The solution to the above problem is a set of Pareto solutions, namely solutions for which improvement in one objective cannot be achieved without worsening of at least one other objective. Thus, instead of a unique solution, a multi-objective optimization problem has (theoretically) infinite solutions, namely the Pareto set of solutions.

The use of Multi-Objective Genetic Algorithms (MOGA), combined with gradient based search techniques in micro-scale exploration and with a utility functions technique for the design evaluation, is advanced in the present paper as a generic type optimization technique for generating and identifying optimized designs through effective exploration of the large-scale, nonlinear design space and a multitude of evaluation criteria occurring in ship design. Several applications of this generic, multi-objective ship design optimization approach by use of NTUA-SDL[3]'s design software system, integrating the naval architectural software package *NAPA*[4], the optimization software *modeFRONTIER*[5] and various application software tools, as necessary for the evaluation of stability, resistance, seakeeping etc. may be found in the listed references.

Two typical application examples of the introduced generic ship design optimization procedure of NTUA-SDL are presented and briefly commented in the following.

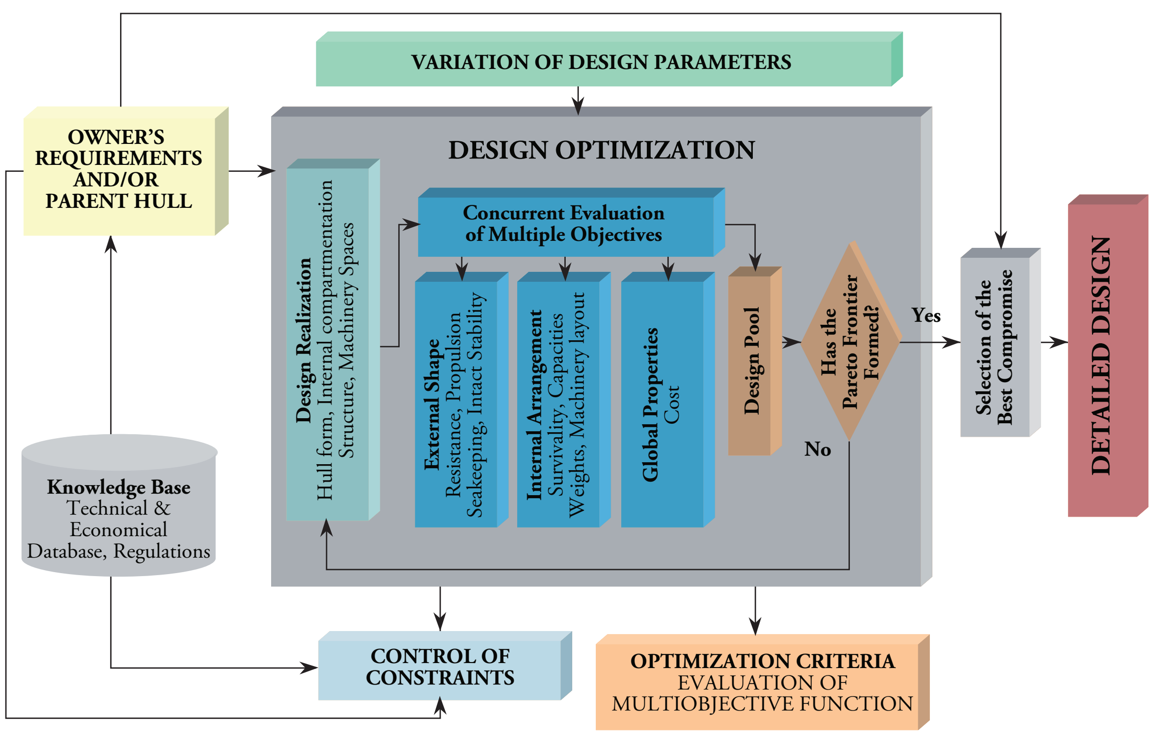
Examples of Optimization of Merchant and Naval Ships

Multi-objective Optimization of Tanker Ships

This application gives an overview of research studies undertaken at the Ship Design Laboratory of NTUA within the framework of the EU-funded project SAFEDOR (2005-2009) and, thereafter, in collaboration with Germanischer Lloyd (*Papanikolaou et al., 2010*). The studies introduce a risk-based parametric optimization of double-hull tankers to achieve innovative designs with increased cargo carrying capacity and improved environmental protection, while challenging

[3] National Technical University of Athens – Ship Design Laboratory, NTUA-SDL, http://www.naval.ntua.gr/sdl
[4] NAPA Oy (2005), NAPA software, http://www.NAPA.fi/
[5] E.STE.CO (2003), "modeFrontier software v.2.5.x", http://www.esteco.it/

Fig. 4. Generic Procedure for the Ship Design Optimization Problem – NTUA-SDL



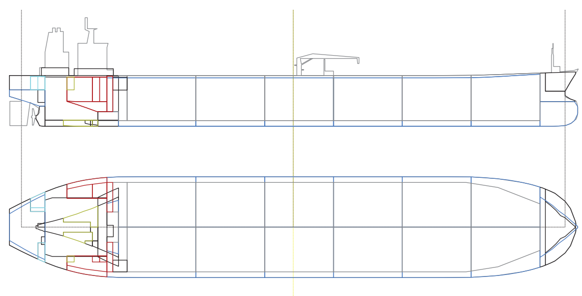
various constraints imposed by the latest MARPOL regulations (*Papanikolaou, 2009c*).

For the design concept development stage, a full parametric multi-objective design optimization platform by using Genetic Algorithms has been developed, taking into account probabilistic oil-outflow calculation methods for side and bottom damages. The resultant Pareto-optimal designs are evaluated from the point of view of oil outflow consequences, cargo capacity, design feasibility, ship maintainability and ballast water extent. Developed alternative designs dispose, compared to a standard double-hull design, increased cargo carrying capability and reduced structural weight, at a comparable or even slightly reduced risk for oil outflow; therefore, from the point of view of both economy and safety, they appear very promising compared to existing standard type double-hull designs. A preliminary economic analysis also showed that despite the anticipated slightly increased building cost, developed alternative designs are related to an appreciable decrease of unit transport cost, making them attractive to the shipping industry.

Reference Design

The, herein, optimized tanker vessel, code-named "Double Venture" is a double-hull construction tanker ship of AFRAMAX size also used in another EU-funded project POP&C (2004-2007). Table 1 presents the basic characteristics of the vessel. A double-skin construction is arranged along the cargo length area, consisting of six (6) pairs of side and bottom tanks for use of water ballast (Fig. 5). Two slop tanks are also provided, aft wards of main cargo area. Cargo handling is by means of centrifugal pumps installed in a pump room, which is located forward of the machinery space. It is noted that the above referenced double-hull design disposes of an increased double side and bottom clearance of 2.5 m, compared to the minimum 2.0 m required, according to MARPOL relevant requirements.

Fig 5. Sketch of Reference Vessel "Double Venture"



Alternative Configurations

Five different configurations were considered,

Table 1. Particulars of reference vessel "Double Venture"

Length, oa	250.10m
Length, bp	239.00m
Breadth, moulded	44.00m
Depth, moulded (main deck)	21.00m
Width of double skin sides	2.50m
Width of double skin bottom	2.50m
Draught scantling	14.60m
Deadweight, scantling draught (comparable with design proposed)	109,800dwt (cargo density 0.868 T/m3)
Cargo capacity Liquid volume, heavy oil, diesel oil, Water ballast	122,375m^3+2,830m^3 (Slop), 3,380m^3, 260m^3 41,065m^3 + 3,500 m^3 (peaks)
Classification	Lloyds Register
Number of Cargo tanks	12 (6x2) plus 2 slop tanks
Cargo Tanks block length	181.44 m

with six or seven tanks in the longitudinal direction, two or three tanks in the transverse direction and flat or corrugated bulkheads. The five different combinations of compartmentation are summarized in Table 2. A total of *21,500 designs* were examined in the present study. In Figs. 6 and 7, *only the feasible designs are shown*. The open circles correspond to dominated designs, while the full circles correspond to designs on the Pareto front. For comparison, the *reference design* is also included, marked by a *full triangle*. It should be noted that the steel weight of the reference vessel is not its actual weight as built, but the weight calculated by the POSEIDON software by Germanischer Lloyd, based on a corresponding structural design according to GL rules. This ensures full comparability with the generated optimal designs.

Discussion of Results

The five alternative configurations were selected to allow validating the characteristics of the reference design, as well as identifying possible improvements through analysis of the respective *Pareto frontiers*. Putting all Pareto frontiers into a single diagram provides a better insight of the relationships between design objectives, design parameters, and alternative configurations.

Fig. 6 clearly shows that the "6x3 flat" Pareto designs dominate all the other designs. Furthermore, there are several Pareto designs with significantly better

Fig 6. Outflow vs. cargo volume – Pareto designs from different configurations

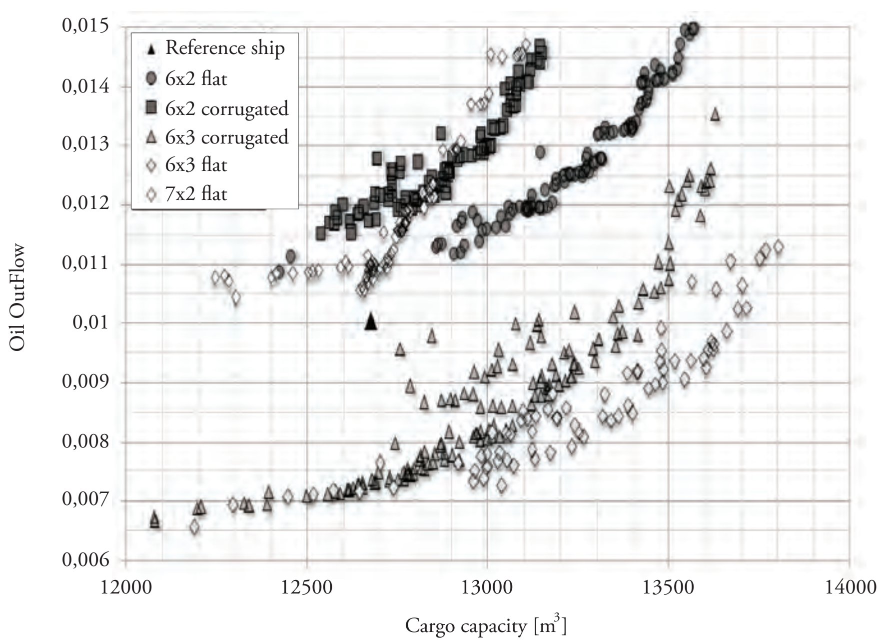


Table 2. Alternative compartmentation configurations

	Arrangement of cargo tanks	Bulkhead type	Number of designs
Configuration 1	6x2	flat	7287
Configuration 2	6x2	corrugated	1738
Configuration 3	6x3	flat	6147
Configuration 4	6x3	corrugated	3270
Configuration 5	7x2	flat	3043

oil outflow (in terms of the MARPOL mean oil outflow index, which must *be less than 0.015* for the reference AFRAMAX tanker) and cargo volume performance than the reference design.

As expected, Fig. 7 shows that for the same cargo volume, most generated "6x2 flat" Pareto designs have less steel weight than all the other configurations, noting that the structural weight of both the generated Pareto designs and of the reference ship were calculated by the same model, namely here based on POSEIDON structural designs. The reference design is here again dominated by several "6x2 flat" and "6x3 flat" designs.

In Fig. 8, the "6x3 flat" designs, as well as the "6x2 flat" designs dominate all other designs. The reference design is again clearly dominated by several "6x3 flat" designs. At the same time, practically all "6x2 flat" Pareto designs have *less steel weight than the reference design at acceptable oil outflow performance.*

Fig 7. Cargo volume vs. steel weight in cargo area – Pareto designs from different configurations

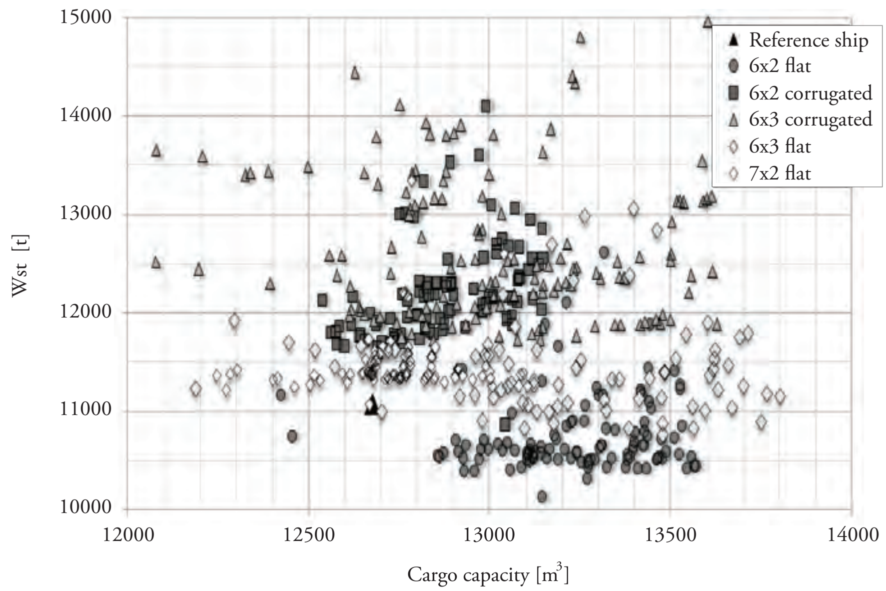
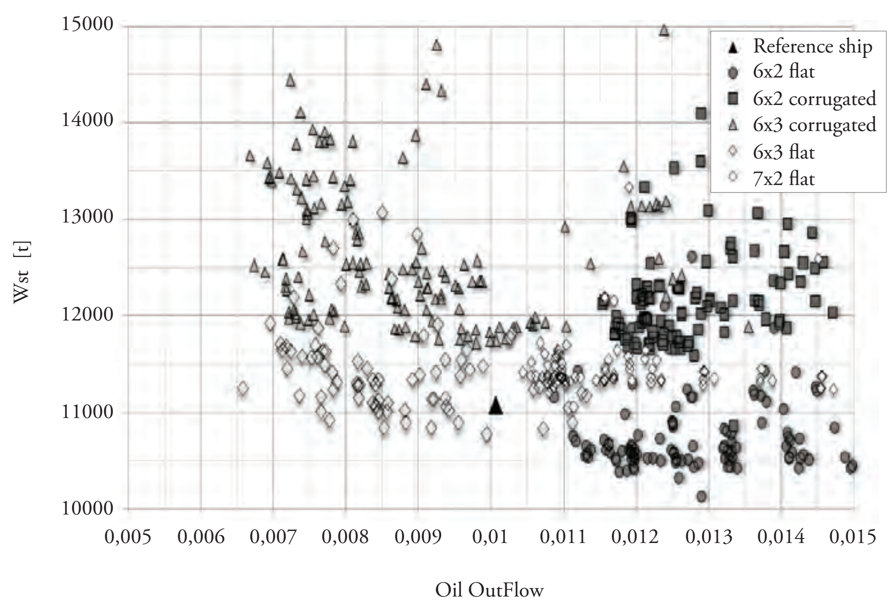


Fig 8. Outflow vs. steel weight in cargo area – Pareto designs from different configurations



In addition to the above, the following observations can be made:

- None of the corrugated arrangements proves better than flat bulkhead designs. This does not mean that the corrugated geometries should be in general disregarded as alternative configurations. They have important advantages with respect to the ease of production and maintenance, which have not been considered in this study. Also, it should be noted that the flat bulkhead structural designs did not include some minor stiffeners, thus the comparison may be not entirely 'fair' in this respect.
- The "7x2 flat" arrangement performed poorly since the steel weight increases without any significant gains in the outflow or the capacity, respectively.

The reference design appears to be on the Pareto front of the "6x2 flat" designs. It was already noted earlier that the reference design is a well-proven design in practice, which was optimized with respect to steel weight (by the yard designer), most likely by use of Finite Element Method (FEM). .

Holistic Naval Ship Design

Introduction to Naval Ship Design

From the system's point of view, a naval ship may be regarded as an integrated, self-propelled combat system. It may be requested to provide accommodation space for personnel of the size of a small village and be hosted within a large mobile structure that continuously operates in a hostile environment (physical and operational); thus, many challenges come in addition to those of a merchant ship design.

In recent years, the task of formulating clearer goals and setting tangible design specifications for naval ships has been significantly improved with the use of the 2010 International Naval Ship Code (INSC, 2010). The INSC is based on a similar philosophy like the Goal Based Standards (GBS), currently discussed for merchant ships at the International Maritime Organization (IMO). It addresses, however, specific naval ship features and methods of operation. The goals are represented at the top tiers of the framework, below which the detailed requirements which the ship has to meet in design, construction, and operational phase are placed. The structure of the NSC 2010 (ANEP 77 v.2, 2010) version of the code is explained in Figs. 9 and 10. The code offers an *off-the-self* safety and performance management system for navies that need to establish a system of self regulation.

Compared to a merchant ship, the complexity of designing a naval ship is further increased by the multitude of disciplines that need to be considered

Fig 8. Outflow vs. steel weight in cargo area – Pareto designs from different configurations

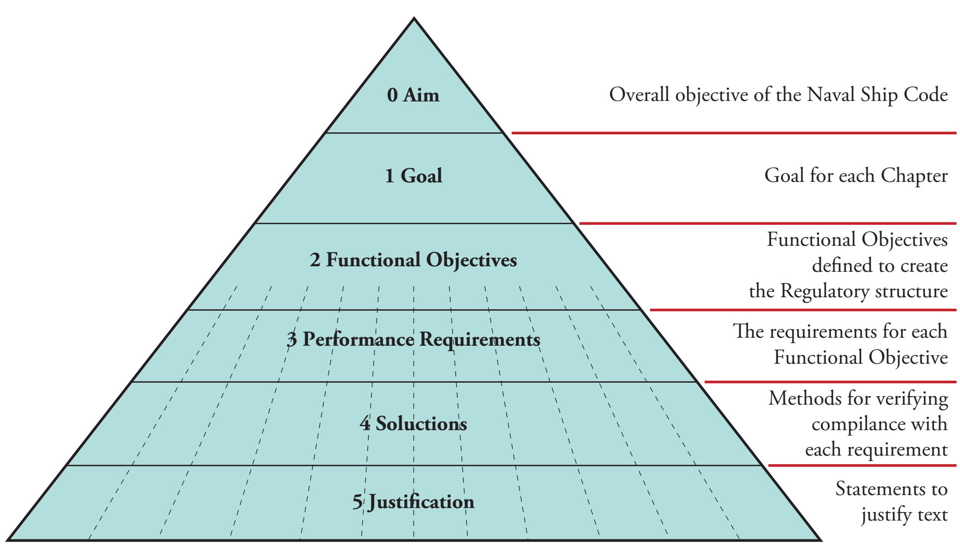


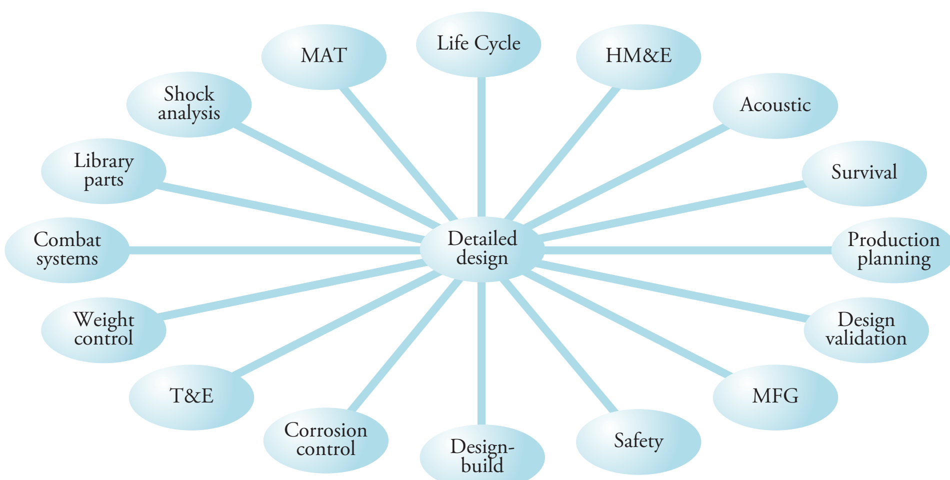
Fig 10. The GBS structure of the NSC (see RINA Warship Technology, 2011)

Tier 0	Aim Scope Introduction									
Tier 1 Goal	Ch I	Ch II	Ch III	Ch IV	Ch V	Ch VI	Ch VII	Ch VIII	Ch IX	Ch X
Tier 1 Functional Objective	General	Structures	Stability	Engineering Systems	Seamanship	Fire Safety	Escape Evacuation	Radio Comms	Navigation	Dangerous Goods
Tier 3 Performance Requirements	Reg 0-21	Reg 0-7	Reg 0-7	Reg 0-25	Blank	Reg 0-13	Reg 0-26	Reg 0-1	Reg 0-1	Reg 0-1
Tier 4 Solutions	Code	Class	National standard	Class	Ch V Blank	Code	Code	SOLAS	SOLAS	IMDG

and integrated in the ship design process, as shown in Fig. 11.

To enable major improvements in acquisition engineering design and analysis processes, many leading navies are working on developing and

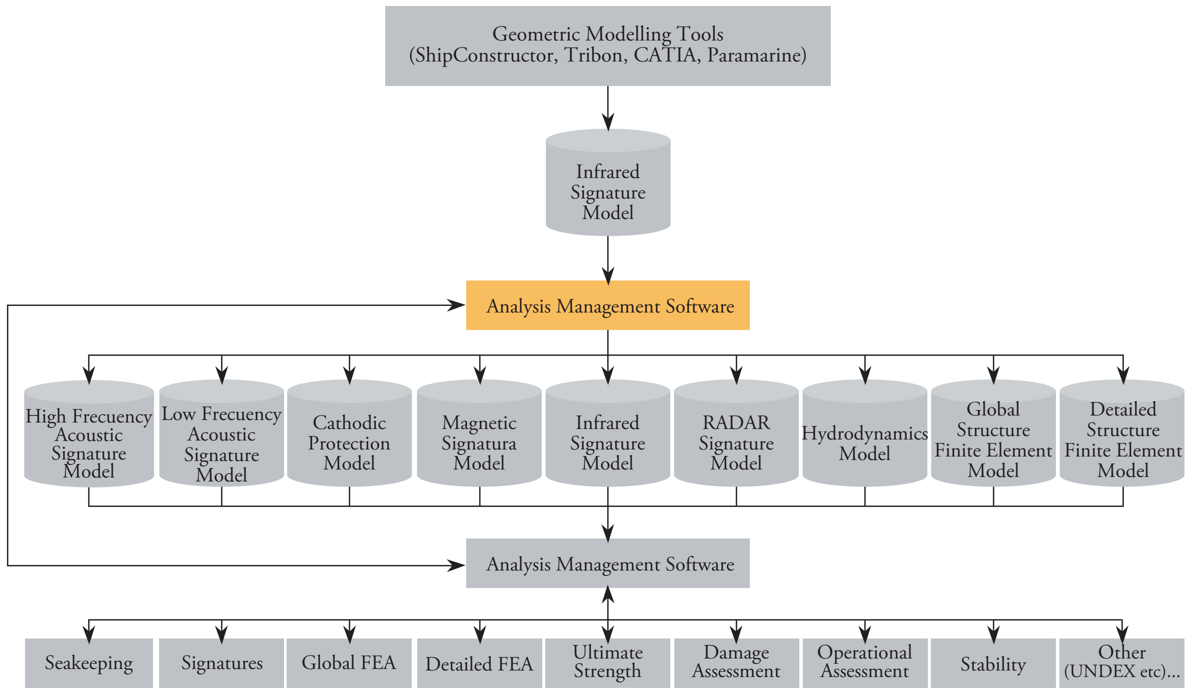
Fig 11. Stakeholders disciplines of naval ship design (see Neu, 2000)



deploying scalable physics-based computational engineering software products aiming to replace empirical design based on historical data and experimental testing with physics-based computational design validated with experimental testing. This will allow the detection and resolution of any design flaws early in the design process before major schedule and budget commitments are made. Additionally, it will allow the innovation by the development of optimized designs for new concept and the integration of the various systems earlier in the acquisition process. The use of such a methodology will increase the acquisition program's flexibility and agility to respond to rapidly changing requirements (*Hurwitz, 2010*).

In that respect, *Holistic Ship Design Optimization* in naval ship design is achieved by the development of an integrated engineering software platform of tools that supports a reconfigurable ship design and acquisition process. This enables the designer to develop cost-effective ship designs on schedule

Fig 12. Sample Integrated Toolset (see ISSC Committee v.5, 2009)



and within budget, able to perform as required and predicted. An example of such an integrated toolset is shown in Fig. 12.

At top level of Fig. 12, there are a number of geometric modeling tools (such as Tribon[6], ShipConstructor[7], CATIA[8], Paramarine[9], NAPA[10] etc.). These software tools generate ship's geometry and related data which are then passed over to the appropriate Analysis Model Synthesizer that uses specialized Analysis Management Software such as (e.g.):

- Davis' ShipIR/NTCS[11] for IR,
- IDS' Ship EDF for Radar Cross Section analysis (see Fig. 13),
- UCL and UoGs integrated PARAMARINE-SURFCON and maritimeEXODUS[12] for design, simulation

[6] Now AVEVA Marine http://www.aveva.com/products_services_aveva_marine.php
[7] http://www.shipconstructor.com/
[8] http://www.3ds.com/solutions/shipbuilding/overview/
[9] http://www.qinetic.com
[10] http://www.napa.fi
[11] http://www.wrdavis.com/NTCS_intro.html
[12] http://fseg.gre.ac.uk/exodus

of evacuation and enhanced operational effectiveness (see Fig. 14).

The development and validation of such integrated tool platforms is a very demanding task; two well known software platforms, which are used and continuously further developed by two major navies, are:

- NAVSEAS (US) Leading Edge Architecture for Prototyping Systems (LEAPS) (*Hurwitz, 2010*)
- QinetiQ-GRC's PARAMARINE software in UK (http://www.qinetiq.com).

The Ship Design laboratory at NTUA has also been developing integrated approaches to naval ship design, namely by utilizing its generic ship design optimization procedure (outlined in Fig. 4) together with a set of specific design tools for naval ship design. These are:

- A naval ship design version of the Parametric Design Tool (PDT) developed

[13] http://www.idscompany.it/page.php?f=176&id_v=2

Fig 13. RCS warship analysis by Ship EDF (IDS Ingegneria dei Sistemi S.p.A.[13])

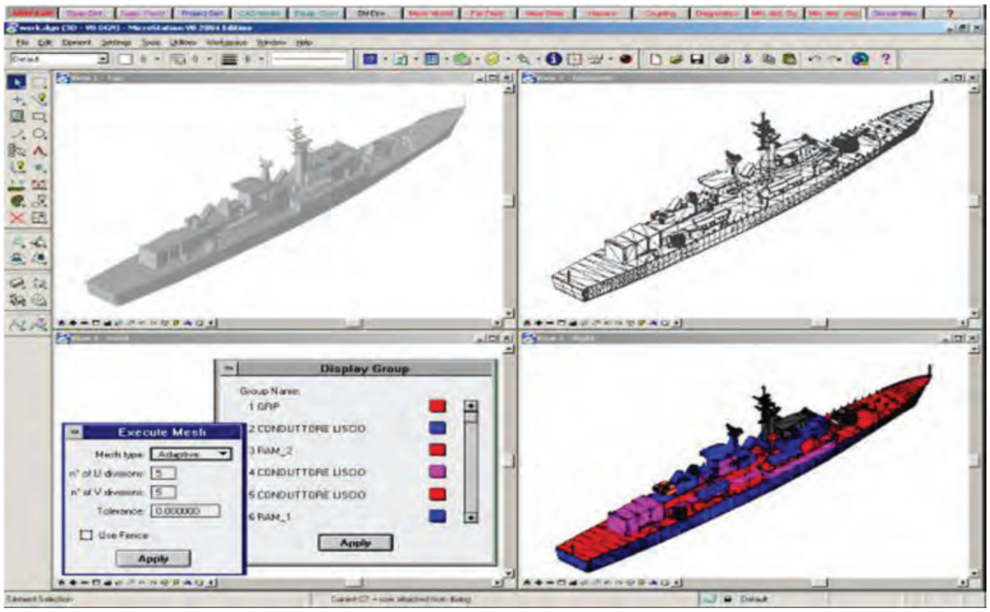
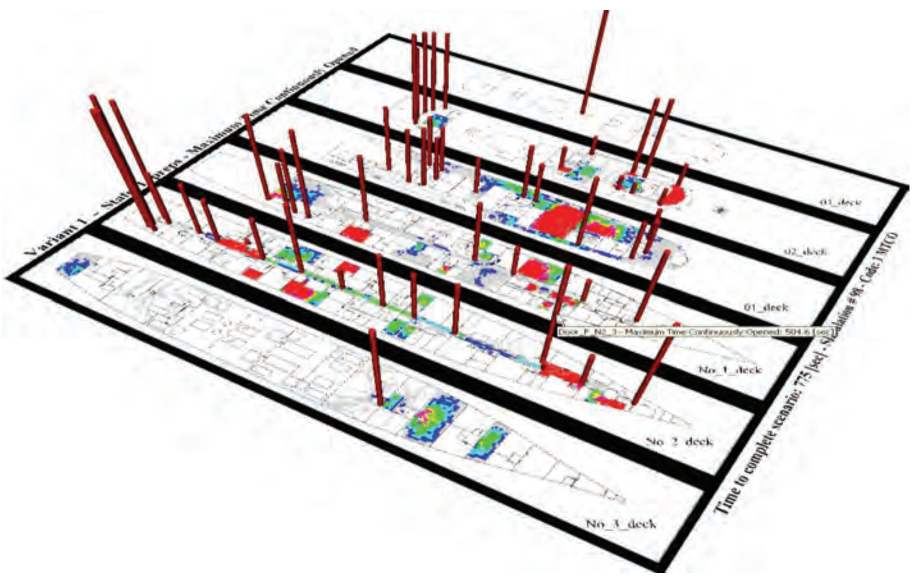


Fig 14. Personnel movement simulation results for RN Frigate (Andrews, 2009)



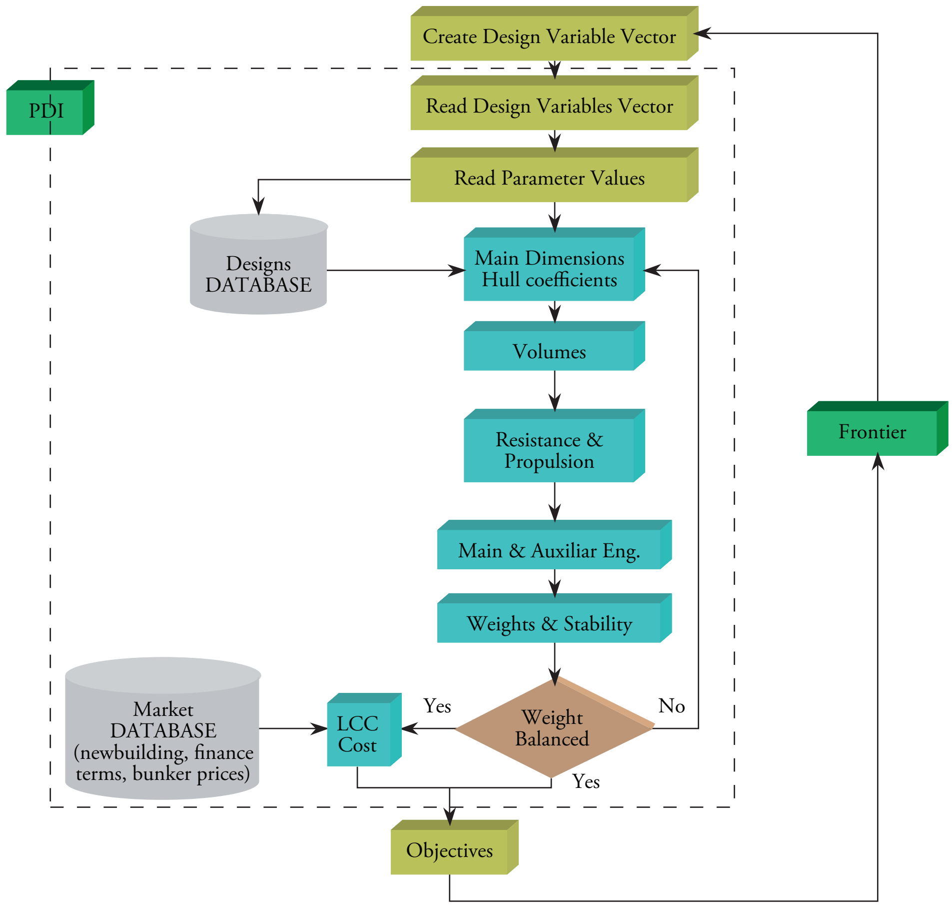
originally for the design of commercial ships (RoRo, tankers, bulkers, containerships) (*Boulougouris and Papanikolaou, 2009*) coupled with the general optimization software modeFRONTIER[14] (see ES.TE. CO, 2003). This is used for the fast population of the design space with conceptual solutions that can be further investigated (Fig. 15).

- An advanced toolset integrating the well-known ship design software package NAPA, modeFRONTIER and a number of external CAE tools such as NUMECA's[15] Fine/Marine CFD code, NTUA-SDL's NEWDRIFT[16] seakeeping (see *Papanikolaou, 2001*), Flowtech's

[14] http://www.modefrontier.com

15 http://www.numeca.com
16 http://www.naval.ntua.gr/sdl

Fig 15. NTUA-SDL Parametric Design Tool Design Space Global Exploitation



SHIPFLOW[17] (see *Larsson, 1990*) and GL's POSEIDON[18] structural design software. In addition a number of tools have been programmed in NAPA macro-language using NAPA BASIC.

- Using a Parametric Design Tool (PDT) the designer has a computationally efficient tool for the parametric exploration of the design space and the identification of the feasible solutions areas. This is basically a global optimization step. After this step, the more sophisticated tools are introduced to perform the local, more in-depth optimization of the design, taking into account the full set of objectives and ranking the designs according to decision maker's preference.

17 http://www.flowtech.se
18 http://www.gl-group.com/poseidon2/

An example of application of this multi-objective optimization of a naval ship using genetic algorithms and including maximization of the survivability as one of the objectives may be found in the listed reference (*Boulougouris and Papanikolaou, 2004)*.

Summary and Conclusions

The present paper provided a brief introduction to a *holistic* approach to ship design optimization, defined the generic ship design optimization problem, and demonstrated its solution by using advanced optimization techniques for the computer-aided generation, exploration, and selection of optimal designs. It discussed proposed methods on the basis of some typical ship design optimization problems of a tanker and naval ships related to multiple objectives, leading to improved and partly innovative design features with respect to ship economy, cargo carrying capacity, safety, survivability, comfort, required powering, environmental protection, or combat strength, as applicable.

It was shown that multi-objective mathematical optimization approaches are very valuable tools and greatly enhance the quality of ship design, even if applied to vessel concepts already optimized by traditional methods. The design developed and optimization methodology may be a useful tool for the designer in the preliminary design stage, facilitating the elaboration of a large number of design alternatives quickly and with little effort. The designer may explore this possibility to investigate the effect of crucial decisions on the vessel's operating performance before proceeding to the detailed design stage. The design methodology may also be effectively used in feasibility studies, providing assistance for the determination on a rational basis of the most suitable vessel size, transport capacity, speed, and other operating characteristics for a selected service. The integration of the parametric ship design application with a multi-objective optimization software facilitates the design space exploration in a rational and efficient way, enabling the identification of favorable and unfavorable areas of the design variables and ultimately for the determination of the optimal designs located on the Pareto Frontier (in case of multi-criteria optimization). Furthermore, once the optimum design has been selected, its detailed NAPA model including (but not limited to) the hull-form and the watertight subdivision is readily available for further elaboration and detailed design work, considerably reducing related effort.

A final comment on the way ahead: though the generic solution approach to the holistic ship design problem appears well established, it remains for researchers to develop and integrate a long list of application algorithms and related software, addressing the great variety of ship design for life cycle. This is a long-term task of decades, requiring profound skills and understanding of the physics and design of ships, a domain requiring properly trained naval architects and scientists from related disciplines.

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