Apostolos Papanikolaou *Editor*

A Holistic Approach to Ship Design

Volume 1: Optimisation of Ship Design and Operation for Life Cycle

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Preface

The face of ship design is changing. The vastly increasing complexity of high-value ships and maritime structures as well as the growing number of rules and regulations calls for novel concepts of product design and testing in short lead times. To address this challenge, a team of 40 European maritime industry and research partners[1] has formed the HOLISHIP (HOLIstic optimisation of SHIP design and operation for life cycle) project in response to the MG 4.3-2015 Call of the European Union's Horizon 2020 Transport Research Programme and received funding to develop the next generation of a ship design system for the European maritime industry.

HOLISHIP sets out to address urgent problems of today's ship design and operation, focusing on future requirements by developing a holistic approach to ship design capable of meeting tomorrow's challenges. Most maritime products are typically associated with large investments and are seldom built in large series. Where other modes of transport benefit from the economy of series production, this is not the case for maritime products which are typically designed to refined customer requirements increasingly determined by the need for high efficiency, flexibility and low environmental impact at a competitive price. Product design is thus subject to global trade-offs among traditional constraints (customer needs, technical requirements and cost) and new requirements (life cycle, environmental impact and rules). One of the most important design objectives is to minimise total cost over the economic life cycle of the product, taking into account maintenance, refitting, renewal, manning, recycling, environmental footprint, etc. The trade-off among all these requirements must be assessed and evaluated in the first steps of the design process on the basis of customer/owner specifications.

[1]HSVA (coordinator), ALS Marine, AVEVA, BALANCE, Bureau Veritas, Cetena, CMT, CNR-INSEAN, Damen, Danaos, DCNS-Naval Group, Deutsche Luft- und Raumfahrt DLR, DNV GL, Elomatic, Epsilon, Fraunhofer Gesellschaft-AGP, Fincantieri, Friendship Systems, Hochschule Bremen, IRT SystemX, ISL, Lloyds Register, MARIN, Marintek, Meyer Werft, Navantia, National Technical University of Athens-Ship Design Laboratory, Rolls Royce, Sirehna, SMILE FEM, Star Bulk, TNO, TRITEC, Uljanik Shipyard, University of Genoa, University of Liege, University of Strathclyde, van der Velde, IRT SystemX.

The HOLISHIP approach brings together all relevant main disciplines of maritime product design under the umbrella of advanced parametric modelling tools and integrated software platforms enabling the parametric, multi-objective and multi-disciplinary optimisation of maritime products. The approach includes market analysis and demand, economic and efficiency considerations, hull form design, structural design, and selection of prime movers and outfitting. Together they form the mission requirements and enable the formulation of a rational foresight analysis for the viability of the product model over its life cycle ("from cradle to cradle"). It considers all fundamental steps of the traditional "ship design spiral", which, however, are better implemented today by a systemic, parallel processing approach and not a serial, step-by-step procedure.

The present book deals with the HOLISHIP approach and the associated design synthesis model, which follows modern computer-aided engineering (CAE) procedures, integrates techno-economic databases, calculation and optimisation modules and software tools along with a complete virtual model in form of a Virtual Vessel Framework (VVF), which will allow the virtual testing before the building phase of a new vessel. Modern GUI and information exchange systems will allow the exploration of the huge design space to a much larger extent than today and will lead to new insights and promising new design alternatives. The coverage of the ship systems is not limited to conceptual design but extends also to relevant major on-board systems/components. Their assessment in terms of life-cycle performance is expected to build up further knowledge of suitable outfitting details, this being a highly relevant aspect especially for the outfitting-intensive products of European shipyards.

The present book derives from the knowledge gained in the first phase of the project HOLISHIP (http://www.holiship.eu), a large-scale project under the Horizon 2020 programme of the European Commission (Contract Number 689074), which started in September 2016 and will be completed in August 2020. It will be supplemented by a second volume dealing with applications of developed methods and tools to a series of case studies, which will be conducted in the second phase of the HOLISHIP project.

The book is introduced by an overview of HOLISHIP project in Chap. 1 by the project manager, *Dr. Jochen Marzi* (HSVA). The holistic ship design optimisation, related concepts and a tanker ship application case study, presented by *Prof. Apostolos Papanikolaou* (NTUA & HSVA), are following in Chap. 2. A state of the art on ship design for life cycle is presented by *em. Prof. Horst Nowacki* (Technical University of Berlin) in Chap. 3. An outline of the effect of market conditions, mission requirements and operational profiles is presented in Chap. 4 by *Mr. Anti Yrjänäinen* (Elomatic). In Chap. 5, a systemic approach to ship design is elaborated by *Mr. Alan Guagan* (Sirehna) and his co-authors *Rafine Benoit and Le Nena* (both from DCNS-Naval Group). Hydrodynamic methods and software tools for ship design and operation are elaborated in Chap. 6 by *Dr. Jochen Marzi* (HSVA) and *Dr. Ricardo Broglia* (INSEAN). Parametric optimisation of concept and preliminary design are elaborated in Chap. 7 by *Profs. George Zaraphontis* (NTUA), *Andreas Kraus and Gregor Schellenberger* (University of Applied Sciences

Bremen). In Chap. 8, the CAESES-HOLISHIP platform for process integration and design optimisation is presented by *Dr. Stefan Harries and Mr. Claus Abt* (both from Friendship Systems). Chapter 9, co-authored by *Prof. Philippe Rigo, Abbas Bayatfar* (both Univ. of Liege) and *Jean-David Caprace* (Federal Univ. of Rio de Janeiro), deals with the structural design optimisation tool and methods. Chapter 10, authored by *Prof. Stein-Ove Erikstad* (Norwegian Univ. of Science and Technology, Trondheim), is dealing with design for modularity. In Chap. 11, issues of the application of reliability, availability and maintenance (RAM) principles and tools to ship design are elaborated by a team from Bureau Veritas led by *Dr. Philippe Corrignan*, co-authors *Vincent le Diagon, Ningxiang Li and Loïc Klein*. In Chap. 12, methods and tools for the life-cycle performance assessment are elaborated by a team consisting of *Prof. Paola Gualeni and Matteo Maggioncalda* (both from University of Genoa), *Chiara Notaro and Carlo Cau* (both from CETENA), *Prof. Markos Bonazuntas, Spyros Stamatis and Vasiliki Palla* (all from Epsilon International). Chapter 13 by *Messrs Sverre Torben and Martijn De Jongh* (both from Rolls Royce) deals with the modelling and optimisation of main machinery and power systems. Chapter 14 by *Dr. George Dimopoulos and Mrs. Chara Georgopoulou* (both from DNV GL) deals with advanced modelling and simulation tools for ship's machinery. Finally, Chap. 15, by *Messrs. Maarten Flikkema, Martin van Hees, Timo Verwoest and Arno Bons* (all from MARIN), outlines the HOLISPEC/RCE platform for virtual vessel simulations. The book is complemented by a glossary/list of acronyms and a comprehensive list of references. Editor of the book's material was *Prof. Apostolos Papanikolaou* (HSVA), assisted by Mrs. *Aimilia Alissafaki* (NTUA).

The present book does not aim to be a textbook for postgraduate studies, as contributions to the subject topic are still evolving and some time will be necessary until full maturity. However, as the topic of the holistic ship design optimisation is almost absent from today's universities' curricula, the book aims to contribute to the necessary enhancement of academic curricula and to address this important subject to the maritime industry. Therefore, the aim of the book is to provide the readers with an understanding of the fundamentals and details of the integration of holistic approaches into the ship design process. The book facilitates the transfer of knowledge from the research conducted within the HOLISHIP project to the wider maritime community and nurtures inculcation upon scientific approaches dealing with holistic ship design and optimisation in a life-cycle perspective.

Thus, the main target readership of this book is engineers and professionals in the maritime industry, researchers and postgraduate students of naval architecture, marine engineering and maritime transport university programmes. The book closes a gap in the international literature, as no other books are known in the subject field covering comprehensively today the complex subject of holistic ship design and multi-objective ship design optimisation for life cycle.

The complexity and the evolving character of the subject required the contribution from many experts active in the field. Besides experts from the HOLISHIP consortium, some renowned experts from outside the HOLISHIP project could be gained and contribute to the book's material. As editor of this book, I am indebted to all authors of the various chapters reflecting their long-time research and expertise in the field. Also, the contributions of the whole HOLISHIP partnership to the presented work and the funding by the European Commission (DG Research) are acknowledged.

Athens, Greece
June 2018

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Horizon 2020
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for Research & Innovation

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About the Editor

Prof. Dr.-Ing. Habil. Apostolos Papanikolaou studied Naval Architecture and Marine Engineering at the Technical University of Berlin, Germany. He was Professor and Director of the Ship Design Laboratory of the National Technical University of Athens (NTUA, Greece) for more than 30 years. He is today Senior Scientific Advisor of the Hamburg Ship Model Basin (HSVA, Germany), Emeritus Professor of NTUA and Visiting Professor at the University of Strathclyde, UK. He headed more than 75 funded research projects and is author/co-author of over 600 scientific publications dealing with the design and optimisation of conventional and unconventional vessels, the hydrodynamic analysis and assessment of the calm water performance and the performance of ships in seaways, the logistics-based ship design, the stability and safety of ships and related regulatory developments of the International Maritime Organisation. He received various international prize awards for his research work and scientific contributions to ship hydrodynamics, innovative ship design and safety assessment, among them in the last 10 years the *Lloyds List 2009 Greek Shipping technical innovation award* (jointly with Germanischer Lloyd), the prestigious *Dr. K. Davidson medal/award* of SNAME for outstanding achievement in ship research in 2010 and the *European Champions 1st prize for Senior Researchers in Waterborne Transport* in 2014. He is Fellow of the Royal Institution of Naval Architects

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Abbreviations

ν-Shallo®	Nonlinear potential flow 3D panel code for wave resistance analysis of ships in calm water by HSVA, Germany
2D	Two dimensional
3D	Three dimensional
A	Attained Subdivision Index (SOLAS damage ship stability)
AAB	Average annual benefit
AAC	Average annual cost
AC	Application case; also alternating current
AFE	Active Front End
AFIS	Association Française d'Ingénierie Système
AI	Artificial intelligence
AIS	Automatic information system
AMFM	Adaptive multi-fidelity metamodel
ANN	Artificial neural networks
API	Application programming interface
ASCII	American Standard Code for Information Interchange
BEM	Boundary element method
BHD	Bulkhead
BIEM	Boundary integral equation method
BLD	Building cost
BOG	Boil-off gas
BRep	Boundary representation
BuDa	Bubble diagram tool
BV	Bureau Veritas (classification society)
BVP	Boundary value problem
CAD	Computer-aided design
CAE	Computer-aided engineering
CAESES®	Computer-Aided Engineering System Empowering Simulation by Friendship Systems AG, Germany
CAPEX	Capital expenditure

CASD	Computer-aided ship design
CAx	Acronym for various computer-aided solutions for design, simulation, engineering, etc.
CED	Cumulated energy demand
CEM	Concept exploration model
CER	Cost estimation relationship
CFD	Computational fluid dynamics
CHAPMAN	Viscous flow analysis code integrated in CAESES
COSSMOS®	Complex Ship Systems Modelling and Simulation Code by DNV GL
COT	Cargo oil tank
CPACS	Common Parametric Aircraft Configuration Schema
CRF	Capital recovery factor
CSG	Constructive solid geometry
CSR	Common structural rules
CVM	Concept variation model
DBB	Design building block
DE	Double-ended (ferry)
DES	Design space exploration
DFMO	Derivative-free multi-objective
DIRECT	DIviding RECTangles
DLR	German Aerospace Research Center
DNV GL	DNV GL (classification society)
DoE	Design of experiment
DoF	Degree of freedom
DP	Dynamic positioning
DPSO	Deterministic particle swarm optimisation
DWT	Deadweight
DXF	Drawing Interchange Format (file)
EBITDA	Earnings before interests, tax, depreciation and amortization
ECA	Emission control area
ECMRF	European Centre for Medium Range Weather Forecasts
EEDI	Energy Efficiency Design Index, a MARPOL measure of CO_2 emission per unit of transport in [gr CO_2/(ton mile)]
EFD	Experimental fluid dynamics
EOS	Equations of state
EPD	Environmental Product Declaration
FANTASTIC	Functional Design and Optimisation of Ship Hulls, European Union FP5 Framework Project
FEA	Finite element analysis
FEM	Finite element method
FFD	Free-form deformation
FFW	Friendship Framework (CAESES)
FMEA	Failure modes and effects analysis
FMECA	Failure modes, effects and criticality analysis

FMI	Functional mock-up interface
FMU	Functional mock-up units
FOWT	Floating offshore wind turbines
FPI	Foreign process interface
FPM	Fully-parametric modelling/Fully-parametric model
FS	Friendship Systems
GA	Genetic algorithm
GBSD	Goal-based ship design
GES	General energy systems
GHG	Greenhouse gas
GM	Metacentric height (SOLAS ship stability)
GRIP	Green Retrofit through Improved Propulsion, European Union FP7 Framework Project
GUI	Graphical user interface
HF	High fidelity
HIL	Hardware in the loop
HOLISHIP	Holistic Optimisation of Ship Design and Operation for Life Cycle, European Union Horizon 2020 Project
HOLISPEC-RCE	HOLISHIP Virtual Vessel Framework
HPC	High-performance computing
HSG	Hybrid shaft generator
Html	Hypertext Mark-up Language
HT-PEM	High-temperature proton exchange membrane fuel cell
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGA	Intelligent General Arrangement
IGES (igs)	Initial Graphics Exchange Specification file is a vendor-neutral file format for the exchange of information data (geometry) among CAD systems
IMCA	International Marine Contractors Association
IMDC	International Marine Design Conference
IMO	International Maritime Organisation
INCOSE	International Council on Systems Engineering
IoT	Internet of Things
IPR	Intellectual Property Rights
ISO	International Organisation for Standardisation
ISP	Ideal ship price
IT	Information technology
ITTC	International Towing Tank Conference
JOULES	Joint Operation for Ultra Low Emission Shipping, European Union FP7 Framework Project
KLE	Karhunen–Loève expansion
KML	Keyhole Markup Language; also, height of longitudinal metacentre above ship's keel (SOLAS ship stability)
KPI	Key performance indicator

LCA	Life-cycle assessment
LCC	Life-cycle cost
LCPA	Life-cycle performance assessment
LF	Low fidelity
LNG	Liquefied natural gas
LOA	Length overall
LPP	Length between perpendiculars
M&R	Maintenance and repair
MARNET	Computational Fluid Dynamics for the Marine Industry, European Union FP4 Framework Thematic Network Project
MARPOL	International Convention for the Prevention of Marine Pollution from Ships (IMO)
MAS	Modular adaptable ship
MBSE	Model-based systems engineering
MCFC	Molten carbonate fuel cell
MGO	Marine gas oil
MID	Modularity in design
MIP	Modularity in production
MIU	Modularity in use
MODHA	Multi-objective deterministic global/local hybrid algorithm
MODPSO	Multi-objective deterministic PSO
MOGA	Multi-objective genetic algorithm for design space exploration and identification of optimal solutions
MOWT	Monopile offshore wind turbine
MPOV	Multi-purpose offshore vessel
MQ	Message queue
MTBF	Mean time between failures
MTTR	Mean time to repair
NAPA®	Naval Architecture PAckage for ship design by NAPA Oy, Finland
NEWDRIFT®	Potential flow 3D panel code for seakeeping analysis of ships and offshore structures by the Ship Design Laboratory-NTUA, Greece
NLP	Nonlinear programming
NOx	Nitrogen oxides
NPV	Net present value
NSGA-II	Non-sorting Genetic Algorithm II (also NSGA 2)
NURBS	Non-uniform rational B-spline curve/surface
OOI	Oil Outflow Index (MARPOL, Tanker ships)
OPEX	Operational expenditures–operating cost
OSV	Offshore support vessel
PAX	Passengers
PCB	Polychlorinated biphenyl
PDAE	Partial differential algebraic equations
PDT	Parametric design tool

PFC	Power flow control
PFD	Process flow diagram
PID	Partial-integral-differential
PIDO	Process integration and design optimisation
Platform	Assembly of disparate systems and tools that are integrated in order to communicate and interact with each other
PLM	Product life-cycle management
PM	Particulate matter; also permanent magnet
PMS	Power management system
Png	Portable Network Graphics (file)
PPM	Partially parametric modelling/Partially parametric model
PSD	Pareto-supported decision-making
PSO	Particle swarm optimisation
PSS	Pre-swirl stator
PSV	Platform support vessel
PTI	Power take-in
PTO	Power take-off
QRA	Quantitative risk analysis
R	Required Subdivision Index (SOLAS, ship damage stability)
R&D	Research and development
RAM	Reliability, availability and maintainability
RANSE	Reynolds-averaged Navier–Stokes equations
RBD	Reliability block diagram; also, risk-based design
RBR	Radial basis function(s)
RCE	Remote components environment
RFR	Required freight rate
RHIB	Rigid hull inflatable boat
ROIC	Return on investment capital
RoPAX	Ro-Ro passenger ship ferry with roll-on/roll-off cargo (mainly trucks and cars)
Ro-Ro	Roll-on/Roll-off
RSM	Response surface model/method
R_T	Total resistance
RTD	Research and Technology Development
SAR	System architecture and requirement tool
SBD	Simulation-based design
SBS	Ship breakdown structure
SBT	Segregated ballast tanks
SCR	Selective catalytic reactors
SDD	Simulation-driven design
SE	Systems engineering
SETAC	Society of Environmental Toxicology and Chemistry
ShipX®	Package for hydrodynamic analysis of ships by SINTEF Ocean, Norway
SIL	Software in the loop

SLP	Sequential linear programming
Sobol	Quasi-random design of experiment, aiming at evenly populating a design space
SOC	State of charge
SOLAS	International Convention for the Safety of Life at Sea (IMO)
SOx	Sulphur oxides
SS	Sea state
STEP	Standard for the Exchange of Product Model Data
STL	STereoLithography file for exchange of geometry data by means of tri-meshes
SWATH	Small-waterplane-area twin hull
TARGETS	Targeted Advanced Research for Global Efficiency of Transportation Shipping, European Union FP7 Framework Project
UAV	Unmanned aerial vehicle
UID	Unique IDentifier
USV	Unmanned surface vehicle
UUV	Unmanned underwater vehicle
VHF	Very high frequency
VIRTUE	The Virtual Tank Utility in Europe, European Union FP6 Framework Project
VTK	Visualisation toolkit
VVF	Virtual Vessel Framework
WARP	Wave Resistance PRogram
WET	Weight estimator tool
WP	Work package
XMF	eXtensible Modelling Framework
XML	eXtensible Markup Language
XPAN	Potential flow code integrated in CAESES
XSD	XML schema definition

Chapter 1
Introduction to the HOLISHIP Project

Jochen Marzi

Contents

Abstract The H2020 European Research Project—HOLISHIP—Holistic Optimisation of Ship Design and Operation for Life Cycle (2016–2020) sets out to substantially advance ship design to achieve much improved vessel concepts for the twenty-first century. This innovative design approach, which is implemented into an integrated design software platform, considers all relevant ship design aspects, namely energy efficiency, safety, environmental compatibility, production and life-cycle cost. In the present chapter, we briefly review historical developments related to the HOLISHIP project and give an overview of the objectives, the adopted approach and the expected outcome of the project. Subsequent chapters of the book elaborate on the holistic approach to ship design, the development and integration of software tools into the HOLISHIP design platform. Volume 2 of the present book, expected to be published after the end of the project in 2020, will include the planned application studies.

Keywords Holistic ship design · Multi-criteria optimisation
Design software platform · Life-cycle assessment

1.1 Historical Review

When the HOLISHIP project kicked-off in September 2016, it marked a major milestone in a long line of developments focusing on different aspects of ship design and more specifically of ship design systems. Rooting back to early attempts at the end of the last millennium, fundamental technical developments in key disciplines evolved

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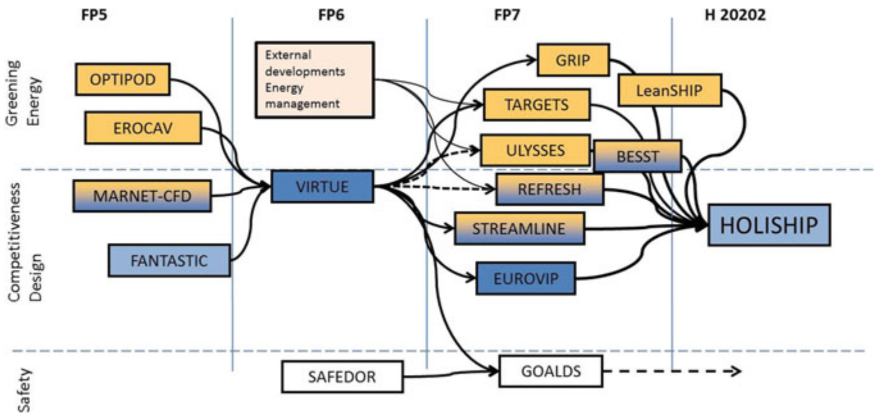

Fig. 1.1 Development line of European Union-funded projects dealing with different design aspects

from a line of European—and other national and international—research projects over a period of at least two decades, all of which addressed particular aspects of ship design. From a hydrodynamic perspective, one of the key technologies involved in ship design, first steps were made, e.g. in the EU Framework 5 project, FANTASTIC which aimed at ship hullform optimisation using—then—state-of-the-art computational fluid dynamics (CFD) simulations to determine the hydrodynamic performance of a hull. Although the optimisation concept and its software implementation were well advanced at the time; the main conclusion of the project was that the quality of the numerical simulations was not good enough to use the process in practical applications. Together with accompanying work in the MARNET-CFD network this resulted in requirements specifications which in the following framework programme (FP 6) led to focussed work on the improvement of CFD, especially in the VIRTUE project. Based on the significant improvements in quality and flexibility of the solutions provided in VIRTUE, framework programme 7 saw a variety of specialised applications in specific ship design disciplines, including but not exclusively propulsion, energy efficiency and safety. This historical view on the evolution of European Union-funded research is indicated in following Fig. 1.1.

The view presented above reflects a hydrodynamic perspective as one core element of ship design. There are, however, numerous other aspects and disciplines involved in ship design and to arrive at a truly holistic ship design system they all need to be considered (see Papanikolaou 2010). This was done in a large series of further activities and development projects, e.g. in disciplines such as ship stability and safety, efficiency and environmental footprint and structural design (see, e.g., Sames et al. 2011; Marzi and Mermiris 2012; Papanikolaou et al. 2013–2014). Once these important building blocks were available, time was ready for implementing the idea of a holistic ship design systems approach that embeds all relevant design disciplines together with relevant tools in a comprehensive, easy-to-use and—most importantly—reliable way. At the start of the Horizon 2020 research framework programme, the pre-requisites for the implementation of the first Holistic Design Optimisation system were in place and systematic development work could start.

Ship building and the associated ship design itself have a very long history. Starting from humble beginnings, the eighteenth century saw the first systematic and scientific considerations and analyses concerning fundamental aspects such as ship stability and only little later hydrodynamic performance. These led the transition from mainly learned tradition towards a more systematic design which opened up the route to not only improve what was there already but also explore new concepts and ideas. The first half of the nineteenth century saw good examples provided by the use of new materials for the construction of the hull as in Brunel's *Great Britain* or *Great Eastern*. With improved material technology, wrought iron was soon replaced by steel which allowed even larger ships to be built. Already before the introduction of the steam engine, making ships independent from wind, saw radical changes to the design of ships. The need to store energy in form of bunker—coal or oil—called for larger vessels to offer comparable transport capacity. In parallel, these became more complex as they had to fulfil different operational requirements. The nineteenth century saw the first attempts towards specialisation. Before, a seagoing ship was supposed to transport almost everything from passengers to cargo and often was deployed as a naval vessel too. Towards the second half of the nineteenth century, passenger ships, naval vessels and cargo ships were clearly distinguishable and even subtypes such as tankers or dry cargo vessels had been established. New requirements called for new technical solutions and even more so for a new approach in ship design as such. It took quite some time to formalise the necessary design steps in a universal approach which today is known as the design spiral, first presented by Evans in 1959 (see Fig. 1.2). Together with several amendments over time such as the inclusion of economic aspects and the improvements to some of the individual tools and methods applied during the individual steps in the spiral, often stimulated by computer hard- and software developments, the approach remains the standard in ship design until the present date. It considers the all relevant design aspects in an iterative way starting from very coarse information, e.g. ship main particulars to arrive at an elaborate design ready for production. The spiral allows to circle around the core—which will later be the real ship and narrow down all uncertainties involved in the initial design. Other than in its beginnings where most of the design steps were performed manually; this concept today involves a number of different IT-based systems—CAD and CAE packages which can be used several times in an iterative process.

The rate of change experienced today in seaborne trade and goods transportation has reached new heights, compared with the situation in the past century and ships need to be more flexible. Over their entire life cycle, they need to be adaptable to changing customer and market requirements, cargo volumes, enhanced ruling for the safety of people on-board and emissions. An increased energy efficiency awareness and general uncertainties regarding fuel cost and future types of marine fuels pose an extra challenge. This calls for significant advances in ship design (and operation) to meet such continuously changing requirements.

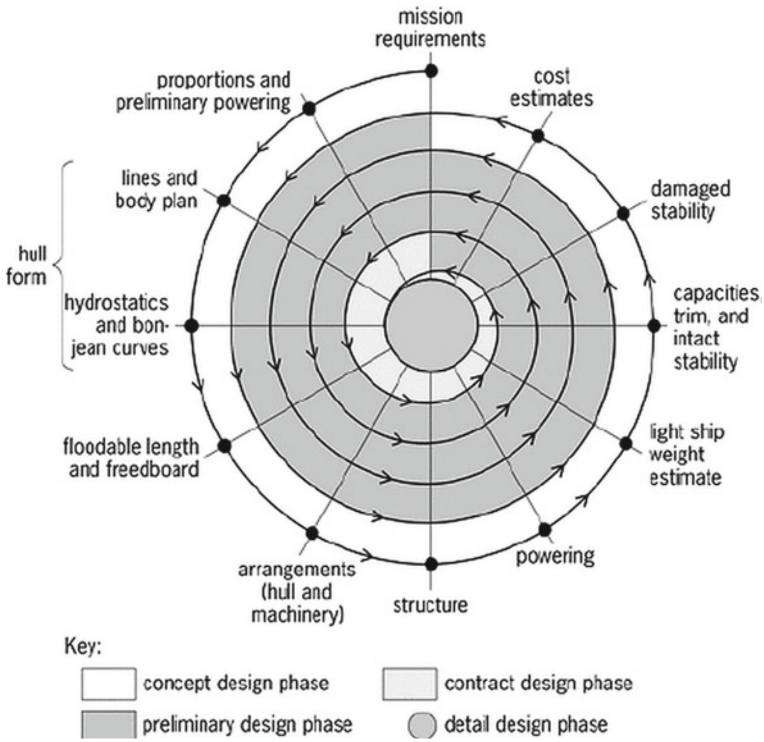

Fig. 1.2 Ship design spiral according to Evans (1959)

1.2 The HOLISHIP Project

The Horizon 2020 European Research project—HOLISHIP—Holistic Optimisation of Ship Design and Operation for Life Cycle, a joint effort of 40[1] European maritime RTD stakeholders, sets out to give answers and provide solutions for ship design in the twenty-first century in form of a new synthesis concept applied in the design process. It can be considered as a global control system for the design process which allows to instantly provide information from one system or one "design discipline" to all related disciplines and propagate changes in one discipline directly to all others, hence assuring that all individual constraints relevant in each discipline are met.

[1]HSVA (coordinator), ALS Marine, AVEVA, BALance, Bureau Veritas, Cetena, Center of Maritime Technologies, Consiglio Nazionale delle Ricerche, Damen, Danaos, DCNS, DLR, DNV-GL, Elomatic, Epsilon, Fraunhofer-AGP, Fincantieri, Friendship Systems, Hochschule Bremen, IRT SystemX, Institute of Shipping and Logistics, Lloyd's Register, MARIN, SINTEF, Meyer Werft, Navantia, National Technical University of Athens, Rolls Royce, Sirehna, SMILE FEM, Starbulk, TNO, TRITEC, Uljanik, Univ. Genoa, Univ. Liege, Univ. Strathclyde, van der Velden, http://www.holiship.eu.

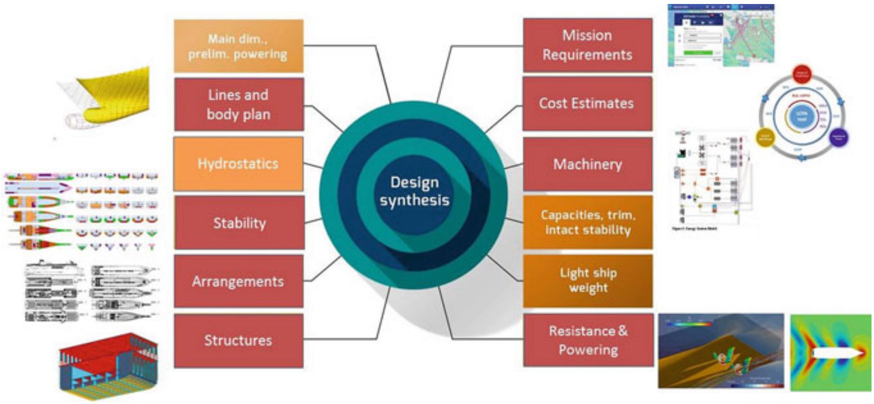

Fig. 1.3 HOLISHIP approach

A detailed description of the synthesis approach adopted in HOLISHIP is given in Chaps. 2 and 8.

This new and advanced design approach is implemented in an integrated software platform which is described in detail in Chap. 8. In its present state, i.e. the implementation in the HOLISHIP project, it considers all relevant ship design aspects related to energy efficiency, safety, environmental compatibility, production and life-cycle cost, which are optimised in an integrated manner to deliver the right vessel(s) for future transport tasks.

Based on a state-of-the-art process integration and design optimisation environment, using the CAESES® platform of Friendship Systems, the HOLISHIP design platform integrates cutting edge first principles analysis software tools from various disciplines relevant to ship design—hydrodynamics, structural analysis, engine simulation—and combines them with advanced multi-objective optimisation methods. Based on a formalised set of design objectives and user requirements as target functions, the platform supports ship design through different stages from concept design through contract design and operational analysis while dedicated cost models allow for permanent control of capital and operational expenditures. The interplay of all design components in form of a design synthesis model hosted on the HOLISHIP platform explores a much wider design space and finally achieves superior designs in less time compared with traditional approaches.

The HOLISHIP concept is illustrated in following Fig. 1.3, visualising design disciplines implemented in the HOLISHIP platform in the course of the project. The practical process integration and design optimisation which form the core part of the project are presented in Chap. 8 of the present volume. Individual aspects of tools integrated in modules representing different design disciplines are presented in other chapters of the present volume.

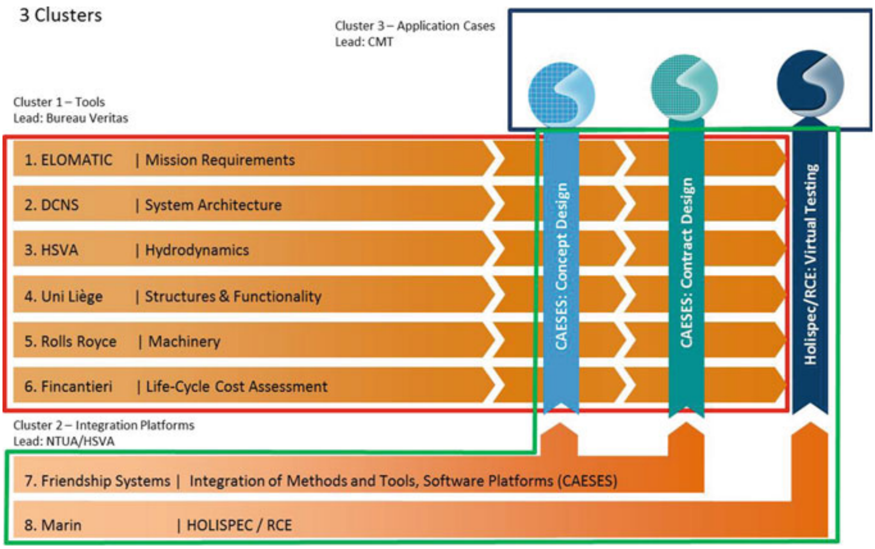

Fig. 1.4 HOLISHIP project structure

All HOLISHIP developments are based on:

- Advanced technology and software developments and their adaptation for design systems,
- Their integration into novel design platforms,
- Their demonstration in form of different application cases covering all or different life-cycle phases, which integrate different aspects of ship design.

Consequently, the project is structured into three main **work clusters**:

Cluster 1: **Tool development**: methods and software tools for the individual design aspects will be developed and adapted to the intended integrated use in the HOLISHIP integrated design platforms.

Cluster 2: **Software Integration**: of software tools developed in Cluster 1 to be integrated into the HOLISHIP design platform (CAESES®) and the HOLISHIP Virtual Vessel Framework (HOLISPEC-RCE® of DLR).

Cluster 3: **Application Cases/Demonstrators**: in which the integrated software platforms will be applied to the design and operation of ship and other maritime assets and the use and benefit of the developed frameworks will be demonstrated.

This overall project structure is shown in the following Fig. 1.4 which indicates the close links that have been established between software developments for tools (in Cluster 1) and platforms (in Cluster 2) with the application cases foreseen in the second half of the project which will be covered in the second volume of the present book.

In the following chapters of the present volume, the approach and special aspects considered in the development of software for the different design disciplines (in Cluster 1) and the integration platforms (in Cluster 2) are highlighted.

HOLISHIP demonstrates the use of the holistic design approach and its practical implementation on the basis of the integrated software platform and a range of design–analysis tools suitable for the application cases covering different ship types. This will include PAX, cargo vessels, OSV, ferries and even an offshore platform. At the time of print, these activities are starting and a detailed account of these design exercises will be presented in the second volume of the present book to be published towards the end of the project in 2020. First example applications of the optimisation procedure have been shown in Harries et al. (2017) and are included in the present volume, e.g. in Chaps. 6, 7 and 8.

Besides its website at www.holiship.eu, the project performs a variety of dissemination activities including regular contributions to relevant ship design and maritime conferences. During the first 18 months of the project, 29 conference papers/scientific publications have been produced, besides 21 press releases and articles in professional journals. A selection of these can be found in the "Publications" section of the project website.

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Dr. Jochen Marzi graduated in 1985 from Hamburg University as Dipl. Ing. Naval Architecture and received his Ph.D. in 1988 from Technical University Hamburg, Harburg. Since then he worked for a shipyard research establishment at Bremerhaven Germany, making first contacts with joint European Projects. In 1996, Jochen Marzi joined Hamburgische Schiffbau Versuchsanstalt—HSVA—working as a senior CFD engineer and project manager both in research and consultancy work, leading several large European Projects such as the VIRTUE IP in FP 6 and presently HOLISHIP in Horizon 2020. He is now Head of the CFD department and responsible for the coordination of European Research at HSVA and active in several R&D projects dealing with CFD, ship design and energy efficiency. Jochen Marzi represents HSVA in the European Council for Maritime Applied R&D (ECMAR) from the beginning in 2007. He served as Chairman from 2009 to 2011.

Chapter 2
Holistic Ship Design Optimisation

Apostolos Papanikolaou

Contents

Abstract The present chapter provides a brief introduction to the holistic approach to ship design optimisation and its historical development. It defines the generic ship design optimisation problem for life cycle and discusses the implementation of the holistic approach to ship design on the basis of a typical ship design optimisation problem with multiple objectives and constraints, namely the design of an AFRAMAX tanker ship. Optimisation results show significantly improved designs with partly innovative features, increased cargo carrying capacity and transport efficiency, reduced required powering and fuel consumption and last but not least increased safety of the marine and aerial environment.

Keywords Holistic ship design · Multi-objective optimisation · Tanker design
Efficiency · Marine pollution

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2.1 Introduction to Holistic Ship Design Optimisation

Ship design was in the past more art than science, highly dependent on experienced naval architects, with good background in various fundamental and specialised scientific and engineering disciplines. The design space was traditionally practically explored intuitively or using heuristic methods, namely methods deriving from knowledge gained through a process of trial and error, often over the course of decades. Inherently coupled with the design process is design optimisation, namely the selection of the best solution out of many feasible ones. In traditional naval architecture, optimisation means taking the best out of 2–3 feasible solutions and it is up to the designer to decide on the basis of his experience about the assessment procedure and applicable decision criterion (or criteria). Of course, the space of feasible design solutions is huge, and the relevant assessment criteria are numerous and complex, as are the design constraints, while the assessment procedure must be rational and not intuitive, thus according to the state of the art, and all this calls for a *step change* of the design process in naval architecture.

In a systemic approach to ship design, we may consider the ship as a complex system integrating a variety of subsystems and their components, e.g. for a cargo ship, 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 (or *functionalities*) may be divided into two main categories, namely *payload* functions and *inherent* ship functions (see Fig. 2.1). For cargo ships, the *payload* functions are related to the provision of cargo spaces, cargo handling and cargo treatment equipment. *Inherent* ship functions are those related to the carriage/transport of payload, namely ship's hull including superstructures, and to the transfer from port A to port B with certain speed, which requires the disposal of certain engine power/propulsion unit and required amount of fuel in ship's tanks. Likewise for passenger ships, the payload functions are trivially referring to the provision of passenger accommodation and public spaces (Papanikolaou 2014b).

Ship design and operation are governed by a series of national and international safety regulations, including the technical standards of an internationally recognised classification society's rules for ship's construction and operation, which should all ensure the safety of people on board (IMO—International Convention for the Safety of Life at Sea: SOLAS) and of the marine (and aerial) environment (IMO—International Convention for the Prevention of Pollution from Ships: MARPOL), as well as the safety of the transported cargo and the ship itself.

Modern, systemic approaches to ship design consider ship's overall system in a modular way, namely as the assembly of a series of modules, which may be replaced by others over ship's life cycle for serving a different transport/operational scenario, besides retrofitting for improved and/or safer transport services. These modular approaches, which found recently wider application in naval and multi-purpose ship design, are known as "Modular-based Ship Design" or "Set-based Ship Design"

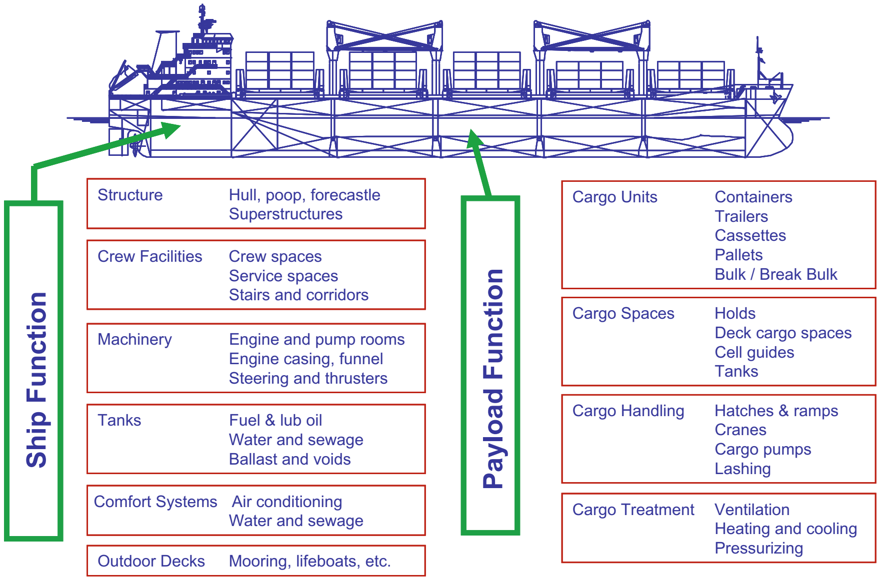

Fig. 2.1 Ship functions, according to Levander (2003)

methods (see e.g. Parsons and Singer 1999; Pahl et al. 2007; Singer et al. 2009; Simpson et al. 2014; Guégan et al. 2017; Choi et al. 2017).

When considering ship design over ship's life cycle, we split the design procedure into various stages that are traditionally composed of the *concept/preliminary* design, the *contractual* and *detailed design*, the *ship construction/fabrication* process, *and ship's operation* with *possible retrofitting* and finally *scrapping/recycling* ("*from cradle to grave*"[1]). It is evident that the *optimal* ship with respect to her whole life cycle is the outcome of a *holistic*[2] optimisation of the entire, above defined ship system over its life cycle. It is noted that mathematically, every constituent of the above defined life-cycle ship system forms evidently itself a complex nonlinear optimisation problem for the ensuing design variables, with a variety of constraints and criteria/objective functions to be jointly optimised. Even the simplest component of the ship design process, namely the first phase (conceptual/preliminary design), is complex enough to be often simplified (*reduced*[3]) in practice.

[1]Or better, "*from cradle to cradle*", assuming *optimal dismantling and reuse* of recyclable materials and ship components.

[2]From Greek ὅλος *holos* "all included, whole, entire", Principle of *holism* according to Aristotle (*Metaphysics-see* Cohen 2016): "The whole is more than the sum of the parts"; thus, systems of different type (physical, biological, chemical, social, economic, mental, etc.) and their properties should be viewed as wholes, not just as a collection of parts.

[3]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

Inherent to ship design optimisation are the conflicting requirements resulting from the design constraints and optimisation criteria (the *merit* or *objective functions*), reflecting the interests of the various ship design stakeholders: shipowners/operators, shipbuilders, classification society/coast guard, regulators, insurers, cargo owners/forwarders and port operators, etc. Assuming a specific set of requirements (the typical *shipowner's requirements for merchant ships* or *mission statement for naval ships*), a ship needs to be optimised for cost-effectiveness, 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 itself as hardware; last but not least, the ship needs to be optimised 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 the radiated wave wash causing problems onshore. Recently, aspects of ship engine emissions and air pollution need to be also considered in the optimisation of ship design and operation, as imposed by the Energy Efficiency Design Index (EEDI) regulatory framework (see, IMO MEPC 2009, 2014). Many of these requirements are clearly conflicting[4] and a decision regarding the identification of the optimal ship design needs to be rationally made.

To make things even more complex but closer to reality, even the specification of a set of design requirements with respect to ship type, cargo capacity, speed, range, etc. is often not trivial, but requires another optimisation exercise that satisfactorily/rationally considers, next to needs of the shipowner, the interests of all stakeholders in the maritime transportation chain and the international market. Actually, the initial set of ship design requirements should be the outcome of a compromise of intensive discussions between highly experienced decision-makers, both from the ship design/shipbuilding side and the shipowner/operator/end-user side. A way to undertake and consolidate this kind of discussion about ship's specification in a rational way has been introduced by the EU-funded project LOGBASED, namely the logistics-based ship design (Brett et al. 2006; Boulougouris et al. 2012). This is in more recent works further promoted by the so-called scenario-based design (see e.g. Choi et al. 2015) and similar approaches.

In summary, the present chapter provides after a brief introduction to the *holistic* approach to ship design optimisation and its historical development, the definition of the generic ship design optimisation problem and its solution by use of genetic

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be regarded as complementary approaches, as they are both needed to satisfactorily address complex systems in practice, like ship design.

[4] An obvious conflicting requirement in ship design is embedded in the recently introduced EEDI regulatory framework for the reduction of toxic gas emissions of marine diesel engines, namely, whereas ship's installed power needs to be kept below a certain limit postulated by the *EEDI Index reference line*, there is a need that this power is also not below the *Minimum Required Power* (MPR) limit for safe operation in adverse weather conditions (IMO MSC-MEPC 2012). Obviously, the maximum limit for the installed power set by the EEDI reference line *should be higher than* the set minimum limit by the MPR regulation. This, however, could not always be ensured in practice for some ship types/sizes and it laid to controversial debates at IMO and redefinition of the margins of the EEDI reference lines.

algorithms and related techniques for the design generation, exploration and final selection of the favoured design solution(s) by the decision-maker (ship designer). It discusses the proposed holistic ship design optimisation methodology on the basis of a typical multi-objective ship design optimisation problem, namely the optimisation of *an AFRAMAX tanker* of enhanced efficiency and reduced environmental footprint. Applications to other ship types, namely RoPax and cruise ships (see Zaraphonitis et al. 2003a; Skoupas et al. 2009; Papanikolaou 2011; Zaraphonitis et al. 2012, 2013; Harries et al. 2017), containerships (see Koutroukis et al. 2013; Koepke et al. 2014; Papanikolaou 2014a; Priftis et al. 2016), may be found in the listed references.

2.2 The Evolution of the Holistic Approach to Ship Design

How has the holistic approach to ship design and optimisation evolved over the years and what is it about?

Initially, ship design optimisation addressed only parts of ship design referring to individual ship properties and engineering disciplines, like ship hydrodynamics and ship structures. Since the middle sixties with the advance of computer hardware and software, more and more parts of the design process were taken over by computers, particularly the heavy computational and later on the drafting elements of ship design. Simultaneously, the first computer-aided conceptual design software tools were introduced, dealing with the mathematical exploration of the conceptual design space by use of parametric models for ship's main dimensions and empirical/simplified formulas for the assessment of ship's performance with respect to specified economic criteria. Pioneering works, in this respect, were chronologically

- the "least building cost" parametric optimisation of main dimensions and characteristics of cargo ships by a semi-automated computerised procedure outlined by Murphy et al. (1965);
- the formalised *random search* optimisation approach to ship's concept design by Mandel and Leopold (1966), which, for the first time, introduced issues of uncertainty of design parameters and multi-objective attributes in the optimisation process;
- and the CAD optimisation of main dimensions and characteristics of tankers by a *gradient-based optimisation* technique for minimum required freight rate (RFR) by Nowacki et al. (1970).

The above approaches referred mainly to the ship's concept design and the determination of optimal main dimensions, whereas ship's properties, like hydrodynamic performance (resistance and propulsion) or strength (structure and weights) requiring multidisciplinary approaches, were considered by use of empirical formulas relating to ship's main dimensions and form parameters. The above approaches may be considered as the first *"holistic" top-down approaches* to the ship design optimisation problem, even though they were restricted to the conceptual design of some specific ship types, while they greatly relied on approximate empirical formulas for the assessment of ship's properties.

Parallel developments were noted in the constituent basic disciplines of ship design. The hydrodynamic optimisation of ship's hull form has a long history, while the introduction of a rational scientific approach to it, particularly to the minimisation of wave resistance, is attributed to Weinblum (1959). Computer-aided studies on the optimisation of ship's hull form for least calm water resistance and superior seakeeping performance (hydrodynamic design optimisation) were enabled much later with the advance of computing codes for the calculation of the wave and viscous resistance, as well as of the ship responses in a seaway (seakeeping). Characteristic works on calm water resistance calculation in the late 70s and 80s are those of Dawson (he introduced the 1st panel code for wave resistance, 1977), Jensen et al. (introduced 3D Rankine source methods for wave resistance, 1986), Nagamatsu et al. (minimisation of viscous resistance, 1983), Larsson et al. (minimisation of total calm water resistance, 1992), Papanikolaou et al. (hydrodynamic optimisation of fast displacement mono- and twin-hull vessels, 1989, 1991, 1996, 1997; Zaraphonitis et al. 2003b); in the area of seakeeping it was the landmark work by Salvesen et al. (introducing strip theory, 1970), whereas 3D panel codes followed in the 80ties, e.g. by Papanikolaou et al. (3D panel source method, 1985, 1992). Similar developments were noted in the optimisation of ship's mid-ship section/structural design for least steel weight (structural design optimisation), see e.g. Hughes et al. (1980), Hughes (1983) and Rigo (2001). Above hydrodynamic and structural analysis tools were further developed in more recent years, namely in line with the advance of computer hardware: Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) methods started being developed and introduced to the naval architectural scientific community until they led to mature software tools for the needs of the maritime industry. Some characteristic works in this respect are: hull form optimisation by use of CFD by Peri et al. (2001), Campana et al. (2006), structural design optimisation by FEA by Zanic et al. (2013), Ehlers et al. (2015). A very useful review of historical developments in computer-aided ship design is due to Nowacki (2010).

With the further and faster advance of computer hardware and software tools, along with the integration of the *application software tools* into powerful hardware and *design software platforms*, the time has come to look at the way ahead in ship design optimisation in a *holistic* way, namely by addressing and optimising simultaneously several and gradually all aspects of ship's life (or all elements of the entire ship life-cycle system), starting with the stages of design, construction and operation; within the *holistic* ship design optimisation, we should herein understand the exhaustive, multi-objective/multidisciplinary and multi-constrained ship design optimisation procedures even for individual stages of ship's life (e.g. conceptual design) with *least reduction* of the entire real problem. Recently introduced scientific disciplines in the general framework of "design for X" (State of the Art report by Papanikolaou et al. 2009; Andrews and Erikstad 2015), namely "design for safety" and "risk-based design" (see Vassalos 2007; Papanikolaou 2008; SAFEDOR (2005–2009); Papanikolaou 2009; Breinholt et al. 2012), "design for efficiency" (Boulougouris and Papanikolaou 2009), "design for production" (Okumoto et al. 2006; Singer et al. 2009; Simpson et al. 2014), "design for arctic operation" (Riska 2009) indicate the need for new scientific approaches and the availability of mature methods and computational/software tools to address *holistically* the ship design optimisation problem.

2.3 The Generic Ship Design Optimisation Problem

Within a *holistic* ship design optimisation, we should herein mathematically understand exhaustive multi-objective and multi-constrained optimisation procedures with *least reduction* of the entire real design problem. The generic ship design optimisation problem and its basic elements are defined in Fig. 2.2, while a generic approach to its solution is outlined in Fig. 2.3 (Papanikolaou 2010).

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 promoted in the present chapter as a generic type optimisation technique for generating and identifying optimised designs through effective exploration of the large-scale, nonlinear design space and a multitude of evaluation criteria (Sen and Yang 1998). Several applications of this generic, multi-objective ship design optimisation approach to the design of specific ship types were studied in recent years by various authors and research teams. We highlight in the following some examples which were generated by use of the design software platform of the Ship Design Laboratory of NTUA. This software platform

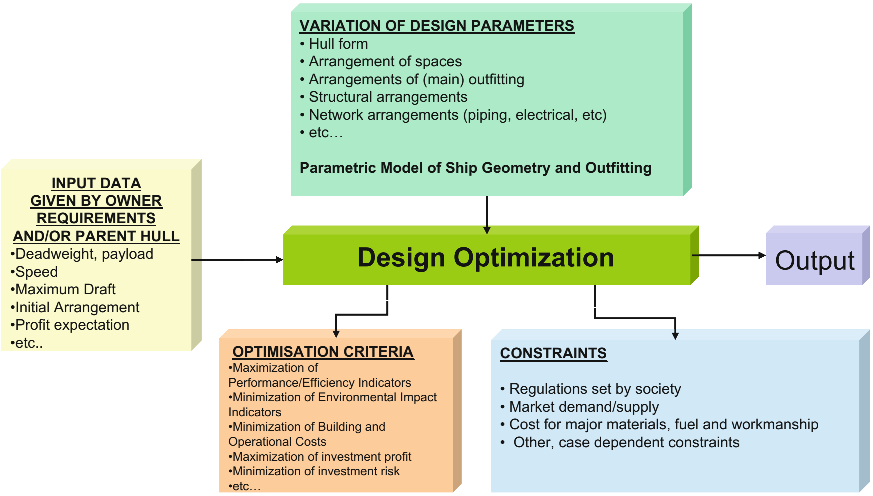

Fig. 2.2 Generic ship design optimisation problem

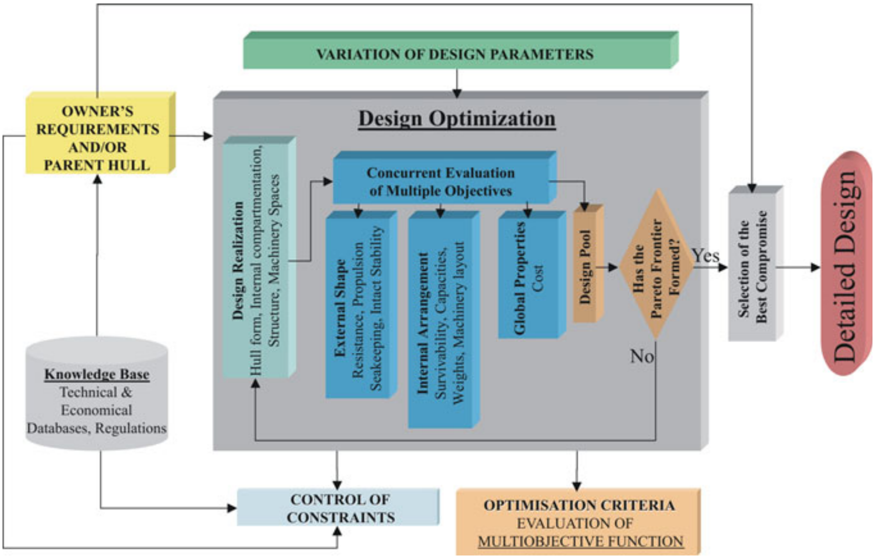

Fig. 2.3 Generic procedure for the ship design optimisation problem

integrates well-established naval architectural and optimisation software packages, like NAPA®, CAESES® and modeFRONTIER®, with various application methods and software tools, as necessary for the generation of ship's hull lines and general arrangements, the evaluation of ship's intact and damage stability, her resistance, propulsion and manoeuvrability, her seakeeping, structural integrity and life-cycle economy. Details of these works may be found in the list of references. The following examples may be highlighted:

- Hull form optimisation of fast mono- and twin-hull vessels for least calm water resistance (Papanikolaou et al. 1991, 1996, 1998).
- Hull form optimisation of a wave piercing high-speed monohull for least resistance and best seakeeping (EU funded project VRSHIPS-ROPAX2000 (2001–2004); Boulougouris and Papanikolaou 2006).
- Hull form optimisation of high-speed mono- and twin-hulls for least wave resistance and wave wash (EU funded project FLOWMART, Zaraphonitis et al. 2003a).
- Optimisation of the compartmentation of a RoPax vessel for increased damage stability and survivability and least structural weight (EU funded project RORO-PROB (2000–2003), Zaraphonitis et al. 2003b).
- Optimisation of an LNG floating terminal for reduced motions and wave attenuation on terminal's lee side (EU funded project GIFT (2005–2007), Boulougouris and Papanikolaou 2008).
- Logistics-based optimisation of ship design (EU-funded project LOGBASED 2003–2006, Brett et al. 2006).

- Risk-based design optimisation of an AFRAMAX tanker for increased cargo capacity and least environmental impact (EU funded project SAFEDOR, Papanikolaou et al. 2007).
- Parametric design optimisation of RoPax and cruise ships for minimum potential loss of lives and economy (EU funded project GOALDS (2009–2012), Zaraphonitis et al. 2012, 2013).
- Parametric design optimisation of tankers for best economy and environmental impact (Joint Industry Project GL-NTUA BEST, Papanikolaou et al. 2010; Sames et al. 2011a, b).
- Parametric design optimisation of containerships for maximum number of deck containers, minimum ballast water and powering (Joint Industry Project GL-NTUA CONTIOPT (2012–2013); Koepke et al. 2014).
- Parametric design optimisation of a tanker's bow for minimum calm water and added resistance in waves (EU funded project SHOPERA, Bolbot and Papanikolaou 2016).
- Parametric design optimisation of various types of ships for EEDI and Manoeuvrability in view of Minimum Powering in Waves (EU funded project SHOPERA, Papanikolaou et al. 2015; Zaraphonitis et al. 2016).

In the frame of the HOLISHIP project (2016–2020), the governing design software platform is CAESES of Friendship Systems, to which a variety of software tools for naval architectural works (like NAPA), as well as software tools of various project partners for the assessment of ship's hydrodynamic performance, structural integrity, energy management and life-cycle cost are being integrated. This platform and an early example of application to the design of a RoPax ferry are being elaborated in other chapters of this book (see, also, Harries et al. 2017). However, we will be outlining in the following an application to an AFRAMAX tanker design, which was earlier developed in the frame of project BEST (BEST 2008–2011), a Joint Industry Project of Germanischer Lloyd (now DNV-GL) and the Ship Design Laboratory of NTUA, supported by Friendship Systems.

2.4 Optimisation of Tanker Design

In recent time, shipping industry's major ecological concerns are more directed to energy efficiency/fuel consumption and associated regulations referring to the greenhouse gas emissions. This comes on top of long-standing concerns regarding accidental oil pollution, particularly by large crude oil carriers. The 2012 guidelines on the method of calculation of the attained Energy Efficiency Design Index (EEDI) for new ships from January 1, 2013 on represent a major step forward in implementing the Regulations on Energy Efficiency of Ships [IMO MEPC 2011—resolution MEPC.203(62)] through the introduction of a series of specifications for calculating the EEDI for various types of ships. There are, however, serious concerns regarding the sufficiency of propulsion power and of steering devices to maintain the manoeuvrability of ships in adverse conditions, hence the safety of ships, assuming that the ship marginally passes the relevant EEDI criterion. This gave reason for additional considerations and studies at IMO (IMO MEPC 2012a, b: MEPC 64/4/13 and MEPC 64/INF7). The EEDI regulations may be understood as an important new constraint in ship design and operation, particularly for tankers, thus it is urgent to look *holistically* into integrated ship design and operational environments and implement multi-objective optimisation procedures in tanker ship design. Optimising for ship's efficiency (EEDI), while ensuring safe ship operation and looking into the right balance between ship's efficiency and economy, safety and greenness was the subject of the recently completed project SHOPERA (2013–2016).

Regarding the safety of tanker operations in terms of accidental oil pollution, the prime reference is the conducted Formal Safety Assessment for tankers by the EU funded project SAFEDOR that was discussed and approved at IMO (IMO-MEPC 2008; IMO-MSC 2012). A more recent comprehensive study on the risk of accidents of various types of ships, including large oil tankers, showed that the potential oil pollution by tanker accidents continues being dominated by grounding and collision events, followed by fire and explosions (Eliopoulou et al. 2016). Enlarged double hull width and double bottom height, enhanced compartmentation and varying size of tanks can lead to improved environmental protection, without compromising on ship's efficiency, as elaborated by Papanikolaou et al. (2007).

While the current tanker capacity appears to outweigh anticipated demand of oil transport, the fleet's ageing is likely to trigger replacements. It is, therefore, safe to assume that new tanker designs will be sought, but it is not obvious what will be the main driving forces, namely:

- Safer shipping by containing or mitigating oil outflow in case of an accident
- Greener operations by reducing fuel consumption and emissions per ton-mile of cargo
- Smarter business by increasing returns (higher cargo capacity and lower fuel consumption).

A reasonable combination of the above is likely to be favoured over extremes, depending on the specific situation and preference of the stakeholders. The more high-quality design data are readily available the easier it will be to understand opposing influences, come to a sound judgment and choose the best compromise on a rational basis. This is the main scope of the below elaborated study.

2.4.1 Multi-objective AFRAMAX Tanker Design

Without compromising on the applicability of the utilised CAESES design platform and the so far integrated software tools, we demonstrate in the following the multi-objective design optimisation of an AFRAMAX tanker for trading in the Caribbean Sea (see project BEST, Sames et al. 2011a, b). This should not only allow the proof of the envisaged integrated CAESES approach, but also enables the identification

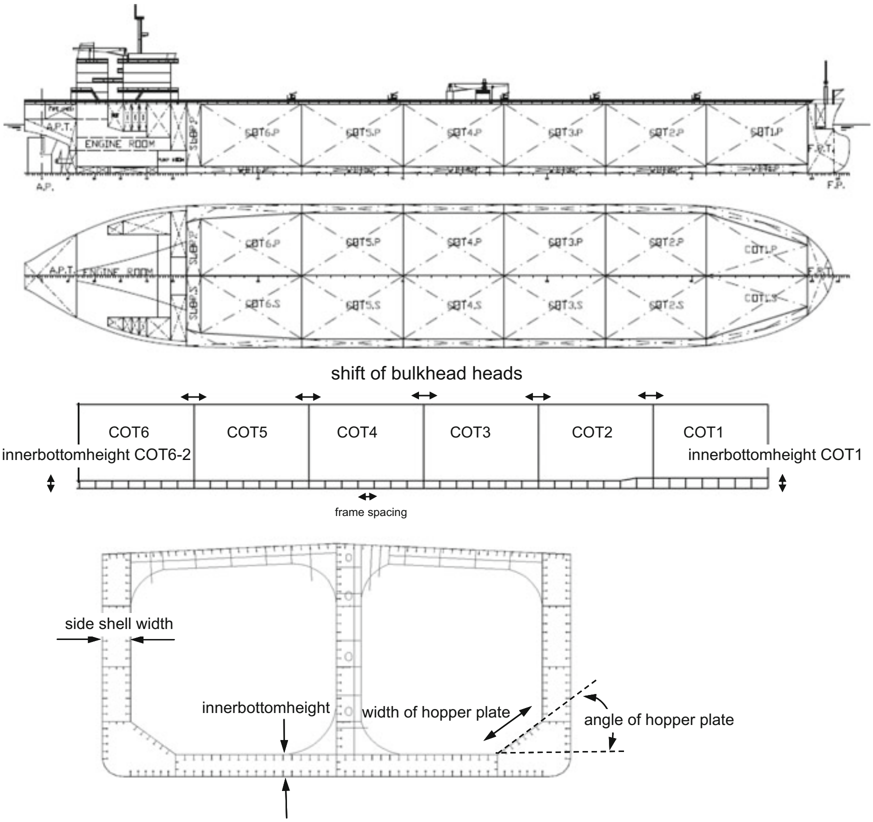

Fig. 2.4 General arrangement along with layout of tanks and selected free variables

of interesting novel design features for a ship type of actually mature design and technology, but imminent commercial interest. The chosen demonstration example and the associated optimisation are governed by a series of regulatory restrictions and constraints related to tanker design and the specific operational region, namely servicing the main US port facilities on the Gulf coastline and crossing the US Emission Control Area (ECA). This means limits on maximum length, beam and draft and an additional demand for tanks to carry marine gas oil (MGO). Requests from ship operators active in the trade were taken into account, calling for relatively high service speeds of well over 15 knots and low discharging times. A conventional 6×2 Cargo Oil tank (COT) layout for the tanks was used as a basis, Fig. 2.4; it should be herein noted, however, that the a 6×3 COT layout proved also very promising for an AFRAMAX design, when optimising jointly for minimum for oil outflow index and maximum cargo capacity/minimum steel weight (see Figs. 2.5 and 2.6 from Papanikolaou et al. 2010). The challenge was herein, however, to identify designs

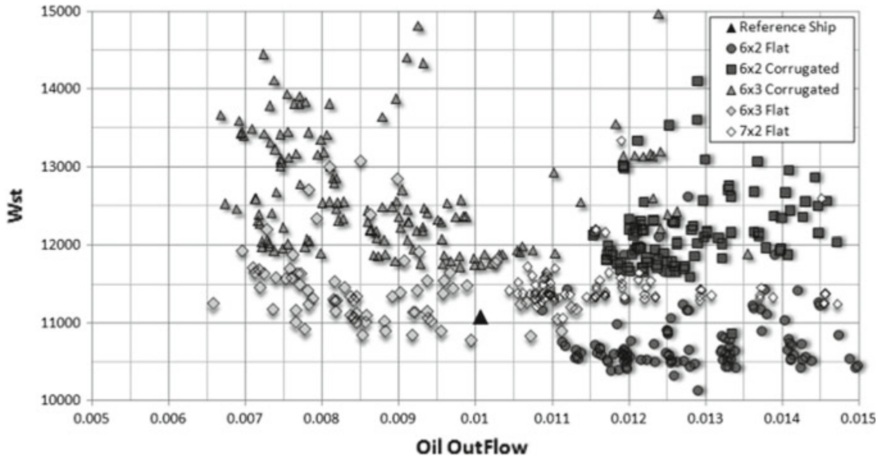

Fig. 2.5 Oil outflow index versus steel weight in cargo area—Pareto designs for different COT and BHD configurations (Papanikolaou et al. 2010)

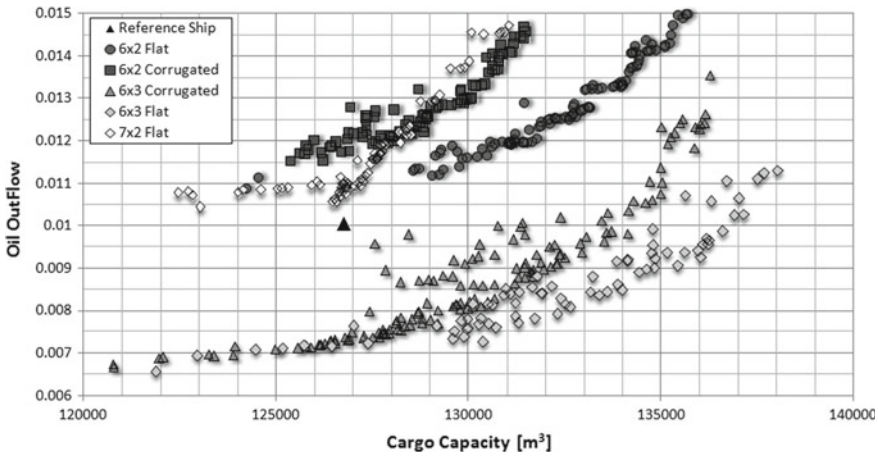

Fig. 2.6 Oil Outflow index versus cargo capacity—Pareto designs from different COT and BHD configurations (Papanikolaou et al. 2010)

that would not deviate too much from conventional practice, but still yield significant improvements, thus the 6×2 COT arrangement was kept.

2.4.2 The Design Approach

The design process/workflow was set up in the FRIENDSHIP/CAESES-Framework (FFW), which is also used in the HOLISHIP project. The present application is combining CAESES with the structural design software of Germanischer Lloyd POSEIDON®, the naval architectural software package NAPA® and the CFD resistance code SHIPFLOW®. The following key measures/quantities were computed and processed:

- Cargo tank capacity in full load and design load conditions,
- Steel weight of the cargo tank area,
- Maximum ship speed at design, ballast and scantling drafts,
- Probability of oil spill in case of accidents measured by IMO's oil outflow index (OOI).

A general flow chart of the design process is presented in Fig. 2.7. For each variant, a hull form is generated within FFW along with alternative tank configurations. The structural design in the cargo block area is then determined with POSEIDON in accordance with the prescriptive part of the Common Structural Rules (CSR) for Double Hull Oil Tankers. The hydrodynamic performance of the design alternatives is determined via a response surface model (RSM) built from a priori flow simulations using the CFD code SHIPFLOW, in connection with the potential flow code (XPAN) and viscous flow analysis (CHAPMAN). This is followed by a batch mode execution of NAPA to get the stability and trim characteristics plus the probability of oil outflow for the generated alternative tank configurations and hull form shapes according to IMO-MARPOL provisions (IMO-MEPC 2004a). The process is complemented by several additional features available within the FRIENDSHIP-Framework, which enable the gathering, synthesis and analysis of the various results from all conducted external simulations (Abt and Harries 2007a, b; Abt et al. 2009).

From the determined values of cargo tank capacity, steel weight and ship speed two combined performance measures (indicators) for ecology and economics were derived:

- Operational impact measured by the Energy Efficiency Design Index (EEDI), combining engine power, deadweight and ship speed according to IMO
- Financial attractiveness measured in terms of Required Freight Rate (RFR), combining the annual cost of transport via capital, fuel and other operating costs with the number of roundtrips times cargo mass per year.

Free variables in the overall optimisation procedure were parameters that control the hull form (outer shell), the tank layout and geometry as well as the inner structure, as given in Table 2.1 and Fig. 2.8.

Having established the most favourable main particulars, cargo tank arrangement and cargo block scantlings, within a global optimisation procedure, the ship's aftbody was subsequently fine-tuned with regard to wake quality and total resistance. In addition, systematic changes were undertaken to study the dependencies of selected

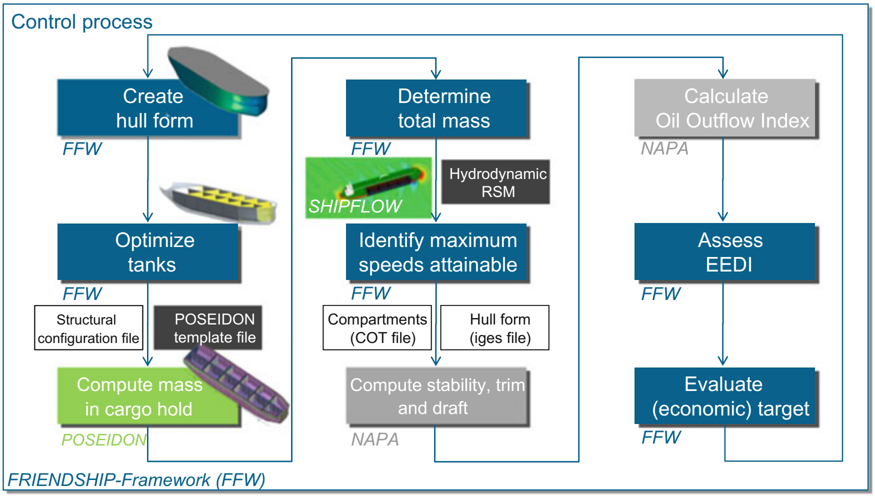

Fig. 2.7 Flow chart of CAESES-NAPA-POSEIDON integrated approach to tanker design (Papanikolaou et al. 2011)

Table 2.1 Free variables and their bounds for the global optimisation

Free variable	Lower bound	Upper bound	Primary influence
Length over all (LOA)	242 m	250 m	Hull form
Beam	42 m	44 m	Hull form
Shift of longitudinal centre of buoyancy	−0.008 LPP	0.008 LPP	Hull form
Block coefficient	0.800	0.885	Hull form
Depth	20.5 m	23 m	Tank geometry
Inner bottom height of cargo oil tanks 2–6 (S+P)	2.0 m	2.7 m	Tank geometry
Lifting of inner bottom of cargo oil tank 1 (S+P)	0 m	1.5 m	Tank geometry
Side shell width	2.0 m	2.7 m	Tank geometry
Angle of hopper plate	30°	60°	Tank geometry
Width of hopper plate	4.8 m	5.8 m	Tank geometry
Shift of the intermediate bulkheads(frame spacing s)	−1 s	+1 s	Inner structure
Number of frames per tank	7	8	Inner structure

measures of merit on specific parameters (sensitivity studies), e.g. the change of oil outflow probability by further increasing the double bottom height of the foremost tanks.

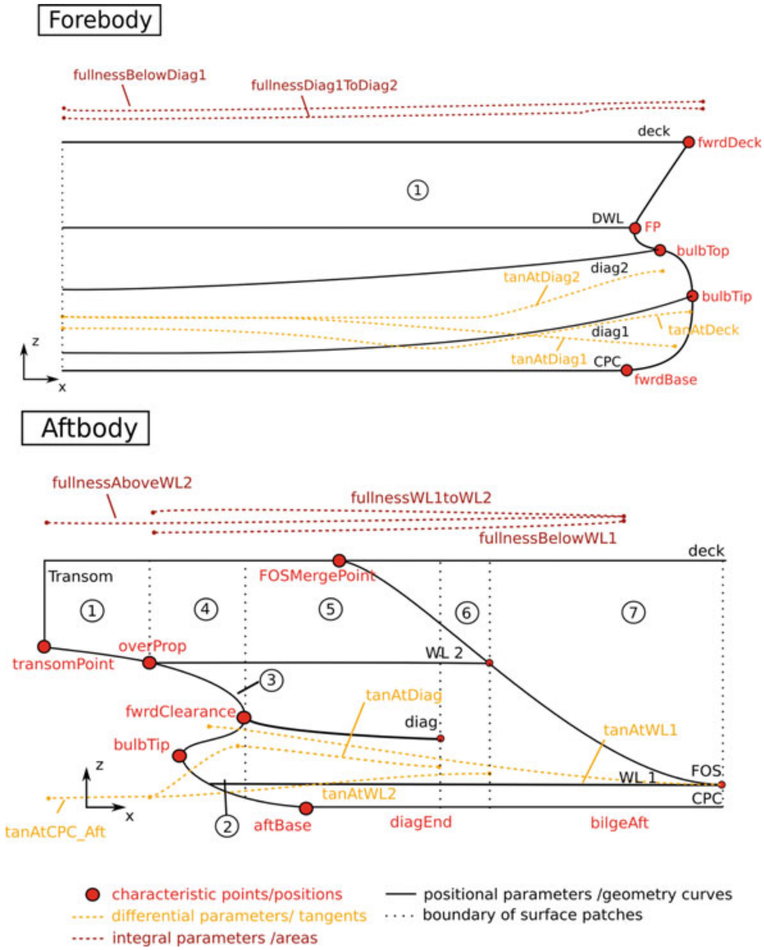

Fig. 2.8 Parametric model of hull form (from Harries et al. 2011)

2.4.3 *Tank Arrangement*

The cargo tanks were generated within CAESES-FFW using the *feature technology* (Brenner et al. 2009). The tanks are generated such that maximum cargo volume is realised while ensuring a minimum distance to the hull form, e.g. 2 m, see Fig. 2.9. The feature takes the hull form, the minimum distance of the inner structure to the hull (outer shell) and the longitudinal position of the engine room's bulkhead as inputs. The collision bulkhead's position is computed according to IMO rules.

During the global optimisation the side shell width at deck height, the double bottom height at amidships, the angle and width of the hopper plate and the step in the double bottom towards the foremost tank were changed. The bulkhead positions

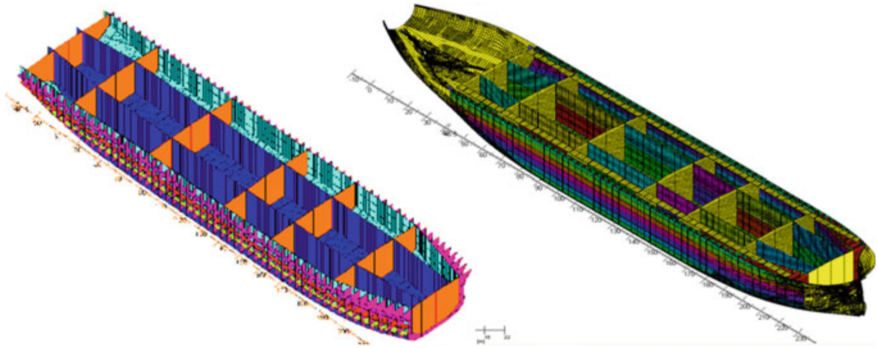

Fig. 2.9 Sample POSEIDON model for 6 × 3 COT without (left) and with (right) outer shell (Sames et al. 2011a, b)

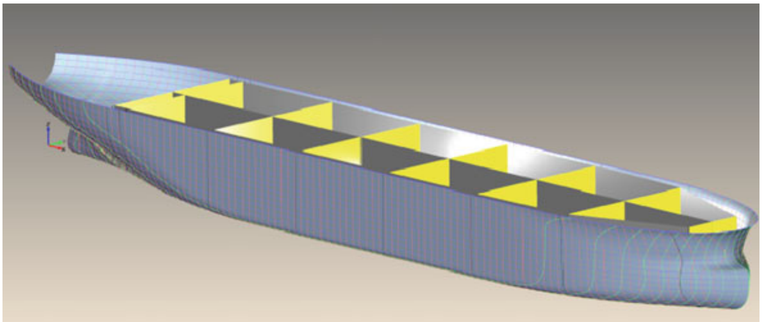

Fig. 2.10 Family of parametrically generated hull forms for 6 × 2 cargo tank arrangements by use of the FRIENDSHIP-Framework (FFW)

were moved discretely according to the frame positions. The total number of frames was controlled by specifying the number of frames per tank. The first tanks (COT1) and the last tanks (COT6) were flexible in length by allowing shifts of the bulkhead positions by one frame distance forward or aft. The tanks associated with a specific design variant were represented as an assembly of planar surfaces within the FFW, Fig. 2.10, and transferred to NAPA by means of the edge points for the bulkheads and hopper plates.

2.4.4 Structural Model

For the structural design and strength assessment, a computational model containing the IACS Common Structural Rules (CSR) for Double Hull tankers was needed. The model had to include information about the main particulars of the vessel, plate distribution and stiffener arrangement of primary and secondary members, tank arrange-

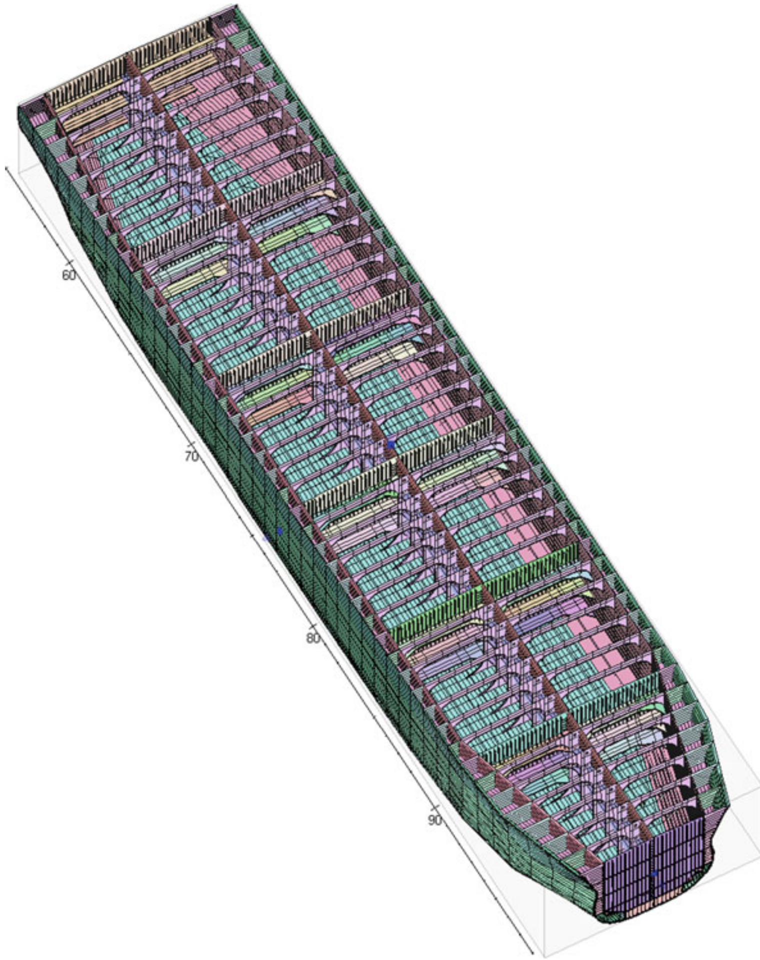

Fig. 2.11 Hull structure modelled within POSEIDON (main deck removed to show inner structure)

ment and load definitions. This was herein accomplished by generating the main structural design externally by GL's POSEIDON software. For the interface to this code, a template database was developed, which considers relevant to the steel structure free variables. This template database specifies the steel structure of the cargo tank area of an AFRAMAX tanker with 6×2 layout and a plate arrangement and stiffener distribution complying with a conventional design, Fig. 2.11:

- Vertically stiffened flat transverse bulkheads with transverse girders
- Longitudinally stiffened main deck, hopper plate, inner hull, inner bottom, stringer decks, longitudinal girders
- Longitudinal bulkhead stiffened with transverse girders
- Regularly positioned web and floor plates

- Main deck supporting transverse girders.

Using a *Python* interface to POSEIDON's database, the template model is being updated continuously according to the characteristics of each generated design. An ASCII file is provided by the FFW, which includes an adaptation of the hull form in POSEIDON's specific offset format, the actual tank compartmentation and the free variables for the inner structure, like the number of frames per cargo tank.

2.4.5 Analyses and Simulations

2.4.5.1 Structure and Strength

For the assessment of the structural design of generated design alternatives, the Common Structural Rules (CSR) for Double Hull Oil Tankers were applied with their different levels of assessment (see, IACS-CSR 2012, as amended in 2015). CSR actually start with the application of prescriptive rules based on beam theory which are followed by Finite Element Analyses (FEA) of primary and secondary members and then finish with detailed FEA for fatigue assessment of structural details in a hot spot approach.

Here, only the prescriptive part of the CSR was applied to determine the strength of the structure (and based on this, the weight of the steel structure). In this sense, the proposed integrated approach yields a "pre-dimensioned" tanker design that needs to be approved—and slightly adapted—in a subsequent step to comply fully with the CSR, while it may be in parallel optimised for minimum structural weight. Each design variant was measured in terms of the steel mass necessary to fulfil the strength requirements. The steel mass computation was performed by POSEIDON's automatic plate sizing capability at given cross sections of the vessel. Characteristic frame cross sections like the mainframe or transverse bulkheads, Fig. 2.12, were chosen to obtain the steel mass of the total cargo block area. Note that the varied structural design parameters referred only to the cargo block area, assuming the remaining parts of the ship (bow, stern and machinery room) remain fixed during optimisation.

2.4.5.2 Hydrodynamics

Since the Computational Fluid Dynamics (CFD) simulations are the most resource intensive of all analyses within the design task, response surface models (RSM) were utilised to capture resistance and propulsion characteristics for different speeds and drafts. In other words: rather than to include a very time-consuming full CFD simulation for each variant during the overall optimisation, the hydrodynamics was pre-computed and then replaced by suitable meta-models (so-called *surrogate* models).

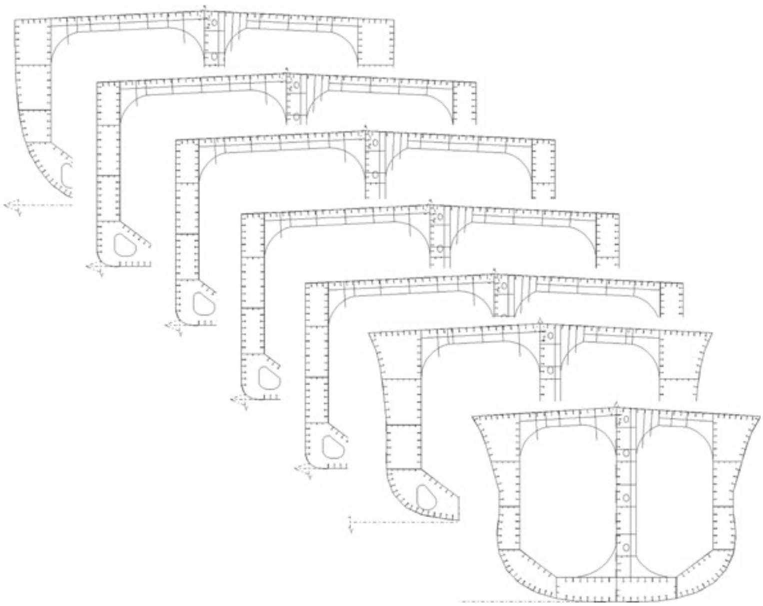

Fig. 2.12 Cross sections of a generated design

Table 2.2 Free variables and bounds for hydrodynamic RSM

Free variable	Lower bound	Lower bound
Length over all	242 m	250 m
Beam	42 m	44 m
Delta XCB	−0.90%	0.90%
Displacement volume	126,075 m^3	136,325 m^3

Four free design variables were chosen, namely length over all (LOA), maximum beam, a relative change in the position of the longitudinal centre of buoyancy (Delta XCB) and the displacement volume. As summarised in Table 2.2, these variables were allowed to vary within meaningful bounds that stemmed from general constraints (like relevant harbour facilities in the Gulf of Mexico), pure hydrodynamic considerations and estimates for expected total displacement.

Hydrodynamic performance was considered at design draft (13.7 m on even keel at rest), scantling draft (14.8 m on even keel) and ballast draft (6 m at FP and 8 m at AP) in parallel. The fully parametric hull model, Fig. 2.8, was utilised to vary the free variables globally.

Both potential flow and viscous computations were performed using the zonal approach offered within the flow solver SHIPFLOW. A sequence of computations was undertaken: a potential flow computation without free surface for the entire hull (XPAN), a subsequent thin boundary layer computation for the forebody (XBOUND) and finally a RANSE computation for the aftbody (CHAPMAN). The propeller was modelled as a force actuator disc, idealising an active propeller for all computations. All viscous computations were performed at full-scale Reynolds number with the model free to sink and trim. For each valid variant, the viscous flow computations provided the frictional and viscous pressure resistance, as well as the wake field in the propeller plane. Additional potential flow computations including nonlinear boundary conditions at the free surface were carried out to obtain the wave patterns, etc.

For the potential flow analysis, a body mesh with 1150 panels and a free surface mesh with 7175 panels were used. The volume mesh for viscous simulations featured 1.7 million cells with a longitudinal stretch towards smaller cells in the skeg region. In order to achieve convergence, 3000 iterations were done for the RANSE solutions of globally changed variants and also for the baseline of the succeeding fine-tuning. One of these computations including potential and viscous flow simulations took about 8 h on a quad core 4×3.0 GHz AMD workstation. Subsequent computations for only locally changed variants, as created during the hydrodynamic optimisation, were restarted from the baseline solution with some additional 800 iterations. The restarted computations then only took about 2.5 h each.

Three response surfaces were finally built, one for every loading condition, assuming quadratic speed-power relationships. The attainable speeds were determined for fixed power installed of 13,560 kW. This value corresponds to a MAN 6S60MC-C at around 100 rpm as a representative engine for AFRAMAX tankers. An engine output of 85% MCR and a sea margin of 10% were assumed. It should be noted that based on a conducted study on the added resistance and powering in waves, the above sea margin covers with 95% confidence all sea conditions in the specified area of operation (Caribbean Sea).

The response surfaces were produced employing a Kriging approach with anisotropic variograms (Harries 2010). The Kriging algorithm ensures that sample points are interpolated while oscillations of the RSM are avoided. Interpolation values are computed using a weighted sum of all samples on the basis of the variograms. Utilising the three response surfaces, it was possible to estimate the attainable speeds at ballast, design and scantling draft directly for a specified power installed, instead of performing an iterative CFD-based search. Each RSM analysis thus took about one minute per variant instead of one to two days of full CFD simulation.

2.4.5.3 Stability and Accidental Oil Outflow

Compliance with the regulatory requirements for stability and oil outflow [IMO-MEPC 2004b, Resolution MEPC.117(52)] was determined within NAPA on the basis of actual tank shapes and hull forms as provided by the FRIENDSHIP-Framework. The hull form is transferred to NAPA using a standard IGES file format representation. A set of parameters is taken as input to recreate the exact geometry of the inner hull and watertight subdivision. Suitable NAPA macros were developed, facilitating the calculation of the mean oil outflow index as well as the assessment of intact and damage stability requirements and the regulatory and operational trim and draft constraints in the various loading conditions.

Resolution MEPC.117(52) (IMO-MEPC 2004b) was taken as the regulatory basis for the evaluation of design variants. Regulations 18, 19, 23, 27 and 28 set the requirements for the segregated ballast tanks capacity, the double hull arrangement, accidental oil outflow and transverse stability in intact and damaged condition. For example, for crude oil tankers of 20,000 tons DWT, Regulation 18 calls for sufficient capacity of segregated ballast tanks (SBT), so that the ship may operate safely on ballast voyages without recourse to cargo tanks for water ballast. The capacity of SBT shall be at least such that, in any ballast condition at any part of the voyage, including the conditions consisting of lightweight plus segregated ballast only, the ship's drafts and trim can meet the following three constraints: moulded draft amidships $\geq 2.0 + 0.02$ L, trim by the stern ≤ 0.015 L and draft aft (T_{aft}) always yields full immersion of the propeller(s). Additional requirements come in via Regulation 19 for ballast tanks (or spaces other than tanks carrying oil), effectively protecting the cargo space with various minimum dimensions.

The accidental oil outflow performance of oil tankers of 5000 tons DWT and above, delivered on or after the 1 January 2010, is evaluated according to Regulation 23, based on the so-called non-dimensional oil outflow parameter or, shorter, oil outflow index (OOI). The upper limit of the mean oil outflow depends on the total volume of cargo oil tanks of the ship. In particular, for ships with a total volume of cargo oil tanks at 98% filling less than 200,000 m^3, as is the case for AFRAMAX tankers, an OOI value not exceeding 0.015 is required. In other words, statistically no more than 1.5% of the total volume of the oil tanks shall be lost.

The oil outflow is calculated independently for side and bottom damages and then combined in non-dimensional form. The calculations of the mean outflows for side and bottom damage are based on a probabilistic approach and take probability distributions for side and bottom damage cases as input. Finally, Regulation 27 sets the intact stability criteria when at sea in the same form that is applicable to most types of ships. In addition, a minimum meta-centric height (GM) of 0.15 m after correction for free surface effects is required at port to ensure minimum stability while loading or unloading. The maximum damage extent for side and bottom damage, along with the corresponding stability requirements in damaged condition is defined in Regulation 28. All these regulations were accounted for in a batch mode execution of NAPA, making them part of the simulations within the optimisation (see Harries et al. 2011).

2.5 Discussion of Results

2.5.1 Exploration

In the course of the herein implemented optimisation procedure, approximately 2500 variants were generated and assessed. To start with, a SOBOL Design-of-Experiment

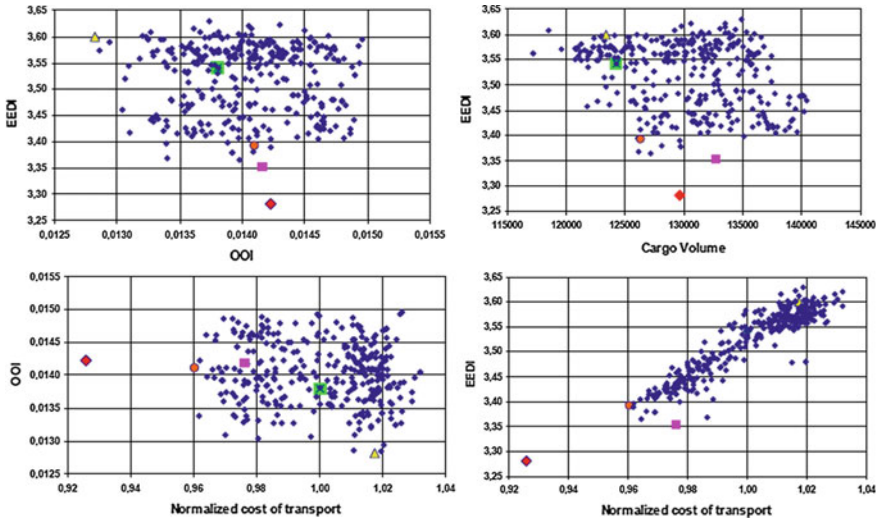

Fig. 2.13 Selected scatter plots of vessel key particulars and design targets

(DoE) exploration of the global design space was performed, yielding a database with all relevant simulation outputs and the key measures of merit, namely herein Required Freight rate (RFR), oil outflow index (OOI) and Energy Efficiency Design Index (EEDI). A conventional AFRAMAX tanker served as a reference (baseline) for comparison and normalisation, see Table 2.3. Plots of primary and secondary design parameters (e.g., length between perpendiculars, beam, draft, double hull width and height) vs. design targets (e.g., speeds at different drafts, EEDI, cargo capacity, oil outflow index) were used to visually identify design trends and to refine the design focus for the next round of DoE. The final DoE delivered about 400 design variants and design targets (cargo volume, oil outflow index, EEDI and cost of transport) presented again in scatter plots to identify the optimum design variants, see Fig. 2.13 which shows selected scatter plots including the Pareto fronts.

The final DoE was used to identify the most promising design variants for the next level of optimisation which was performed by a *Tangent Search* optimisation method applied to fine-tune the design with a particular focus on hydrodynamic improvement to increase attained ship speed. Cost of transport—the ratio of annual total costs to annual cargo transported—and Required Freight Rate (RFR), which also accounts for the annual income, were used to guide the optimisation in the final stages, see Fig. 2.14. In this Figure, the RFR has been normalised by the respective value of the reference design. The reference design is an existing AFRAMAX oil tanker design, developed and built *before the CSR* entered into force, and it is considered to be a very good design in terms of cargo capacity and oil outflow index. The *Pareto front* of optimum designs is clearly visible and the best designs in terms of OOI, EEDI and cost of transport are labelled explicitly. It can be seen that the best design in terms of the EEDI is a large DWT design and this is because the EEDI favours larger

Table 2.3 Main particulars of reference and favoured design

Parameter	Reference design	Favoured design
Length over all (m)	250	250
Beam (m)	44	44
Depth (m)	21.0	21.5
Design draft (m)	13.7	13.7
Block coefficient	0.83	0.85
Inner bottom height COT 2–6 (S+P) (m)	2.50	2.10
Inner bottom height COT 1 (S+P) (m)	2.50	2.75
Side shell width (m)	2.50	2.65
Angle of hopper plate (deg)	50	37
Width of hopper plate (m)	5.25	5.20
Frame spacing (m)	3.780	4.400
Shift of bulkheads (m)	0	0
DWT (tons)	111,436	114,923
Maximum cargo volume ($m^{3)}$	124,230	129,644
OOI/max. permissible	0.0138/0.0150	0.0142/0.0150
Speed at design draft (kn)	15.1	15.6
Speed at ballast draft (kn)	15.9	16.8
EEDI/max permissible (g) CO_2/(ton sm)	3.541/4.197[a]	3.281/4.135[b]

[a] Acc. to IMO Res. MEPC.203 (62), Reg. 20/21, this design is complying with Phase 1 requirements for newbuildings and equivalents (January 1, 2015–December 31, 2019), while it is missing Phase 2 (January 1, 2020–December 31, 2024) and Phase 3 (after January 1, 2025) requirements; the IMO-MEPC approved reduction rates for the permissible EEDI are 10% (Phase 1), 20% (Phase 2) and 30% (Phase 3), compared to the EEDI reference line requirements (Phase 0 was for Jan. 1, 2013 to Dec. 31, 2014)
[b] Missing Phase 3 requirements

vessels. On the other hand, the best design in terms of oil outflow index is a small DWT design with higher cost of transport and lower RFR, which is due to the larger double hull clearances for this design variant.

2.5.2 *Refinements*

Since a good number of generated designs exhibit nearly the same RFR, see Fig. 2.14, the variant with the best OOI among them was selected for further refinements. A *local* hydrodynamic optimisation, utilising a deterministic search strategy, was under-

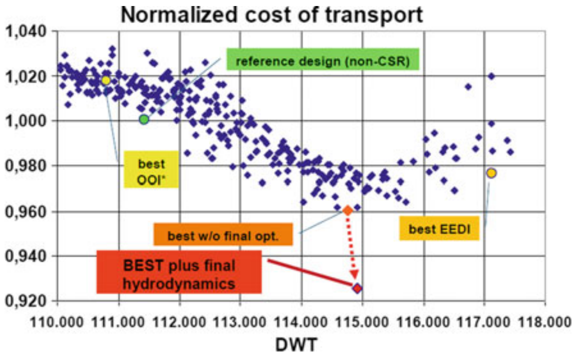

Fig. 2.14 Selected scatter plots of vessel key particulars and design targets

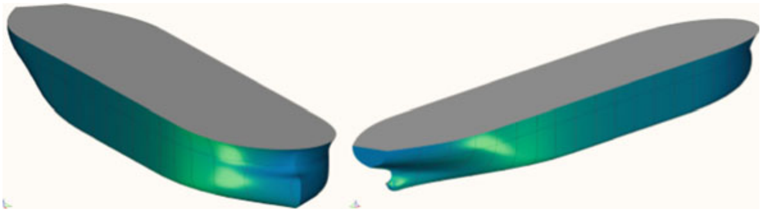

Fig. 2.15 Hull form of favoured design

taken for the aftbody, focusing on the quality of the wake field as an objective. The aftbody was allowed to change such that the impact on the cargo tanks previously established in the global optimisation was negligible. The fine-tuning of the hydrodynamics yielded a further increase in the achievable speed, such that the tanker could be expected to attain 15.6 kn at design draft and 16.8 kn at ballast draft with a level of confidence of $\pm 1.3\%$.[5] The main characteristics of this favoured design are summarised in Table 2.3 and compared to the reference design. The associated hull form is presented in Fig. 2.15. The lines stem from the associated parametric model and were realised within the FFW without further interactive work, i.e. they are a direct result from the optimisations. The EEDI value of the BEST+ optimal design, as compared to IHS reference ship data, is shown in Fig. 2.16.

2.5.3 Sensitivities

Finally, in order to investigate the robustness of the established design with regard to small modifications of the ensuing design parameters, a separate Design of

[5] Accounting for the added resistance in common seaways, as specified by relevant wave spectrum generated on the basis of statistics in the area of operation (see Sames et al. 2011a, b).

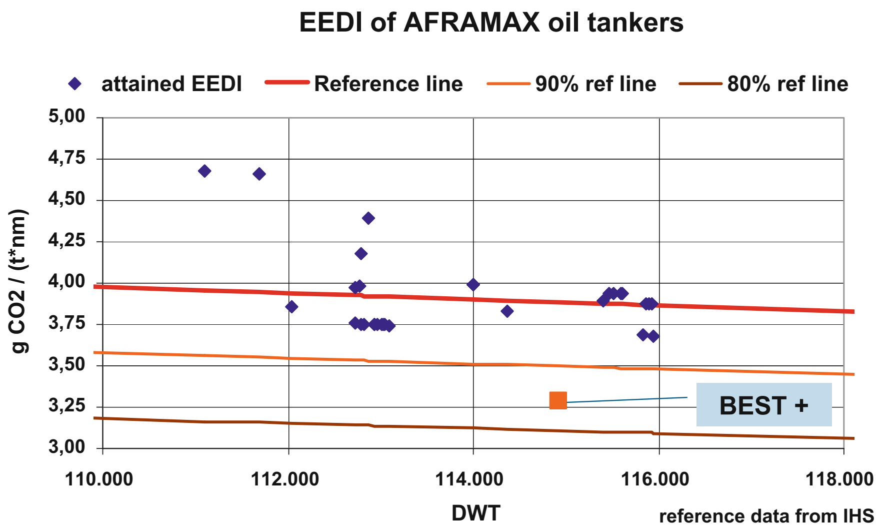

Fig. 2.16 EEDI of optimum design compared to similar designs

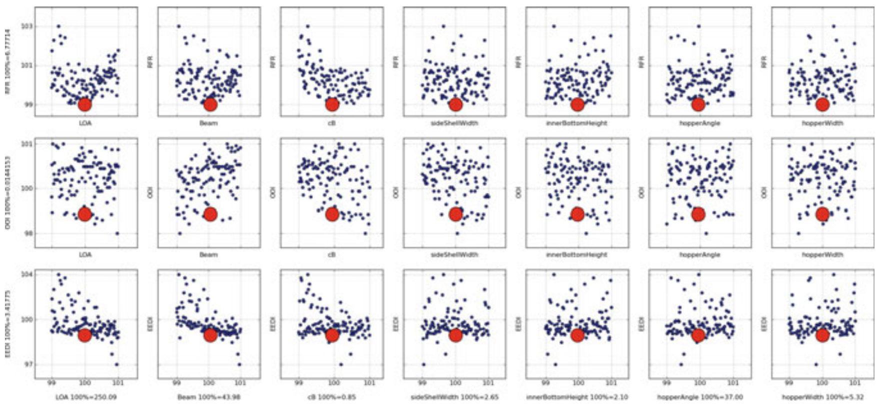

Fig. 2.17 Sensitivity of best RFR design (marked by red bullets, bandwidth of abscissas ±1%)

Experiments-DoE (sensitivity study) was performed. About 150 additional variants were generated, whose free variables were changed within ±1% of the corresponding parameters of the favoured design. Figure 2.17 presents a selection of sensitivities, with changes in RFR displayed in the upper row and changes in OOI and EEDI in the middle and lower row, respectively. The favoured design can be regarded as a (local) optimum for RFR while in its vicinity only few variants perform slightly better with regard to OOI and EEDI. In general, the sensitivity of parameters is quite limited. This indicates that the favoured design does not represent an extreme breed of parameters with respect to just one criterion.

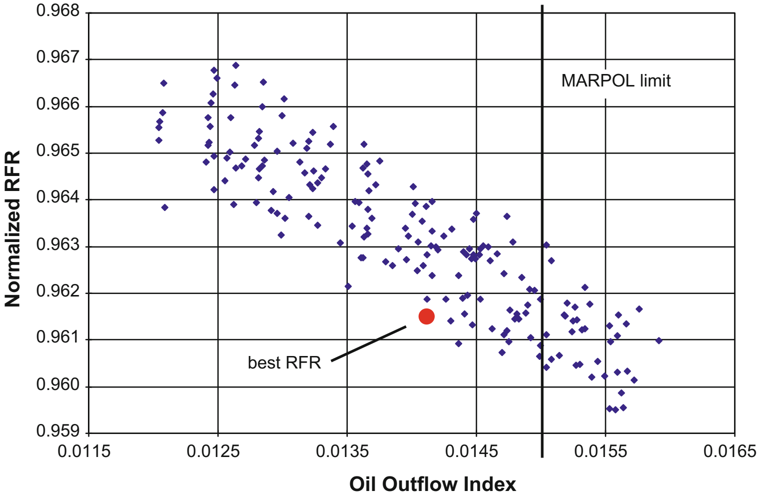

Fig. 2.18 Economics versus environmental safety in AFRAMAX tanker design (Project BEST+, Sames et al. 2011a, b)

A stochastic approach to life-cycle ship design, in which the uncertainty of certain major design and operational parameters, like ship's service speed, cost of fuel and even the uncertainty of weather conditions is considered, was introduced by Plessas and Papanikolaou (2015) and is being further elaborated in Plessas et al. (2018).

2.5.4 The RFR-OOI Sensitivity Study

The relationship between RFR and OOI was further investigated utilising the integrated CAE FFW approach. The tank geometry was systematically varied within specified bounds for the inner bottom height, the side shell width and the hopper plate geometry, while freezing all other variables at the values of the best RFR design. Figure 2.18 enables a view on the compromise between economy (ordinate) and safety (abscissa). The smaller the accidental oil outflow the higher the cost of transport and RFR. This is not unexpected but the diagram quantifies how much an operator needs to pay for a safety margin beyond the regulatory limit set by MARPOL. Relaxing the normalised RFR from 0.961 to 0.966, i.e. taking just 3.4% gains instead of 3.9% in comparison with the reference tanker, leads to a further reduction of OOI from 0.015 to 0.012. In Fig. 2.18, the design called best RFR is highlighted. It is evident that this design is a good solution for both economic performance and environmental safety. Figure 2.19 offers a synthesised-artistic impression of the finally selected ship.

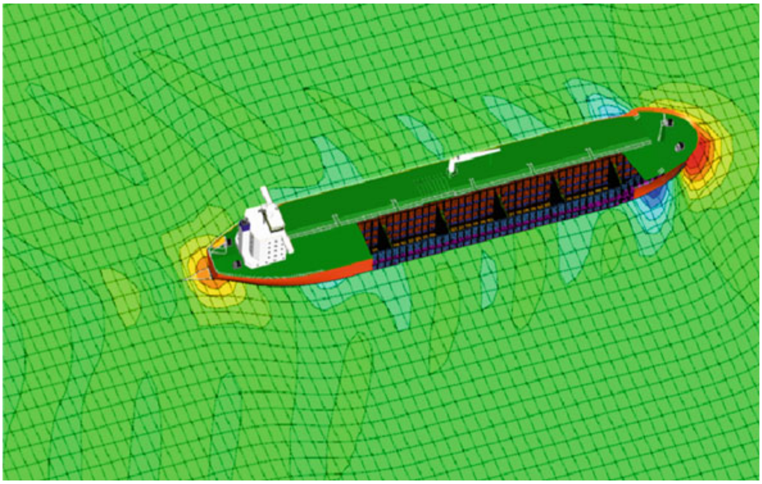

Fig. 2.19 CFD computed wave field plus cutaway showing the inner structure of proposed 6 × 2 AFRAMAX design (Project BEST+, Sames et al. 2011a, b)

2.6 Conclusions

The present chapter provided a brief introduction to the holistic approach to ship design optimisation and its historical development. It defined the generic ship design optimisation problem and demonstrated its solution by use of Genetic Algorithms and the associated integrated ship design optimisation procedure and parametric modelling. The introduced approach covers in a *holistic* way a multitude of aspects of early ship design, namely the selection of main dimensions, development of hull form, assessment of hydrodynamics and powering; design of structures and assessment of strength; weight estimates; assessment of ship safety, including intact and damage stability; assessment of the environmental impact, in terms of likely oil pollution and toxic gas emissions of the engines; assessment of economics; and of all relevant regulatory requirements. An example application was presented for an AFRAMAX tanker with the aim of realising better environmental safety (lower oil outflow index), efficiency (lower Energy Efficiency Design Index) and economics (lower Required Freight Rate). Formal explorations and exploitations were combined to investigate the design space and, subsequently, advance competing design proposals into certain directions. About 2500 design variants were realised by use of developed computerised parametric models, each of them having its individual hull form (outer shell), tank compartmentation and an inner steel structural design.

The implemented software system brings together sophisticated software tools for the analysis and simulation of ship design features. Challenging issues, like time-consuming CFD hydrodynamic simulations, can be implemented by systematic numerical series and suitable meta-surrogate models of response surfaces (RSM). This not only speeds up the time needed for investigations by several orders of magnitude, but it also reduces the complexity associated with CFD analyses and, hence, allows to already utilise them early in the process when gains are potentially the highest.

The presented example showed that once a (quasi-randomly created) database of variants is available it is quick and easy to search for the preferred combination of measures of merit. One may then choose a more conservative design, being a balanced all-rounder, or deliberately decide to favour a more extreme solution, featuring excellent performance in one measure of merit. Additional investigations can be done easily once the present CAE environment is fully established, for instance, to gain an appreciation of the relationship between costs and safety or to check the robustness of the favoured design.

Setting up an integrated approach still requires quite some effort at this point with respect to the required expertise and time. Nevertheless, the necessary software platform is now available in the form of CAESES, and the presented project proved feasibility that can be now utilised in the HOLISHIP project. Major prerequisites are parametric models for various ship types, which allow automation of design procedures. This has been in recent time dealt with by various research teams and the prospects on the way ahead are encouraging. It proves that significant design improvements can be realised in short lead time even for moderate deviations from currently established design practice, and all this is a *step change* in the traditional design process in naval architecture.

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Chapter 3
On the History of Ship Design for the Life Cycle

Horst Nowacki

Contents

Abstract Maritime transport in its history after two world wars has developed an increasing significance in securing our welfare and prosperity in a global world. At the same time, the world has become aware of growing risks involved in marine transport technology by a number of shipping disasters, catastrophic losses and damages to the maritime environment. The maritime community has responded to these challenges by intensified research and developments. New ship types, new design methodologies and tightened safety standards and regulations have been introduced and are in further development. This chapter deals with the driving forces in this new situation and describes new achievements and current trends in the methodologies of ship design for safer, cleaner and more economical ships.

Keywords Lifecycle ship modelling · Holistic ship design
Multiobjective optimization · Genetic algorithms

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3.1 Introduction

Design is a decision process. Design aims at finding a solution within a set of possible alternatives. This process may be informal by plain trial and error. Modern rational design, however, is usually based on a formalized model of the decision process. Such models are generally built on the basis of modern decision theory (Chernoff and Moses 1986).

Design can be modelled as a formal decision process in mathematical and hence computational terms if a specific design paradigm is adopted. A rather generic paradigm models the design process by means of the following elements (Fig. 3.1).

D = design variables, free decision variables.

P = parameters, state variables of the design, usually a function of the free variables, but not under the designer's control.

M = M (D, P) = measure of merit function (also objective function), determined by the designer's preference. A design may be stated to have several objectives.

C = C (D, P) = constraint functions. The state variables of the design are usually subject to constraints (of equality or inequality type), i.e. functional, technical, physical, regulatory, safety, environmental, aesthetic and other side conditions. They serve to define the permissible range of variation in the design, thus to recognize the feasible space.

The criteria **M** and **C** may contain probabilistic elements in their definitions so that the whole model may have distributions of probabilistic results, e.g. different values for different lifecycle stages. These influences of uncertainties will be taken into account statistically according to their frequency of occurrence.

The elements **R** and **S** contain input information to the design process, while the variables of design assessment and of ship properties are outputs.

R contains design requirements by the owner and by authorities.

S denotes the given bounds on variable search ranges and the like. It also includes databases for fuel and material costs and other information about the market. The outputs denote all information that is needed to evaluate the ship by the chosen criteria, but in addition they contain many other design features which will help to evaluate ship performance as a by-product of assessing many systems in the ship.

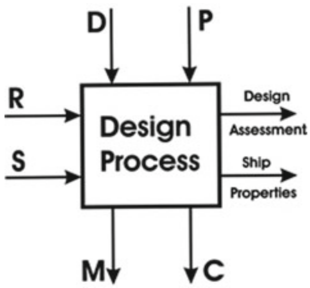

Fig. 3.1 Elements of the design process (Nowacki 2009)

In this chapter, the historical development of design decision modelling will be reviewed from its early beginnings in manual design practice, but mainly during the computer era, when elaborate lifecycle assessment became feasible in early design stages. The story will demonstrate how in the course of time more and more relevant elements of the design process of ships were included in design, production and operational decisions under the aspects of the whole life cycle of ships.

3.2 Ship Design Decision Models

3.2.1 Ship Design as Optimization

Figure 3.1 describes the elements of a design process and at the same time of Systems Analysis. Systems Analysis and ship design are special cases of a decision process.

Systems Analysis deals with the task of finding a *best* solution within a set of feasible alternative systems under given constraints. The systems may be *products* at a given time or time-dependent *processes*. *The existence of a measure of merit for the system calls for and permits optimization*.

Ship Design, i.e. the design of ship characteristics, ship production processes and ship operations, in fact, of all lifecycle phases of ships, is a special case of Systems Analysis. Accordingly, the design task is also modelled as an optimization problem with constraints. This was recognized very early, e.g. in 1968 by Woodward et al. (1968).

The common denominator of these types of modelling applications is essentially the following problem statement:

> Minimize (or maximize) a measure of merit function $\mathbf{M}$ $\mathbf{(D, P)}$ of a system subject to constraints $\mathbf{C}$ $\mathbf{(D, P)}$, i.e. equalities $\mathbf{h} = \mathbf{h}\ \mathbf{(D, P)} = \mathbf{0}$ and inequalities $\mathbf{g} = \mathbf{g}\ \mathbf{(D, P)} \geq \mathbf{0}$.

If at least one constraint function and/or the measure of merit is a nonlinear function of the free design variables, which is common in ship design, then this problem type is known as "*nonlinear programming*" (*NLP*) (Fiacco and McCormick 1968). Thus, the integrated overall ship design problem and a great variety of ship design subproblems can be treated as nonlinear optimization problems with constraints (NLP).

3.2.2 The Stagewise Structure of the Ship Design Process

The development of a ship product model, i.e. the description of the entire ship with all its features and systems, goes through many decision stages as shown for ship product design in Fig. 3.2.

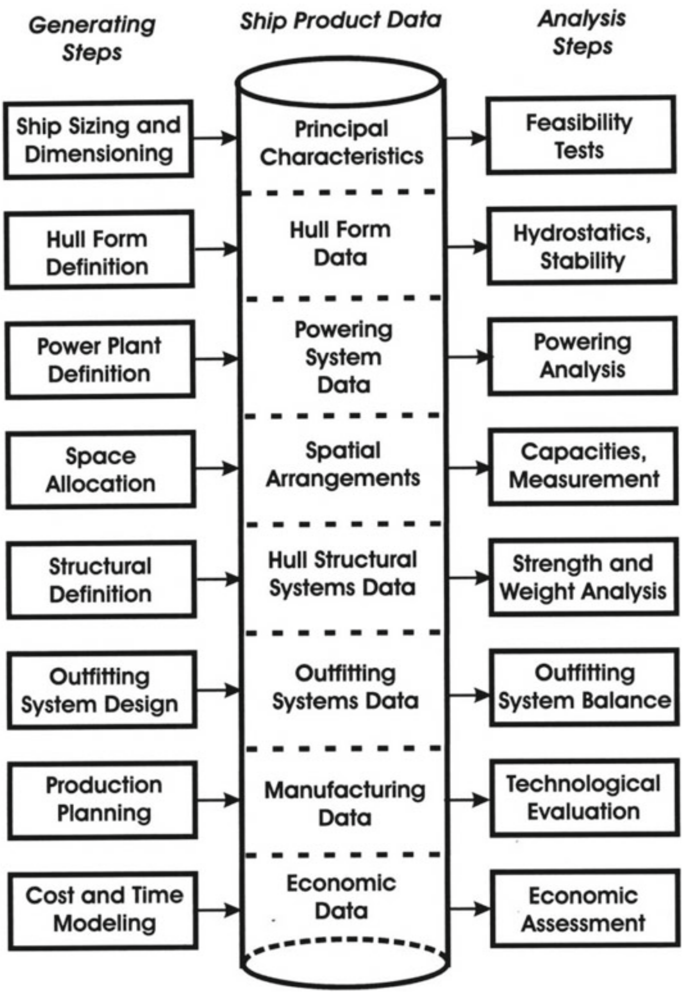

Fig. 3.2 Stages of the ship product modelling process (Nowacki 2009)

Ship design includes the following stages:

- Principal characteristics
- Hull form
- Speed and powering
- Spatial arrangements
- Structural design (strength and weight)
- Hydrostatics and stability
- Outfitting
- Damage stability and control

- Ship safety
- Ship environmental impact
- Cost and time

Each part of the product model is derived by a *synthesis* step from its requirements and constraints, and is then checked by an *analysis* step for compliance with requirements and constraints. Feasible and infeasible solutions are reported and corrected if necessary. This is an iterative process because the results from certain stages have effects on other stages. The sequence of steps need not be prescribed, but is flexible and problem dependent. In the end, when the process has converged and all constraints are met, one achieves at least a *stagewise* optimal and permissible result. To optimize all stages together in the end, one must apply a global measure of merit to the set of stages. The global optimum does not have to coincide with the sum of the stage optima.

While stagewise optimization was common practice in the past, current trends are towards integrated optimization of all relevant stages.

3.2.3 The Generic Ship Design Model

In the context of ship design, the elements of the optimization model are as follows (Nowacki 2009).

D = design variables, free variables of the design: Hull form principal dimensions (L, L/B, B/T, L/D, C_B), speed when free, free spatial arrangements, structural and outfitting variables.

P = parameters, dependent variables, i.e. state variables not under the designer's control: owner's functional requirements, available water depth and width, speed when limited, weather and seaway conditions, port and cargo-handling conditions, environmental conditions, safety conditions.

M = M (D, P) = measure of merit, measure of the quality of the design, one or several indicators, based on the interests of the stakeholders (builder, operator, safety and environmental authority, the public).

C = C (D, P) = constraints (permissibility conditions), depending on ship type and functions, applied to size and speed, safety and environmental hazards, upper and lower bounds on design and state variables.

The NLP format accommodates in practice any combination or subset of these modelling elements. Depending on the aims of the design optimization study in practice, most design investigations have dealt only with special cases of this generic ship design model depending on the purpose of the study and the interests of the stakeholders. Examples will be discussed in Sect. 3.3.

3.3 Specific Cases of Ship Design Optimization Studies

3.3.1 Generations of Ship Design Models

The history of ship design optimization has developed continuously and rather rapidly from simple beginnings to more and more elaborate formulations. This was largely driven by advances in modelling ship safety and environmental regulations. Table 3.1 shows a succession of design methodologies in computer-aided ship design studies.

Engineering design optimization based on physical principles and mathematical models has had a fairly long history and has involved some famous scientists. In the context of fluid dynamics and later ship design, the following may be claimed to be precursors of hydrodynamic and structural optimization, applicable or applied to ships: Newton (1726), Bouguer (1746), Euler (1749), Chapman (1775), J. S. Russell and I. Brunel (the builder and designer of the famous *SS Great Eastern* in 1858, respectively), Froude (1868, see, Duckworth 1955), Michell (1898), Weinblum (1932), Wigley (1935), Taylor (1943). However, these early precursors of ship design optimization confined their activities to special features of ship design, such as powering requirements or structural weights. The effort of manually computing ship properties at the early design stage was simply too prohibitive for a comprehensive layout and analysis of the whole design, and essential data were missing. A serious attempt at coping with the full complexity of early stage ship design, although it might have contributed many benefits, was not made feasible before the advent of computers in the design office and the spreading of Systems Analysis techniques for design. Lifecycle evaluations of engineering products and operations were foremost requirements in engineering design and in ship design.

I would date the modest beginnings of such design applications around 1960. The extended scope of ship design to the full life cycle was an important added value to the design process. An economic analysis justifying the investment in a ship cannot be performed without looking at the cost and benefits of the vessel for the whole life cycle from early and detailed design through the operating phase to the final disposal of the vessel.

Such a view has to take into account the vested interests of all parties involved in the ship's lifetime, i.e. the builder's and operator's goals and criteria, as well as those of the suppliers, classification societies, legal authorities, insurance companies and the general public as customers for transportation of passengers and cargo. There is also a general public interest in safe and environmentally clean ships. All of this now belongs to a lifecycle evaluation of a new design, which is continually widening the scope of modern design studies. The results of course are not unique, but depend on the viewpoints taken by the parties.

During the decades since 1960, the scope and depth of the lifecycle evaluation of ship design have grown systematically so that one can recognize four distinct generations of lifecycle ship design models (Table 3.1).

Table 3.1 Generations of ship design optimization models

Model type	Ship type	Design variables	No. of functions	No. of constraints	Optim. approach	Measure of merit	References	Years
Synthesis model	Tanker, bulker, general cargo ships	Principal dimensions, size, speed	1	Few	NPL: penalty Fct, gradient methods, SLP, direct search	LCC, RFR, NPV, CRF	Murphy et al. (1965), Mandel and Leopold (1966), Kuniyasu (1968), Nowacki et al. (1970), Söding and Poulsen (1974), Nowacki and Lessenich (1976), Nowacki et al. (1990)	1965 until ca.1990
Multiobjective model	Tanker and any other ship types	Principal dimensions, size, speed	Multiple, some probabilistic	Many	NPL: Pareto optimization, utility Fcts., graphical visualization	Economics, safety, environment, etc.	Papanikolaou et al. (2011), Papanikolaou et al. (2010b)	2010 and forward
Holistic design model	Merchant and naval ships	Geometry, safety environmental impact, etc.	Multiple, some probabilistic	Many	NPL: Pareto optimization, utility Fcts., graphical visualization	Economics, safety, naval criteria, environment, etc.	Papanikolaou (2011a), Papanikolaou (2010a), Boulougouris et al. (2011), Köpke et al. (2014)	2010 and forward
Risk-based design model	Cruise ships, RoPax, tankers, bulkers, etc.	Geometry, safety environmental impact, etc.	Multiple, some probabilistic	Many	NPL: Pareto optimization, utility Fcts., graphical visualization	Economics, safety, naval criteria, environment, etc.	Boulougouris et al. (2004), Vassalos (2009), Papanikolaou (2009a, 2009b)	2004 and forward

Where *NLP* nonlinear programming, *NPV* net present value, *LCC* lifecycle cost, *RFR* required freight rate, *CRF* capital recovery factor, *SLP* sequential linear programming

Table 3.2 Synthesis models

Authors	Year	Ship type	Measure of merit	Approach	References
Murphy, Sabat and Taylor	1965	General cargo ship	Lifecycle cost	Systematic variation, interpolation	Murphy et al. (1965)
Mandel and Leopold	1966	Tanker and general cargo ship	Lifecycle cost, NPV	Exponential random search, unconstrained	Mandel and Leopold (1966)
Kuniyasu	1968	Tanker, bulk carrier	Capital recovery factor	Parametric studies	Kuniyasu (1968)
Nowacki, Brusis and Swift	1970	Tanker	RFR	NLP: penalty Fcts. and direct search	Nowacki et al. (1970)
Söding and Poulsen	1974	Bulk carrier	Average annual cost	NPL with slack variables	Söding and Poulsen (1974)
Nowacki and Lessenich	1976	Tanker, bulk carrier, general cargo ship	RFR	NLP: penalty Fcts., feasible directions	Nowacki and Lessenich (1976)
Nowacki, Papanikolaou, Holbach and Zaraphonitis	1990	SWATH ferry	RFR, NPV	NLP: penalty Fcts., feasible directions	Nowacki et al. (1990)

where *RFR*—required freight rate = (mean annual operating cost plus capital cost discounted to first investment date)/(annual transport capacity) in \$/ton, *NPV*—net present value = all in and out cash flows, discounted back with current and estimated future interest rates to the investment date. NPV is more speculative depending on future income and loss estimates, but may account for future profits and losses more directly than RFR

3.3.2 Synthesis Models

Synthesis models (see Table 3.2), the first generation of design models, assume a single measure of merit, usually a measure of the economy of the design (lifecycle cost, required freight rate, net present value, cost-benefit ratios). All other design requirements are treated as constraints: owner's requirements, legal and statutory requirements and classification rules. In particular all safety requirements (stability, freeboard, fire, collision and grounding, etc.) are represented as inequalities denoting the borders between feasible and infeasible design spaces.

The goal of the design process, then, is finding the economically best design, which does not violate any constraint. The result is usually unique unless some designs have identical measures of merit.

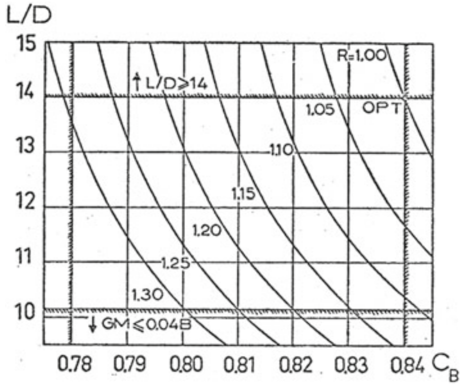

Fig. 3.3 Tanker dimensionless required freight rate *R* as a function of *L*/*D* and C_B for optimum values of *T*, *B*/*T*, *L*/*B*, dwt and speed (Nowacki et al. 1970)

As an application example, let us look at an early case study, a VLCC or ULCC tanker of 1970 vintage, designed by Nowacki et al. (1970). The ship is designed for crude oil transport from the Persian Gulf around the Cape of Good Hope to Rotterdam for a draft limit in the access to the port of Rotterdam of $T_{\text{MAX}} \leq 20.0$ m. There are further constraints imposed on $L/D_{\text{MAX}} \leq 14.0$ for strength and stiffness purposes, $C_B \leq 0.84$ for hydrodynamic reasons and on GM ≥ 0.4 B for intact stability. The available cargo and the permissible speed in full load were considered unlimited as was common in crude oil trades. No further constraints were imposed for other risks such as damage stability, environmental damages, fire, collision and grounding. This was before safety and environmental rules were later much stiffened. This situation tends to yield the ship of the greatest permissible size, determined by the draft constraint and the limit on C_B, while the economic speed is determined by the fuel price.

The optimization problem is of nonlinear programming type. The solution is governed by two or more constraints, here by those on T_{MAX}, GM, C_B and L/D_{MAX}. Figure 3.3 shows a planar intersection through the multidimensional design space in the plane of the optimum. The optimum in this synthesis model is unique. The constraints are linear functions of the design variables. Here the single optimum is located in a corner of the feasible space.

Synthesis models were relatively successful whenever a single purpose was served by the ship and a few constraints were dominant (Table 3.2). It is remarkable that an economic orientation for the measure of merit for the whole life cycle (lifecycle cost) was present in the earliest optimization studies of 1965 (and before) although the details became more refined later. However, the number of constraints grew with the increasing complexity of the design applications so that such requirements were expressed by further constraints and became equivalent and independent objectives of the design.

3.3.3 Multiobjective Models

Ships have usually more than a single purpose in their lifetime. This is the rule and not an exception. Ship design must account for all of the potential purposes that may occur in the ship's lifetime. The various roles in the life of the ship must be made explicit to the designer, usually in the building contract and in all legal rules and regulations that are pertinent.

There are many different reasons why multiple objectives may occur. It is the designer's responsibility to make sure to respond to all of them.

(1) ***Multiple tasks***

A ship may be assigned to perform varying tasks, either during a single voyage from leg to leg or during successive voyages in varying trade scenarios. Ore/Bulk/Oil carriers (OBOs) are a typical example.

(2) ***Multiple parties***

A ship design project involves several distinct stakeholder parties who have different objectives: the designer, the builder, the owner/operator, the user/customer, the general public, the disposal agent, etc. Many other parties and institutions also play a role: classification societies, coast guard, legal authorities, insurance companies, banks, port authorities, maritime equipment vendors, subcontractors, etc. These parties have conflicting interests which come to bear during the life of the ship. Design decisions usually require compromises between conflicting interests. But the conflicts must be pronounced before they can be resolved.

(3) ***Basic interests***

In ship design, at least three basic interests exist that will always be part of the design task:

Economic efficiency (in monetary units)
Safety (probability and magnitude of risk)
Environmental impact (probability and value of environmental damage)

These three objectives use different units to measure their magnitude. Thus, they cannot be integrated into a single criterion by simple conversion and addition. This is why multiobjective models are frequently a necessity.

(4) ***Measures of magnitude***

In comparisons of ship designs, in contract negotiations and in optimization studies, one needs standardized measures of magnitude that all parties understand. In international legislation, IMO has taken a leading role in defining such standards. The following are some of the most dominant criteria used:

For economic effectiveness

RFR = Required Freight Rate = Average Annual Transport Cost/Annual Transport Tonnage of Cargo ($/ton)

NPV = Net Present Value of the investment = sum of all in and out cash flows, discounted back with current and future interest rates to the investment date ($)

EEDI = Energy Efficiency Design Index = a measure of CO_2 emission per unit of transport in [gr CO_2/ton mile].

For safety

Probability of compliance with SOLAS safety rules: compliant or not.

For environmental protection

OOI = Oil Outflow Index = a MARPOL probabilistic estimate of the accidental oil outflow performance of a vessel, probability of oil spill and/or

EEDI = Energy Efficiency Design Index = a MARPOL measure of CO_2 emission of per unit of transport in [gr CO_2/(ton mile)].

(5) ***History***

Economy and safety have always played a significant role in ship design. The technical maturity in ship technology has grown in centuries and has found its documentation in international rules and regulations such as intact and damage stability rules, load line regulations, life-saving equipment rules and rules for the protection of the marine environment. The passing of new rules was slow, also due to wartime delays of two world wars. So the Titanic disaster of 1913 resulted in new international rules concerning flooding hazards not before SOLAS 1948.

The significant growth of ocean oil transport after World War II and sad accidents with tankers causing dramatic oil pollution in the ocean and on shores resulted in growing concern over the threat of oil pollution in the maritime environment. This concern was addressed under the auspices of IMO at the MARPOL 73/78 conventions, which went into force in 1983. To limit the potential oil outflow in the event of tanker damages by collision or grounding, the MARPOL regulations require from all new tankers of more than 20,000 tons deadweight the arrangement of segregated ballast tanks (clean tanks) in protective locations in order to shield the cargo tanks. This has led to new compartment configurations in "double hull" tankers with clean ballast tanks along the sides and in the double bottom. Such arrangements also result in more empty spaces, which add to the reserve buoyancy, but also to effectively not exploited ship spaces.

How this reserve can be best used has been the subject of everlasting discussions and optimization studies. The "double hull" concept as a "safety belt" against not too deep collision and grounding damages has also been adopted in RoPax ship design and was a consequence of the SOLAS 90 (introduced in the late 80s) deterministic damage stability requirements for passenger ships. However, in less than two decades later, SOLAS 90 was replaced by SOLAS 2009, which is a probabilistic damage stability regulatory framework, in which the extent of collision damages is not confined to a deterministic range (20% of ship's beam) and this led to a new shift in the design practice, with most RoPax ships today being designed and built as single-hull and double-bottom ships. Nevertheless, the survivability of passenger ships actually suggests the arrangement of a double skin as an elegant and safe solution and this maybe imperative for the survivability of ultra-large cruise liners in case of shallow-wetted shell damages.

(6) ***Solutions***

Multiobjective design problems require their own solution procedure to obtain concrete solutions despite the non-unique problem statement. In principle, two approaches are often chosen:

- The utility function approach
- The visualization of design solution spaces with identification of Pareto-optimal boundaries of the feasible design spaces

Often, these two methods are combined.

The utility function approach

In this multiobjective case, let M_1, M_2, M_3 be three distinct objectives, then a combined objective function (utility function) will be:

$$M_{\text{System}} = f_1 M_1 + f_2 M_2 + f_3 M_3 \tag{3.1}$$

where f_1, f_2, f_3 are arbitrary, humanly chosen weighting factors, which will bring the measures M_1, M_2, M_3, which are usually of different units, combined into a joint measure in consistent units. For more than three objectives, likewise.

This has the added advantage of offering the choice of looking at each of the objective measures M_1, M_2, M_3 separately, to study the trade-offs by looking at the relative weighting of the measures and in this way to be able to control the relative influences of the measures transparently. This enables open discussions among the stakeholder parties.

The measures for each influence can be modelled as desired and suitable. A frequent choice in recent studies is:

M_1 = measure of ship economic effectiveness = NPV or RFR, where:
NPV = Net Present Value of the investment P (or NPVI = NPV/P),
RFR = Required Freight Rate = Average Annual Transport Cost/Annual Transported Tonnage of Cargo,
M_2 = EEDI = Energy Efficiency Design Index (an IMO Index). EEDI = measure of CO_2 emission per unit of transport work in [gr CO_2/(ton mile)],
M_3 = OOI = Oil Outflow Index = probabilistic calculation of the accidental oil outflow performance of a vessel (an IMO Index).

The weighting factors may serve to avoid an overemphasis.

The visualisation of design solution spaces with identification of Pareto optimal boundaries of the feasible design spaces

After optimizing the initial candidate set and eliminating all infeasible designs and retaining in the end the most promising feasible designs only, one plots the ship

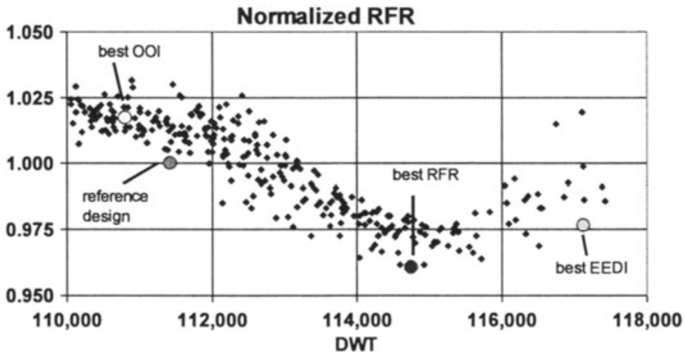

Fig. 3.4 Scatter chart for tanker design (Papanikolaou et al. 2011) showing the interdependence of RFR and DWT with references to best RFR, EEDI and OOI designs

Table 3.3 Multiobjective models

Authors	Year	Ship type	Measure of merit	Approach	References
Papanikolaou, Harries, Wilken, Zaraphonitis	2010	Aframax Tanker	RFR, EEDI, OOI, speed	Multiobjective optimization, POSEIDON and IMO rules	Papanikolaou et al. (2011)
Papanikolaou, Zaraphonitis, Skoupas, Boulougouris	2010	RoPax ferry	Geometry, stability, seaway, NPV	GA: mixed continuous and discrete design variables, TRIBON structural design	Papanikolaou et al. (2010b)

criteria values against two of the merit criteria, using a third one as a parameter. See Fig. 3.4 as an example. One can then construct an envelope curve or surface so that only the feasible designs are on one side of the envelope. See Fig. 3.5 for an example. Designs that lie exactly on the envelope are called *Pareto-optimal designs*; they are the best designs for at least one of the criteria. One can similarly find the pareto-optima for the other criteria as shown in Fig. 3.5. One may look at plots of any pair of multiple criteria and thus identify the *Pareto-optimal curves or surfaces* and on these the optimal points for each criterion. The user must now set priorities and pick any Pareto-optimum or any compromise between them. They are all feasible designs. The following examples will illustrate these techniques (Table 3.3).

Example 1 Aframax Tanker (Papanikolaou et al. 2011)

In this design case study, dating back to 2010, an Aframax Tanker was to be designed in compliance with current IMO-MARPOL rules for a trade route in the

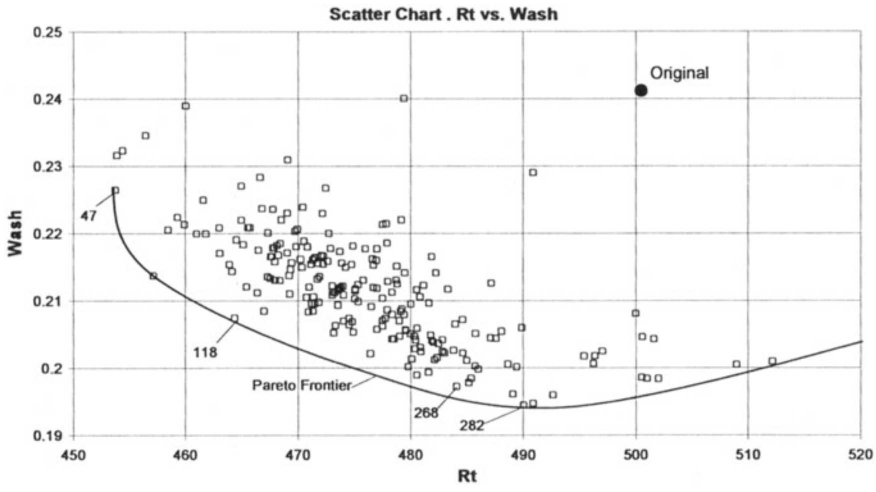

Fig. 3.5 Scatter chart, feasible designs, monohull, two objectives: total resistance R_T and wash W, plotted with ships of final sample, showing the pareto-optimal frontier as the lower envelope of all feasible design candidates (Papanikolaou 2010a, 2011a)

Caribbean from the Maracaibo area to St. Eustacius in the US Gulf Coast in the US Emission Control Area, a route of some 1600 miles one way. The design was subject to all pertinent national and international rules and regulations, especially those of Resolution MEPC.177 (52) and the requirements for Segregated Ballast Tank (SBT) capacity.

The designs were to be ranked by the *key objectives* of RFR, EEDI and OOI, hence by economy and environmental protection, while safety was implied by the MARPOL rules as constraints.

The software was subdivided in modular form into a ship design platform and into an optimization module. In a majority of case studies in connection with EU-supported projects, a random search optimization software was used for optimization in order not to miss any parts of the feasible space, viz. the application-independent Multiobjective Genetic Algorithm (MOGA) software under modeFRONTIER.

The ship design platform was tailored to each application. For the Aframax study, the following Naval Architecture software systems were combined under Friendship Framework: NAPA, POSEIDON and SHIPFLOW. For the purposes of optimization, these systems had to be reconfigured and linked so that they could be addressed by parametric free design variables. In addition to the objective functions and constraints, this set of design calculation modules also computed the following key measures:

- Cargo tank capacity in full-load and design-load conditions
- Steel weight of the cargo tank area
- Maximum ship speed at design, ballast and scantling drafts
- Probability of oil spill, OOI, in case of accidents

Some 50 form parameters were needed for the hull form definition in total, but only 12 free variables during the form optimization in this study. The tank arrangement here was fixed in the usual 6×2 configuration. The distance of the inner bulkhead from the shell was a free variable (≥ 2 m). The parametric model for the steel structure in the cargo domain is generated by POSEIDON in accordance with the prescriptive part of the Common Structural Rules (CSR), hence for a preliminary dimensioning. This serves to estimate the steel structure weight.

The hydrodynamics of this tanker are calculated by CFD solvers (SHIPFLOW, XPAN, XBOUND, CHAPMAN). Response surfaces were fitted through these raw data points to save much computing time during the optimization run for these most time-consuming computations.

The search for the optimum was started by a reference ship, an existing modern Aframax tanker. The results of this study for the tanker are visualized in Fig. 3.4. Deadweight DWT, RFR (normalized by the reference design), EEDI (MARPOL's Energy Economic Design Index) and OOI (MARPOL's Oil Outflow Index) are the criteria of main interest in this study. The designer has the choice of which one to favour since all are close to Pareto-optimal. Figure 3.4 shows that the best RFR design is achieved for a value of about 3000 tons DWT above the reference ship, whereas the best EEDI design is bigger yet and the best OOI ship is a bit smaller than the reference ship. But since the losses in RFR and EEDI for this ship were small, the study team favoured the best OOI vessel. The possible trade-offs between the different criteria are evident.

Example 2 RoPax Ferries (Papanikolaou et al. 2010b)

In this investigation by NTUA, promoted by the Elefsis shipyard, a set of three monohull RoPax ferries was developed for exploration and demonstration. Ship sizes of these target vessels were given as:

Ship 1: 500 passengers, 9 trucks, $V_S = 18$ knots
Ship 2: 590 passengers, 12 trucks, $V_S = 19.5$ knots
Ship 3: 1300 passengers, 35 trucks, $V_S = 23.5$ knots

The route was intended for a distance of 21 nautical miles between Kylini, Western Peloponnese and Zakynthos in the Ionian Sea. NPV was chosen as the only objective function. All other requirements were handled as constraints (owner's preference). This included many other design calculations such as: initialization of hull forms in the feasible domain from parametric hull form definitions, a parametric tank arrangement, a parametric structural design software using GL's POSEIDON, structural analysis by FEA analysis software, hydrodynamic assessment by SHIPFLOW, stability assessment for intact and damaged condition, MARPOL rules analysis for OOI and EEDI. These data provide a rich supply of information for systematic comparisons of the designs.

The optimization is performed by the probabilistic, multiobjective optimization software MOGA, a module available under modeFRONTIER. It goes through several steps:

Step 1: Initially the magnitude of the computational task must be limited. Beginning with exploratory, stagewise optimization runs according to the stage structure shown in Fig. 3.2, the free variables for each stage are picked in reasonable practicality, but liberally, and each stage is randomly sampled by the optimization software MOGA within modeFRONTIER in order to find promising candidate designs for each objective and by eliminating infeasible designs. The random sampling by MOGA avoids the omission of candidates in remote corners of the decision space. The first generation of MOGA furnishes only eight initial feasible candidates.

Step 2: For each new generation of MOGA, from now on, the search around temporary candidates is intensified, moving from rather uniform to very selective sampling. The probability of success in finding new candidates with feasible objective values increases in each generation. Here some 100 further generations were sampled with increasingly modest improvements.

Step 3: The final best designs are then fully elaborated to contract and specification level using the best software design tools for all stages.

The shipbuilding software platform here supports the parametric design of RoPax ferries by integration and parametric adaptation of Naval Architecture (NA) software, such as NAPA for geometry and layout, semi-empirical hydrodynamic modules, an internal layout template, a preliminary structural design module based on DNV class rules, steel weights by direct calculation, empirical formulas for other weights, intact and damage stability (NAPA) based on SOLAS 90, itemized economic performance assessment.

The user has a choice of several objective functions: minimization of lifecycle cost, maximization of annual revenues or a full economic analysis based on NPV or RFR can be chosen. Other performance criteria like stability margins, seaway motions and comfort can be included as objectives or constraints. This is the advantage of a multiobjective formulation and a modular, parametric software structure.

The optimal designs were further elaborated by the Elefsis shipyard using the TRIBON Hull software. Thus, contractual design-level documentation and detailed shipbuilding specifications were obtained.

3.3.4 Holistic Design Models

The purpose of holistic design models (Table 3.4) is to look at *all* economic and non-economic measures simultaneously, though by separate indicators. In particular the safety-related and the environmental impact-related criteria are initially expressed in non-economic terms. These models are thus multiobjective and multiconstrained models for the whole life cycle of the ship.

The attributes used to perform a holistic, i.e., comprehensive whole lifecycle evaluation are in three categories, viz. economic, safety and environmental impact indices. The economic performance of the ship can be measured by the Energy Efficiency Design Index (EEDI), defined by IMO in its MARPOL regulations as an interim measure of ship size and fuel consumption, hence indirectly of CO_2 air pollution. This does not yet take into account the engine efficiency and the propulsive

Table 3.4 Holistic design models

Authors	Year	Ship type	Measures of merit	Approach	References
Papanikolaou	2011	High-speed passenger ship monohull, Twin-hull RoPax ferry	Total resistance R_T, wave wash and safety	Genetic algorithm (GA), Pareto scatter diagram	Papanikolaou (2011a)
Boulougouris, Papanikolaou, Pavlou	2011	Container Ship	EEDI, ISP, displacement, speed	NAPA, modeFrontier, parametric design tool	Boulougouris et al. (2011)
Papanikolaou	2012	Merchant and naval ships	RFR, safety, environmental impact	GA: direct search, PDT, NAPA, POSEIDON, SHIPFLOW	Papanikolaou (2011b)
Köpke, Papanikolaou, Harries, Nikolopoulos, Sames	2014	Container feeder vessel	RFR, EEDI, capacities, low emissions, low weight	GA for multiobjective design using FFW	Köpke et al. (2014)

efficiency. They might be added to the list of objectives, but more traditional RFR or NPV can be used instead or in addition.

Safety and environmental protection cannot be measured directly in currency units. These criteria must be assigned indices to collect all contributions in each category over the lifetime and must use these sums as separate objectives together with the economic indicator in the same manner as explained in multiobjective optimization, viz. with assigned utility functions or by displaying Pareto space maps or other visualization aids (scatter diagrams). Thereby the results of holistic optimization can be judged by three (or more) independent indices as well as by some weighted combination of all individual measures taken according to the preferences of the parties involved in the design. Table 3.4 gives an overview of several holistic design studies.

The term “holistic” design, if taken literally, requires that in fact *all* influences are taken into account in the design study. In practice, I would recommend a softer definition: “A holistic study takes into account *all* influences that are relevant to the issue under investigation”. It should be understood that in a modern ship design context, every design issue has an effect on the overall economic, safety and/or environmental performance of the ship. Thus, the explicit or sometimes hidden presence of these three elements should be a minimum requirement to classify a design study as “holistic”. This section of the text should help to clarify this terminology by concrete examples.

Example 3 High-Speed Passenger Monohull (Papanikolaou 2010a, 2011a)

In this example, studies were performed by the same partners as in Example 2, though for a different scenario and ship type, for various RoPax ferry service routes between the Aegean islands and the Greek mainland. The routes varied between 20 and 80 nautical miles. High-speed transport was desired with targets of 30 knots and above. Similar assumptions as in Example 2, but a different design modelling methodology, were used. A single key objective, the NPV, as a measure of merit, reflecting the viewpoint of the ship owner, was adopted, whereas all other requirements of the scenario were modelled as constraints. This worked equally well methodically demonstrating the legitimacy of this approach.

The exploratory case study deals primarily with the design of a high-speed monohull. It is destined for a ferry service between the Greek mainland (port of Lavrion) and islands in Aegean Sea, e.g. the island of Mykonos, a route of 75 nautical miles one way. High-speed transport was desired with targets of 30 knots and above.

However, the level of elaboration in the design software tool was much extended for the modelling of the design stages, again using a similar breakdown for the stage-wise initialization procedure. The tools available here included NAPA, SHIPFLOW and the ITTC 1957 formula for the frictional resistance or optionally systematic series results like a regression formula by NTUA, an interior layout topology module, DNV class rules for structures, intact and damage stability software by NAPA and a detailed cost assessment module. These modules were combined into an integrated system of design evaluation by linking these software components. In this way, an integrated system of design assessment for each single design was created, which combined the modules of design variation, design assessment and design optimization. The optimization software modeFRONTIER with MOGA worked for this form of Integrated Model as well as it did in the case of multiple objectives. The constraints were ascertained in the calculation process for each ship. The high-speed monohull was a demonstration example.

The hull form of a reference ship was parameterized for variation by form parameters (points and angles). This defines a grid from which surface representations can be interpolated and faired. The hull form can now be modelled parametrically using NAPA macrolanguage. Compliance within the series with geometric constraints is checked and ensured. The resulting hull representations are then processed for hydrodynamic performance by SHIPFLOW, augmented with semi-empirical viscous flow data.

A starting set with promising favourable hydrodynamic properties is identified and becomes the input to the optimization.

While the ship owner was interested mainly in NPV, the optimization approach was multiobjective in this article. Two objectives were pursued here, they consisted of the total resistance R_T as a measure of hydrodynamic effectiveness and the wave wash, taken as the average wave height along a longitudinal wave cut at a certain distance (0.25 L or 0.5 L) off the centreplane. This second objective is regarded as a measure of the potential damage done to the ship's environment in narrow waters.

Table 3.5 Comparison of original ship with the Pareto-optimal designs

	R_T (kN)	W(m)	H_{Max}(m)
Original vessel	500.5	0.205	1.0515
Hull no. 47	449.3	0.173	0.8840
Hull no. 118	464.3	0.160	0.7890
Hull no. 282	494.4	0.155	0.7473

Although this case is a very crude model of a two-objective optimization, it does illustrate the decision process.

The modular optimization software used is again the stepwise method by the random search system MOGA under modeFRONTIER described in Example 2.

Figure 3.5 illustrates the result of the search and design decision process. A scatter chart plots the resulting cloud of feasible designs of the final candidate set against the two objectives R_T and Wash W. A solid line is fitted so that all feasible sample points lie above or on that line, none below because those are infeasible. This boundary of the feasible domain is the *Pareto frontier.* Designs lying exactly on this frontier are the *Pareto-optimal designs*. They are characterized by meeting at least one objective exactly. Here designs 47, 118 and 282 are *Pareto-optimal.* The user can now choose among these from secondary considerations. The trade-offs are in the direction of a least wash for a medium resistance, hence design 282. The best design shows significant improvements over the original reference design, a built ship, in the order of up to 28% for the wash or up to 10% for R_T, though not for the same vessel, but for one or the other. But all Pareto-optimal results are improvements relative to the original design, the original reference ship.

A multistage, multiobjective optimization was performed following the stepwise pattern described in Example 2. The following results were obtained (Papanikolaou 2010a, 2011a), where R_T is the total resistance, W is the wash and H_{Max} (m) is the maximum wave amplitude in a longitudinal wave cut $L_{PP}/2$ off the centreplane (Table 3.5; Fig. 3.6).

For more than two objectives, the logic of the decision process must be generalized to multidimensional optimization with scatter diagrams for each pair of objectives and with multidimensional *Pareto frontier surfaces* and Pareto-optimal results thereon. Software utility tools within *modeFrontier* help to locate these. A random search following MOGA after several generations with more and more local search density, each with several iterations, follows and yields a final result close to a Pareto-optimal set. The results are now prepared for a final choice of candidates for optimization by multiple criteria as described in Fig. 3.4.

It was shown in this example study that multiobjective optimization approaches are valuable ship design tools and in deviating from the former rule-based MARPOL regulations are able to improve the economic and technical performance of new designs relative to existing ships while complying with increasing safety and environmental protection requirements.

Example 4 Twin-Hull RoPax Ship (Papanikolaou 2011a)

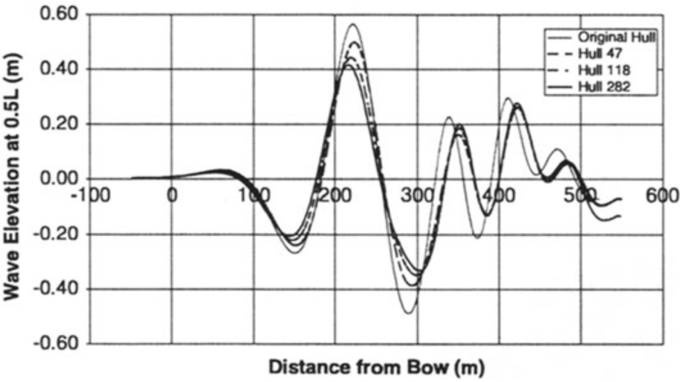

Fig. 3.6 Longitudinal wave cuts of original and Pareto-optimal monohulls, LPP/2 off centreplane (Papanikolaou 2010a)

The second example treated in (Papanikolaou 2011a) deals with the design of a high-speed twin-hull RoPax ship of catamaran type. It is destined for the same sort of ferry service between the Greek mainland (port of Lavrion) and islands in Aegean Sea, as in Example 3. The desired service speed was held at 30 knots. The configuration was that of a twin-hull semi-SWATH.

Comprehensive *design calculations* were performed, which included:

- Hull form development (with 23 form parameters, but only five of these as independent variables)
- Resistance and propulsion estimates (SHIPFLOW and semi-empirical formulae)
- Development of the internal layout (using NAPA, controlled by form parameters)
- Preliminary structural design (DNV rules, for aluminium and/or steel, 12 free variables)
- Weights' estimate (many weight categories)
- Intact and damaged stability (actual GM vs. required GM for relevant loading conditions)
- Seakeeping performance, if desired (crew comfort and cargo safety)
- Assessment of economic performance (mainly NPV, but also RFR, EEDI, OOI)

The *optimization* was again performed by random variation of the free variables in all stages of the design as in earlier examples accounting for continuous and some discrete variables. The optimization software modules of MOGA under modeFRONTIER were used again.

The results obtained in Examples 3 and 4 are only approximate by several assumptions, but have produced encouraging success for the holistic approach. The results are still reliable since the approximations do not distort the ranking of the designs.

Example 5 Tanker and Container Ship (Boulougouris et al. 2011)

The studies presented in this paper, developed in the frame of the EU project LOGBASED, address the issue of a changing market environment during the lifetime of the ship. The reduction of greenhouse gas emission (Water vapour, CO_2, NOX, SOX) will be of growing significance in the next few decades for worldwide increases in average temperatures, i.e. for the ships being designed now. Ships need to be designed to be flexible enough to be adjusted to operate in changing scenarios, standards and rules. How can these requirements be accommodated in today's design methodology? The answer lies in holistic design for a time variable set of requirements. The methods can be applied to the design of a single new ship as well as to the design and management of a whole fleet of current and future ships.

The EU project LOGBASED has built up an empirical database with all applicable data of all relevant ship types, here for tankers and container ships. EEDI is recorded as a criterion in multiobjective design. Many other properties are also collected in the database. This database serves to initialize optimization runs for new ships. These runs are performed by a random search software in MOGA and modeFRONTIER. The model uses the appropriate constraints for each ship type, e.g. the MARPOL regulation standards for the Aframax tankers for the given deadweight. The objective functions in this study are EEDI and ISP = Ideal Ship Price. Similarly, the same objectives were used for a containership of reduced speed. In the multigeneration runs, about 4000 ships are sampled. The most promising subsets are sorted out for final optimization and elaboration.

The study thus presents recommendations for ship design in a gradually or abruptly changing economic and technical environment.

Example 6 Merchant and Naval Ships (Papanikolaou 2011b; Boulougouris and Papanikolaou 2013)

In these articles, the basic similarity of holistic optimization of ship design for the life cycle for merchant and naval ships is emphasized. Both design tasks can be handled in the category of holistic design, although with quite different technical evaluations. The owner's requirements for the merchant ship are replaced by the navy's mission requirements. The internal subdivision into compartments plays a major role for both ship types. Both ship types are equipped with double hulls for safety purposes. The placement of the side tanks and the height of the double bottom are design variables in order to explore the reserve capacity in buoyancy when the outer hull is damaged in side or bottom by collision or grounding. As it turns out, the damaged ship may still be safe if the GM in this position is sufficient. The longitudinal bulkhead and the double bottom must be placed far enough inboard to protect them from penetration. The lost cargo volume can be made up for by raising the freeboard and thus enlarging the effective tank volume. For naval ships, the same measure increases the survivability.

For the reference merchant ship, the side tank width and the double-bottom height is placed 2.5 m away from the outer skin, while the MARPOL rules require only 2.0 m. This necessitates a correspondingly increased freeboard. The object functions are cargo capacity and Oil Outflow Index. The tank configurations range from

6×2 to 6×3 and 7×2 designs. The 6×3 configuration dominates the others in terms of its oil outflow performance. The 6×2 solution has the advantage of lower steel weight.

For the naval ship, many requirements were included in the list of the naval ship code NSC 2000. An integrated toolset on top of the software of TRIBON, PARAMARINE, CATIA, NAPA, etc., provided a platform for a preliminary global optimization by means of Parametric Design Tool (PDT). The objectives included in this tool are: ship's economy, cargo carrying capacity, safety, survivability, comfort, required powering, environmental protection, combat strength, as applicable.

The project has demonstrated the applicability of holistic, multiobjective, early design studies for a variety of ship types and operating scenarios. More software will be needed for evaluating later design and operational stages.

Example 7 Container Feeder Vessel (Köpke et al. 2014)

This study explores the influence of draft constraints in intra-Asian ports on the dimensions of feeder container ships for local distribution. These ships tend to have wide beams and shallow drafts because of the shallow water depth in the access waterways. The design speed is derived from analysing different intra-Asian routes. Transit times depend on delays in port. Port efficiency for faster voyages is one of the objectives in this study to minimize cargo-handling delays, hence also a trend to shorter hulls.

In the initial design of experiment stage, existing ships for this service are analysed and collected in an empirical database. The number of containers in a row across the beam, in practice 6 or 7 here, is an integer design variable resulting in gaps in the data. The solution can again be based on holistic design with changing objective functions with time. The methods can be applied to the design of a single new ship, but also to the management of a whole fleet during the lifetime of current and future ships.

The presented method has been integrated into the FFW design software platform and allows the fully automated generation of valuable containership designs with superior design characteristics. The obtained results indicate significant improvements regarding the IMO EEDI, major reductions of the RFR and an improvement of the herein defined port efficiency. Another step forward is the reduction of the required ballast water by almost 40% and the increase of carried containers (nominal capacity and containers on deck) that can be loaded without the need for using ballast for stability purposes. The homogenous weight for this condition is close to the statistically observed homogenous weight for containers (approximately 12–15 tons). This means that in most real-life loading cases, the ship can waive ballasting with the exception of some limited loading of the aft and fore peak tanks for trim improvement purposes. The increased port efficiency that was defined within the methodology based on previous research activity allowed the designers to lower design speed with no implications in the supply chain of the intra-Asian trade studied in this paper. This reduction is beneficial in terms of both fuel costs, and emissions and efficiency without sacrificing the competitiveness of the vessel (in terms of trips per year).

3.3.5 Risk-Based Design Models

The design of complex systems operating under hazardous conditions and subject to immense damages in the event of catastrophic failures has become a specialized discipline, now commonly called risk-based design. This approach has been a necessity in the nuclear industry for many decades and has also prevailed in aerospace design and in other industries with great public and economic risks. In the maritime field, the offshore oil industry first introduced this approach by legislation based on risk analysis for offshore systems, e.g. in Norway in 1986, in the UK in 1992. For ships, IMO is currently following a strong trend towards risk-based ship design in the development of new safety standards (Sames 2009; Skjong 2009).

This entails a number of methodical elements:

> Future standards and some current pilot regulations are intended to replace, at least in part, the traditional rule-based approach of classification and regulations, which describes in technical detail how a safe design is to be realized, by Goal-Based Standards, where a safety goal is set regardless of how it will be achieved. This requires quantitative risk analysis (QRA) with quantified risk assessment. Goal-Based Ship Design (GBSD) aims at an optimal solution for the overall safety of the ship. This is to be achieved in the most cost-effective manner.

The risks will be defined for each hazardous operational scenario in probabilistic terms by the predicted probability of occurrence of the hazardous event multiplied by the economic value of the consequent damage. All damages, whether to the public, the ship owner or to individual humans, are to be included in the analysis. The total risk is evaluated by combining the risks of all scenarios. The total risk will be compared to the acceptable risk, chosen either relative to ships designed by existing IMO rules or in absolute terms based on forthcoming new IMO risk acceptance criteria (Sames 2009).

In optimizing designs simultaneously for their economic viability and their safety, safety is no longer regarded as a rule-based constraint but is treated as an objective in its own right. After all, the owner's and the public's interest lies in both economy and safety. Risk analysis quantifies safety in comparable units as the functional economic measures.

The historical EXXON Valdez accident 2009 in Prince William Sound in Alaska has led to the legal banning of single-hull tankers first in US waters (OPA 90), later internationally by IMO-MARPOL for any new tankers today. The risk of oil spillage by tanker accidents should be kept as low as possible. The EU has funded several projects on modern design issues, notably the SAFEDOR project and up to the present HOLISHIP project.

The risk-based design models are actually built like the holistic models for multi-objective modelling with constraints for the whole life cycle except that the uncertain safety hazards are quantified differently as probabilistic risks. The cumulative risk will then serve as a safety term in the measure of merit. This opens the door for goal-based justification of safety features. Thereby the overall safety of the ship can be enhanced if the equivalence of the goal-based design to a rule-based reference design is demonstrated. This approach may result in safer and/or more economic

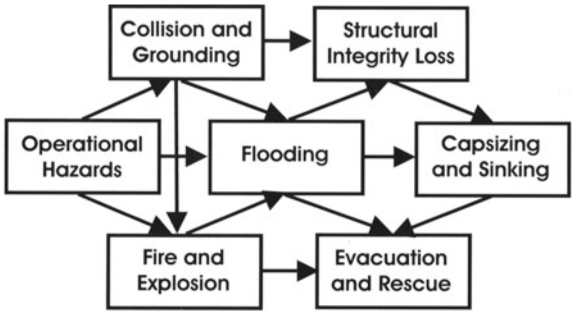

Fig. 3.7 Structure of hazardous scenarios in ship safety (Vassalos 2009)

solutions than prescriptive rule-based design. A good overview of this approach is presented in the book on Risk Based Ship Design, edited by Papanikolaou (2009a), which summarizes the main results of the EU-funded project SAFEDOR.

An example of the structure of Quantitative Risk Analysis for ships, which will comprise all hazardous events, is given in Fig. 3.7 (Vassalos 2009), which is a basis of current standardization activities at IMO SOLAS regulatory level.

Example 8 Risk-Based Aframax Tanker (Papanikolaou 2010b)

The main objective of the addressed risk-based studies (first two in Table 3.6) was to reduce the risk of accidental oil outflow by optimizing the cargo tank arrangement while at the same time minimizing the steel weight and maximizing the cargo capacity. A generic optimization framework developed earlier by NTUA-SDL was adapted to the present optimization problem by adding methods and software tools for the structural design and probabilistic assessment of the oil outflow. The design pool in the heart of the framework is based on a parametric ship design and systematic variation of design parameters. The approach allows integrating an arbitrary number of objective functions and constraints (constrained multiobjective optimization). The whole process is initiated by relevant owner's requirements from a technical database. The optimization procedure is implemented by integration of the following software tools:

NAPA (geometric modelling and Naval Architecture calculations)
POSEIDON (structural design and analysis software, developed by GL)
modeFRONTIER (a general-purpose optimization software from Esteco).

The reference design in this study makes use of higher double bottoms and wider side tanks of 2.5 m each compared to MARPOL requirements of 2.0 m each (for ship as built). This configuration with six tanks longitudinally and two transversely is compared with other arrangements of the cargo tanks in configurations of 6×3 and 7×2 sets of tanks, where each set is optimized with respect to Pareto-optimality in cargo capacity and oil outflow. Figure 3.8 shows the results for several configurations. The 6×3 "flat" arrangement, i.e. without corrugation of the tank walls, dominates all others, but has a higher steel weight and hence lower cargo capacity than "6×2 flat". The steel weight in the additional bulkhead for the 6×3 option defeats

Table 3.6 Risk-based design models

Authors	Year	Ship Type	Measures of Merit	Approach	References
Papanikolaou	2009	Tanker: Aframax Built on class rules by GL	Mean oil outflow index, steel weight in cargo area, cargo capacity	GA with random search and direct search	Papanikolaou (2010b)
Papanikolaou, Zaraphonitis, Boulougouris, Langbecker, Sames	2010	Aframax Optimized Tanker, Naval Ships	Cargo capacity, deadweight, outflow index	GA, direct search: NAPA, POSEIDON, modeFrontier	Papanikolaou et al. (2010a)
Vassalos	2009	Passenger cruise ship	Economics, risks of fire, collision, grounding, damage stability	GA: Economy and safety	Vassalos (2009), Project GENESIS, Vassalos and Papanikolaou, (2015)
Plessas and Papanikolaou	2015	Bulk carrier	RFR	Stochastic lifecycle design, six design variables	Plessas and Papanikolaou (2015)

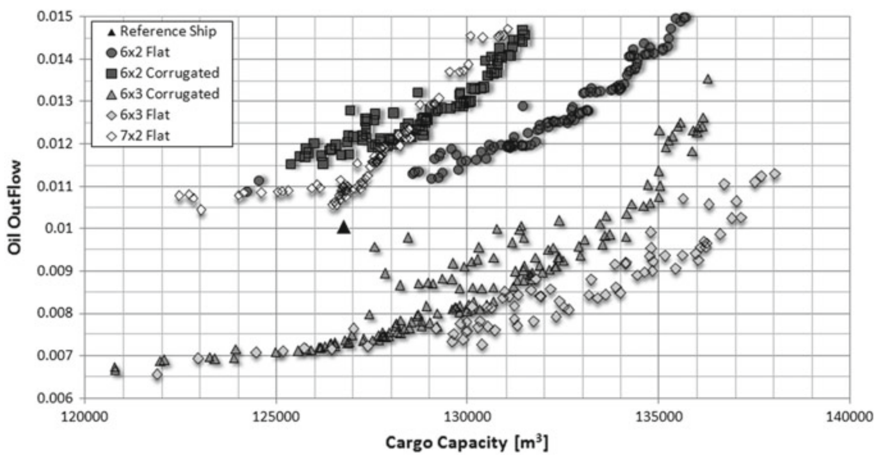

Fig. 3.8 Oil outflow versus cargo capacity for Aframax Tanker, optimized, for several tank configurations, flat and corrugated tank walls (Papanikolaou et al. 2010b)

the benefits of this option. Thus, "6 × 2 flat" seems to be the most practical option, since it allows more cargo capacity. Figure 3.8 adds some information as to the possible gains in cargo capacity versus the loss of oil outflow.

Table 3.7 Project GENESIS main particulars (Vassalos 2009)

Length	361 m
Beam, WL	47 m
Draft	9.15 m
Depth	22.55 m
Height, above WL	72 m
Gross tonnage	225,000 RT
Number of passengers	5400
Number of crew	2166
LSA capacity	8460
Passenger decks	16
Speed	22.6 knots
Propulsive power	3×20 MW

Example 9 Passenger Ships (Vassalos 2009; Vassalos and Guarin 2009; Vassalos and Papanikolaou 2015)

The reference Vassalos and Papanikolaou 2015 is a state-of-the-art report of May 2015 on the "Design for Safety, Risk-Based Design, Lifecycle Risk Management" presented by Dracos Vassalos and Apostolos Papanikolaou to the 12th International Marine Design Conference held in Tokyo in May 2015. It is not the description of any particular design. But it explains the general approach taken by IMO and related institutions in assessing and managing the risks that exist during the lifetime of a ship. This combines the passive risk control measures at the design stage with the prevention/reduction of risks as a design objective and the active control at the operational stage by lifecycle risk management. Thereby safety rules are being replaced by safety objectives.

Nonetheless, the article describes ongoing developments in ship safety research for a few particular projects of Lifecycle Risk Management from two perspectives, the EU SAFEDOR project perspective and briefly the general perspective of lifecycle risk management, introduced by the Health and Safety executive of the EU. SAFEDOR was an EU Project accompanying the development of the major shipbuilding cruise ship project GENESIS. See Table 3.7 and Fig. 3.9. The prototype "Oasis of the Seas" was the largest cruise ship ever built, when delivered in 2009.

For the *design* phase, risks are evaluated comprehensively for all hazards shown in Fig. 3.7. Risk is quantified as the probability of occurrence multiplied by the value of the loss resulting from the event using statistical data and extensive simulations. The value comprises all damages, whether to the public, the ship owner or individual humans. The investigation for project GENESIS involves a case-by-case explicit dynamic flooding simulation for 342 collision scenarios alone (3rd study in Table 3.6).

For the *operational* risk, the issue is how to manage the residual risk which every design possesses over the lifetime of the ship. In addition to providing sophisticated

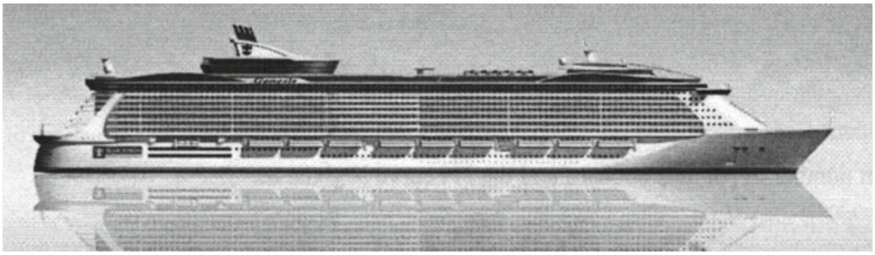

Fig. 3.9 Project GENESIS

computer-based support and surveillance of the on-board safety systems and continuous monitoring of shipboard sensors for tank levels, door states, water ingress alarms, wind and waves, etc., it is necessary to create the required risk awareness and preparedness for crisis management on the part of the crew. Structured action plans exist and are being further developed for lifecycle risk management by the crew. *Training and awareness*, promoted by systematic IMO-based inspections, are a *key element* in the continuing progress of lifecycle risk management.

Example 10 Time-varying Values—Stochastic Optimization (Plessas and Papanikolaou 2015)

Certain parameters in a design model are always uncertain, among them the fuel price in the lifetime of the vessel. This study examines the effects on a design of time-varying fuel prices. It investigates how the resulting main dimensions of a tanker are affected if one assumes a time-varying fuel price (4th study in Table 3.6).

The variation in fuel price is given by a probability distribution around a mean value, rather than a fixed rate. The reference design is a tanker operating at a constant speed in its life of 14.5 knots and a mean value of the fuel price of $500 per ton. The optimization for the fixed fuel price with the principal dimensions as design variables yields a deterministic optimum design and the stochastic modelling of the fuel price a stochastic optimum design, as shown in Table 3.8.

Thus, whoever is expecting a tendency of falling (in the mean) fuel prices should hedge by ordering a somewhat smaller and fuller vessel. *Take this with a grain of salt.*

The main point is that varying financial environments in the life cycle of a ship, if sufficiently well known in advance, can be taken into account in planning and properly designing the ship for its lifetime.

3.4 Conclusions

Maritime transport in its continuous development, especially after two world wars, has become an indispensable factor in the world economy and helps to secure our

Table 3.8 Deterministic and stochastic optimization of tanker design for varying fuel price

Optimum dimensions for the same engine rating	Deterministic optimum	Stochastic optimum
Mean value of fuel price ($ per ton)	500	264
Service speed (knots)	14.5[a]	10.9 for fuel price $500/ton
Length (m)	232.8	223.6
Beam (m)	38.8	37.3
Draft	16.0	16.0
Depth	21.8	21.8
CB	0.79	0.85
RFR ($/ton)	22.68[b]	20.65

[a]the speed of the deterministic design can be optimized based on the assumed fuel price for minimum RFR: $V_{opt} = 11.25$ kn
[b]can be reduced to 21.04$/ton, if the speed of the deterministic design is optimized (e.g. $V_{opt} = 11.25$ kn)

welfare and prosperity in a more and more globally coherent world. The world fleet as a means of transport is bigger than ever before.

At the same time, the risks of maritime transport have also steadily grown with the size of the fleet and the complexity of maritime technology. The public is increasingly aware of the risks of potential damages to the ships and shores, to the world's natural maritime environment and to human lives aboard on land and sea. Major disasters with catastrophic ship losses like the *Exxon Valdez* drama and the *Estonia's* sinking have acutely raised the awareness of the public of necessary action for the safety on sea.

In the last several decades, national and international authorities and institutions have worked intensively on increasing maritime safety. Under the leadership of IMO, the international maritime community has responded to the challenge and has issued modern new safety rules and standards, which are gradually going into effect. This chapter has attempted to give a synopsis of the most important developments.

It is also important that safety awareness must still grow in ship operations. Crew training with regular practice and inspection is a key element in maritime safety over the life cycle.

The developments and research studies performed in recent years by the ship design and research community on the basis of the objectives of risk-based ship design have been broad and successful. They ought to be continued in many details. For now they are providing a reliable methodical approach to designing safer, cleaner and economically more effective ships.

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Software friendship systems. https://www.friendship-systems.com/

Software mode.FRONTIER, a general purpose optimization software by ESTECO. www.esteco.com/modefrontier

Software NAPA solutions for design and operation of ships. https://www.napa.fi/

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Horst Nowacki, born in Berlin in 1933, studied Naval Architecture and Marine Engineering at the Technical University of Berlin from 1951 to 1958. There he obtained a NAME engineering diploma (1958) and doctorate (1964). His practice includes a period at the ship model basin of Duisburg (1958/59), a teaching and research assistantship at TU Berlin (1959–64). He spent ten years as a professor at the University of Michigan (1964–74) and 24 years at TU Berlin (1974–1998), both in teaching and research of ship design and computer-aided design. His main areas of activity include ship hydrodynamics and dynamics, hydroelasticity, computer-aided design, ship product and process data modelling. He published more than 200 articles and made contributions to 5 books.

Chapter 4
Market Conditions, Mission Requirements and Operational Profiles

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Abstract The present chapter deals with the modern ship design from the perspective of an experienced European ship design and engineering office, namely Elomatic Oy. When a shipowner sees the opportunity to expand his business or replace existing vessels to enhance the productivity of a fleet, newbuilding(s) come into consideration. These newbuildings are based on the experience of the shipowner but may also contain innovative solutions, such as the use of new types of machinery and novel cargo handling systems. Increasingly, strict environmental rules and regulations also impact new designs. The interested shipowner needs to analyse the shipping environment and its development first. This analysis covers the activities of other players in the market and various influencing parameters. The market analysis of associated shipping is conducted by collecting data about vessels that are similar to the application cases. This data is used to identify relationships and important design factors for the initial sizing. Price data is also collected. Based on the collected data and derived equations, a ship concept can be created. All the collected data supports the global optimisation of the concept. The shipowner also determines the transport task and/or other tasks that need to be fulfilled. This defines the mission requirement for the shipping business. After having analysed the external parameters, the vessel itself and its operation need to be defined. A parametric model allows designers to handle and elaborate on a ship concept. This helps the naval architect to optimise the concept for a defined purpose. As the main topic of the HOLISHIP project is optimisation, the connectivity of the parametric model is important. This is herein enabled by the introduction of an intelligent general arrangement software tool (IGA), the development of which is elaborated in the following.

Keywords Market analysis · Mission requirement · Operational profile
Intelligent general arrangement · Optimisation platform

4.1 Introduction

When a shipowner sees the opportunity to expand his business or replace existing vessels to enhance the productivity of a fleet, newbuilding(s) come into consideration. These newbuildings are based on the experience of the shipowner, but may also contain new solutions such as new types of machinery and novel cargo handling systems. New demands are placed on vessels by new rules and regulations that are continuously introduced.

The interested shipowner needs to analyse the shipping environment and its development first. This analysis covers the activities of other players in the market and various influencing parameters. The market analysis of shipping is conducted by collecting data about vessels that are similar to the application cases. This data is used to identify relationships and important design factors for the initial sizing. Price data is also collected. Based on the collected data and derived equations, a ship concept can be created. All the collected data supports the global optimisation of the concept. All the collected data supports the global optimisation of the concept. This is discussed in Sect. 4.2.

The shipowner also determines the transport task and/or other tasks that need to be fulfilled. This defines the mission requirement for the shipping business, which is discussed in Sect. 4.3. After having analysed the external parameters, the vessel itself and its operation need to be defined. The vessel itself is discussed in Sect. 4.4, while its initial sizing and operational profile are presented in Sect. 4.5.

A parametric model allows designers to handle and elaborate on a ship concept. This helps the naval architect to optimise the concept for a defined purpose. As the main topic of the HOLISHIP project is optimisation, the connectivity of the parametric model is important. The principles of an *intelligent* general arrangement (IGA) are presented in Sect. 4.6. The introduced 3D general arrangement is demonstrated in HOLISHIP by a double-ended ferry application case on the optimisation platform.

The vessel types in focus in this chapter are defined in the following section. RoPAX vessels double-ended ferries and OSVs provide the most comprehensive application cases for HOLISHIP and concept design. The application cases define the operational environment of the vessels and the transport task. The operational profile is explained on the basis of OSVs. A more detailed description of the application cases and the optimisation workflow will be included in volume 2 of this book.

4.1.1 RoPAX

RoPAX vessels play an important role in the transportation of goods, vehicles and passengers. The European region is one of the most active RoPAX markets. More than 60% of the total Ro–Ro fleet (by vessel capacity) is operating in the European market, focussing on the Mediterranean, Northern Europe and the Baltic regions. It is actually difficult to exactly define the RoPAX market, as it comprises a rather diversified group of ship subtypes. In contrast to pure passenger ferries and pure Ro–Ro cargo ferries, “RoPAX” vessels are able to transport passengers, cargo and vehicles, usually on short sea routes. The RoPAX segment includes all ships with a car deck that carry more than 12 passengers. RoPAX vessels often have a complex design and are specially designed for specific routes and special needs (freight or passenger oriented, night vessels, including restaurants, arcades). They provide regular services between fixed ports. As a result, the ship dimensions and configurations are quite diverse, making it difficult to directly compare these ships or their operational areas (Fig. 4.1).

Fig. 4.1 RoPAX vessel «MS Colour Superspeed 2», delivered 2008, a fast ferry with passenger spaces for day travellers. Capacity: 1928 passengers and 2034 lane metres (http://www.faktaomfartyg.se/superspeed_2_2008.htm)

4.1.2 Double-Ended Ferry

Double-ended ferries are usually rather small, but versatile vessels. In addition to ordinary ship systems and areas, they contain car and passenger areas like those found on ferries. Operation in both directions also results in special requirements for arrangements, hull shapes and propulsion. It forms, therefore, an interesting platform for showcasing how a parameterised ship could be designed and optimised on a dedicated platform.

Double-ended ferries are used widely in European waters, from the Greek archipelago to the Nordic countries, where they have a long tradition of connecting shorter routes over rivers and at sea. The operational areas and, therefore, the requirements as well as operational profiles of the vessels vary heavily.

Double-ended ferries have been divided into three different size classes in the HOLISHIP project. These size classes are used as initial designs for further development. They are parametrised and can also be modified topologically, with different features such as motoring selections and public spaces as options.

Fig. 4.2 Ice-going road ferry "Pluto", a type of double-ended ferry (Uudenkaupungin Työvene Oy)

A special characteristic of a double-ended ferry is the variety of powering options available. Currently, hybrid systems and a full range of electric solutions are widely considered as options for novel vessels. This is the case, especially, where short routes allow regular charging between voyages (Fig. 4.2).

4.1.3 Offshore Support Vessel

An offshore support vessel (OSV) is dedicated to a wide range of transport tasks required by offshore platforms. In HOLISHIP, it is used as an application case for power system configuration. An OSV has several different operational models, and, therefore, the power system set-up is complex. North Sea environmental conditions, in particular, may be harsh and affect the vessel's operations. For cargo operations at offshore platforms, the vessel is in dynamic positioning mode. Being on standby is a part of the vessel's duty.

The versatile operations make an OSV an interesting subject from an operational profile perspective. In this book, the operational profile tool is demonstrated based on an OSV in Sect. 4.5 (Fig. 4.3).

Fig. 4.3 Typical offshore supply vessel (OSV) type RR UT 776 «MS Island Condor», delivered 2014, 4700 dwt (https://www.islandoffshore.com/fleet/fleet-overview/psv)

4.2 Market Analysis of the RoPAX Vessel Segment

4.2.1 Introduction

The market analysis within HOLISHIP concentrated on vessel types that are of interest to the European maritime industry and which formed the basis for the most comprehensive application cases within the project; namely, among others, RoPAX vessels and double-ended ferries (DE). This enables a clear insight into current and future developments for both vessel segments as market-based information input for the HOLISHIP platform.

RoPAX vessels play an important role in the transportation of goods, vehicles and passengers. The European region is one of the most active RoPAX markets. More than 60% of the total Ro–Ro fleet (by vessel capacity) is operating in the European market, focussing on the Mediterranean, Northern Europe and the Baltic regions. However, defining clearly the RoPAX market is difficult as it comprises a rather diversified group of subtypes. In contrast to the pure passenger ferries and pure Ro–Ro cargo ferries, RoPAX vessels are able to transport passengers, cargo and vehicles, usually on short sea routes and the RoPAX segment includes all ships with a car deck and carrying more than 12 passengers. RoPAX vessels often have a complex design and are specially designed for regular services on specific routes and special needs (freight or passenger oriented, night vessels, including restaurants, amusement arcades). Therefore, ship dimensions and configurations are quite diverse which in turn makes it moreover challenging to compare these ships or the corridors in which they are operating directly.

Hence, the market analysis comprises the structure of the RoPAX fleet based on relevant vessel parameters in terms of size, capacity, speed, etc., as defined within the relevant application cases and the corridors where the vessels are operating.

4.2.2 *The RoPAX Vessel Segment*

Following the most characteristic vessel parameters defined by HOLISHIP, the European-owned RoPAX fleet built from the year 2000 onwards and with a length range of 140–220 m was analysed.

At the start of 2017, the European-owned fleet comprised 267 vessels of a combined 4.8 million GRT and 290,000 lane metres, thereof 116 vessels in the relevant range of 140–220 m. In terms of length classes, most of the ships belong to the size class <140 m[1] (143 vessels), and the class over 220 m is occupied by only eight units, all were delivered before 2015. Of the 16 RoPAX vessels delivered since 2015, only five were in the range 140–220 m (see Table 4.1).

Considering the new ship deliveries since 2010, out of the 75 vessels only 22 units were in the range between 140 and 220 m vessel length confirming a trend towards smaller sizes <140 m ordered by European operators—interrupted in 2016 with an increasing size with 9115 GRT and 794 passengers on average (see Table 4.2). Here, noteworthy is Tallink's newest LNG ferry "Megastar", the most modern RoPAX ship in the Baltic Sea (49,000 GRT, 2800-passenger capacity), which started operation in January 2017.

In the RoPAX shipbuilding sector, a number of different smaller yards are active as operators or shipowners often favour local or national yards. For example, all 14 ferries currently being built in Japanese yards were ordered by Japanese owners. At the start of 2017, the order book for RoPAX vessels ordered by European owners

Table 4.1 European-owned RoPAX fleet (built from 2000 onwards), January 2017 (Shippax 2017)

Year of built	Vessel length (m)			Total
	<140	140–220	>220	
2000–2004	47	58	1	106
2005–2009	46	36	4	86
2010–2014	39	17	3	59
2015–	11	5[a]	–	16[a]
Total	143	116	8	267

[a]Including RoPAX ferry "Megastar", built 1/2017

[1]46 m was the lowest length.

Table 4.2 Deliveries to RoPAX fleet since 2010, European owners (Shippax 2017)

Year of delivery	Vessel length (m)			Total	Average GRT	Average PAX
	<140	140–220	>220			
2010	11	5	3	19	18,758	885
2011	6	6	–	12	18,217	1037
2012	9	2	–	11	9224	734
2013	5	3	–	8	13,329	830
2014	8	1	–	9	6426	578
2015	5	–	–	5	2598	275
2016	6	4	–	10	9115	794
2017	–	1	–	1	49,000	2800
Total	50	22	3	75	13,250	803

Table 4.3 RoPAX vessels on order for European owners (Shippax 2017)

Estimated completion year	Vessel length (m)			Total	Average GRT
	<140	140–220	>220		
2017	9	2	–	11	6792
2018	13	2	–	15	7040
2019	–	2	1	3	38,300
2020+	–	2	–	2	40,000
Total	22	8	1	31	12,106

stood at just 31 units (see Table 4.3), but with several innovative vessels. In the relevant segment of 140–220 m length, only eight RoPAX vessels were on order (see Table 4.3), while most of the ordered units have size classes <140 m. However, the average size of all newbuilding orders and fleet deliveries has been declining. In gross ton terms, the average size of ships on order is 13,200 GRT (compared to 18,000 GRT in the current fleet). While ships to be delivered in the next two years are even smaller with around 7600 GRT, in the following years the average size will rise to 39,000 GRT.

Between 2012 and 2016, 38 European-owned RoPAX vessels of a combined 464,000 GRT were reported as sold to breakers—on average ~8 vessels p.a. With an average economic life of ~38 years, RoPAX vessels are by far the ships, reaching the highest age before scrapping compared with other ship types of the world merchant fleet. The average size of scrapped vessels is bigger than those delivered. In 2016, the average size for RoPAX vessels scrapped was 14,700 GRT (see Table 4.4), while the average size for newbuildings delivered in 2016 was just 9100 GRT.

The average age of RoPAX vessels sent for demolition has been around 38 years, e.g. in the range between 21 and 51 years (see Table 4.4). Looking at the defined vessel size segment, the average age of the analysed active RoPAX fleet is about eleven years. Thus, the first vessels in this segment will reach the (expected) demolition age in about 20 years.

With regard to market operations, the European RoPAX services are concentrated in three regions, i.e. the North Sea, the Baltic and the Mediterranean regions. Among these, about half of the fleet considered operated in the Mediterranean (53 vessels). By number, significant shares of this fleet are operating in the Western Mediterranean (33%) and in the Baltic Sea (27%). Combined, there have been ~80 individual services, with 45 connections. Regarding the major ship operators, seven services were provided by Stena Lines (11 vessels), six services by Brittany Ferries (6 vessels), while DFDS and Tallink operated four services each.

Table 4.5 shows average values for the observed fleet according to trading areas. By number, significant shares of the observed vessels operate in the Western Mediterranean (33%) and in the Baltic Sea (27%). The average vessel size varies between 36,000 GRT (Continent-UK) and around 27,000 GRT (Med East). The average passenger capacity is 1506, and the average lane metres are ~2000.

Table 4.4 RoPAX vessels scrapped 2012–2016, European owners (Shippax 2017)

Scrapping year	Vessel length (m)			Total	Average GRT	Average Ag
	<140	140–220	>220			
2012	7	4	–	11	8330	40.9
2013	1	8	–	9	17,400	32.8
2014	3	2	–	5	11,045	39.9
2015	4	2	–	6	9770	41.6
2016	3	4	–	7	14,670	35.8
Total	18	20	–	38	12,300	38.1

Table 4.5 European RoPAX fleet: average sizes on certain routes (Shippax 2017)

Corridor	No. of vessels	Average GRT	Average service speed (knots)	Average PAX capacity	Average lane metres	Average vehicles
Baltic Sea/intra-Scandinavian	31	34,007	23.4	1610	1835	494
Continent-UK	18	36,119	23.6	1257	2550	445
Intra-British Isles	7	35,033	23.3	1131	2483	566
Mediterranean West	39	30,410	25.9	1597	1854	437
Mediterranean East	14	26,838	27.8	1627	1720	481
Others	7	23,426	25.0	1313	1510	329
Total	116	31,684	24.9	1506	1958	460

4.2.3 The Double-Ended Ferries Market Segment

As described in the previous Sect. 4.2.2, RoPAX vessels play an essential role for transports of vehicles, trucks and passengers. Here, the smaller double-ended ferries (DE ferry) constitute a specific type of RoPAX ships, which usually operate on short distances, domestic routes and shallow waters. Double-Ended ferries have bow and stern-sided ramps for quick loading, allowing them to shuttle back and forth between terminals without having to turn around. This type of ferry is widely used in Scandinavian waters—most Norwegian fjord ferries are double ended—and in all European waters, especially between the Greek islands. The relevant vessel characteristics for DE ferries have been defined in HOLISHIP as follows:

- double-ended ferries of lengths between 80 and 120 m;
- passenger capacity min. 100 persons;
- lane metres min. 100 m;
- European routes.

In the beginning of 2017, the relevant DE ferry fleet consisted of 114 ships. The data includes three Greek-owned ships on order (newbuildings), which will enter the active fleet shortly. Due to the typically short travel distance, electrical propulsion systems are already a reality in the ferry industry. The DE ferry fleet includes two electrical ferries, operating in Norway and Finland. Of the 114 vessels, at least 102 units have been built on EU shipyards.

The average size of the fleet was 3180 GRT, the average passenger capacity was 620, and the average car capacity was 142. The majority of the vessels belong to the range of 80–100 m, whereas only one smaller vessel of less than 90 m entered the fleet since 2012. The average age of the fleet was 17.0 years. Ten out of the 114 vessels were operating on international voyages (SOLAS requirements), e.g. between Denmark and Germany as well as Denmark and Sweden. All other DE ferries have their route situated in the same country. A quarter of these 114 ferries were built before 1992, around one-third of the DE ferry fleet was delivered with the past ten years.

Looking at the deliveries between 2012 and 2016, only 14 units were added to the European-owned fleet, thereof nine vessels in 2016. As mentioned before, operators or shipowners often favour local or national yards; for example, from the 14 ferries delivered in the past five years, 12 have been built on European yards. The majority of the new vessels were in the range between 90 and 110 m length. The average GRT size of fleet deliveries was 1860, compared to 3100 GRT in the current fleet. Noteworthy is that car capacity[2] is the main influencing parameter in defining the size of the vessel. It is worth mentioning, that even small DE ferries with car capacities up to 100 are able to accommodate more than 800 passengers. With regard to speed, the variation within the ferry fleet is very high due to specific schedules or operational

[2]Car capacities: Small (S) = up to 100, Medium (M) = between 100 and 150 and Large (L) = 150 and above.

requirements—having a range from 8.0 to 22.0 kn with an average service speed of 13.5 kn in the defined DE ferry segment.

Regarding the market operations, the European DE ferry fleet is concentrated in two areas: the Mediterranean Sea (Med) and Scandinavia, especially in Norway. The "international trade" comprises links between Germany and Denmark, Sweden and Denmark, Cyprus and Turkey, whereas the international trade does not necessarily implicate long distances (e.g. Puttgarden–Rodby). Other routes include domestic services in Russia/Ukraine (Black Sea), Germany, Estonia and the UK.

The fleet trading in the Med outnumbers that of the other regions in terms of the number, GRT and car capacity. About half of the fleet considered operated in the Med (51 vessels) and a further 39 vessels in Scandinavia. A significant share of the intra-Scandinavian trade took place in Norwegian waters (35 vessels). Ten vessels were operating on international voyages. The analysed fleet includes the world's first electric-powered DE ferry "Ampere". This ferry was delivered in October 2014 and operates across Sognefjord between Lavik and Oppedal in Norway. A second electric-powered hybrid DE ferry "Elektra" has entered the active fleet in June 2017 and operates between Parainen and Nauvo in Finland. "Elektra" measures 97.92 m long and 15.20 m wide and has a capacity of 95 cars and 373 passengers.

Table 4.6 gives an overview of ship's dimensions in the different trading areas. Naturally, DE ferries on international (longer) routes show the highest average sizes with 6155 GRT, 387 lane metres and 173 cars. The max vessel size varies between 11,000 GRT and around 940 GRT. The comparison of the most important areas (Med and Scandinavia) shows that vessels in the Mediterranean are equipped with higher capacities with regard to cars and passengers.

As it can be seen from Table 4.6, there are no specific differences with regard to the defined sizes between the trading areas. Generally, large ferries mainly operate on international, longer distances. Two "international" German ferries with capacities less than 100 cars operate on short voyages between Germany and Denmark (Puttgarden–Rodby and List—Havneby/Romo).

In general, DE ferries which operate in Norwegian fjords are smaller units while larger types (>150 cars) are more common in the Mediterranean Sea (see Table 4.7).

4.2.4 Conclusions for the Future Development in the RoPAX Vessel Segment (Including DE Ferries)

At the beginning of 2017, there have been 82 RoPAX vessels on order in Europe (including DE Ferries). As mentioned before, ferries operating on different routes (areas) show different characteristics, which is, e.g., reflected in ship dimensions, as the sizes range from 1000 gross tons to over 50,000 gross tons, passenger capacity ranging from 200 to 2800 and lane metres from 100 to over 3300. With view to the current situation, the RoPAX business today is more freight-oriented. While the average sizes of newbuilding orders have been getting smaller in recent years,

Table 4.6 DE ferry fleet by trading areas at the start of 2017 (Elomatic based on Shippax 2017)

Trading area	No. of vessels	Average lane metres	Average PAX capacity	Average cars	Average GRT
International trade	10	387	702	173	6155
Scandinavia of which Norway	39	195	392	115	2907
	35	171	375	114	2824
Mediterranean of which Italy	51	275	733	146	2575
	15	296	627	141	3241
Greece	11	400	723	178	2225
Croatia	11	261	958	142	2822
Turkey	13	258	680	129	1718
Others (West Europe, Black Sea)	14	210	783	190	4010
Total	114	272	620	142	3180

Table 4.7 DE ferry fleet by trading areas and ship sizes at the start of 2017 (Elomatic based on Shippax 2017)

Trading area	Ship size[a]			Total
	S	*M*	*L*	
International trade	2	–	8	10
Scandinavia of which Norway	12	22	5	39
	11	19	5	35
Mediterranean of which Italy	8	24	19	51
	2	9	4	15
Greece	–	2	9	11
Croatia	–	9	2	11
Turkey	5	4	4	13
Others (West Europe, Black Sea)	–	3	11	14
Total	22	49	43	114

[a]Car capacities: Small (S) = up to 100, Medium (M) = between 100 and 150 and Large (L) = 150 and above

ships sizes will rise again from 2019 onward. Newbuilding activities may intensify to meet the requirements of current and future Emission Control Areas (ECAs). Hence, the order book contains several innovative vessels including LNG-powered and battery-driven units, but it is also worth mentioning, that the numbers of ferries with alternative propulsion systems are significantly below initial predictions. Therefore, ship designs complying with environmental regulations are becoming more and more important. At present, most of RoPAX vessels on order for European owners will be either dual-fuelled (LNG), hybrid or electric.

Based on the current and future technological and legislative developments, it is assumed that

- stricter environmental regulations will continue to become more stringent in the shipping and hence also in the RoPAX segment in the future, e.g. regulation on Energy Efficiency Design Index (EEDI);
- LNG and battery systems will become more and more popular;
- damage stability is another important theme in future: the research has focused much more on requiring the "unsinkable ship" (in June 2017, the IMO Maritime Safety Committee adopted new damage stability requirements for ferries and passenger ships).

It has to be stated that the RoPAX market is a very particular segment in the overall shipping sector. Ship operators concentrate often on domestic regions, aiming at optimisations of routes, fleets to achieve optimal economies of scale. Here, RoPAX vessels often have a complex design and are specially designed for specific routes and special characteristics (e.g. route length, focus on freight or passengers, etc.) according to the requirements by the operator. Therefore, ship dimensions and configurations are quite diverse which leads to the fact that comparisons of ships or corridors in which vessels are operating directly can hardly be done. However, newbuilding activities will intensify to meet environmental framework requirements, and thus, energy-saving, cost-effective, environment-friendly engineering is one of the new key areas of the RoPAX vessel segment.

4.3 Mission Requirement

The ship design process starts at the concept exploration stage where the mission and operational requirements (such as the required speed, seakeeping characteristics, cargo capacity) are defined by the relevant stakeholders.

4.3.1 Transport Task

The ship will be designed for a dedicated task. It can be a very specifically defined and long-term obligation with a clear vision of future traffic, based on the current situation and experience from the past. The vessel can be very well optimised because the required transport and related costs can be analysed far into the future. The optimisation can be performed over a long-time frame over the whole life cycle of the vessel. There is, naturally, also significant uncertainly regarding certain cost elements such as fuel cost development. A RoPAX on a given route and schedule would be a good example of such a scenario.

At the other end of the spectrum is the scenario where the freight amount and transport needs vary, which affects the freight rates. Tanker and bulker markets are examples of such shipping environments. In such environments, the optimisation perspective is shorter, because a newbuilding has to compete against the existing fleet upon delivery.

As indicated before, the main focus of HOLISHIP is on vessels of interest to the European shipbuilding industry and this includes RoPAX and double-ended ferries. The transport task, route and operational scenarios are well defined by the ensuing application cases, which will be elaborated in volume 2 of the present book.

4.3.2 Defining the Vessel

The shipowner and ship operator (if not the same) define the transport task and mission of the vessel. However, they commonly represent the party who supplies the vessel and its transport capacity (or any other task to be performed) to the shipping market. Diverging viewpoints are also evident for persons in different organisational roles. Technical personnel have to be convinced of the feasibility of the mission and the functionality of the vessel, as well as safety factors. Seafarers' viewpoints also have to be taken into account. The different perspectives for a new design can be summarised as follows:

- The general functionality of the vessel;
- Operational characteristics;
- Manner in which cargo handling and other ship operations are handled;
- Ship spaces; cargo areas, technical areas, service areas and accommodation areas; principal arrangements in these areas;
- Competitiveness in the shipping market;
- Safety issues in view of a continuously changing regulatory environment.

4.4 Initial Sizing

The first step in ship design is defining the main particulars of the new design, creating feasible values for the ship concept. Commonly, there is a starting point, a reference vessel, which is elaborated on for the future task. This is a solid base for assessing the many aspects that need to be considered in the design. The more reference materials available, the better the new concept can be assessed. Different non-dimensional ratios and meaningful charts can be derived from the reference database.

Payload efficiency is one measure of a ship's design quality. An extensive study was conducted on RoPAX and double-ended ferry spaces by the National Technical University of Athens (NTUA). The goal was to study the payload efficiency.

4.4.1 Definition of Concept Design

A concept may refer to fidelity stages of a design that is rather different. It may also refer to a simple sketch that demonstrates a novel ship solution or rather elaborate new design with a comprehensive design package.

The content and purpose of the different early design phases vary according to the vessel type and local shipbuilding traditions. Early design is associated with feasibility studies, concept design, initial design, early design, preliminary design, and contract design—all of which precede the basic design phase. There is no universal understanding of the scope of these activities. In this book, we consider the concept phase to be the first design phase. It is the design phase where feasibility is checked and where the main particulars are optimised. The concept phase includes a GA and other principal drawings, as well as the outline specification defining the main components. The concept phase accounts for only 1% of all design and engineering work. The impact on the design is, however, global and, therefore, crucial.

The concept design phase is followed by basic design where the concept design is fine-tuned. The following tasks are also performed while related documents are generated:

- classification drawings;
- arrangements of all spaces;
- system diagrams required calculations and operational descriptions based on technology supplier documentation;
- full specification;
- all data required as the basis for detailed design.

In some cases, ship contracts are signed based on concept-level documentation only, but may also include content from the basic design phase. This varies from one shipyard to another and according to the vessel type. As such, the content of the design contract may vary and does not necessarily exactly match the content of the design package.

4.4.2 Regression Analysis

Initial sizing is traditionally based on knowledge of comparative data of existing vessels and the experience of the designer in applying that knowledge for the future project. A reference vessel is used as a starting point for further modifications to meet the given task and other requirements. Projects are very seldom done from scratch. The reason for this is that the shipowner (and the financing institutions behind it) requires a proven design based on validated information to demonstrate the cash flow analysis for the project. As such, novel solutions are only rarely implemented. In many cases, really new concepts require a funding instrument to cover the inherent risk of innovations or R&D to be conducted.

In the HOLISHIP project, the RoPAX and double-ended ferry application cases are the subjects of the concept design phase, i.e. the subjects of main particular optimisation. Therefore, the parameters were studied for these vessel types. However, this data was used as reference, by means of ratios and factors derived out of the data.

For the *double-ended ferry*, the following limitations were set to collect the reference material:

- Load between 80 and 120 m;
- Over 100 lane metres and capacity of more than 100 PAX;
- Operation in Europe.

The reference materials consist of 118 vessels, of which only 10 operate on international routes subject to SOLAS regulations. Based on this analysis, several regressions were drawn, which formed the basis for the initial sizing of the double-ended ferry. Three ferries of different sizes were produced. The transport capacities of these vessels and a comparison with the reference data are illustrated in Fig. 4.4.

Beyond the capacity, all the meaningful main particulars were also collected and processed into equations and ratios to define the initial main particulars and to compare the generated initial concepts to the existing fleet of similar types of vessels. The following regression-based initial main particulars were defined for the presently proposed three double-ended ferries: L, B, T, H, Dwt, GT. These three initially defined main particular sets serve as the starting point for the detailed design

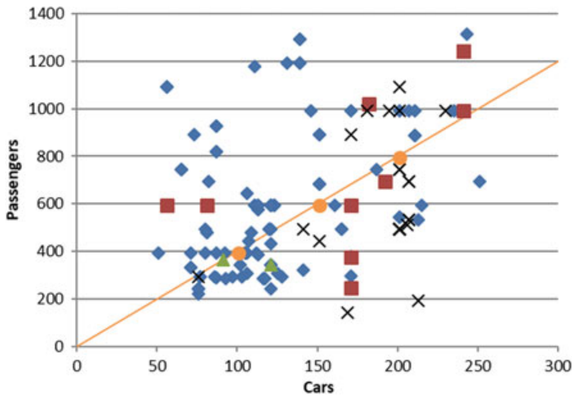

Fig. 4.4 DE ferries by transport capacity. The SOLAS ferries are marked in red and the non-SOLAS ferries are marked in blue. Electric/hybrid ferries are marked in green. Additional Greek-built ferries are marked with black crosses. The present DE ferry proposal data is marked in orange

to be elaborated in volume 2 of this book. It will be optimised for a given operational environment, transport task and operational profile.

All the main particulars are subject to variations because of the optimisation process. Each optimisation task/scenario is assumed in terms of general arrangements and main outfitting topologically identical, e.g. the number of propulsors does not change, but the required output may change depending the resistance of the vessel. The variations can be optimised separately if needed. Topologically, different solutions can be compared with each other in order to find the best solution.

For the RoPAX application case, a comprehensive study of the main particulars was also done in order to allow comparison and the assessment of the existing fleet. This will be elaborated in other chapters and in volume 2 of the present book.

4.4.3 Other Stakeholders and Their Impact

A ship concept is studied from different viewpoints by various parties and stakeholders in the early design phase. It is necessary, therefore, that all the required information is based on accurate and up-to-date design materials, which form the basis of the general arrangement. It is also important that all the documents are based on the same information, calculations, and drawings and that no conflicts exist. The main stakeholders are the shipowner (and operator if different), possibly the ship operator's customer, and authorities such as classification societies and flag authorities (see Fig. 4.5).

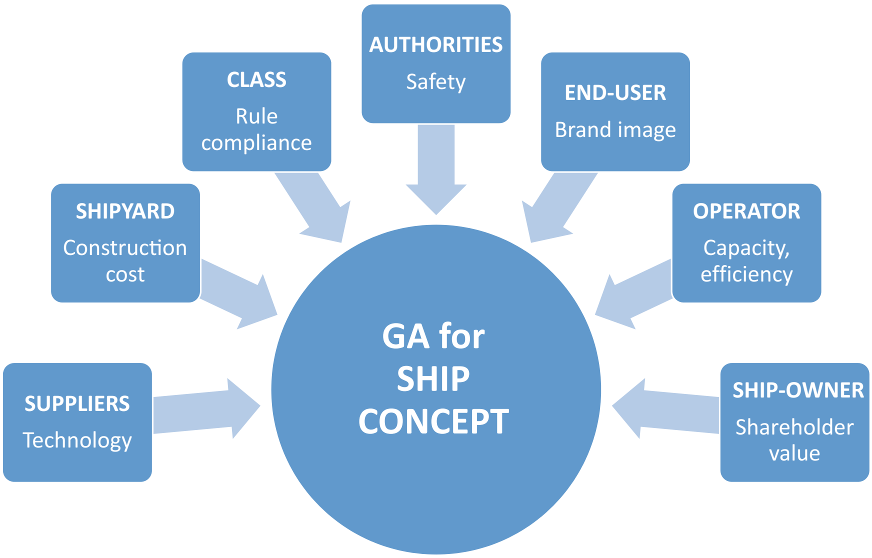

Fig. 4.5 General arrangement requirements and different stakeholders that have a major influence on the ship concept development and their dominant viewpoints. The naval architect confirms that all relevant requirements are considered in the ship concept

As a builder, the shipyard needs the GA and other concept phase documentation as a basis for the succeeding design phases. The concept will be verified and validated according to the shipyard's own experience, while possible elaborations will be made. This forms the basis for cost estimates of the ship contract process. It is important, therefore, that all parameters that influence costs are fixed for the cost estimate. Also, the performance of the vessel has to be indicated, but needs to be verified. Factors that affect the ship's building process are not included in the concept design.

All classification societies' and flag authorities' requirements need to be taken into account. However, the target of the task is fulfilling the ship operator's transport mission, while the requirements of other parties are constraints for the concept. A good design is well optimised and competitive in the shipping market, but fulfils the requirements of all related parties.

4.5 Operational Profiles

Operational profiling is the study of the tasks performed by a vessel or intended to be by a not yet realised concept craft. The input data for such a study will typically be a sailing route, weather along this route, amount of cargo and sailing speed. Combining these data may give an indication of the workload, and thus the margins of the vessel, or give guidelines for the design of a new concept.

An operational profile gives information of how a vessel accomplishes a set of tasks. These tasks may be sailing, station keeping utilising dynamic positioning (DP), towing, etc. Depending on environmental or economic factors, the tasks may be accomplished in several ways (modes), e.g. different possible power settings, choice of speed, different number of generators running and choice of heading. The mode combined with the operational limits and the efficiency of the vessel results in a varying time to complete a task.

4.5.1 Other Stakeholders and Their Impact

The task of creating an operational profile is increasing rapidly as the amount of data for it to be based on increases and considering, e.g., both cargo load and weather to be combined into speed losses along a route may be an extensive job. Thus, development of a dedicated software tool is a natural path to obtain detailed and accurate operational profiling.

Such a tool should derive an operational profile depending on

- Vessel hydrodynamic performance on the basis of statistical data;
- Weather data from various digital data services (e.g. metocean data);
- Sailing pattern data;
  - Based on geographical routes consisting of waypoints;
  - Mission comprising tasks and modes (e.g. sailing, port call, DP, etc.).

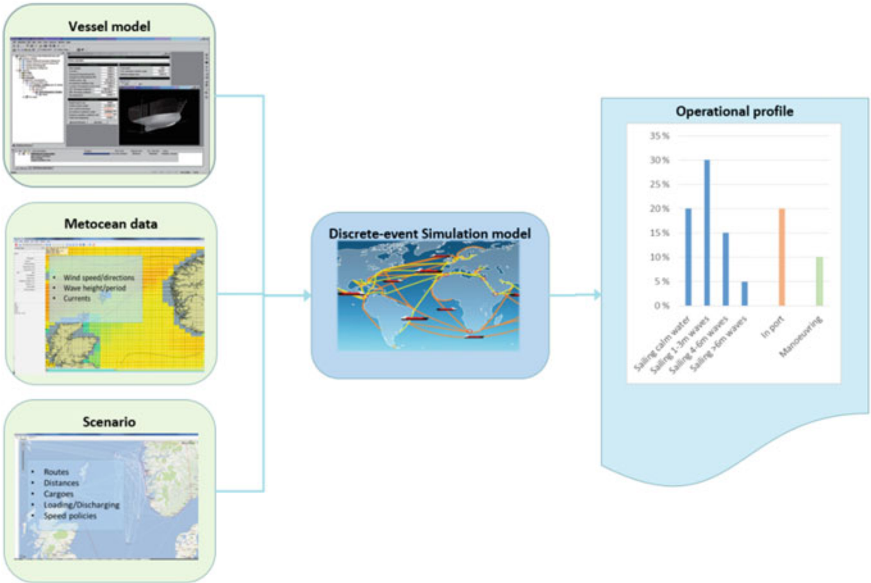

Fig. 4.6 Information flow between the different modules of the profiling tool by SINTEF

The output of the operational profiling tool should give an indication on the vessels overall performance on the specified tasks as one or more Key Performance Indicators (KPI), making it achievable to compare competing designs and vessels. Such KPIs may be

- Time spent for different tasks;
- Power consumed;
- The modes applied to accomplish the tasks;
- Environmental and economic footprint.

The software tool is divided into vessel, scenario, weather and simulation modules. Figure 4.6 shows the data flow between the modules.

4.5.2 Operational Profiling Tool—Input

4.5.2.1 Vessel Model/Data

A vessel model to be used to solve the tasks defined in the mission set-up may be of varying detail. At the most basic, the vessel may be assumed without information on power and hydrodynamic factors, simply sailing the given route at the requested speed. In this case, the operational profiling will be reduced to weather profiling, as no power consumption will be available in the output, and all tasks will be accomplished at a predefined time.

On the other hand, a vessel model may take into account the hydrodynamic performance, giving varying resistance dependent on the weather state, propulsors reflecting the efficiency to convert mechanical power into thrust, and a machinery model calculating the necessary fuel required to generate the needed power.

The choice of level of detail of the vessel model will be decided from the required output from the operational profiling, as well as the availability of detailed models at different stages of a design process.

4.5.2.2 Historical Weather (Metocean) Data

Historical statistical data for wind and waves in relevant areas may come from open hindcast models of various sources, or from user-defined weather profiles. For the operational profiling performed in the HOLISHIP project, the "ERA-Interim" and "ERA5" weather hindsight model from the European Centre for Medium-Range Weather Forecasts (ECMWF) are used. This model is based on real-world weather observations at discrete points, to give a global estimate of various weather conditions, e.g. the sea state at any given time and place.

4.5.2.3 Scenario Set-up

Geographical information about the geographical area the ship in intended to operate within is extracted from historical track records, such as from the automatic information system (AIS), or routes that may be imported from Keyhole Markup Language (KML) files. Either way, this information will specify static places such as ports, offshore installations or standby points as latitude/longitude pairs, and possible routes between these places as lists of waypoints.

Further, the geographical information is applied in a mission set-up, defining the tasks of the vessel, and to a certain extent which mode will be utilised to accomplish the tasks. Some logic for automatically choosing the mode and handle operational limits is available, such as breaking DP operation if the weather becomes severe and reducing the sailing speed if enough propulsion power is not available.

The final scenario is a mission comprising a set of tasks to be performed once or repeatedly by the vessel in question.

4.5.3 Operational Profiling Tool—Simulation

The operational profiling is done by simulating the vessel during the specified scenario. However, as the profile may need to reflect several years of operation, several groups of simulation strategies need to be considered. First, there may be dynamic simulations of ship's movement/motions by means of the solution of partial differential equations and these simulations should be close to the physical world; however, simulations of this type are usually very time-consuming and thus unsuitable for such time frames, while they handle discrete events poorly (Siprelle and Phelps 1997). Second, there is discrete rate simulation, which typically mixes discrete events with continuous simulation by solving the differential equations at each discrete event (Béchard and Côté 2013). The third group comprises discrete event simulations, where the simulation clock advances in unequal relatively large steps due to some events. The latter approach was chosen, as avoiding solving differential equations during simulation is likely to keep the time consumption at a minimum.

A subgroup of discrete event simulation is agent-based simulations. This group is suitable for problems where there is interaction between the items or some planning is involved (Bonabeau 2002). When the simulation clock advances, all items, here called agents, are woken up and can respond to the changed situation. Each agent finishes its cycle by requesting the next time it should be sampled and falls asleep.

The simulation performed for operational profiling involves at least a weather agent and a ship agent. Given that the simulation currently is at time t_i the weather agent will submit next time that the weather data changes, say t^w_{i+1}, while the vessel agent submits the time that the vessel will arrive at the next waypoint, t^v_{i+1}. The simulator will choose the time that is closest to t_i, and simulation will proceed to t_{i+1} by sampling all agents using the simulation state of time t_i. Figure 4.7 illustrates this concept.

The result of the simulation is a time series, typically with time steps of a few hours length. The recorded simulation state between each time step is considered constant, representing a statistical interpretation of the state, e.g. significant wave height and average vessel speed.

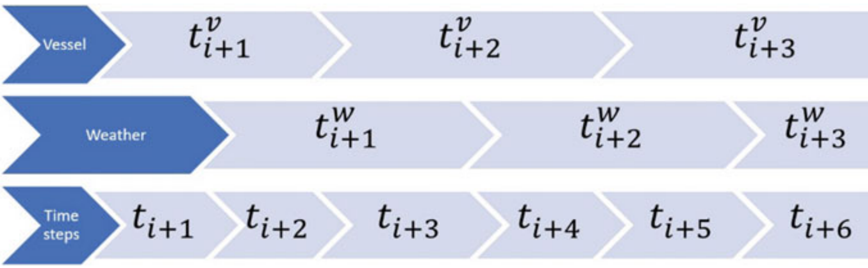

Fig. 4.7 Illustration of discrete event simulation using agent-based modelling

4.5.4 Operational Profiling Tool—Results: RoPAX Application Case

To demonstrate the tools' capability to generate a weather profile, an application case using a Roll-on–roll-off passenger vessel (RoPAX) is analysed (vessel illustrated in Fig. 4.8). The particular case is a design by Uljanik Shipyard, of 217 m overall length, and 10,000 tons of deadweight. The vessel is intended to operate between Barcelona and Ibiza. Figure 4.9 shows the route imported into the operational profiling tool.

From the designer, it is known that the vessel is estimated to use 8.5 h to Ibiza when leaving Barcelona at 10 pm, and 6.5 h back to Barcelona when leaving at 11:30 am, sailing at 19 and 24 knots, respectively. In addition, one hour is estimated to berth at each port; however, this is neglected in the profiling as the berthing operation is executed in the waterfront. Figure 4.10 shows the mission set-up page in the operational profiling tool for the application case. Note that the "at port" event is set up to wait for a time of day, to reflect the timetable that the vessel will serve. As Fig. 4.11 shows simulation starts at January 1, 2017, and ends at January 1, 2018. The start time at 10 pm and initial position of Barcelona matches the timetable described above. Weather data is retrieved from ECMWF "ERA5" weather model.

As no dynamic model of the vessel is available in the operational profiling tool, a simple model that keeps the desired heading and speed regardless of the weather is used. This is efficient for weather profiling on repeating routes, as any delays due to weather are likely to be compensated by a shorter port stay. However, no power consumption is available from this model.

The operational profiling tools post-processor can produce a histogram showing the relative time spent on different tasks, shown in Fig. 4.12. Due to the simplicity of the vessel model, it is trivial to predict the relative time spent at port versus time spent sailing, i.e. 37.5 and 62.5% respectively, indicating that the strategy for reproducing a timetable in the tool works as intended.

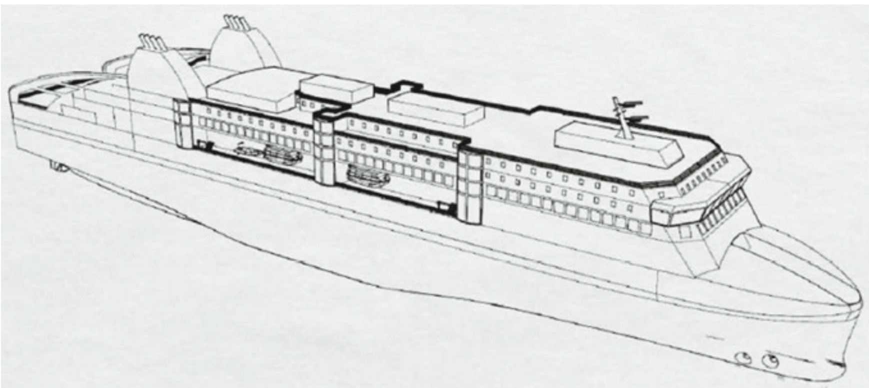

Fig. 4.8 RoPAX sketch by Uljanik Shipyard

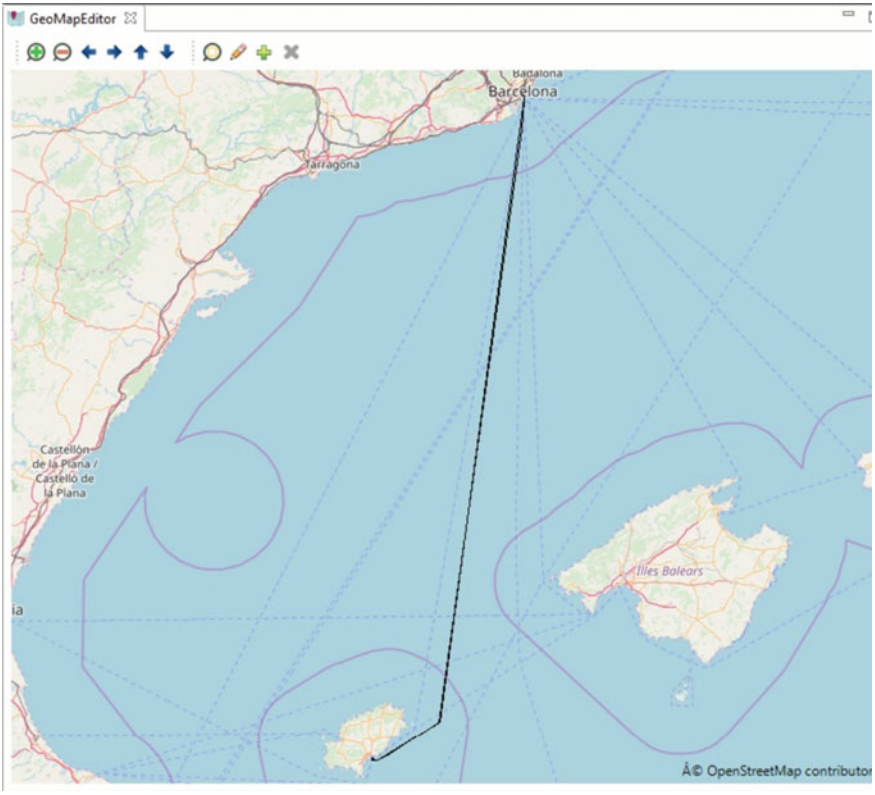

Fig. 4.9 Route used in RoPAX application case

Post-processing of the time series may give valuable statistical information of the environment that the simulated vessel encounters during operation. Figure 4.13 shows extracted histograms of significant wave height, and Fig. 4.14 average wind speed. These clearly indicate that the significant wave height is usually between 0 and 1 m, and rarely above 2 m. Such statistics are likely to be useful when optimising the hydrodynamics of the vessel, as it gives indications of the weather that will be most relevant while solving the tasks at hand.

Scatter charts may be generated, for further insight into the behaviour of the sea. For example, comparing significant wave height and wind speed gives good indications of how these correlates; see Fig. 4.15.

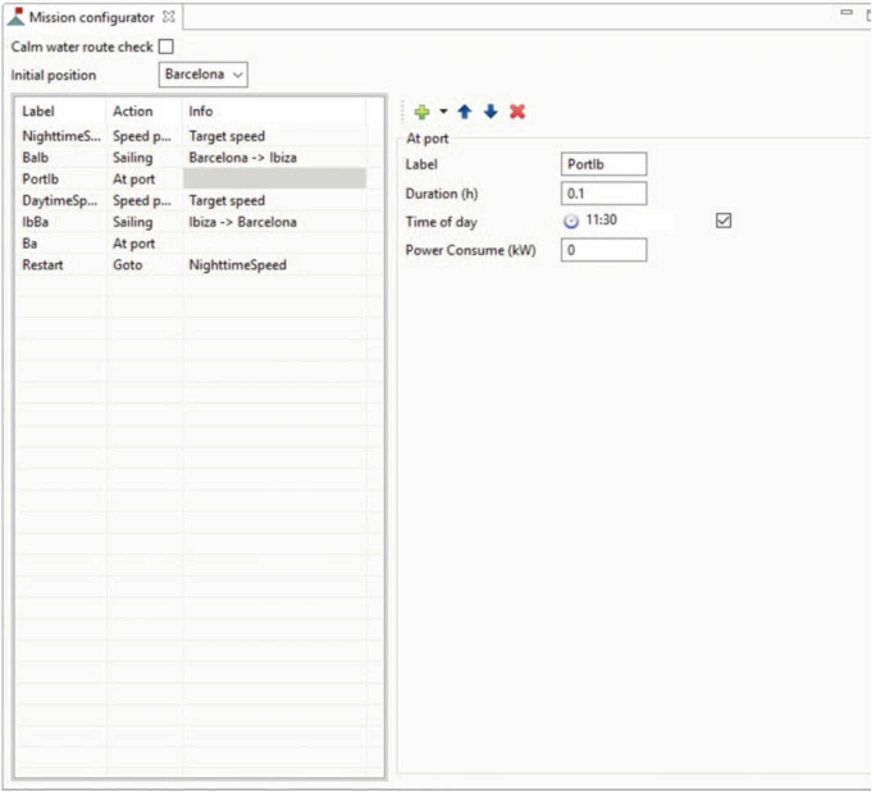

Fig. 4.10 Screenshot from tool set-up in RoPAX application case, showing mission configuration screen

4.5.5 Operational Profiling Tool—Results: DE Ferry Application Case

For an application case with a high level of scheduling, double-ended ferries are an interesting segment of vessels. These carry both passengers and vehicles, are usually relatively small compared to their RoPAX counterparts and serve relatively short routes. These types of vessels are widely used in Europe, from sheltered inland waters to harsher conditions in the coastlines of the North Sea (Yrjänäinen and Florean 2018). This makes operational profiling significant, to reveal the expected conditions in the area that a new concept vessel will operate.

For a reference scenario, Yrjänäinen and Florean (2018) suggest a route with a round-trip length of 10 nautical miles (NM), 15 daily round trips, each lasting 1 h. Further, a terminal stay is estimated to 2 min, and additionally 3 s for each car that is loaded/unloaded. A suitable route is the Korpo–Houtskar route in Finland, illustrated in Fig. 4.16, having a round-trip distance of almost 10 NM. This route is operated

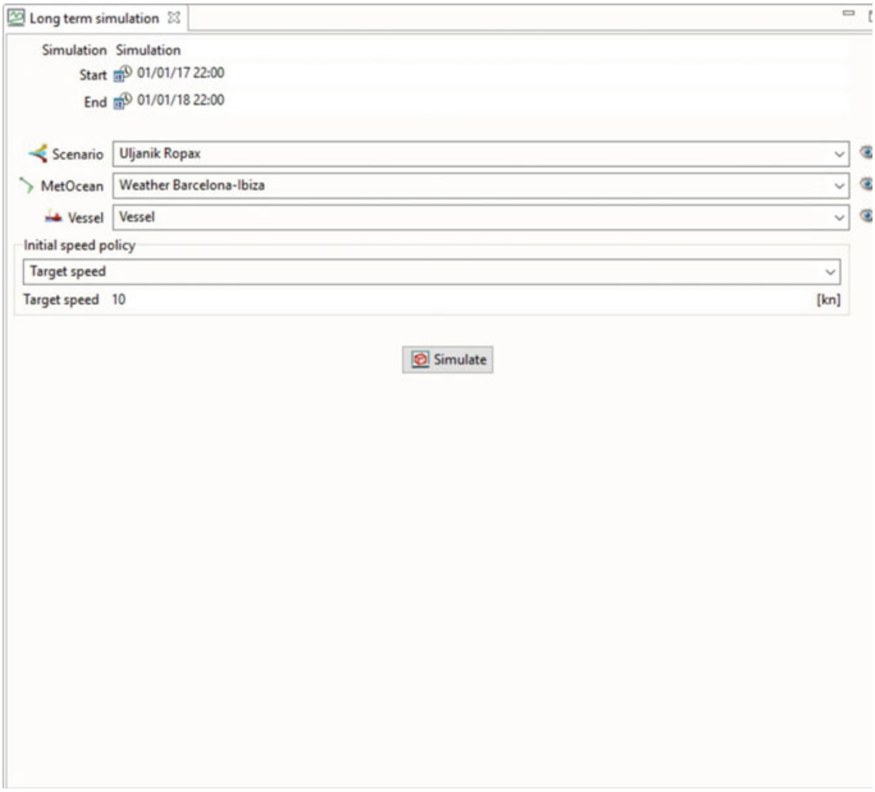

Fig. 4.11 Screenshot from tool set-up in RoPAX application case, showing simulation configuration screen with start and end time screen with start and end time

by two ferries capable of carrying 27 and 65 cars (Finferries: Finland Archipelago Shipping, 2018); thus, it seems appropriate to choose a ferry in the "small" category in Yrjänäinen and Florean (2018), capable of carrying 100 cars. This will imply an estimated loading/unloading time of 12 min. To keep a schedule of 1 h for each round trip, considering the time needed for loading/unloading, the vessel must keep an average sailing speed of 15.9 knots. For simplicity, the schedule is chosen to start at 7 am each day, repeating the round trip 15 times, ending the day's service at 10 pm. The vessel then stays at the port until 7 am the next day. Figure 4.17 illustrates how the schedule is modelled in the operational profiling tool, and Fig. 4.18 shows the resulting mission set-up page in the operational profiling tool.

As in Sect. 4.5.4, no dynamic model is available, and a simplified model is chosen. This model will still follow the route and schedule; however, any delays due to harsh weather conditions and variable power consumption will not be accounted for in the simulation. Considering the constant time spent at port and sailing, the distribution should be 37.5% sailing and 62.5% at the port, which Fig. 4.19 confirms.

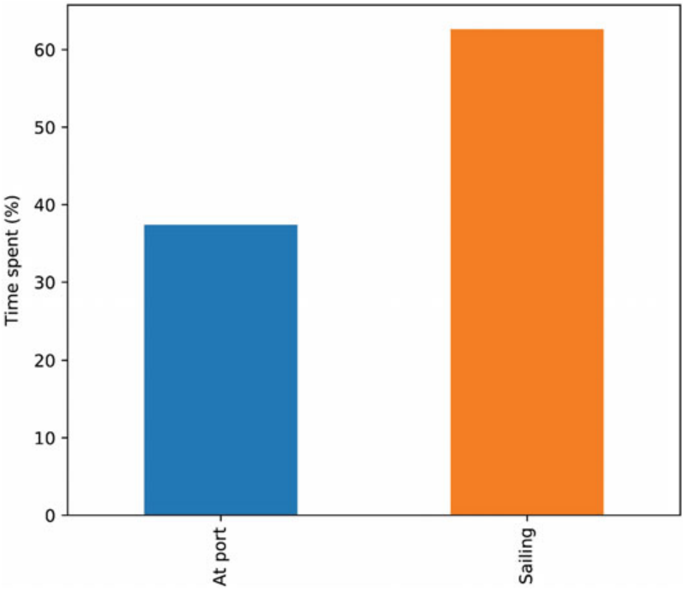

Fig. 4.12 Histogram for time spent sailing versus at port in RoPAX application case

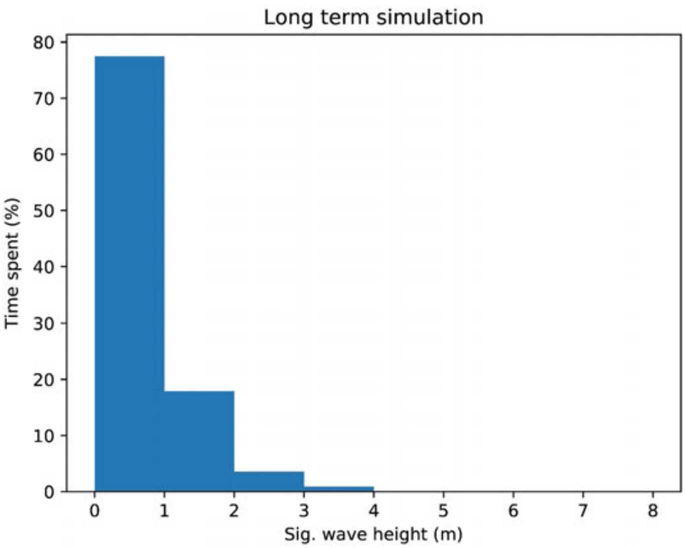

Fig. 4.13 Histogram for time spent in various sea states in the RoPAX application case

Figures 4.20 and 4.21 show the distribution of significant wave heights and wind speeds, respectively. The significant wave height is below 1 m approximately 90% of the time, which should be an important input in the vessel design phase. The

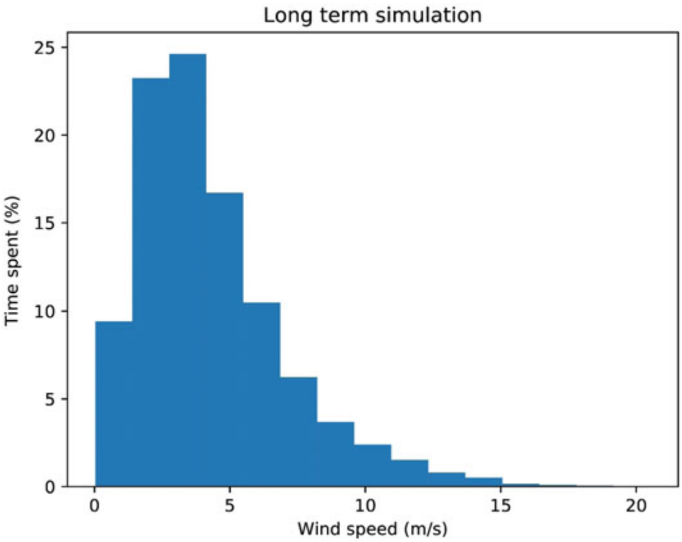

Fig. 4.14 Histogram for time spent in various wind speeds in the RoPAX application case

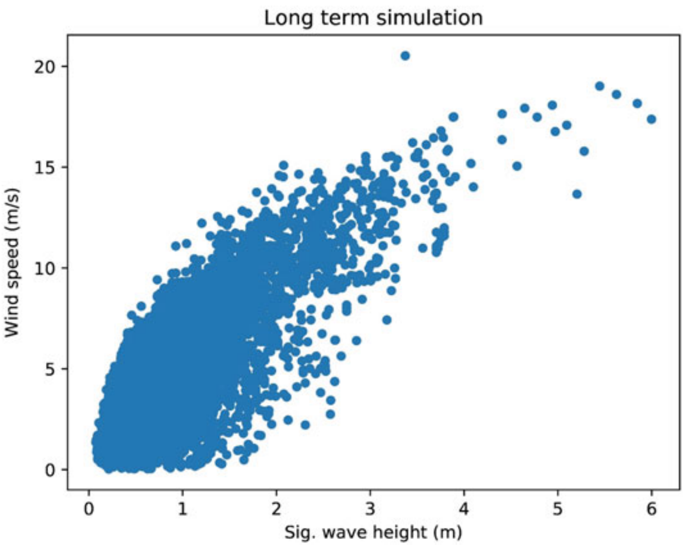

Fig. 4.15 Scatter chart correlating significant wave height and wind speeds in RoPAX application case

distribution of wind speeds may also be used when designing the superstructure of the vessel, giving guidelines on how much aerodynamics should be considered.

To get more insight into how the wave heights and wind speeds are distributed across the simulation, the average values of these may be found on a monthly basis,

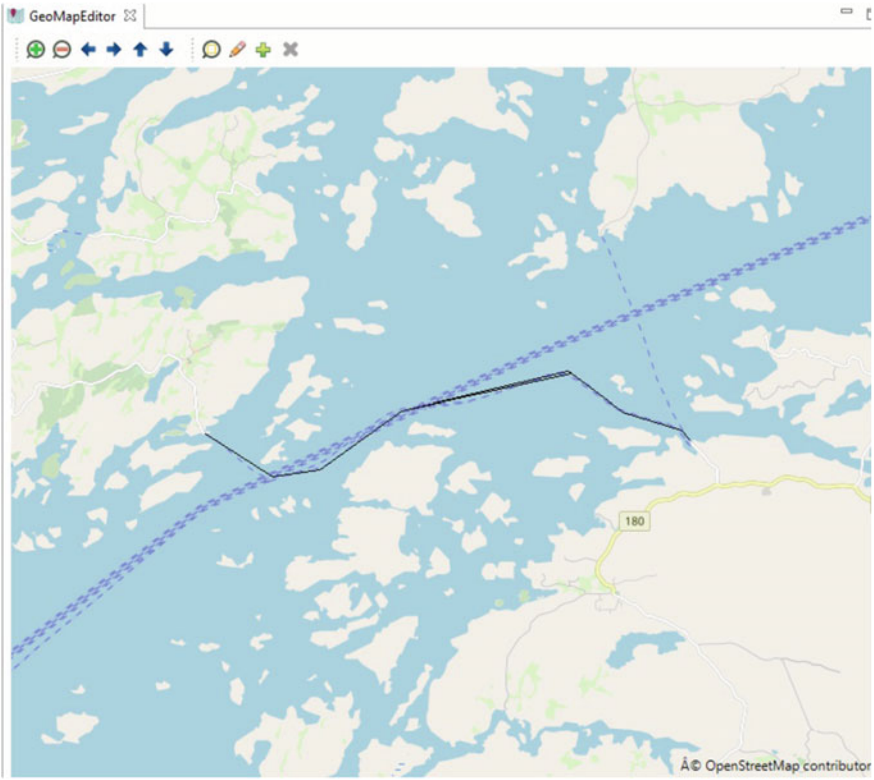

Fig. 4.16 Route between Korpo and Houtskar in Finland, used in DE ferry application case

as shown in Fig. 4.22. This illustrates, as may be expected, that the weather is harsher during the winter months. If the schedule of the vessel alters during the year, this information may be applied to evaluate the significance of Figs. 4.20 and 4.21. Also, Fig. 4.23 shows a significantly higher correlation between significant wave height and wind speed than in the equivalent analysis in the RoPAX application case. This is noteworthy, as both application cases apply weather data from the same source (ECMWF ERA5). An explanation of this may be that the ferry operates in relatively sheltered waters, where swells from the Baltic Sea are reduced by the surrounding land masses, while the route in the RoPAX application case is more exposed to the Mediterranean. In any case, this correlation between wind and waves may be exploited in the design phase of the ferry to identify the worst-case weather conditions that the vessel must be designed to handle, leading to a less conservative and more effective design.

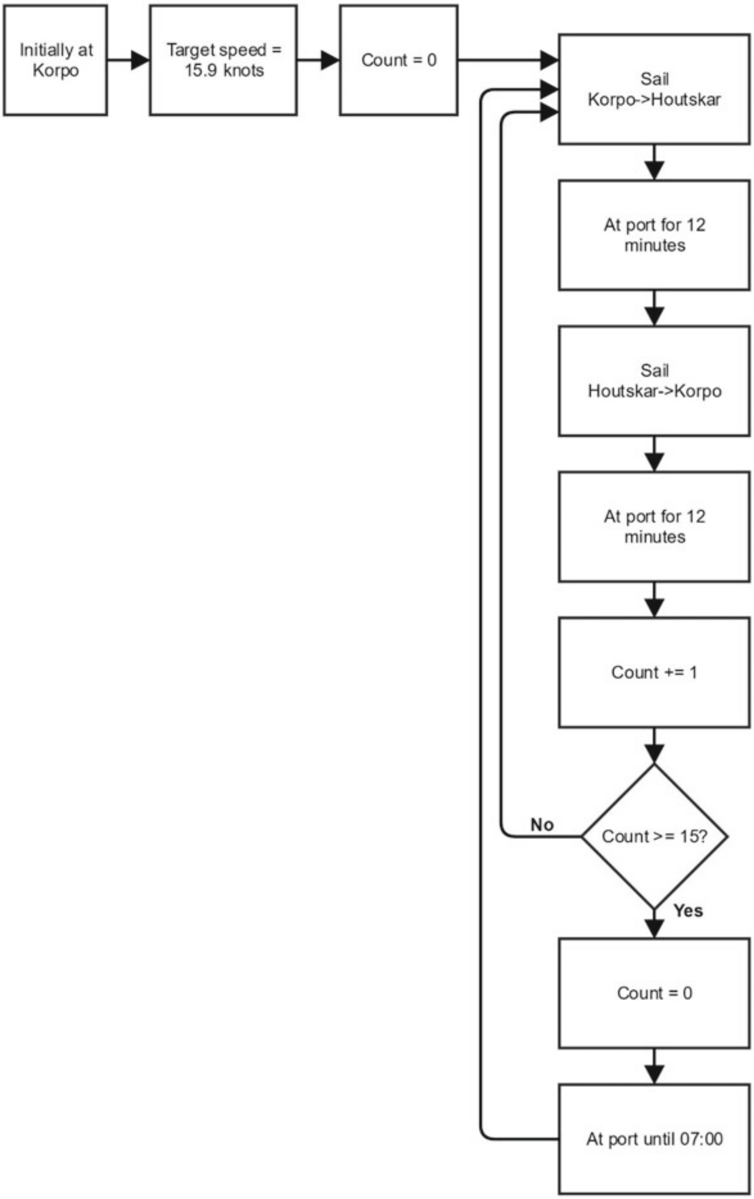

Fig. 4.17 Flowchart illustrating the mission set-up in DE ferry application case

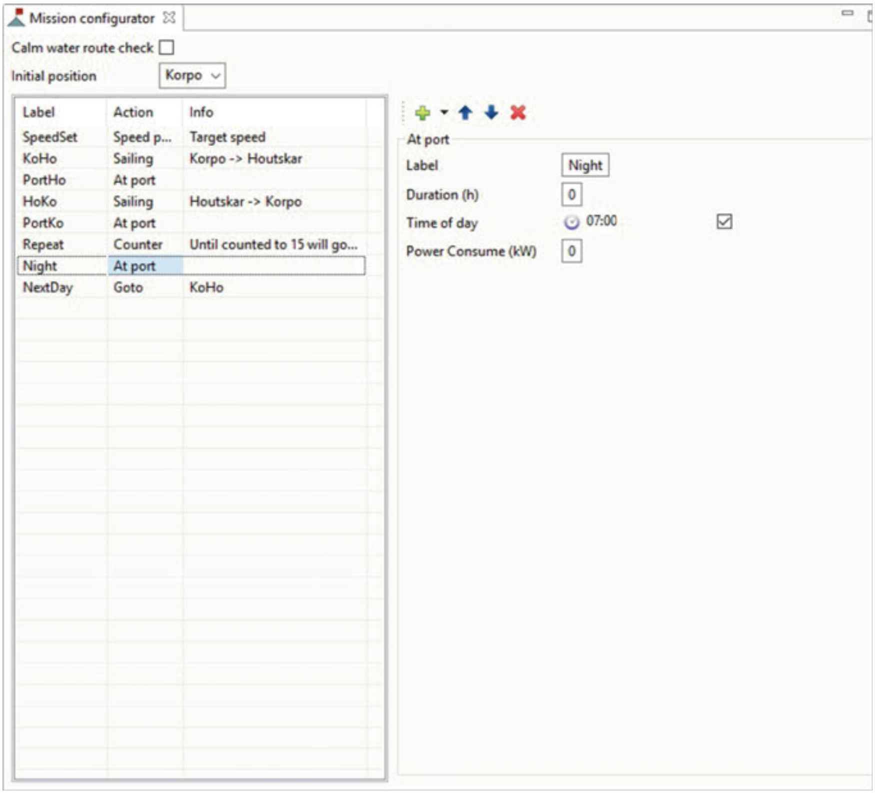

Fig. 4.18 Mission set-up page in the operational profiling tool in DE ferry application case

4.5.6 Operational Profiling Tool—Results: OSV Application Case

As an example application of the operational profiling tool, an offshore supply vessel (OSV) is chosen (see Fig. 4.24). An OSV is designed to carry cargo to and from a relatively stationary installation at sea, e.g. oil platforms. It has typically a large cargo deck, and the ability to do station keeping using dynamic positioning (DP), while loading to and from the installation.

As this type of vessels often have relatively long, but still repeating and predictable sailing patterns, they are well suited for operational profiling.

The Rolls Royce UT776 Work Package is a large OSV and suited to demonstrate both port calls, sailing and DP operations.

A fictive, though realistic route from the harbour of Ågotnes, to the Ekofisk oil fields south-west of Norway is created, illustrated by Fig. 4.25. The mission comprises sailing from Ågotnes to Ekofisk at 12 knots, stay for 8 h in DP mode, sail Ekofisk–Ågotnes, where the vessel will remain at port for 24 h. During the sailing,

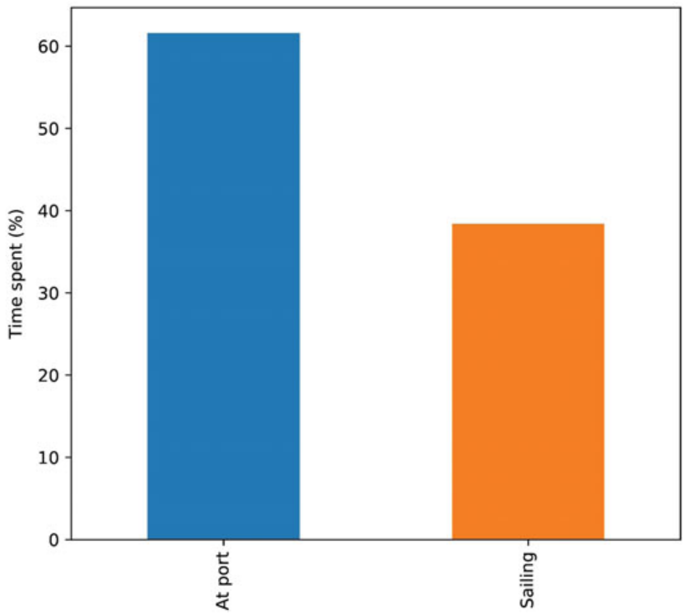

Fig. 4.19 Histogram for time spent sailing versus at port for DE ferry application case

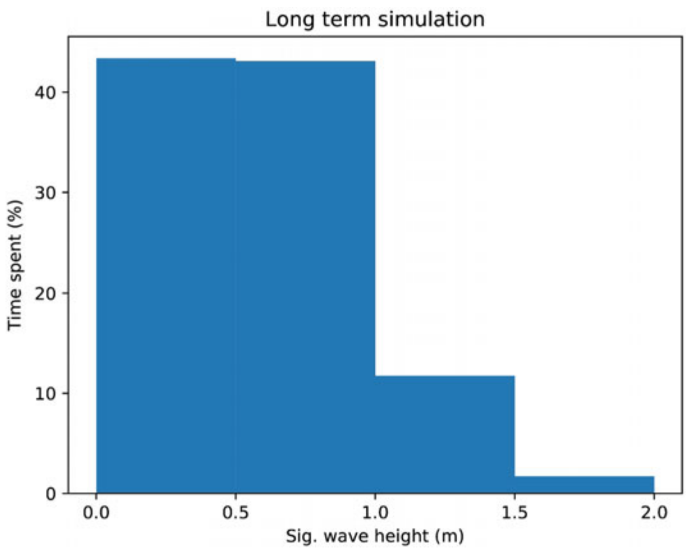

Fig. 4.20 Histogram showing relative amount of time the vessel spends in various significant wave heights in DE ferry application case

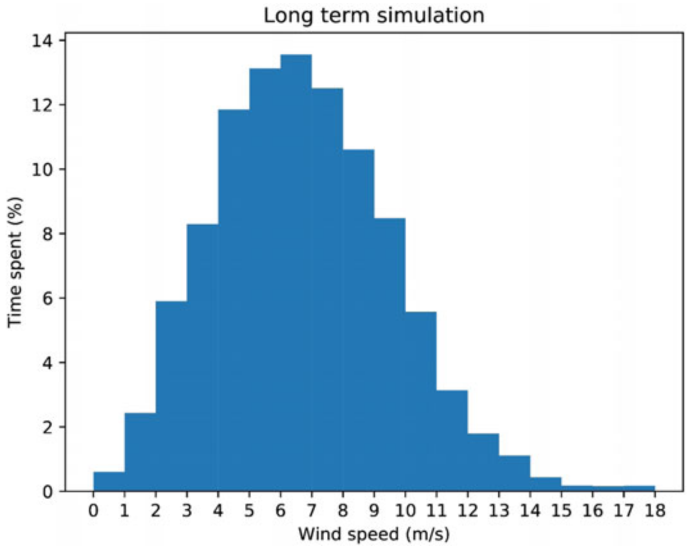

Fig. 4.21 Histogram showing relative amount of time the vessel spends in various wind speeds in DE ferry application case

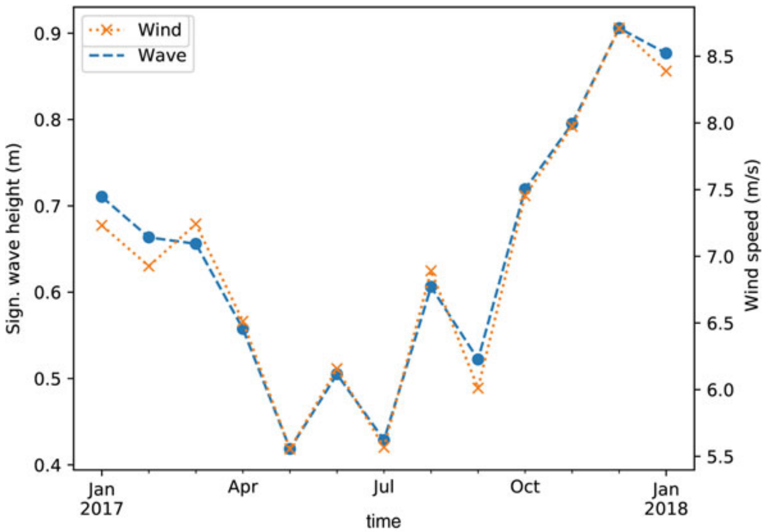

Fig. 4.22 Average wave height and wind speed on monthly basis for DE ferry application case

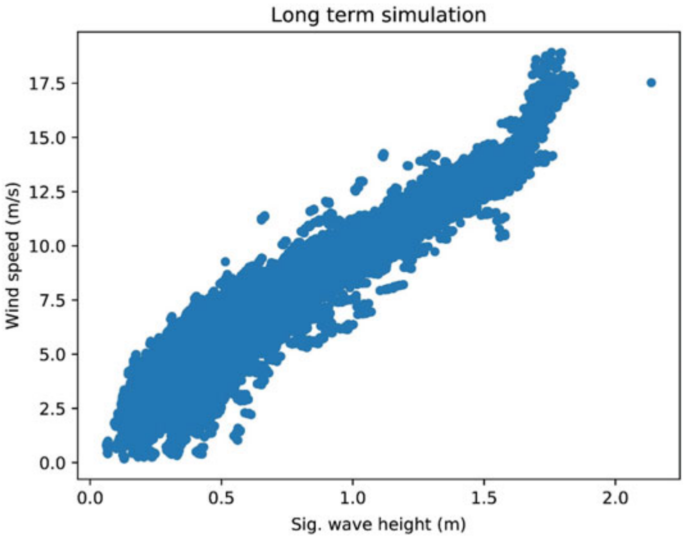

Fig. 4.23 Scatter chart correlating significant wave height and wind speed for DE ferry application case

Fig. 4.24 OSV used in the application case example (Roll Royce Marine)

a power limit of 4400 kw is applied, such that if the required power becomes more than this, the speed will be reduced to satisfy this constraint. The mission is then restarted.

A fictive, though realistic route from the harbour of Ågotnes, to the Ekofisk oil fields south-west of Norway is created. The mission comprises sailing from Ågotnes to Ekofisk at 12 knots, stay for 8 h in DP mode, sail Ekofisk–Ågotnes, where the vessel will remain at port for 24 h. During the sailing, a power limit of 4400 kw is applied, such that if the required power becomes more than this, the speed will be reduced to satisfy this constraint. The mission is then restarted.

Fig. 4.25 Geographical route used in the OSV application case

As the simulation progresses, different factors will affect how long the vessel will remain in each task; for example, the achieved sailing speed will determine how much time is needed to sail a given route. The time at port and in DP is predetermined in the mission set-up; however, severe weather conditions may force an early termination of a DP operation. Thus, a basic and interesting analysis is the relative time spent accomplishing each task, as illustrated in Fig. 4.26.

The output from the simulation is a time series consisting of samples of the state of the simulation. However, in contrast to a traditional time domain simulation, the variables in the series represent the average state of the vessel and environment between the sample points. Figure 4.27 shows a snippet of 160 h from the 8747 h of simulation. As Fig. 4.27 illustrates, at around simulation time 800 h, when the wave height becomes severe, there is not enough power installed to maintain 12 knots; thus, the speed must be reduced. Further, the 24 h at port and 8 h in station keeping can be seen repeating as the vessel speed becomes zero in these tasks.

Post-processing of the time series may give valuable statistical information of the environment that the simulated vessel encounters during operation. Figure 4.28 shows extracted histograms of significant wave height and average wind speed in the time steps. Such statistics are likely to be useful to optimise the hydrodynamics

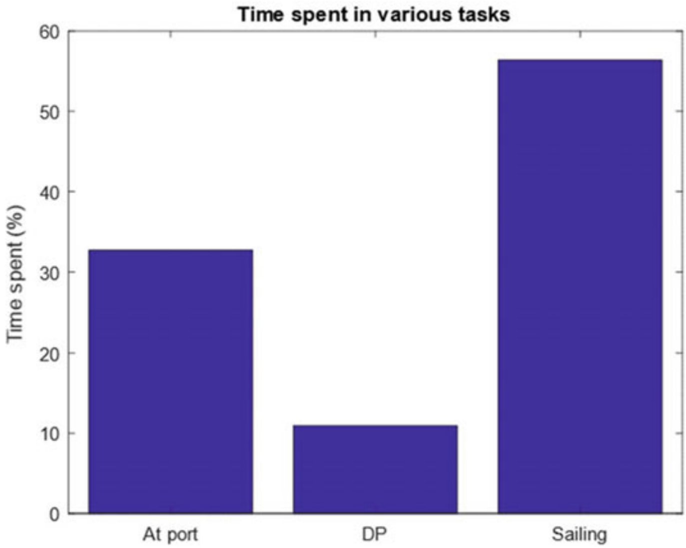

Fig. 4.26 Histogram showing relative time spent by an OSV in each task

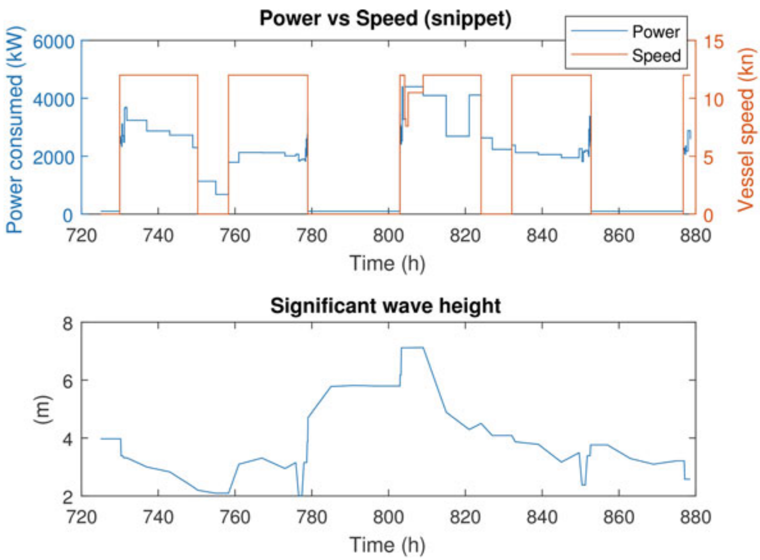

Fig. 4.27 Power, speed and wave height time domain output from simulation of an OSV operation

of the vessel, as it gives indications of the weather that will be most relevant while solving the tasks in hand.

Further, post-processing of the time series gives valuable statistical information of the power consumed for propulsion; see Fig. 4.29. This chart may be correlated

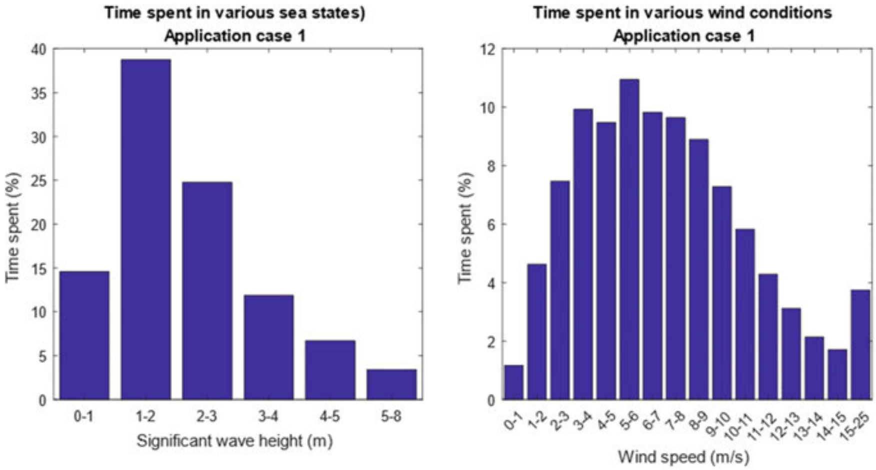

Fig. 4.28 Histogram of significant wave height and wind speed during OSV simulation

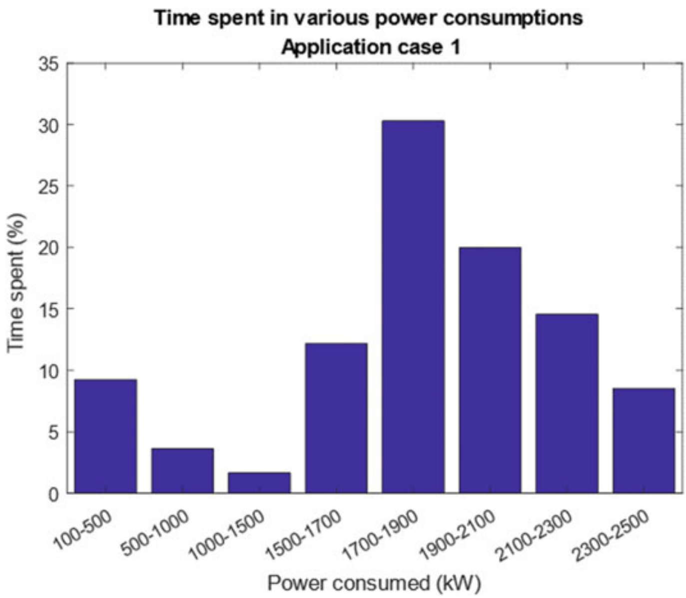

Fig. 4.29 Histogram of different power consumptions of OSV during sailing

with the different power modes of the vessel and will typically give an indication if the power plant of the vessel is operating at an optimal level. In a design phase, it may give input to a possible reconsideration of the size or type of power plant to ensure effective operation.

Note that there are two peaks in the histogram, counterintuitive to the single peak of the wave height and wind speed. This is due to the relatively low power consumption while in DP, as well as a static 100 kW power consumption while at port.

4.5.7 Operational Profiling Tool—Discussion

Operational profiling may be used for different purposes, in different phases of a vessel life cycle, from early concept design to route planning for an existing vessel. Common for all use cases is that an operational profile gives the designer or ship operator a more robust basis for decisions with great economic and environmental impact.

A dedicated tool for generating operational profiles lowers the threshold for this discipline, while it opens the opportunity for usage of large data amount in the creation of the profiles. The ability to base the profile upon several years of statistical data gives the results high credibility.

A promising next step is to integrate the operational profiling tool with automatic optimisation tools as being developed in the HOLISHIP project, to optimise the vessel's hull, routes and other relevant variables by evaluating a large amount of operational profiles over ship's life cycle.

4.6 Designing a Ship Concept for a Given Task by the Use of the Intelligent GA

The general arrangement of a ship is the principal document used to present the ship's basic dimensions and features. It is drawn up by a naval architect based on prior knowledge and experience. The design of a ship is a creative process, but it is often heavily based on an existing ship, a proven design, which is incrementally elaborated on in every generation of the vessel. It is also updated with every generation to respond to actual external parameters, such as fuel costs and the latest requirements of the authorities and classification societies. Naturally, the technical development of systems and equipment is incorporated into the vessel design Papanikolaou (2014).

The objective of the HOLISHIP project and the intelligent general arrangement elaborated in this chapter is to improve the traditional Evans' design spiral (Evans 1959), where a ship concept's general arrangement (GA) is usually created in the form of a drawing. The goal is to rapidly create the first GA version, which is a functional and innovative design approach that greatly facilitates designer's work. The intelligent GA (IGA) produces ship models that will be optimised, while they comply with safety regulations such as those of the IMO. It includes all aspects of ship design such as weight analysis, seakeeping, stability, strength, propulsion. The amount of information in the ship model will be augmented. One of the goals of IGA is to enhance the output and to ensure that all required 2D deck plans, and other related documentation can be obtained from the basic GA model. The model serves as the starting point for the next design phase, namely the basic design.

In order to improve the traditional ship design process and, in particular, the concept phase, we are developing a novel way of easily creating and handling ship models from the concept phase through to basic design and detail design. This will be achieved with the development of IGA.

IGA is primarily a design and analysis tool that can be used to create, modify and analyse a ship's general arrangement, while considering all associated effects of possible variations. The tool can support qualified naval architects during the entire design process. Therefore, IGA includes several modules or supporting tools, such as a weight calculator tool and hydrostatic tools, as necessary for the ship design process. GA consists not only of internal modules but has also interfaces to external software modules, such as strength analysis and hydrodynamic tools for optimisation.

The IGA tool is designed to allow a single naval architect to draw up a rough ship design concept, to which specialists from different disciplines can simultaneously add more precise details. It allows the optimisation of the design on a dedicated platform, and this will be demonstrated in the course of the HOLISHIP project.

4.6.1 Design Tool Requirements

The naval architect creates the initial illustration of the GA based on the vessel's task and ensures that the rules and regulations, as well as other aforementioned requirements are met. The entire package has to be competitive in the shipping market. The creative process is iterative, but also requires more flexibility to handle the design.

In addition to the functions required by the shipowner and authorities, the naval architect needs the following requirements to be met in the general arrangement (model):

- Easy handling of the model;
- Malleability and flexibility of the model for modifications and alternatives;
- Working interfaces with other software programmes and calculation tools.

In a 2016 survey, respondents were asked about their preferences regarding the most beneficial way the 2D drawing of a GA could be replaced by a 3D model; see Fig. 4.30 (Jokinen 2016).

Based on these results and further discussions, the functionality of IGA was defined.

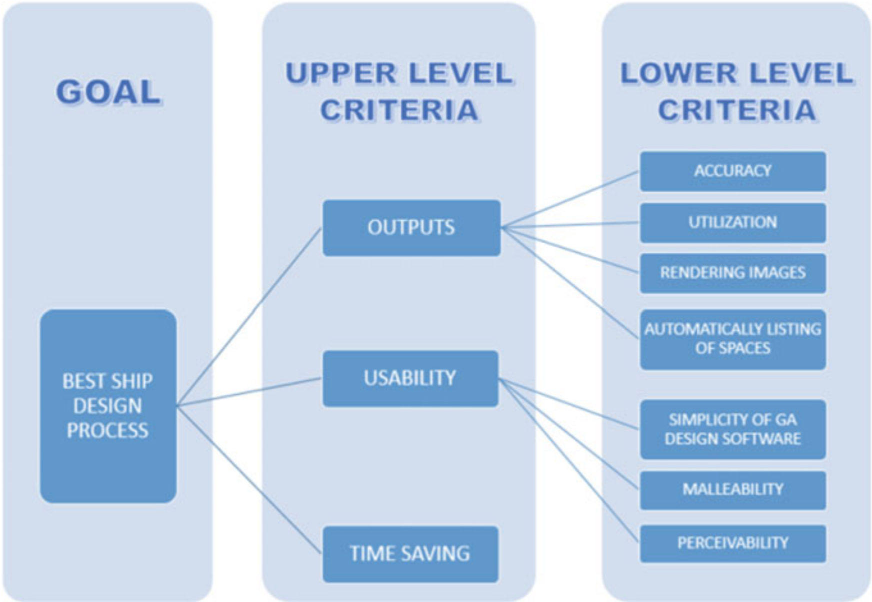

Fig. 4.30 Criteria according to which the GA design process is evaluated (Jokinen 2016)

4.6.2 3D General Arrangement in Concept Phase of Design

The concept phase of ship's general arrangement is usually created by use of a 2D software tool. Other software tools may be also utilised at the same time; these include NAPA®, dedicated tools for hydrostatic characteristics and hydrodynamics, and propulsion performance. Weight calculations are usually done with the use of spreadsheets, unless a dedicated software is preferred. The main concerns in this regard are data handling without automatic interfaces and the inflexible and time-consuming manner in which modifications are made. The malleability of traditional 2D design is generally poor. This problem area is also addressed by the intelligent GA (IGA).

The ship design process is traditionally described using Evans' spiral, called the ship design spiral (Evans 1959). It was developed in the 1950s to describe sequentially proceeding and gradually converting design processes. According to Lamb (2003), the traditional design spiral is a rather ineffective method of designing ships. This is mainly due to the task structure that adheres to a design-evaluate-redesign logic ("trial and error"). The problem with the traditional design spiral is that designers make an initial assumption based on reference ships, for example, about the general arrangement, after which they only seek to make improvements to the design. In other words, the design becomes "stuck" in the initial configuration of the GA and, therefore, different design solutions are not explored.

The Evans' spiral is thus a rather inflexible design process, which is not particularly suitable for the current demands on ship design, nor it exploits the present advanced state of computer hardware and software. The current trend is to employ a simulation-based (SBD), modular 3D design building block (DBB) approach, which is a holistic and more flexible ship design process. This method takes advantage of 3D modelling already in the concept stage. The main benefits of this approach include the increased amount of data (3D model vs. 2D) and the ability to conduct different simulations (virtual reality, evacuation simulations, seakeeping, etc.) (Tibbitts et al. 1993; Andrews 2006).

Three-dimensional modelling allows different tasks to be conducted simultaneously; a synthesis of a concept that is elaborated on to create the final vessel. In its ultimate form, the ship concept is the digital twin of a ship that can be utilised in simulations of ship's operation, to assist ship both designers and operators and to improve performance and safety during the lifespan of a ship.

In this part of the HOLISHIP project, the design process is created and database structures are developed based on the Intelligent GA. The process is developed in such a way that relevant software tools work together to ease concept design and ensure design quality. It allows the effective and precise creation of malleable ship concepts. This supports the innovativeness and creativity of ship designers, which was identified as a major disadvantage of the traditional Evans' design spiral (Lamb 2003).

4.6.3 Intelligent GA Tool

The intelligent GA (IGA) is a design tool that will assist naval architects to do their work. It does not aim to be an automated ship configurator. The intelligent GA will be used to create innovative concepts and to support naval architects in all design phases, from concept design to detail design.

The main features of the intelligent GA are a new interface to easily sketch a ship's general arrangement plan and a model that communicates with external and supporting modules (see Fig. 4.31). Some modules are internal, e.g. the weight estimator module, while others, e.g. the structural strength module, are external. This supports the naval architect in creating a feasible general arrangement with a single user interface.

Once the mission requirement of a vessel has been defined (mission requirements module, external), the initial sizing of the ship model is defined (initial sizing, supporting module). The main dimensions and other ship-related parameters are stored in a databank. This is combined with the model, drawings and output module to form the core of the intelligent GA. In addition, the intelligent GA consists of several independent internal and external (linked) modules that are organic parts of the intelligent GA.

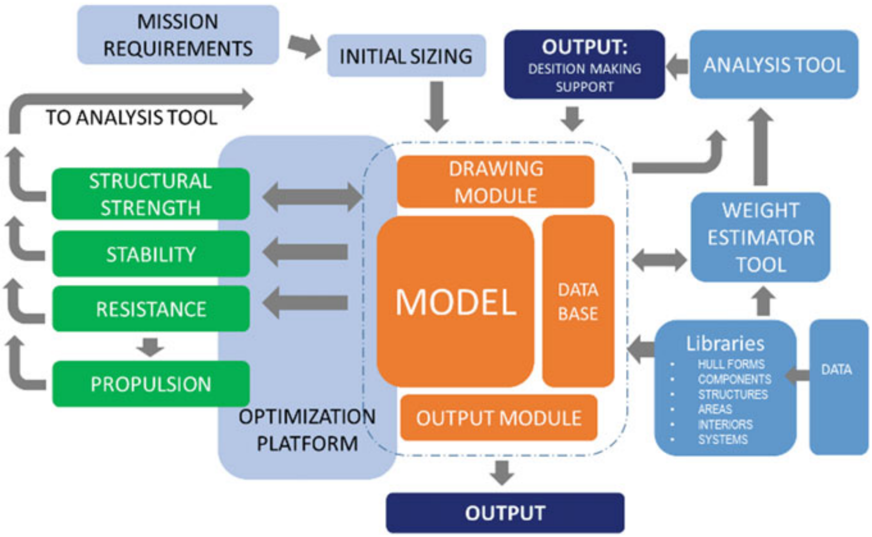

Fig. 4.31 Structure of the intelligent GA (IGA). The core of the intelligent GA is presented inside the dotted line. The supporting tools and modules that are handled by the tool are on the right side. The linked (external) modules are left side. The output is displayed below. All these elements together form IGA. That is working on the optimisation platform (CAESES®) as shown in this figure

The drawing module is the naval architect's working tool in the Intelligent GA; it is the interface to the model. The intention is to keep the interface as simple as possible.

Different libraries are available to speed up modelling in the drawing module. These libraries include objects such as hull forms from existing reference vessels, 3D components/equipment and systems. The object information is stored in the databank. This object-oriented hierarchy allows naval architects to select the hull forms and systems to be used in the drawing module. Objects can be modified in the drawing module and replaced, if necessary. This ensures the high malleability of the ship model, including topology and the GA.

The database not only supports naval architects in drawing, but also provides inputs for the analysis tool used in decision-making (further improvements to the model). The database module is linked to external modules via the optimisation platform. These external modules utilise the database information (current status of the model) and provide the analysis/decision-making tool with calculation results (strength, stability, hydrodynamics, etc.).

The output module within the intelligent GA provides outputs for the stakeholders highlighted in Sect. 4.4. The outputs include the 2D GA, tables and curves regarding ship characteristics (e.g. dimensions, strength, stability, performance and price) or other data.

A more detailed description of the modules in the intelligent GA and the optimisation platform are provided in the following subsections.

4.6.4 Internal Modules

Some of the features of the intelligent GA are integrated with the design tool as internal modules, while those that are considered to be linked tools, are discussed later.

Weight Estimator Tool

The ship's lightweight (LW) estimate is one of the most important tasks in ship design, especially in the concept phase. In the early phase of ship design, the lightweight is estimated based on factors related to the main particulars, volumes, and areas of the ship. However, when the design proceeds and the main components are defined, more accurate calculations can be performed.

Different weight groups have diverging factors that affect the ship's weight. In this project, it is natural for the model and the decision-making tool to be linked to the weight estimator tool (WET) as presented in Fig. 4.32.

The WET is based on the reference material of the selected vessels. These statistics are used in equations in order to calculate estimates for the different weight groups or subgroups. The structure of the weight estimator tool is demonstrated in Fig. 4.32. The result depends on the quality of the statistics and reference vessel selection.

The estimation of the structural weight of the ship is the most crucial weight group. This is normally followed by machinery and auxiliaries. Other groups have a lesser impact on the ship's design, depending to some degree on ship type; however, all weight groups remain crucial in defining the total weight.

Libraries

The intelligent GA consists of several libraries where, for example, different hull forms, 3D components (main engine, funnel, cabin modules, etc.) and steel structures are stored. These libraries supply a selection of predefined materials according to the naval architect's selection. The entities may be elements of given features, such as weight and dimensions, or may be subject to defined parameters.

These libraries serve the designer, but the data also includes weight information. The data and how it is transferred to the weight estimator tool and other modules need to be defined.

Powering the vessel

An internal tool is available to define the principal powering solution. It is used to define the main components of the propulsion train and its weight. This can be used to define the fuel consumption in conjunction with the resistance prediction.

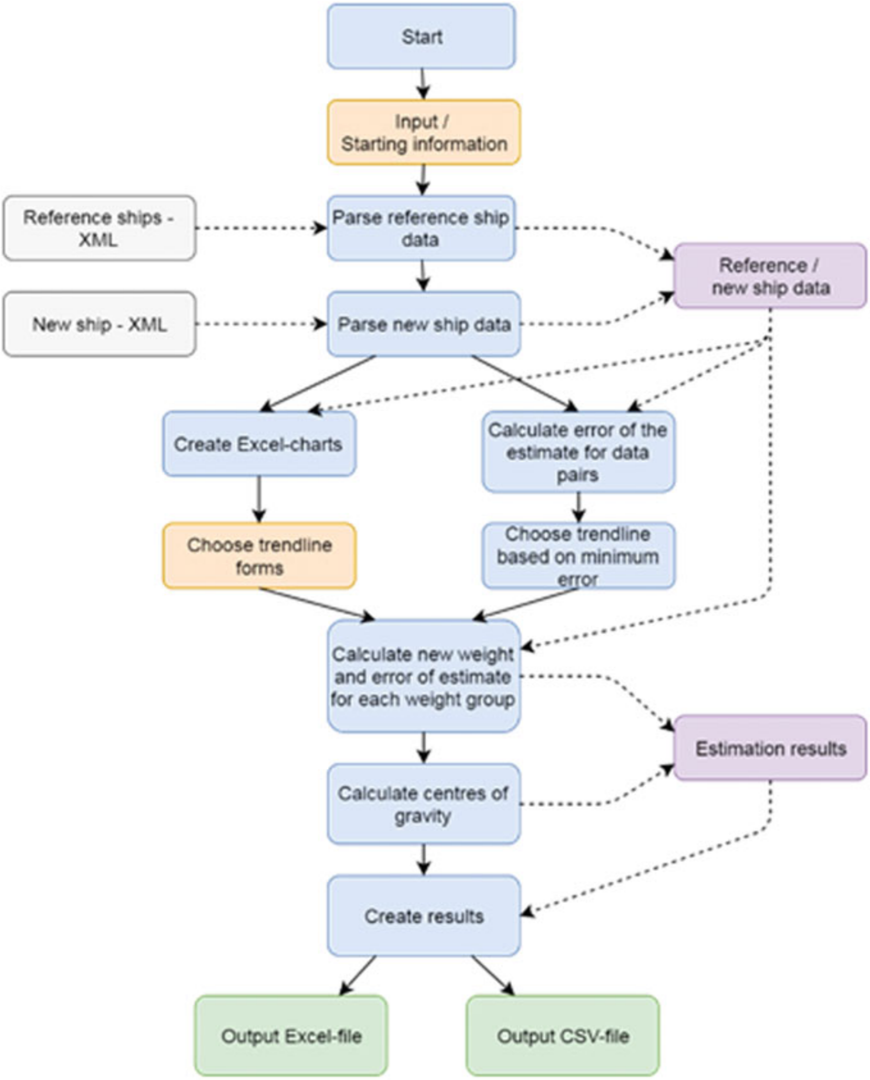

Fig. 4.32 Structure of the weight estimator tool. The blue colour indicates the function of the tool, orange is the input from the user, grey indicates input files, purple indicates data structures, and green is the output. The solid arrows illustrate the execution order of the tool, while the dashed lines illustrate the information flow (Kahva 2017)

Analysis tool

The analysis tool analyses and presents data for designers to support design work. The tool analyses the project ship's characteristics, but also compares these characteristics with data analysed in supporting databases. The analysis tool provides the naval architect with up-to-date information about selected ratios, figures and factors and compares this information with the reference vessel data. The top-level ratios include L/B, B/T, and Froude number, as well as space and volume analyses of different room types.

Furthermore, the analysis tool calculates the equipment number of the vessel. This value is used to define the related deck outfitting part and its weight. This is then used (with a certain factor for handling the rest of the weight of that weight group) as the initial value in the weight estimator module prior to the optimisation process.

The analysis tool supports the naval architect's decision-making and keeps him/her on track to design a feasible vessel. All crucial deviations from the reference materials are brought to the designer's attention.

Output tool

As indicated earlier, different stakeholder parties with diverging needs have to be satisfied with the ship model that replaces the general arrangement. However, the traditional general arrangement plan forms part of the output. Furthermore, other types of output can also be derived from the intelligent GA. The output module creates the required outputs from the model, which include

- GA in 2D format, as a traditional general arrangement plan;
- 3D model for visualisation purposes;
- 3D GA for marketing purposes.

All these output forms are necessary as outputs of the vessel concept. By using the intelligent GA, all these forms are based on the same model and therefore the risk of conflicts is avoided.

4.6.5 Linked Modules

As previously indicated, the intelligent GA tool is open to external software such as strength, hydrodynamics and hydrostatic analyses tools. These tools are commonly used in ship design, but in this case they are linked to the model and, therefore, all data remains up to date across the different software programmes. These modules are either directly integrated with the intelligent GA or via the optimisation platform.

4.6.5.1 Strength and Structural Weight

The strength of the vessel is calculated with a rule-based calculator, which is integrated into the intelligent GA tool. It defines the scantlings for the first estimate of the vessel.

The model receives the unit weights as calculated from the main frame section and allocates these unit weights to other structural elements. This is rather simple for longitudinal structures, but may require more effort for other structures.

The main frame section defines the unit weights in the first phase. These unit weights are used for structures throughout the vessel. There are also some further requirements, for example, the collision bulkhead has to be reinforced according to the rules. The next step concerns the ends of the vessel. The goal is, however, to keep the process as simple as possible to calculate the steel weight rapidly and in the most efficient way.

4.6.5.2 Hydrostatics and Hydrodynamics

Ship's stability is calculated with an external module linked via the optimisation platform. It receives the required information from the intelligent GA and returns the calculated values. The required stability according to safety rules has to be met in order to achieve the minimum viable level for a concept. This module is a domino, which can be used if integrated with the optimisation platform.

The resistance of the vessel is estimated by use of the *ν-Shallo* panel code method developed by HSVA. That is facilitated by use of a surrogate model created with the response surface method and validated with CFD calculation. The surrogate model and its use are directly integrated into the CAESES optimisation platform, to which the IGA tool is interfaced.

4.6.6 Optimisation Platform Integration

The intelligent GA is integrated with the CAESES optimisation platform that functions as the interface between the external/linked modules. In order to allow the concept design to be optimised, it has to be fully integrated into the optimisation platform. This is a key feature of the entire HOLISHIP project. Of course, before starting the optimisation process, the ship concept has to be completed by the designer and it has to be topologically sound. A comparison of different solutions, such as vessels that are electrically driven or diesel engine driven, is done separately and the selection has to be done before entering the optimisation loop phase. However, both alternatives can be optimised and later compared with each other.

One of the considerations is the operational profile and its integration with the optimisation platform. It can be considered that the operational profile for the initial concept is valid for the whole range of the optimisation space. However, if there is any doubt that the main particular variations have a significant effect on the results, the operational profile has to be inside the optimisation loop, which may lead to rather complicated calculations.

As presented in Fig. 4.31, the optimisation platform requires a ship model that is imported from the Intelligent GA. This model includes the topology, weights, materials and costs of the structures and systems, and other ship-related parameters. These parameters are used, for example, in hydrostatic calculations, as well as in calculations with hundreds of variations regarding performance and costs over the vessel's life cycle.

The optimisation of the main particulars is based on the defined external operational scenarios of the vessel and the vessel's internal technical limitations and restrictions. The variations are automatically generated within given constraints. The vessel itself is designed by a qualified naval architect, but the optimisation is carried out by a computer in batch mode without the manipulation of designers.

The full implementation of optimisation of the model on the basis of a RoPAX case study will be demonstrated in the forthcoming volume 2 of the present book.

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Chapter 5
Systemic Approach to Ship Design

Romain Le Néna, Alan Guégan and Benoit Rafine

Contents

Abstract The design of complex systems such as aerospace or transportation systems is a difficult task. It usually involves several teams working in close collaboration, over extended periods of time, and it is a true challenge to demonstrate that the requirements for these systems are satisfied. The complexity of ships has recently increased, driven by on-board electronics and digitalization. The idea behind a dedicated work package of the HOLISHIP project is to adapt systems engineering methods from the aerospace and other industries to the specific challenges of the shipbuilding industry. A Systems Architecture & Requirements management tool, called the SAR tool, has been developed in order to support systems engineering methods during the design process of ships. This chapter provides a short description of the method and the SAR tool; it elaborates on material originally published in (Guégan et al. in A systems engineering approach to ship design, 2017) and (Guégan et al. in Compliance matrix model based on shipowners' operational needs, 2018a).

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System architecture · Systems engineering

5.1 Ship Design Driven by Operational Scenarios

5.1.1 Operational Scenarios as a Complement to Technical Requirements

Current design methods are based on technical specifications listing all technical requirements. The hypothesis is made that the requirement referential is well described, non-ambiguous and well allocated to all subsystems and equipment. From a practical point of view, preparing a clear specification with thousands of requirements linked to hundreds of pieces of equipment is a very difficult matter and especially at early design stage. Moreover, the cost of the project and its successful achievement is directly impacted by the specification definition.

From this statement, a new approach is emerging that may be called a "scenario-oriented approach"; see, for instance, (Guégan et al. 2017) and (Issad et al. 2015). This approach suggests defining a set of scenarios complementing the requirement list. The number of scenarios and the level of details depend on the design phase and can be easily discussed with all stakeholders. This approach has the advantage of defining only the necessary scenarios corresponding to the design phase needs in full agreement with the customer. As all discussions are based on understandable scenarios, validation track is clear and easy to check.

In software and systems engineering, a scenario is a list of actions or event steps, typically defining the interactions between an actor and a system, to achieve a goal. The actor can be human or other external systems. In systems engineering, scenarios are used at a higher level than within software engineering, often representing missions or stakeholder's goals. The detailed requirements may then be captured as contractual statements.

5.1.2 Technical Requirements

In classical systems engineering method, the approach is predictive; from the beginning of the project, a contractual requirement referential is agreed upon and the design and construction is performed in order to fulfil all requirements.

Within the SAR management tool, a list of requirements is necessary to adapt the project to existing predictive methods involving specifications. Requirements are then linked and completed by operational scenario definition.

The requirement management is ruled via standards in systems engineering, for instance, the following definition is given in reference (ISO/IEC/IEEE 2007).

A requirement is a "Statement that identifies a product or process operational, functional or design characteristic or constraint, which is unambiguous, testable or measurable, and necessary for product or process acceptability."

The following types of requirements are identified by Association Française d'Ingénierie Système AFIS (French systems engineering organisation related to the International Council on Systems Engineering INCOSE):

- Operational
  - Example: the ship shall be able to launch a rigid-hulled inflatable boat (RHIB) at five knots in SS4
- Process and Management
  - Example: a monthly report shall be delivered each month to assess design advancement
- Not operational
  - Example: the ship shall be have a blue hull
- Constraints
  - Example: the ship shall fulfil Bureau Veritas (BV) Naval Rules 467

The requirement definition shall contain at least a short title to identify quickly the subject of the requirement and the complete textual description. The SAR management tool user shall keep in mind that a specific focus is made on operational requirements within this tool: operational needs are justifying the acquisition of a new system.

In a classical technical specification, requirements are allocated to system blocks. In this approach, it has been chosen to highlight operational purpose of the system by defining operational scenario as base of the operational specification. Therefore, links between scenarios, requirement and system blocks are made via user subscription creating a community of interest see Sect. 5.3.

The technical requirement specification is an input to define the list of scenarios. For each scenario, a batch of operational requirements will be associated. The designer responsible of an operational scenario will be in charge to identify and subscribe to all requirements in association with its scenario.

Table 5.1 gives an example of operational requirement organization applied to a Multi-Purpose Offshore Vessel (MPOV) ship.

The above example will be used as a template to build the operational requirement specification and later on the compliance matrix. Table 5.1 considers all operational requirements specifically linked to operational scenarios and generic missions.

Scenarios are defined from generic missions, and they are linked to operational requirements. One requirement can be allocated to several scenarios, and a scenario can be complemented by several requirements.

Table 5.1 Operational requirement specification frame example

ID	Description
R001	Max speed 22 kts
R002	Navigation radar range: 20 nm
R003	Ship shall be equipped with Navigation Sonar
R004	Special operation crew: 6
R005	Ship shall be equipped with blue flashing lights
R006	Ship shall be equipped with VHF radio
R007	Ship shall be equipped with loudspeakers—2*300 W
R008	Etc

5.1.3 Inferring Operational Scenarios from Requirements

By the time when the design of a ship is initiated, both the shipowner and the shipbuilder have a vision of what the operational activities of the ship will be. The requirements provided in the technical specification are a firm basis to build a common understanding of the operational scenario.

The definition of an operational scenario can be found in (ISO/IEC/IEEE 2011):

> Description of an imagined sequence of events that includes the interaction of the product or service with its environment and users, as well as interaction among its product or service components.

To infer operational scenarios from the list of requirements and the knowledge of the shipbuilder and the shipowner, it is necessary to:

- Describe the environment of the ship (weather condition, other ships, crew, etc.),
- Describe the specific features on-board the ship: payload, crew number, skills and organization, etc.,
- Draw the list of the most relevant operational situations,
- Describe for each operational situation a sequence of events that matches the experience of the shipowner and that takes into account the characteristics of the ship to be built by the shipyard.

With the SAR tool, ship designers can draw the list of technical requirements (in the "requirements management" part of the SAR tool), then link these requirements with scenarios that they are free to describe and amend, in the "scenarios management" part of the SAR tool.

By linking requirements and scenarios within the same tool, ship designers have the ability to trace requirements to relevant scenarios. This is a novel feature with respect to standard ship design tools that has been inspired by recent advances in systems engineering (see, e.g., Issad et al. 2015).

Table 5.2 provides one such example of a scenario that has been inferred from the list of requirements in Table 5.1. Requirements R001, R002, R004, R005, R006 and

Table 5.2 Operational scenario description example: control of fishing activities

ID	Title	Description
S003	Control of fishing activities	A fishing vessel has been reported to the MPOV. The MPOV sails to towards the fishing vessel at high speed (22 kts) and closes in with the help of its navigation radar. The MPOV tries to establish contact by VHF. After several unsuccessful trials, the MPOV turns its flashing lights on and gets in the vicinity of the fishing vessel. The MPOV crew tries to establish contact with the loudspeakers. The fishing vessel slows down, and the MPOV is able to come closer and the special operation crew climbs on-board to control the fishing activities

R007 can be found, in context, in the description of the scenario. In the SAR tool, these requirements are all linked with scenario S003.

5.2 Modelling the System Architecture of the Ship

Operational scenarios have been described in Sect. 5.1; this section describes how the system architecture of the ship can be described with the SAR tool, by using the BuDa workshop provided with the SAR tool. A more detailed description of BuDa can be found in (Guégan et al. 2017).

5.2.1 A Multi-level Architecture Model

The large number of components and interfaces in a complex system (e.g., a multi-purpose vessel) makes it difficult to visualize the architecture of the system. Building on existing approaches (e.g., the SysML language), we have developed a tool that allows users to:

– Map the components and their interfaces (including interfaces with the environment outside the ship),
– Group components to form "components" of higher level, or break down larger components into smaller parts,
– Propagate interface properties up and down the component breakdown of the ship according to automatic procedures, which greatly improve the work of the system architect.

Figure 5.1 provides one such example of architecture mapping. The ship is displayed as a "macro component" in interface with a fuel supply (from which fuel is loaded in harbour), the atmosphere (for fuel combustion) and seawater (allowing the propeller to exert a propulsion effort).

The components inside the ship are displayed as well. This enables the designer to keep track of all the inner interfaces between components (trivial in this example, but more than often challenging in actual ship design).

Figure 5.2 shows the fuel circuit in more detail. The BuDa tool enables users to navigate through detail levels very easily, and it generates synthetic views such as this one, where only the components in interface (here, the fuel supply and the main machinery) with the component of interest (here, the fuel circuit) are displayed. The global model can also be displayed (see Fig. 5.3), although for an actual ship this view becomes rapidly intractable due to the number of components and their interfaces.

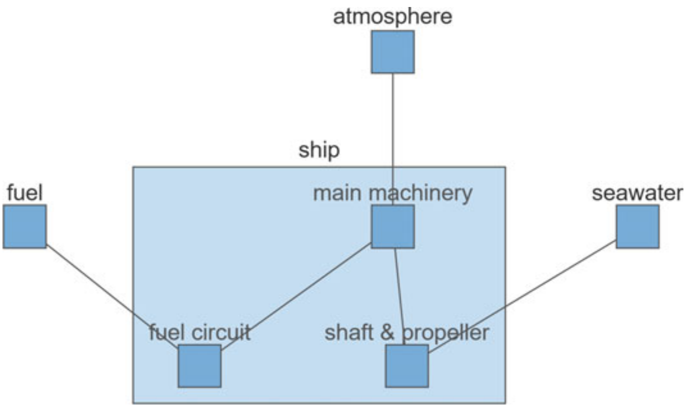
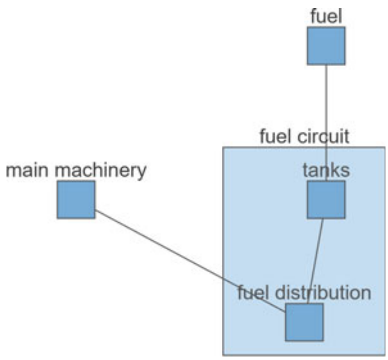


Fig. 5.1 Architecture mapping at high level

Fig. 5.2 Architecture mapping of the fuel circuit



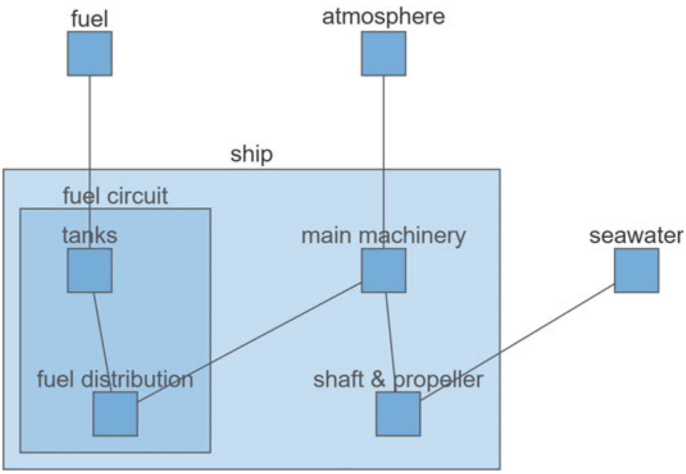


Fig. 5.3 Architecture mapping of the entire ship (all components displayed)

5.2.2 Architecture Analysis—Circuits and Networks, Functional Chains

The multi-level architecture model can be refined by introducing the concepts of circuits (networks) and functional chains. Circuits are, for instance, seawater circuits, freshwater circuits, steam circuits, electrical distribution, on-board ethernet, etc.

The architecture modelling tool BuDa allows users to specify the type of circuit each interface supports, and to highlight the interfaces that support a given circuit. The advantage of BuDa over many other modelling tools is that circuit properties are shared across design levels with an automatic routine. Figure 5.4 shows how the fuel circuit of the ship is highlighted in BuDa.

The architecture modelling tool BuDa also allows users to specify the components that participate in specific operational modes or specific functional chains. Functional chains are highlighted in the same way as circuits, with circles and bold lines. In addition, interfaces with components that are not supposed to participate in the functional chain but that have an interface with it are automatically highlighted in dashed lines.

This enables the user to identify potential sources of failure of the functional chain—for instance, if the gearbox is engaged, cold start might be compromised. Functional chain properties are also shared across design levels with an automatic routine. Figure 5.5 shows how the components participating in the “cold start” phase are highlighted in BuDa.

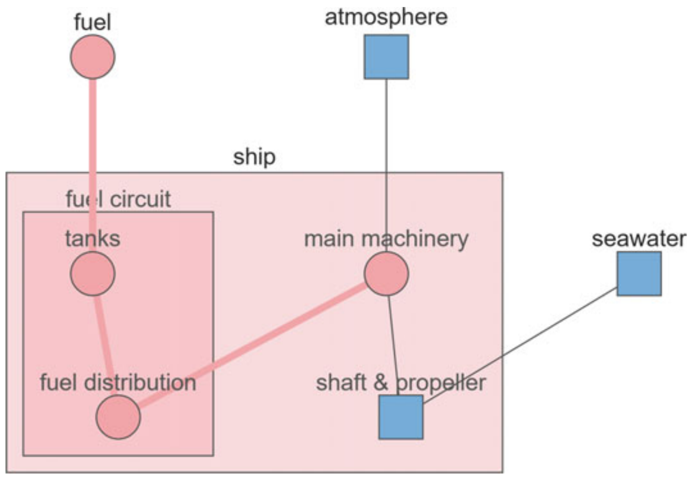


Fig. 5.4 The fuel circuit (bold lines) and its components (circles)

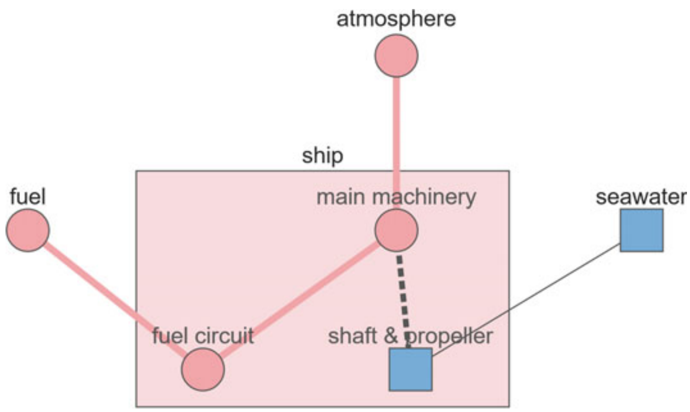


Fig. 5.5 Cold start of the main engine (bold lines and circles). Items that are not operative during the cold start phase are displayed as rectangles. If one such item has an interface with the functional chain supporting "cold start", this interface is highlighted as a dashed line

5.2.3 System Architecture as the Basis for Performance and RAM Analysis

System architecture provides a general view of the ship that proves useful in a number of analyses. For instance:

– The components and their interfaces can be implemented in a single model, while the synthetic views provided by the tool ensure that the model remains tractable.
– The components that shall be powered by the electrical circuit are clearly identified, which is useful to evaluate the energy balance on-board the ship.

– The components that contribute to each operational phase are clearly identified. This is useful to evaluate operational scenarios.

The recent IMDC publication (Corrignan et al. 2018) provides an example of how BuDa can be used in a design process to help performance evaluation and reliability, availability and maintainability (RAM) analyses. BuDa offers a simple yet exhaustive model of the system architecture of the ship that provides a solid ground for the design process and the evaluation of operational scenarios. BuDa and the operational scenarios management tool make up a basic systems engineering environment which is the foundation for the collaborative design process described in Sect. 5.3.

5.3 Managing the Design Process with "Communities of Interest"

5.3.1 Ship Design: A Collaborative Design Process

Designing a ship is a challenging endeavour that involves the collaboration of numerous teams with various technical backgrounds and experience. This collaborative development process is expected to deliver a ship with the following characteristics:

– The ship shall be able to support operations at sea with the performance specified by the shipowner (including emissions and fuel consumption),
– Manufacturing of the ship shall be as easy as possible and in all cases compatible with the industrial capability of the shipyard,
– On the whole, OPEX & CAPEX shall be consistent with the shipowner's requirements,
– The ship shall be compliant with safety regulations.

Ship design processes have been facing new challenges in recent years:

– New technical missions are often assigned to single multi-purpose ship in order to reduce costs,
– More than ever before, ships interact with external and internal assets of various types and sizes (onshore communication centres, surrounding ships and aircrafts, UAV, USV, UUV, satellites, etc.),
– Today's ships are expected to integrate complex subsystems with high connectivity and modularity,
– Most of all, remote collaboration has become the rule, with the shipowner, the naval architect and the design officer, the shipyard and the equipment suppliers being located thousands of kilometres apart.

Novel design methods have been introduced over the years and some of them are reviewed in (Andrews and Erikstad 2015). The HOLISHIP project addresses these challenges by developing systems engineering methods associated with numerical modelling and simulation tools. The contribution of the present work to the HOLISHIP project is the development of a tool to handle system architecture and requirements (SAR management tool) altogether and simultaneously during the collaborative design process.

HOLISHIP partners had to address several issues induced by the collaborative nature of the design process. First, technical data is generated by a large number of people with skills in various technical domains. By essence, the data handled during the design process is ***heterogeneous***. Electrical circuit diagrams are managed in parallel with hull structure plans, hydrodynamic models, certification documentation, etc.

Second, since subsystems share a lot of interactions, the design process is ***iterative*** by nature: the behaviour of every subsystem in its environment cannot be defined a priori, and the design proceeds by consecutive adjustments.

In the general case, design processes have well-defined, synchronized milestones that take into account their iterative nature. Still, in the process of designing a ship, technical inputs are generated on a daily basis, depending on the work of the many engineers involved; the flow of technical information produced during the design process is ***asynchronous*** by essence, which is the third issue we had to address. The goal of the SAR tool is to support the design teams during the design process and help them address these three issues with improved efficiency.

In practice, the process by which design teams handle heterogeneity, iterations and asynchronicity is characterized by formal activities and milestones (e.g., design reviews), but it also relies on more informal communication: team members meet on a daily basis, they share information by phone, by email or at the coffee break. All in all, ***communities of interest*** develop around topics of particular significance for the design process such as specific operational scenarios, system safety and energy consumption.

With the SAR tool, we seek to provide support to the communities of interest that emerge during the design process. The development of social networks over the Internet has given rise to innovative software architecture that is extremely well suited to the management of heterogeneous, asynchronous, evolving data to the benefit of communities of interest. In the current version of the SAR tool, users have the ability to handle system architectures (BuDa), requirements and scenarios (requirements and scenario management tool). The architecture of the SAR tool has been chosen from the very beginning to be able to connect more domain-specific tools in addition to these basic tools. In the following section, the characteristics and the advantages of this architecture are described.

5.3.2 Collaborative Software Architectures

Companies such as Netflix and Amazon manage enormous quantities of data that pours in from many sources (customers, suppliers worldwide, etc.). Data generation is asynchronous, data evolves constantly, and it is highly heterogeneous, ranging from catalogues of products to videos and personal (user) data.

The business of these companies relies heavily on software, the prime quality of which is stability to ***scale up***. A new type of software architecture called "Microservices" has emerged in recent years (Newman 2017). By contrast with what they call "monolithic" software, the supporters of microservice architectures slice up their software in extremely small, extremely specialized ("context-bounded") pieces of software. Each of these elementary pieces of software provides elementary services such as user acknowledgement, video streaming and catalogue management, and each of them is viewed as a consumer and producer of data.

The data that is produced and consumed is shared as "messages" that are managed with a message queue (MQ) service the role of which is to ship data from a given producer to whichever consumers need it. Several MQ software are available, including the open-source RabbitMQ solution that we have used in the SAR tool.

The MQ is the way by which asynchronicity and heterogeneity are managed. The principle is the following:

– Microservices that produce or consume data are free to create or subscribe to "Queues" within the MQ.
– A reduced set of rules dictates how messages are stored and retrieved from a queue. The most used is the simple rule by which any consumer that has subscribed to a given queue is free to read the data from the queue; once the data has been retrieved by a consumer, it is removed from the queue and the other potential consumers do not see it anymore.
– The data is encapsulated in "messages" that are characterized by a part called "header" that holds information on, e.g., the type of data the message contains, and a part called "data" that holds whatever type of data has been produced by the producer.
– MQ manages the queues: which message shall be shipped to which queue, which message shall be deleted or stored, etc.

A software that implements these principles has the ability to manage:

– Heterogeneous data: messages can transmit data of any kind, as long as the format header—data is satisfied.
– Asynchronicity: producers may generate data at any time and consumers can receive data whenever they are ready to use it, since messages are buffered within queues, and the MQ ships messages to consumers on due time.
– Iterations: the iterative nature of the design process is "built-in" since any update in the data is readily available to any potential "consumer" for its own activities.

Originally, Microservices architectures have been designed with the goal to provide massively scalable software. Scalability is obtained by the fact that services are small, interchangeable and distributed. A single service, for instance, can be implemented in several instances deployed on several servers around the world. In the SAR tool, we are not using Microservices for their ability to scale up, but rather for the "side effect" that they are able to manage asynchronous, heterogeneous data flows in a very efficient way. The following section describes how Microservices are used in the SAR tool.

5.3.3 Architecture of the SAR Tool

The architecture of the SAR tool is sketched in Fig. 5.6. SAR management tool and associated user manual are described in HOLISHIP deliverable D2.3 (Guégan et al. 2018b).

The architecture is organized around a message queue service. Each technical domain is supported by a specific tool (or "microservice") displayed on the left of Fig. 5.6 (requirements, scenario and architecture management tools). The design team can use each of these tools to specify operational scenarios or design system architectures. Each time a model, a scenario or a requirement is changed, and the domain-specific tool sends a message to the message queue.

The project management tool at the bottom left of Fig. 5.6 receives all the messages from the message queue. Its role is to:

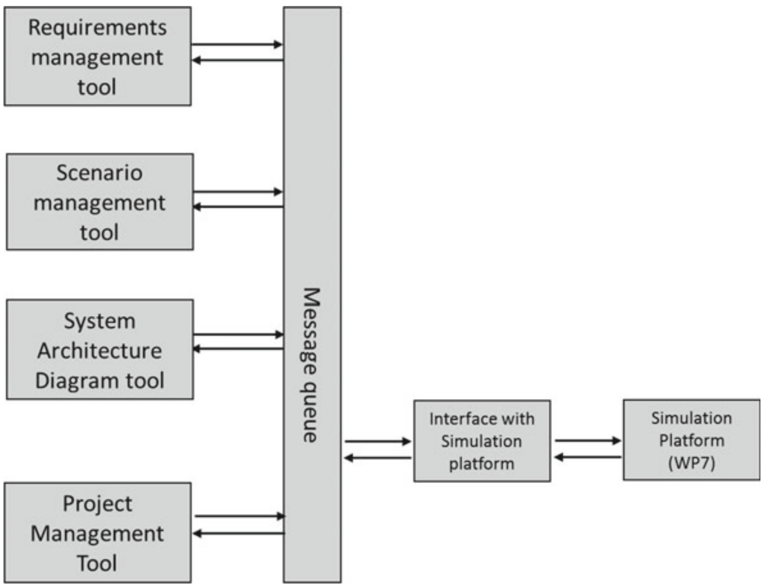


Fig. 5.6 Architecture of the SAR tool

- Handle the list of users (designers) and of the items they have subscribed to (architecture components, scenarios, etc.)
- Generate notifications to the users, based on the messages it has received from the MQ, to inform them that the items they have subscribed to have changed.

The SAR tool has an interface with the HOLISHIP/CAESES® design simulation platform (bottom right in Fig. 5.6, see Chap. 8 of the present book). Through this interface, the simulation platform can be informed that something has changed in the architecture, in a requirement or in a scenario, thus requiring additional simulations. Like the project management tool, the "interface with simulation platform" service receives all the messages from the domain-specific tools and generates alerts to the people in charge of the simulations based on these messages.

The following section provides a description of how the SAR tool contributes to the creation of communities of interest to the benefit of the design process.

5.3.4 A Human-Centred Design Process

With the software architecture we have implemented in the SAR tool, each designer can perform its design activities in a domain-specific design tool, say the architecture management tool (BuDa), and be informed about the work performed by its colleagues and partners in other technical fields, e.g., if a scenario has been changed (scenario management tool). The information that each designer receives is tuned specifically to his needs that he has specified by subscribing to the design artefacts he is interested in.

In current design approaches, design artefacts are connected by *traceability links*. For instance, requirement R001 may be assigned to architecture block B006 and scenario S002. It is common practice to use requirement management tools that keep track of changes in the requirements or in their allocation patterns—whether the requirement has been assigned to a new block, or who has implemented this change, etc. Still, the allocation process is only a trace of the design activity and of the fact that *people* (from the design team) have identified a relationship between design artefacts.

The SAR tool aims at tracing the relationships between design artefacts in a more natural way: when someone in the design team has subscribed to two or more design artefacts, then this means that these artefacts are related in some way. The subscription patterns of the design team reflect the relationships between design artefacts. In the example above, one would expect the designer in charge of requirement R001 to have subscribed to block B006 and scenario S002.

The advantages of this approach are many:

- Communities of interest of many types emerge from the subscription patterns of individual designers. For instance, all the individuals that have subscribed to scenario S002 make up the community of interest around S002, that is, all the members of the design team that contribute to achieving scenario S002.

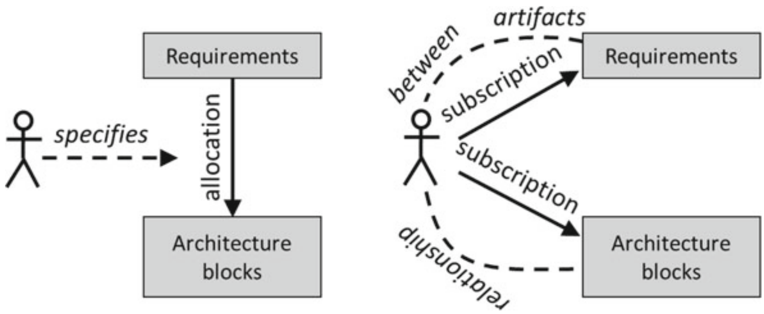


Fig. 5.7 The current allocation process (left): requirements are assigned to blocks through (explicit) traceability links that are specified by members of the design team. In the process proposed with the SAR tool, artefacts are in relationship (dashed line) through the people that have (explicitly, solid line) subscribed to them

– Each member of the design team is able to identify all the other members that may be impacted by a change in his own design artefacts, or that may generate impacts on his scope. For instance, the expert in charge of the electrical circuit knows who needs electrical power on-board based on who has subscribed to the "electrical power budget" item. If any of the consumers' needs more power, for any given reason, then the electrical specialist will be informed by a notification from the project management tool.
– The list of interfaces between a system and its environment can be drawn from the list of design specialists that have subscribed to the system. Similarly, the list of people that should be invited to the design review or first article inspection of any given item on-board the ship is readily obtained from the list of people that have subscribed to the item.

These advantages make the SAR tool a powerful way to support the design process, by allowing the emergence of communities of interest built on individual subscription patterns. It might even happen that some of today's traceability links can be replaced eventually by the subscription patterns of the design team. As stated above, traceability links are only a trace of design activities performed by *people*. We expect that, if the traceability of the design activities with the subscription patterns is robust enough, then implementing explicit traceability links between design artefacts will be made redundant by the fact that the design artefacts are linked through their subscribers, as sketched in Fig. 5.7.

The SAR tool might be a way to move from a requirement-centric design process in which humans are sort of "hidden" behind the allocation process, to a process in which each member of the design team will participate in several communities of interest, in a more human-centred approach that will improve collaborative design. Testing this last hypothesis will be one of the goals of the MPOV application case that will be presented in volume 2 of the book in hand.

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Chapter 6
Hydrodynamic Tools in Ship Design

Jochen Marzi and Riccardo Broglia

Contents

Abstract Ship hydrodynamics is a key discipline in ship design. It determines, to a large extent, two fundamental properties inherent to any new design: the safety of a ship on one hand and the efficiency on the other. While the entire, holistic ship design as anticipated in the HOLISHIP (www.holiship.eu) project aims to balance the two requirements in an optimised way, hydrodynamic considerations will form a set of boundary conditions for the achievable optimum. The present chapter introduces the

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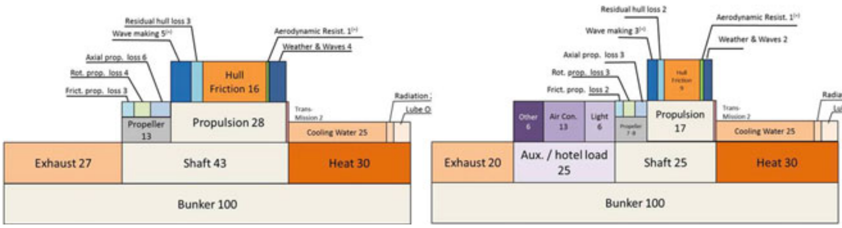


Fig. 6.1 Use of propulsion energy on board of a cargo vessel (left) and a cruise vessel (right), Basis: IMO (2009) and TARGETS (Marzi and Mermiris 2012)

key elements requiring hydrodynamic analysis and presents relevant tools available to achieve adequate results during different design stages for a new ship. The focus is placed on the tools which are or will be integrated into the HOLISHIP design platforms during the project and how they can be put to use during different stages of ship design.

Keywords Hydrodynamics · Performance analysis · Resistance · Propulsion Seakeeping · Manoeuvring · Multi-objective optimisation · CFD · Potential flow RANS

6.1 Hydrodynamic Challenges in Ship Design

Hydrodynamic forces acting on a ship hull are the main effects influencing the overall performance of the vessel and thus its efficiency. For many ship types, hydrodynamic effects are typically the prime cause of energy consumption. The following figure from IMO's 2nd GHG study (IMO 2009; Marzi and Mermiris 2012) illustrates the fact that more than 50% of the potential energy included in the bunker fuel is lost in the conversion process in the engine and only 43% of the bunker energy is available for practical purposes. Out of this fraction, more than 85% is used to counteract hydrodynamic forces on the hull during sail. This holds for a typical cargo vessel as indicated in the left part of the figure. The situation does, however, change completely for a cruise vessel (PAX) which is indicated in the right part of Fig. 6.1. This is based on an analysis performed in the European TARGETS (Marzi and Mermiris 2012) project concluding that about 25% of the total available (bunker) energy is used for auxiliaries and hotel loads on board a cruise vessel. The share of propulsion energy drops from 43% in case of the cargo vessel to only 25% for the PAX. Comparing only the "useful energy", i.e. excluding heat and exhaust losses, still some 50% of the useful energy on board a PAX is required for propulsion, while the rest is used for hotel loads. For the cargo vessel, almost all "useful energy" is assigned to ship propulsion.

This indicates that for most practical applications hydrodynamics play a fundamental role to assure a proper energy efficiency of ship operation. And even though the share of overall consumption is smaller in case of complex passenger ships, the total amount of energy consumption of an average passengers (PAX) vessel is still in the region of that for a cargo vessel, the extra consumers for hotel loads are simply on top of the propulsive power requirements.

With efficiency being the key sales argument in a competitive market for commercial vessels, operating costs (OPEX) of a new ship design are the decisive factor when comparing alternative design variants for most ship operators. Therefore the fact that e.g. attainable speed for a given engine rating during sea trials is still the prime condition in a contract between a shipyard and its customer. Typically, only small margins are allowed before the client may refuse the acceptance of the newly delivered vessel. While technical developments in terms of machinery are important to reduce losses, the plain hydrodynamic performance in terms of resistance and propulsive efficiency is the relevant parameters for the designers to influence and improve the vessel's performance. This underlines the importance of hydrodynamic (performance) analysis and optimisation and clarifies the important role that model basins play when assessing the performance of a new design beforehand. The importance of experimental investigation which is based on a long tradition and experience is further enhanced by the fact that, at the time of writing, the need to verify the attained energy efficiency design index (EEDI) specified by IMO can only be achieved through a model test.

While efficiency is clearly high up on the agenda for each new ship design, safety is equally important to assure an acceptable operation under all relevant conditions. This chapter of ship design is similarly complex and involves a mixture of different disciplines. Again, hydrodynamics play a vital role in determining the exterior forces acting on a ship hull and thus its behaviour in a natural environment up to the survivability in extreme sea conditions and during damage cases.

Last but not least, the very important aspect of integrated systems must be addressed. Where hydrodynamics is at the core of each design process, it is of utmost importance to assure that all relevant analysis tools are properly integrated in a complex, holistic design environment to assure that whenever there is a need during the design process to use hydrodynamic data, these can be made available without loss of time and consistency. In the HOLISHIP project, a large number of hydrodynamic tools applicable to various design tasks are identified and integrated into the HOLISHIP platform (for more details, see Chap. 8). Consequently, fulfilling the prerequisites for a sound integration into the overall platform is a must for all tools which are described in the following.

6.1.1 Ship Resistance

Ship resistance is comprised of different components: (i) the pressure or form related wave resistance, (ii) the viscous drag and (iii) the added resistance due to wind and

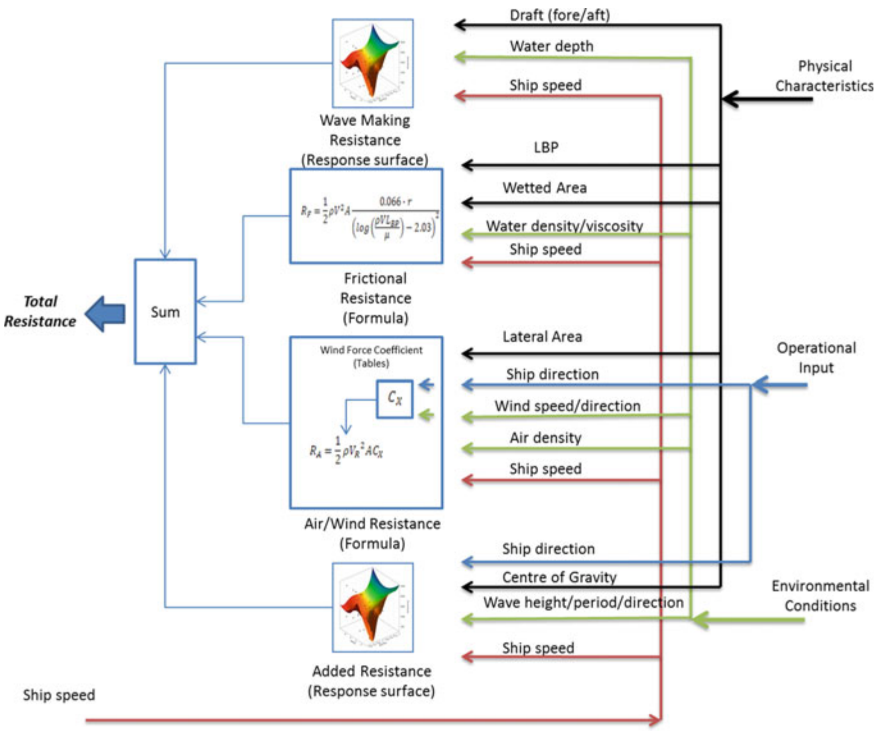


Fig. 6.2 Decomposition of ship resistance

waves. These are responsible for up to 70% of the power required on board a merchant vessel. Due to the different causes of the resistance components, either related to (hull) pressure or (surface) friction, they need to be treated with different tools and they must be considered at different stages of the vessel's life cycle. Pressure-related components depending on the hullform are a design feature which is determined by the hullform at a very early stage. On the other hand, viscous resistance largely hinges on the surface quality and size. While the latter is a design feature too, the former depends on both the initial production quality and the hull coating and maintenance during operation. Especially, the latter is clearly related to the operational stage of the vessel. The same holds for added resistance due to wind and waves which can be influenced through weather routing and to some extent also through clever design. Figure 6.2 indicates the decomposition of ship resistance typically used in design and analysis work.

With different physical laws ruling individual aspects of ship resistance, e.g. gravity and viscosity of the fluid, there is hardly any single practical means to predict operational ship resistance as a total. Although modern state-of-the-art Reynolds-averaged Navier–Stokes (RANS) codes theoretically offer the potential to compute the total resistance of a ship, this is typically limited to clearly defined, standard conditions, e.g. a new vessel during trial conditions. An application of RANS codes to a complete design and optimisation problem which often requires the analysis of several hundred variants and including even all relevant—resistance—components will be prohibitive due to time requirements. The number of free parameters typically used in a hullform optimisation will be too high for a complete analysis using complex CFD codes. Further factors imposed during operation over the life cycle of a vessel include hull fouling, added resistance in a seaway which still need to be superimposed on the basis of simpler, often empirical methods.

During the design of a new ship when a large number of different design alternatives need to be considered, the situation becomes even more complex and further simplified methods need to be applied. At present, a sensible combination of tools at different levels of complexity and fidelity still appears to be most promising for early design and optimisation tasks.

Fluid dynamic forces acting on a solid body are typically expressed as a product of speed, body size, fluid density and a coefficient. Ship resistance is hence typically expressed as:

$$R_T = c_T \frac{\rho}{2} v_s^2 S \tag{6.1}$$

where ρ is the density of water, v_s is the ship's speed, and S is the wetted surface. The coefficient c_T is the (total) resistance coefficient.

Following a classic naval architecture approach, resistance is typically decomposed into simpler components which are later superimposed. According to Froude's hypothesis, the total resistance of a ship is made up from two components, surface friction and the residual resistance:

$$R_T = R_{F0}(\mathrm{Re}) + R_R(F_N) \tag{6.2}$$

Where the first part (friction component) is supposed to depend only on the Reynolds Number $\mathrm{Re} = v_s L/\nu$, and the second part (residual) only on the Froude Number F_N, which is defined as $F_N = \frac{v_s}{\sqrt{gL}}$. In the previous relations, ν denotes the kinematic viscosity of water and L a reference length (typically the ship length). Both Reynolds Number and Froude Number are main parameters resulting from similarity laws which are necessary to scale the initial (and still in use) physical model testing results to the full-scale ship. While the Reynolds Number is used to scale viscous effects, which change with size, the Froude Number scales gravity effects which can be simply determined using the scale factor. While the initial Froude method includes some inherent deficiencies, more accurate methods have been developed over time which account for viscosity-related pressure effects initially included in the residual component. A convenient approach is the Hughes–Prohaska form factor method or a specific full-scale correlation factor which is used in several model basins to the prediction full-scale data. Following the similarity concept, these are best expressed using a coefficient formulation:

$$c_T = (1 + k)c_{F0} + c_R \tag{6.3}$$

for the Hughes–Prohaska form factor approach, where k is the form factor derived from either very low-speed experiments, where the residual resistance tends to zero, or from numerical prediction of a submerged double model of the hull, where k would result from the difference between the total resistance and the flat plate friction estimation according to $c_{F0} = 0.074\text{Re}^{-1/5}$. The residual resistance coefficient c_R can be taken from a model test. The alternative method uses a correlation factor approach:

$$c_T = c_{F0} + c_R + c_A \tag{6.4}$$

In the formula above, c_{F0} is based on the International Towing Tank Conference (ITTC 1957) formula $c_{FITTC} = \frac{0.075}{(\log \text{Re} - 2)^2}$ and needs to be predicted for ship and model scale, c_R is the residual resistance coefficient taken from model tests, and the allowance coefficient c_A is based on the analytics of the model basin. The way in which the value of c_A is predicted is typically described in the model test report.

For detailed descriptions of the model test approach and the analysis and use of data from model tests, a large number of publications exist. Good overview presentations are included in (Schneekluth and Bertram 1998) or (Molland et al. 2017) which guide the reader through the complex matter.

During the early design stages of a ship, model tests are rarely available and the designer will need to rely on prediction methods to make a first estimate of the resistance and subsequently the power requirements of a new vessel. As indicated above, a complete solution of the problem using RANS or similar approaches to solve the governing equation is a theoretical option; however, time and effort required to do so will be extensive and hardly available during early design stages. On the other hand, quick and simple solutions are required to get a first indication of resistance and power requirements when working on a new design. The simplest approach is certainly the use of a parent hullform as a basis for a prognosis. An early example, still widely in use, for such a comparative method is the Admiralty formula for the power requirement $P_D = \frac{\Delta^{2/3} v_S^3}{A_c}$. Here, Δ denotes the displacement of the ship and A_c is a coefficient determined from a—geometrically similar—parent hullform.

Empirical Methods

Having established the prediction of the friction resistance based on Froude's hypothesis or later improvements, the remaining task concentrates on the prediction of the wave resistance which is inherently a function of the hullform of the vessel. This offers a way forward to use simpler predictive methods than the complete RANS solution mentioned before. Over time, numerous statistical prediction methods have evolved. Most of them are based on the analysis of existing ships and are thus inherently a reflection of the time in which they were developed. This is obvious from the comparison of typical hullforms which form the basis of such methods. An early example is the Series 60 method which originates from the 1950s, e.g. in Todd and Forest (1951) and Todd and Pien (1956). This method is based on classic hullforms of the time which still follow a pre-war design philosophy. Later, other methods have been developed, e.g. by Guldhammer and Harvald (1963), which were published a decade later. This was followed by the still widely used Holtrop–Mennen method which originates from 1982 (Holtrop and Mennen 1982). A more recent method was developed by Hollenbach (1998) who developed a statistical method for resistance and powering prediction of single- and twin-screw ships. The latter is of course based on most recent, typical hullforms and widely in use today. The common ground of all methods addressed is of course a statistical evaluation of a large set of experimental data, available either from the literature or in a normalised form directly from a model basin. Understandably, the quality of such analysis largely depends on the main parameters identified during the development of the method. At the time, these were largely restricted to main dimensions and overall ship parameters and ratios.

Today's advanced data analysis tools allow for dedicated tailoring of methods to improve quality, once a sufficiently large data basis and information on relevant hullform parameters is available. Within the HOLISHIP project, an attempt has been made to customise the Hollenbach method specifically for twin-screw RoRo and RoPAX vessels. This is achieved by re-evaluating influence parameters on the basis of up-to-date database information for such vessels. The results obtained from such improvements compare significantly better with model test data (Gatchell 2018). Further work in this direction is expected to provide much improved statistical methods for different base types of vessels in the future.

Empirical tools exist in a number of stand-alone solutions. In HOLISHIP, several promising methods are integrated into close coupling with the core system, the integration platform which provides all necessary input information.

Potential Flow Codes

Although such empirical or statistical methods are applied during the early stages of almost any ship design, the majority of resistance analysis work is, however, assigned to fast and flexible potential flow methods during the next steps, e.g. once main dimensions and the basic hullform have been found. Using a detailed geometrical description of the ship hull as a basis, these tools allow capturing the influence of main geometrical features of a hull and specifically the bulbous bow and other large appendages. The hull model consists of surface panels which are generated on the basis of the geometry kernel. Moreover, since their CPU time requirements are rather reasonable with respect to more sophisticated viscous flow solvers, potential flow solvers are usually adopted as hydrodynamic tool in an optimisation process during early design stages (see Sects. 6.3 and 6.4).

Typical results of such methods are the detailed pressure distribution on the hull as well as the wave elevation around the ship as indicated in Fig. 6.3 and integral forces including the resistance.

These detailed contour maps reveal a lot of information to an experienced designer who will use them as a basis for decision-making on possible hullform modifications to improve the resistance characteristics. Considered in isolation as a purely hydrodynamic problem, this is still a very sensible approach today as it allows to treat possible issues directly from the cause. This may be the size of and distribution

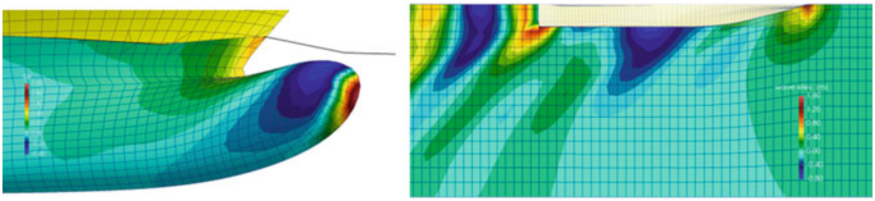


Fig. 6.3 Pressure distribution on the bulbous bow and wave elevation around the hull of a RoPAX ferry

of volume in a bulbous bow, its positioning in relation to the forward shoulder, the waterline entrance angle, etc. However, in an automated optimisation environment as planned in HOLISHIP, the individual decision-making on the basis of the—visual—inspection of results obtained for several hundred of design variants considered in a multi-objective, multi-criteria optimisation would simply be prohibitive. Therefore, other ways of preparing information for—automated—decision-making are required to make such tools fit for use in optimisation processes. As in most cases the tools produce a reliable ranking of the resistance of design alternatives, R_T is often used as criterion in a formal optimisation. This is a relevant and valid choice in many cases, but it requires some pre-check of the validity of results. For an automated optimisation process, it will always make sense to check a few extreme geometrical solutions beforehand to make sure that neither the flow code nor the panel mesh generation produces wrong results simply because their inherent constraints have been violated during a geometry modification. As a precaution, it is further advisable to compute for each design variant not only the resistance but also some monitoring data which can instantly indicate if the prediction would leave its confidence interval. A good choice in this case would be minimum and maximum wave elevation or extreme values of the pressure distribution on the hull.

Integration of potential flow codes into a design system is of course of great importance to assure a quick and reliable analysis. In case of HOLISHIP, the CAESES platform includes the parametric geometry kernel as a basis. Where in the past different types of panel mesh generators have been used to provide the input data to the flow codes, present work has achieved a first step towards harmonisation so that a single-panel mesh format can be generated in the platform which will then be used by different codes. A first example is the common format for HSVA's calm water code ν-Shallo and NTUA's seakeeping and added resistance code NEWDRIFT (see Sect. 6.4).

Viscous Flow Codes

Although panel codes give a good insight into overall resistance characteristics and can be used to determine and optimise principal hull parameters, the overall accuracy of such predictions is often not sufficient to base a full power prognosis on these results. As details such as breaking waves, flow separation, the influence of viscosity on the pressure resistance and in particular the stern flow topology can either only be approximated or not accounted for at all, further analysis is required to obtain

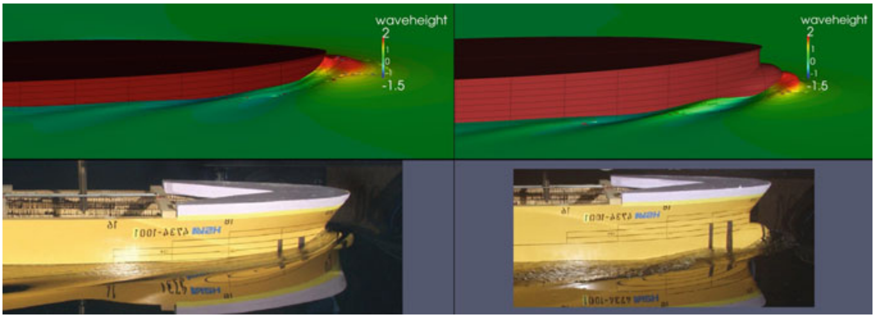


Fig. 6.4 Wave formation at the bow for a bulk carrier at design draft (left) and in ballast (right), comparison of RANS predictions and model test

tangible information on ship resistance. More complex CFD simulations based on RANS equations promise a way forward. These are of course more demanding in terms of effort and time requirements than potential flow predictions. However, with progressing time during the design process and once the overall solution space has been further limited, using more complex methods comes within reach. With fixed main parameters and hull features also RANS predictions are applied in the design process to (i) predict reliable resistance (and propulsion) forces for a given design and (ii) to analyse the effect of specific details, e.g. hull appendages, openings, often found on complex and unconventional ships. Figure 6.4 shows a comparison between RANS predictions (using HSVA's in-house code FreSCo$^+$) and model tests for a bulk carrier at design and ballast draft from (Marzi and Gatchell 2012). The images show that the numerical method is capable of capturing even small details such as the breaking bow wave and the formation of the secondary wave on the hull in ballast. Another advantage is the capability of modern RANS methods to predict resistance in full scale, thus circumventing any scaling procedure following the segregation of resistance forces into friction and pressure-related parts as discussed before.

Applying RANS codes during the design process for a new ship requires great care. Besides specifying the appropriate parameters required for the computation, the provision of a proper computational grid is of utmost importance. Industrial experience shows that there is a large variation in quality of predictions which can in many cases be attributed to errors or inconsistencies during grid generation. A close inspection of appropriate mesh generation strategies is thus required. The MARNET-CFD best practice guidelines (Marnet-CFD 2003) do provide a good introduction to the topic and should be closely followed. Depending on the code applied, users should gradually build up their own recommendations for a best practice over time.

6.1.2 Propulsion

While ship resistance typically accounts for as much as 70% of the energy required to move a ship through water, the propeller or better, the efficiency of the propulsion device, accounts for the rest. For a known resistance of a ship R_T, the effective power is: $P_E = R_T\ v_s$ where v_s is the ship's speed. P_E hence depicts the power necessary to tow a vessel (without propulsion) at a given speed. For a self-propelled vessel, however, the delivered power $P_D = 2\pi Qn$ is decisive, where Q is the torque of the propulsor and n is the rotary speed. Delivered power relates to the engines break power by considering also the efficiency of the shaft and gears as well as power take-offs if available. From a purely hydrodynamic point of view, the relation between delivered power and effective power describes the quality and efficiency of the propulsion system:

$$\frac{P_E}{P_D} = \frac{R_T v_s}{2\pi Qn} = \eta_D \tag{6.5}$$

Here, η_D describes the total propulsive efficiency, the primary measure for the quality of a propulsion device of a ship in operating condition. The design target for a new vessel, with respect to improved energy efficiency, will most certainly be the minimisation of P_D. This offers two possibilities, the minimisation of the resistance R_T or the maximisation of η_D. In practice, designers will attempt to do both.

To capture the individual influences of the overall system propeller and hull on the overall efficiency, a decomposition into main contributors has been established earlier on. The main contributors are:

- **Open-water efficiency**: The propulsor/propeller converts rotary power P_D into thrust. In an isolated view with homogenous inflow, the open-water efficiency of a propeller is defined as:

$$\eta_0 = \frac{T v_A}{2\pi Q_O n} \tag{6.6}$$

  where T is the thrust generated by the propeller and v_A is the incoming flow velocity. The subscript O for the propeller moment indicates the "open-water" condition.
- **Thrust Deduction**: Measuring the propeller thrust behind a ship hull typically indicates that this is significantly higher than the pure resistance of the hull. This results mainly from the suction effect that a rotating propeller has on the hull due to the acceleration of the flow. The resulting change of the pressure distribution on the hull typically yields a higher resistance. This suction effect leads to a reduction of the propeller thrust (compared to the open-water condition) and is one of the propeller hull interactions which occur in a real operating condition. The thrust deduction factor t is expressed as:

$$R_T = (1 - t)T \text{ or } t = 1 - \frac{R_T}{T} \tag{6.7}$$

- **Wake**: The ship hull itself has an effect on the propulsor too. While thrust deduction is a part of the hull–propulsion interaction caused by the propeller, the wake is caused by the ship hull acting on the propeller inflow by reducing the inflow velocity and the incoming momentum. This is due to the displacement of the ship and the viscous boundary layer which leads to decreased flow speeds and loss of momentum. The velocity loss is expressed by the wake fraction w which is defined as:

$$(1 - w) = \frac{v_A}{v_S} \tag{6.8}$$

where v_A is an equivalent homogeneous velocity in the propeller plane. Due to the shape and the boundary layer, the actual velocity distribution is typically very inhomogeneous. In a first step, the integral over the velocity in the propeller plane yields the mean value v_A which replaces the homogenous inflow v_S.

Practical procedures during ship design

For practical reasons during ship design, a split into different influencing factors to predict propeller performance has been established since long. η_D defined above is thus divided into components related to open-water efficiency—η_O as described above, the hull efficiency $\eta_H = (1 - t)/(1 - w)$ using the thrust deduction and wake fraction introduced above and the relative rotative efficiency $\eta_R = Q_O/Q$ where Q_O is the propeller moment obtained in open-water condition and Q the moment when operating behind the ship hull. The overall propulsive efficiency is then: $\eta_D = \eta_O\eta_H\eta_R$. For all of these individual efficiencies, a large variety of data exist which have been derived from model tests and statistical analyses. Appropriate ranges for the individual efficiencies to be used for preliminary design purposes are given in the literature, e.g. in Schneekluth and Bertram (1998), Krüger (2004), Rawson and Tupper (1993) or Molland et al. (2017).

Further advanced steps during the design process will of course make use of more sophisticated procedures to predict propeller performance. As the prediction of the wake fraction w necessarily requires the analysis of the ship boundary layer, the use of RANS codes is inevitable. However, when using an appropriate propeller model (see Sect. 6.2.4.1) in an integrated environment such as the HOLISHIP platform, RANS propulsion predictions can be performed also during relatively early design steps within reasonable time.

Standard Procedures

For the selection of the propeller, before a detailed design which is adapted to the specific wake of a new hullform will be made by a propeller manufacturer, typically series models are used to determine propeller open-water performance. One of the most popular and well-known propeller series is the Wageningen B-Series (B-Series Propeller 2017) which offers a wide range of propeller parameters such as number of blades, area ratio, pitch over diameter ratio *P/D*, hub diameter to be varied to find an optimal propeller open-water performance. A wide range of tools is available to generate such B-Series propellers.

Over time, a wide range of dedicated extensions to the original B-Series have been made in addition to other propeller series following different design philosophies. The EU project TARGETS has produced an extensive enhancement of existing propeller series such as the Meridian Series originally developed by Stone Manganese Marine. Modern design and analysis tools nowadays allow to further enhance the efficiency of propellers and thus helping to save energy.

6.1.3 Seakeeping

The foremost quality of any new ship design must be its seaworthiness. This rather general term describes its ability to remain at sea and perform the tasks it was design for in all conditions it was designed for. Once these conditions are exceeded, the vessel should still be able to safely return to a port of refuge. These emergency conditions call for special considerations regarding the survivability of a ship. But already under normal operating conditions, the performance of a vessel will be strongly influenced by environmental forces such as waves and wind. Other than in calm water conditions, the ship is exposed to such forces which cause motions, speed losses in waves and due to wind forces, deck wetness, heavy spray and slamming. All of these have structural implications which must be considered during structural design of a new vessel, but they do have an impact on the hydrodynamic performance as well and hence must be considered in the early design stages to assure that the new design is capable to operate safely and efficiently in its destined environment.

Ship motions are the most obvious consequences of operation at sea. Excessive amplitudes of motion are undesirable in any respect. They can make shipboard tasks hazardous or even impossible and reduce crew efficiency and passenger comfort as well as safety. This includes also effects such as wetting of decks due to large relative movement of the bow and local wave development leading to local flooding or even massive spray which can have a similar effect.

From an efficiency point of view, additional power requirement associated with increased resistance and speed losses in waves is an important feature which needs to be considered already at an early design stage. This becomes even more relevant as the optimisation of the hullform for calm water performance is much further advanced and more potential for improvements can only be found when looking into operation in waves.

Bow and—for some designs—also stern slamming (pounding) may occur in rough conditions due to large motions and sudden changes in vertical accelerations which are typically caused by flared frame sections. The resulting high-pressure forces due to such excitations can cause significant damage to the structure.

As a consequence, seakeeping considerations become increasingly important in ship design, even for merchant ships. Today, first analyses of the seakeeping behaviour of a new vessel are a substantial part of the hydrodynamic design process.

Tools

Due to the complexity and time/frequency dependency of the problem, fast and efficient methods are required to perform seakeeping predictions. Today, a variety of potential flow-based methods including (nonlinear) strip theory codes as well as panel methods are available to address the most important questions during the design stages. Section 6.2.3.2 will give an example for a panel method to be used for seakeeping predictions. Although significant advances have been achieved in the application of RANS codes also for transient seakeeping predictions, it must be concluded that the time requirements for running viscous computations during the design stage are too high to include them into an efficient design process. They are, however, applicable to special analyses, e.g. of critical cases and to validation of results predicted with simpler methods.

6.1.4 Manoeuvring

Manoeuvrability is another important hydrodynamic quality of any ship; this general term describes the ability of a ship to follow prescribed routes and/or to perform specified manoeuvres or change of direction. However, in the ship hydrodynamics context, the prediction of the manoeuvring capability of a vessel is one of the most challenging problems; the flow being dominated by intense vortical structures detached from the hull and the appendages with mutual interactions, as well as by complicated separation regions along the whole body. The hydrodynamic interactions between hull, rudder and the rotating propeller(s) remarkably increase the complexity of the flow, especially towards the stern. All these aspects make the accurate evaluation of the local and global hydrodynamic forces and moments very difficult.

The evaluation of the ship steering capabilities is traditionally addressed by simplified mathematical models (the so-called system-based models) that strongly rely on information from dedicated manoeuvring experimental tests (i.e. oscillatory motion or circular planar motion tests) or, partially, from potential theory. Usually, simplified mathematical models solve the 3DoF motion of the vessel in the horizontal plane. The increase of operational speed and the need to develop a general platform for the analysis of the whole ship system during a realistic operational scenario as well as the need to better investigate the phenomena related to coupling with the transverse motion (in particular, heel motion) for some vessel typology (container, planning craft) encouraged the development of 4DoF and 6DoF solvers. In Martelli et al. (2014), a 6DoF manoeuvring model, coupled with an engine model, is presented for the analysis of the propulsion system behaviour of twin-screws ships equipped with unconventional propulsion configuration; in Yasukawa and Yoshimura (2014), an improved 4DoF model is developed for capturing the nonlinear coupling of roll motion with the sway–yaw motion. An improved numerical method, based on potential theory, was developed in Lin et al. (2010) for the prediction of ship response in both calm water and in waves. With respect to previous models, it allows a better estimation of the loads on real geometries, without the need of (computationally costly) Navier–Stokes solvers.

Therefore, it is particularly useful for novel designs or unconventional geometries, being able to include the effects related to the rotating propeller; nevertheless, empirical corrections (for viscous damping or to take into account the flow acceleration on the rudder caused by the propeller slipstream, for instance) are still required. However, several previous analyses clearly proved that the details of the flow in the stern region, which is of paramount importance for an accurate prediction of the manoeuvring abilities of a ship, cannot be easily summarised by simplified manoeuvring mathematical models. Although for a single test case, specific towing tank tests with a planar motion mechanism could improve the prediction for a particular vessel (Lewis 1988), a "universal" model able to capture the behaviour of these vessels is still to be devised. In Dubbioso (2011), a simplified manoeuvring model has been adopted for the analysis of the manoeuvring capabilities of a tanker like vessel with two different stern appendage configurations. In particular, a standard twin-rudder twin-propeller configuration and a rather unconventional twin-propeller single-rudder one have been investigated. It has been observed that semi-empirical regressions completely fail in the evaluation of the manoeuvring capabilities in case of the (unusual) single-rudder configuration, and its poor course keeping behaviour is largely overestimated. On the contrary, the dynamic behaviour of the twin-rudder configuration (course stable) is reasonably well captured.

These results clearly demonstrate the limit of simplified approaches, although they remain extremely useful in particular in the early stage design because they are incomparably faster and easier to use than any Navier–Stokes solver. On the other hand, CFD, although demanding in terms of CPU time requirements, has been proved to be mature enough for ship performance prediction in manoeuvres. The key to its success lies in the possibility to predict accurately the details of the flow field that, in turn, allows an accurate analysis of the ship behaviour during a manoeuvre. In addition, the different propeller–rudder arrangements or any other modification on the control devices can be inspected in details and possible critical situation can be amended. For an overview of the state of the art, the interested reader can be referred to the latest workshops on CFD in marine hydrodynamics (Stern et al. 2011; Simonsen et al. 2014). From the mathematical point of view, this problem is tackled by coupling the equations of rigid body motion with the unsteady Reynolds-averaged Navier–Stokes equations. Computationally, difficulties arise from the presence of bodies in relative motion, for which some tricky aspects must be carefully considered. In the context of RANS solvers, the sliding mesh or the dynamic overlapping grid methods can be conveniently implemented in order to let the ship move in a fixed background and to allow the rudder move with respect to the hull. Moreover, due to memory and CPU requirements, reasonably accurate results can be obtained only by using efficient parallel codes. However, in spite of all these difficulties, CFD techniques based on the RANS equations have now reached a satisfactory degree of accuracy for their application to analyse manoeuvring-related problem (either prescribed or predicted manoeuvres). However, since the extremely high time requirement and the need of high level of expertise needed for their use, CFD-based tools are applied up to now only to special analyses and to validation of results predicted with simplified mathematical tools or simpler methods. In Sect. 6.2.4, an example of a CFD analysis for the study of a particular manoeuvring-related problem will be shown.

6.2 Different Types of Hydrodynamic Tools

The ship design process typically covers different project phases. Starting from the proverbial empty sheet of paper, first estimates for the sizing and displacement will quickly be followed by first sketches of the hull and estimates of the power requirements for a given speed. This will over time gradually improve towards more tangible data. While in the past a more or less clear distinction between initial design to provide estimates and contract design to give proven results for a new ship could be made, these borders vanish more and more in recent years. The requirement to deliver tangible information in early design stages becomes more and more urgent and the design processes have to adapt to fulfil such requests. The HOLISHIP project was conceived in view of such necessities to develop and deliver design solutions which give more flexibility and a higher accuracy of results in a fast, integrated and holistic approach. This includes of course hydrodynamic analysis tools.

Although significant improvements have been achieved in terms of performance and flexibility of (more) high-fidelity analysis tools over the years, it still will make little sense to start with the most complex viscous flow prediction to determine the required propulsive power for a new ship design once not even the main dimensions are known. This indicates that there is still a need to consider very fast and simplified integral assessment methods based on statistics to make first estimates for a new ship.

As soon as main dimensions are known, a first hullform can be created, either based on an existing shape and adapted through transformations or developed completely anew. At this moment, CFD tools will be ready to perform more detailed analysis and, more importantly, to start form optimisations. As at the early stages of a design, a larger number of parameters determining the hull shape will still be available, fast tools are required to “cover the ground” and determine the most promising options. This will typically not be possible using complex and more time-consuming viscous CFD codes (RANS) but require less time-consuming analysis methods such as potential flow codes. These will typically allow assessing a large number of design alternatives or parameters in reasonable time using moderate computing facilities. Given the speed and flexibility, especially when integrated into a design environment such as the HOLISHIP platform and combined with a parametric hull model, potential flow analysis nowadays can already be used at the very beginning of the design process when determining the main dimensions, thus blurring the borders between statistical methods and simpler CFD analysis.

The use of full-blown viscous flow codes marks the third level of hydrodynamic analysis tools which will be applied during further advanced design steps after principle design options have been investigated and decided to determine accurate figures, e.g. for power requirements.

6.2.1 Fundamental Considerations

A surface ship generates waves which vary with speed (displacement) of the vessel. Generating these waves requires energy which is attributed to the losses generally known as "wave resistance". This wave resistance forms a significant part of the overall ship resistance during sailing, especially at higher speed, while the other main contribution—friction—will dominate the overall resistance at lower speeds. The wave resistance results from the interaction of two-wave systems, the primary wave system of the hull which is formed by wave crests at the bow and the stern (stagnation points, in ideal fluid) and a typically accelerated flow resulting in a wave trough along the hull. This is superseded by a secondary wave system resulting from the travelling pressure point first described by Kelvin in 1887 and formed by diverging longitudinal waves crossing the advance plane at an angle of 19.47° (in deep water) and a series of convex transverse waves intersecting the longitudinal waves at their end. Their energy is a measure of the wave resistance acting on the pressure point. Wavelength λ in relation to ship speed v_s is:

$$\lambda = \frac{2\pi}{g} v_s^2 = 2\pi F_N^2 L \tag{6.9}$$

where $F_N = \frac{v_s}{\sqrt{gL}}$ is the dimensionless Froude Number.

The overall wave system of a practical ship is made from a number of pressure points all travelling at the same speed and generating their own wave system. The prime contributors to the overall wave system are the bow, the forward and aft shoulders and the stern, all generating waves with the length λ according to the above formula. These wave systems interfere with each other, and favourable situations are achieved when wave crests from one system interfere with wave troughs from another.

Selecting the "right" length for a ship

For the primary wave system, an interference of bow and stern wave is achieved when the ship length is an odd multiple of λ/2, i.e. when:

$$L/\lambda = 1.5, 2.5, 3.5, \ldots = 1/2\pi F_N^2 \tag{6.10}$$

Table 6.1 Favourable and unfavourable Froude Numbers

Favourable interference		Unfavourable interference	
L/λ	F_N	L/λ	F_N
1.5	0.325	1.0	0.399
2.5	0.252	2.0	0.282
3.5	0.213	3.0	0.230
4.5	0.188	4.0	0.199
…	…	…	…
$(2j + 1)/2$	$\sqrt{\frac{1}{2\pi L/\lambda}}$	j	$\sqrt{\frac{1}{2\pi L/\lambda}}$

whereas unfavourable Froude Numbers result from a ship length equalling an integer multiple of the wavelength, yielding the following favourable and unfavourable Froude Numbers (Table 6.1):

While the first set of Froude Numbers with positive interference is often denoted as "Hollow Froude Numbers", the latter is often referred to as "Hump Froude Numbers". Where possible, a ship length corresponding to a "Hollow Froude Number" should be selected.

This is of course not always possible, due to other boundary conditions of the design and to varying operational profiles of a ship which may sail at rather different speeds where not all of them will match a favourable F_N. However, it will still be possible to find positive interferences in those cases when adjusting the forward and aft shoulder in a way that cancellation effects can be achieved. Here, a bulbous bow can play an important role as it will shift the maximum bow wave elevation back. Fine tuning this with the position of the forward shoulder often leads to positive results. An early example was the development of the hullform for the German transatlantic passenger ships *Europa and Bremen* in the 1920s. These were among the first ships with practical bow bulbs (though still small compared by today's standards). Marzi et al. (2014) revisited the design of the two ships and confirmed the positive interference of the bulb with the remaining wave system of the hull as indicated by Kempf (1930). Figure 6.5 shows a comparison of the conceptual considerations presented by Kempf with present potential flow computations.

For a new building project, it is often not possible to freely choose the length on the basis of purely hydrodynamic considerations. The optimisation examples shown throughout the present volume of the HOLISHIP book indicate that modern design optimisations are inevitably multi-objective optimisations taking a number of—often conflicting—boundary conditions into account. However, it will always be a good starting point for a newly developed design, if the entire process starts on the basis of approved knowledge. Where possible a designer should thus choose main parameters for the new design from best practice in the past and especially the length of the vessel so that it will sail at a favourable Froude Number most of the time.

Once these prerequisites are fulfilled hydrodynamic design optimisation can be taken to the next step which will include the application of empirical methods and the use of CFD tools to perform dedicated hullform optimisations.

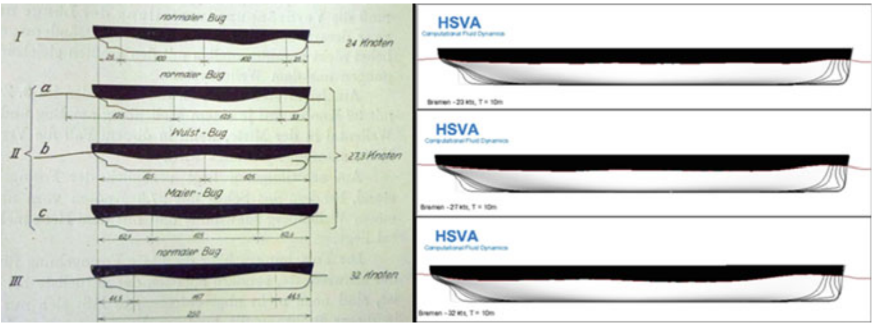


Fig. 6.5 Comparison of theoretical considerations considering wave interference from the 1930s with present time potential flow predictions for the transatlantic liner *Europa*

6.2.2 Empirical Tools

Empirical tools are—due to their simplicity—traditionally used in very early design stages to get first estimates of resistance, power requirements and sometime even assess seakeeping and manoeuvring capabilities. During the last century, a wealth of empirical methods has been developed for a large variety of applications. Good overview presentations can be found, e.g. in Schneekluth and Bertram (1998) and Molland et al. (2017).

During its initial phase, the HOLISHIP project has integrated a set of selected empirical methods also in the design platform. These include:

- *Holtrop–Mennen Method* (by University of Strathclyde): method for resistance and propulsion prediction. Each of the six aspects of the ship resistance (frictional, appendage, wave, bulbous bow, immersed transom and model-ship correlation) is calculated using the guidelines suggested by Holtrop and Mennen (1982). Then, a power calculation takes place using the proposed method to get estimation for the shaft horsepower.
- *Modified Hollenbach Method* (by HSVA): prediction of calm water resistance of twin-screw RoPAX vessels at even keel, design drafts. The method utilises the original Hollenbach method with new data sets for modern RoPAX vessels. Using both, an artificial neural network as well as a particle swarm approach, the main parameters and coefficients of the original Hollenbach method have been adapted to tailor the method specifically for RoPAX vessels. This successful example leads the way to further extension of the approach to other ship types.
- *Wageningen B-Series* (by University of Strathclyde): the tool uses the Wageningen B-series polynomial approximation to predict the thrust and torque propeller characteristics. Main purpose of the tool is to estimate the propeller characteristics during preliminary design phase, when only some main dimensions and ratios of the installed propeller are known. Also, the correction for Reynolds Number (if $Re > 2.0 \times 10^6$) has been incorporated.

The CAESES software connector concept is highly flexible and will in the future allow the inclusion of further methods.

6.2.3 Potential Flow Codes

Potential flow codes still provide the workhorse of CFD analysis during ship design. Their relative speed compared to more complex viscous analysis tools provides the main advantage to quickly look into a larger number of design alternatives and evaluate their relative potential. During early (design) stages where optimisation of larger components or the entire ship hull plays an important role, they are an indispensable means.

A large variety of potential flow codes has been developed for specific use in ship design over the past decades. A variety of which will be implemented into the HOLISHIP design platform at the end of the project. In the following a few examples are given to illustrate the breadth of applications. In addition to what is shown here, alternative tools can be considered.

6.2.3.1 Calm Water Resistance

ν-SHALLO—HSVA

The wave resistance flow code ν-Shallo (Marzi and Hafermann 2008) is a fully non-linear, free surface potential CFD method computing the inviscid flow around a ship hull at a free surface. Ship hull and the water surface are discretised by means of panel meshes. ν-Shallo allows computing a large number of different flow cases including (unlimited,) deep-water conditions, shallow water, monohulls/conventional ships, multi-hulls (catamarans, SWATH, trimarans, asymmetric ships (monohulls as well as catamarans) and submarines.

Standard outputs of a computation are the pressure distribution on the hull and the wave elevation around the ship and integral results such as forces, trim and sinkage. ν-Shallo is based on the principals for treating the nonlinear free surface boundary condition iteratively in a collocation method as described by Jensen et al. (1986) and the patch method for treating the body boundary condition and pressure integration described by Söding (1993).

The flow is described by a potential function in space generated from the superposition of the parallel flow and a distribution of Rankine point sources

$$\phi = -Ux + \sum_i m_i \frac{-4\pi}{r_i} \tag{6.11}$$

In this equation, m_i denotes the strength of each point source and r_i is the distance between the point source and the location where the potential is computed. Velocities

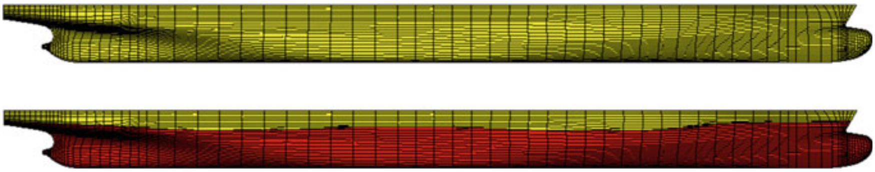


Fig. 6.6 ν-Shallo panel mesh initial (top) and during iteration (bottom)

and accelerations can be computed in the usual manner as the derivatives of the potential $\boldsymbol{V} = \nabla\phi$.

In this method, the point sources are located outside the flow regime to avoid singularities in the equations. Sources are distributed inside the wetted part of the ship hull and above the free surface. The flow code determines the unknown source strengths, the equilibrium floating condition (trim and sinkage), the wetted part of the ship surface and the location of the free surface in an iterative procedure after some initial preparations.

The surface of the body is discretised using triangular and rectangular patches. Starting from an initial—input—mesh, these are modified during iterations to capture the position of the actual free surface (Fig. 6.6).

A point source is located near the centre of each wetted panel and shifted inside the body depending on size and shape of the panel. There are no panels on the transom, which is simply left open (i.e. dry transom stern condition is enforced).

A mesh of collocation points is distributed on the free surface around the hull. The total length and width of the grid, as well as the spacing, are determined automatically based on the Froude Number. Also, the lateral distance of the innermost row of collocation points is preset, based on the Froude Number. In case of a submerged transom or very blunt water line at the stern, additional rows of collocation points are generated behind the transom. In the initial step, an undisturbed free surface is assumed. For each collocation point on the free surface, the flow quantities like velocities and accelerations that are used in the free surface boundary condition are interpolated from the previous step. This iteration starts assuming parallel flow with the ship velocity.

Point sources are generated above each collocation point on the free surface mesh. They are located at a distance depending on the longitudinal spacing of the undisturbed free surface (Fig. 6.7). To enforce the radiation condition there is no point source above the most upstream collocation point in each row. Instead, there is an extra point source downstream from each row of collocation points.

A system of linear equations is set up treating the strengths of the point sources as the unknowns. There are two types of equations: on each collocation point on the free water surface, the combined kinematic and dynamic free surface boundary conditions shown in Jensen et al. (1986), linearised around an approximate solution for the free surface location and flow potential, is applied.

On each patch on the submerged body, an equation is set up requiring that the total the total flow across the patch must be zero (Söding 1993).

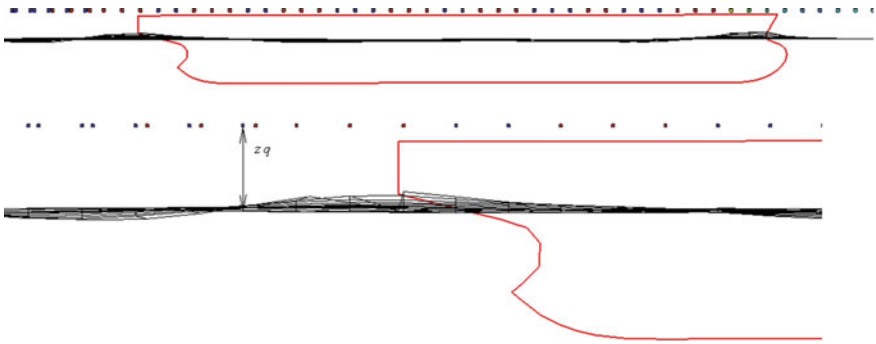


Fig. 6.7 Distribution of sources on the free surface, desingularisation height *zq*

Thus, a linear system of equation with a full coefficient matrix and relatively weak diagonal dominant is derived. To solve for the unknown source strength, a solver combining elimination and iteration steps is used. The potential and its derivatives are then easily determined on each collocation point and panel corner. Using the potential and its derivative on the patch corners, the pressure is computed to determine the pressure force. Also, the hydrostatic term in Bernoulli's equation is considered in the pressure integration. In addition, the square of the velocity on the body is determined to compute an approximation for a friction form factor:

$$k = \int\limits_{S_{\text{wetted}}} \vec{v}^{2} \mathrm{d}S / U^2 S_{\text{initial}} \tag{6.12}$$

This form factor accounts for the change in wetted surface as well as for the inhomogeneous velocity distribution. It should be noted that k must not be compared to the form factor determined as the zero Froude Number approximation from experiments by the Hughes–Prohaska method. Trim and sinkage are estimated based on the vertical forces, and the body grid is moved accordingly.

The wave elevation at the collocation points is computed from Bernoulli's equation. The wave elevation along the hull is determined either by projecting the innermost row of collocation points onto the hull along the local slope of the water surface or from Bernoulli's equation.

Practical Applications

Potential flow codes are ideal tools to perform hullform optimisations at an early design stage when a larger number of free parameters are available. Shape and size of a bulbous bow are a prime example for their application. Figure 6.8 (Marzi and Gatchell 2012) shows an example for a bulbous bow optimisation for a container ship using a systematic variation of several parameters defining the bulb (length, height of tip).

Over time, a number of different process chains have been established to perform either fully or semi-automated optimisations. The latest development performed in

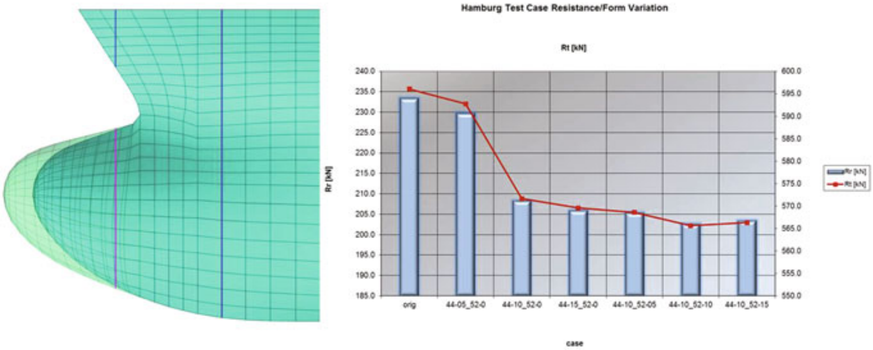


Fig. 6.8 Bulb optimisation—evaluation of wave resistance

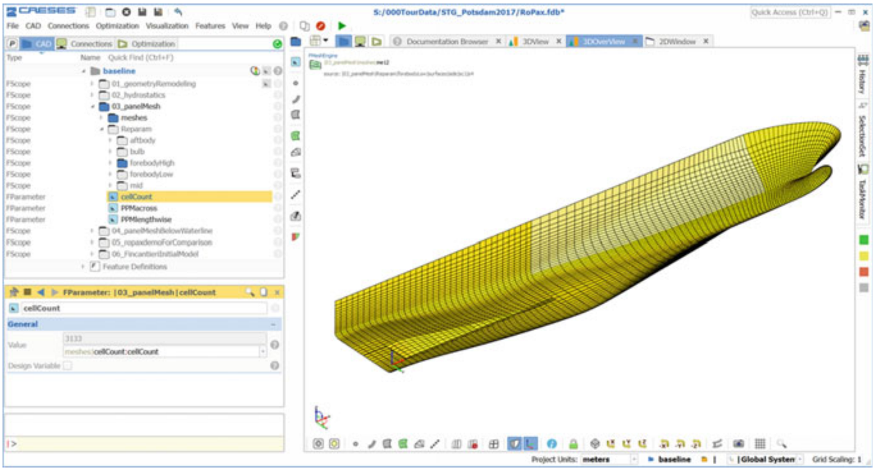


Fig. 6.9 ν-SHALLO interface in the HOLISHIP design platform (CAESES)

HOLISHIP has integrated ν-SHALLO into the HOLISHIP design platform (see Chap. 8) to be used as a sub-module in an overall design optimisation. The user interface is shown in Fig. 6.9.

WARP (CNR-INM)

The Wave Resistance Program (WARP) solver is aimed at the estimation of the wave resistance for submerged bodies as well as mono- and multi-hull surface vessels. The solver is based on the linear potential flow theory. The simplest linear formulation (Kelvin linearisation) is obtained by assuming that the actual flow is slightly perturbed from the free stream, and its potential function is given by $\varphi = Ux + \widetilde{\varphi}$, which provides the Neumann–Kelvin problem for the Laplace equation. A further linearisation, suggested by Dawson (Dawson 1977), is based on the assumption that the flow near the body is perturbed around the double model flow, and its potential

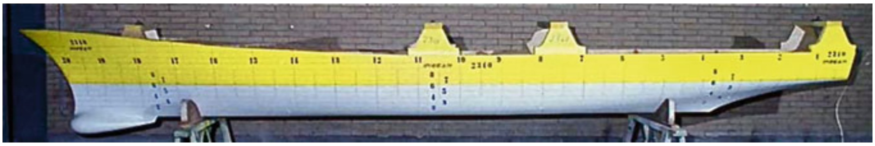


Fig. 6.10 The DTMB 5415 (CNR-INM model 2340)

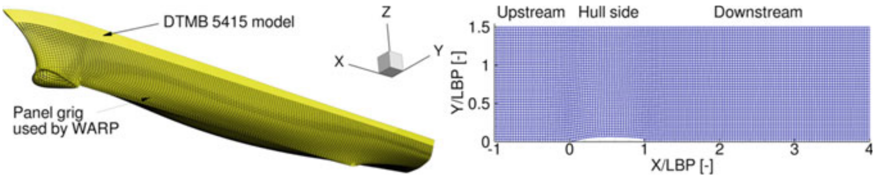


Fig. 6.11 Computational panel grid for WARP

function is given by $\varphi = Ux + \varphi_d + \widetilde{\varphi}$. The Neumann–Kelvin problem is usually reasonable for slender bodies and high speeds, whereas double model is usually more suitable for wider bodies and low speeds.

Once the flow is solved, the wave resistance is evaluated by both a pressure integral over the body surface and the transverse wave cut method. The frictional resistance is estimated using a flat plate approximation, based on the local Reynolds Number. The steady two degrees of freedom equilibrium (i.e. the prediction of the sinkage and the trim) is achieved by iteration of the flow solver and the body equation of motion.

The tool has been proved to provide reasonable results for the initial design phase with an overall good validation against computational and experimental results. Specific attention must be paid to the potential flow formulation used and the computational grid, especially for very low and very high Froude Numbers, and whenever flow separation is expected to occur.

Practical Applications

The WARP solver has been used for the prediction of calm water performances of several naval vehicles; comparison with experimental data and with RANS simulations have been demonstrated the reliability of the results. As an example, the predictions for the DTM5415 naval combatant (see Fig. 6.10) of the total resistance, sinkage and trim for a large range of advancement speeds are reported here.

The computational mesh consists of: 150×30 panels on the hull surface, whereas for the free surface, 30×44, 30×44 and 90×44 panels have been used on the upstream, side and downstream patches, respectively (the mesh and the extension of the computational domain are reported in Fig. 6.11).

In Fig. 6.12, computational results by WARP are compared with experimental data (Olivieri et al. 2001) and RANS simulation (Serani et al. 2016). Good agreement is seen for the resistance (at least at lower and medium speeds) and the trim, whereas disagreement is reported for the estimation of the sinkage. The same vessel reported here will be adopted to show an example of shape optimisation in Sect. 6.3.1.

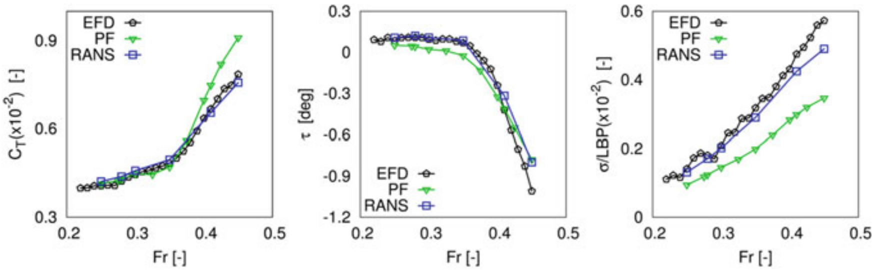


Fig. 6.12 Total resistance coefficient, trim and sinkage prediction by WARP compared with experiments and RANS estimation

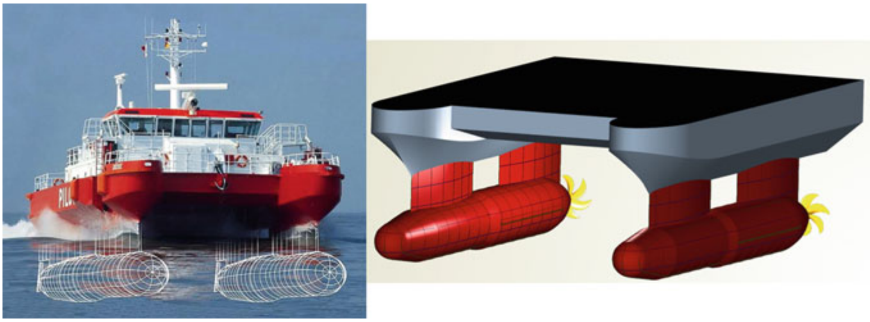


Fig. 6.13 Small waterplane area twin hull (SWATH); left, real vessel, right, CAESES® model

An additional example of practical application is the estimation of the calm water prediction of a small waterplane area twin hull (SWATH) (see also Pellegrini et al. 2018); the geometry is shown in Fig. 6.13. In this case, the model is fixed at the ballast conditions. The same model will be considered as an example of hullform optimisation by using the adaptive multi-fidelity metamodel (AMFM) algorithm, where WARP is used as the low-fidelity solver (Sect. 6.3.2).

Figure 6.14 shows a comparison of the solutions computed by Xnavis (described in Sect. 6.2.4) and WARP of the original SWATH geometry advancing at the design speed F_N=0.489, showing wave elevation, pressure on hull and hydrodynamic resistance. It is worth noting that Xnavis computes a higher wave elevation than WARP, both at bow and stern.

The estimation of the wave elevation from the single-phase level set methodology shows a large wave trough at the trailing edge of the aft strut and the subsequent high rooster tail with the presence of a steep wave including wave breaking phenomena. The wave pattern is linked to the pressure field on the hull. Differences are clearly due to some viscous effects (such as boundary layer separation), not taken into account in the WARP estimation. Similarly, viscous effects are responsible for the difference in the resistance estimation, where Xnavis computes a higher hydrodynamic resistance than WARP for 2 m/s $\leq$ U $\leq$ 3.2 m/s.

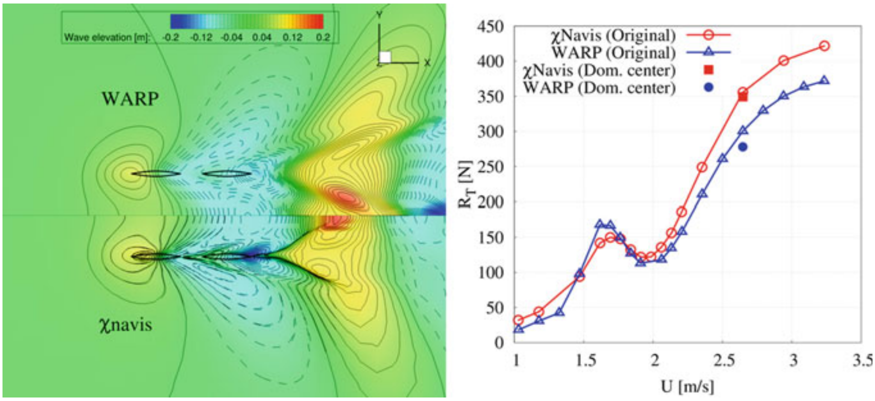


Fig. 6.14 WARP versus Xnavis computations for SWATH. Left: wave patterns; right: total resistance

As already pointed out, potential flow solvers can provide reasonable hydrodynamic results at low computational cost, resulting in a viable option as the hydrodynamic tools for optimisation in ship design. The use of the WARP tool in this framework is reported in Sect. 6.3.

6.2.3.2 Seakeeping and Added Resistance

NEWDRIFT (NTUA)
NEWDRIFT is a frequency-domain 3D panel code based on Green function's method which can be employed for the evaluation of motions, wave loads and mean second-order forces on ships and floating structures subject to incident regular waves (Papanikolaou 1985; Papanikolaou and Zaraphonitis 1987, 1992). A comparison of first-order motions calculated with NEWDRIFT with experimental measurements from CEHIPAR for a fast round-bilge monohull sailing in head regular waves at a speed of 20 kn (F_N=0.3) is presented in Fig. 6.15 (heave RAO) and Fig. 6.16 (pitch RAO) (Papanikolaou et al. 2000).

NEWDRIFT+ was developed from the original NEWDRIFT code by adding software tools for the calculation of added resistance of ships in waves. The NEWDRIFT+ code has been adapted for the optimisation studies required in the HOLISHIP project. In particular, in NEWDRIFT+ the far-field method of Maruo for the calculation of the added resistance in waves has been included (Liu et al. 2011). A semi-empirical short-wave correction has been also considered, which yields the very good results for the added resistance in seaways represented by realistic wave spectra, along with an improved empirical formula, which is applicable for fast preliminary calculations. A comparison of numerical predictions for added resistance with experimental results is presented in Figs. 6.17 and 6.18 reproduced from Liu

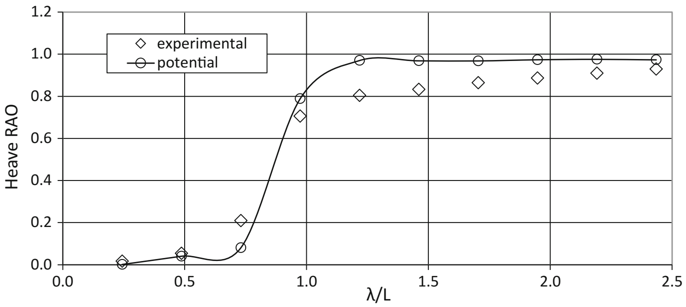


Fig. 6.15 Heave RAOs (NEWDRIFT results versus experimental measurements from CEHIPAR) for a fast round-bilge monohull in head regular waves at 20 kn (F_N=0.3)

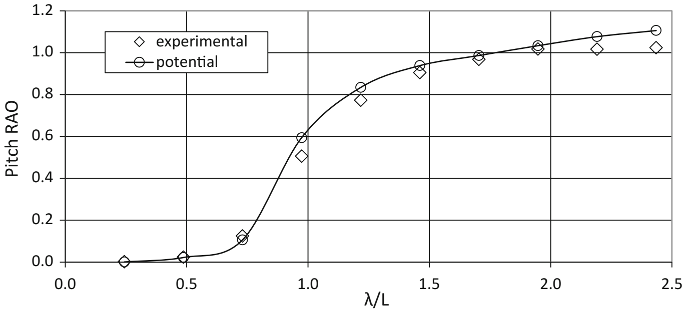


Fig. 6.16 Pitch RAOs (NEWDRIFT results vs. experimental measurements from CEHIPAR) for a fast round-bilge monohull in head regular waves at 20 kn (F_N=0.3)

and Papanikolaou (2016). The numerical results are derived by NEWDRIFT+ using the far-field method and the simplified semi-empirical method for short waves as well as the STA2 method by MARIN and the method of Jinkine and Ferdinande (1974). The experimental results for the KVLCC2 tanker are from Guo and Steen (2010) and for the S175 ship from Takahashi (1988).

NEWDRIFT+ has been already used in various optimisation studies for the FINCANTIERI RoPAX presented in a series of papers (Harries et al. 2017) and (Marzi et al. 2018) where added resistance along with calm water resistance predictions has been used for the calculation of the propulsion power.

AEGIR (NAVATEK Ltd.)

AEGIR is a time-domain seakeeping code, based on a high-order boundary element method for the 3D potential flow. AEGIR is specifically tailored for ships, mono- and multi-hull. It encompasses models and numerical methods for linear radiation, diffraction, Froude–Krylov forces and equation of motion, as well as nonlinear Froude–Krylov forces. It also implements linear and nonlinear body boundary conditions, linear and nonlinear steady-state solution. Transom stern conditions may be applied. The numerical solution is based on a non-uniform rational B-spline

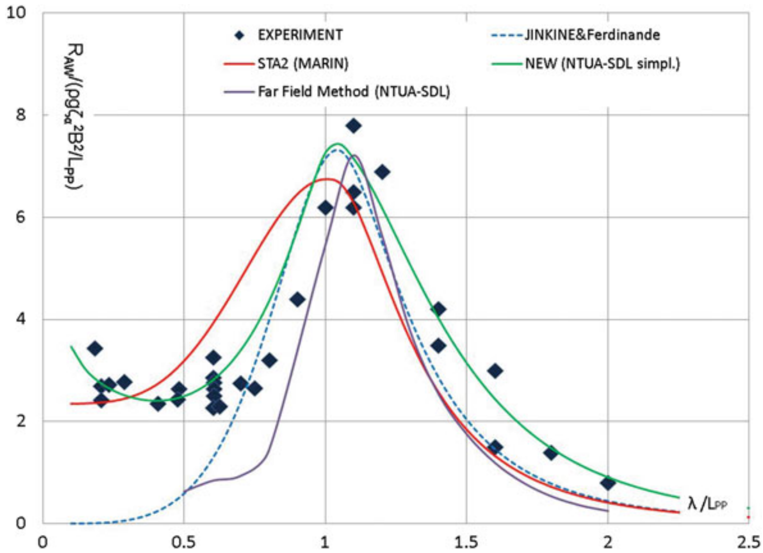


Fig. 6.17 Added resistance of KVLCC2 ship in head waves, $F_N = 0.142$

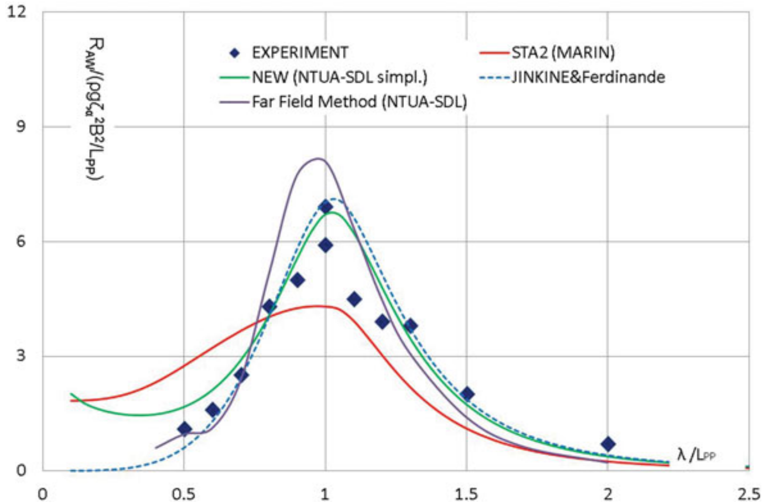


Fig. 6.18 Added resistance of S175 containership in head waves, $F_N = 0.15$

(NURBS) representation of the geometry. Further details of the formulation, numerical implementation and validation of seakeeping predictions may be found in Kring et al. (2008) and Datla et al. (2009).

An example of a typical output is shown in Figs. 6.19 and 6.20 where the polar diagram of the heave motion with different confidence intervals and the heave motion,

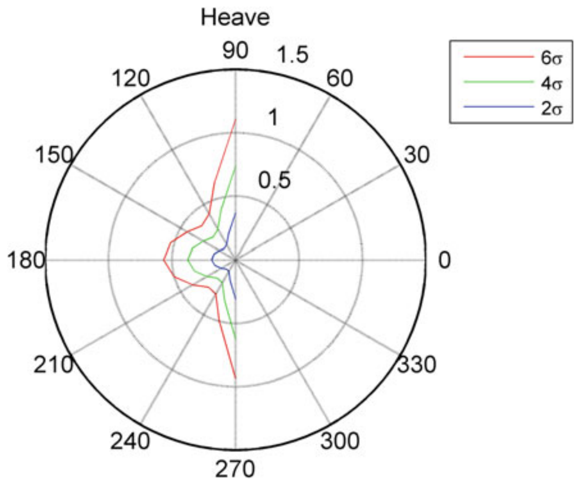


Fig. 6.19 Polar diagram of the heave motion of a catamaran with different confidence intervals in irregular wave with Bretschneider spectrum

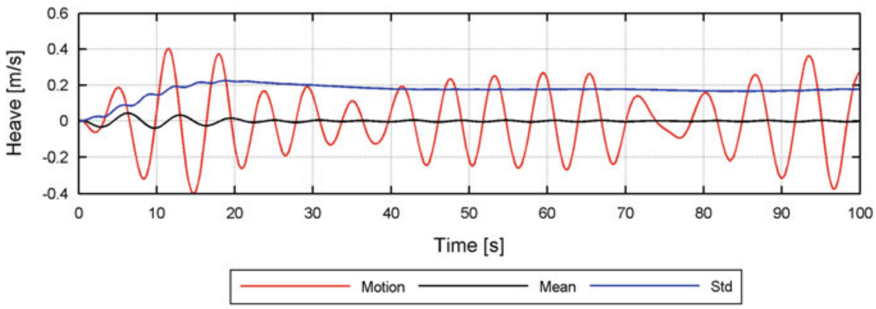


Fig. 6.20 Heave motion of a catamaran with different confidence intervals in irregular wave with Bretschneider spectrum

mean and standard deviation of a multi-hull in irregular wave with Bretschneider spectrum are reported. In general, Aegir is also able to provide the ship motions (surge, sway, heave, roll, pitch and yaw) as well as the forces and moments on the hull. Unsteady computations can be performed in regular and irregular wave with several sea states and spectra, also varying the heading and Froude Number.

6.2.3.3 Propeller Codes

QCM (HSVA)

QCM is a propeller method developed by HSVA on the basis of the quasi-continuous method originally proposed by Nakamura (1985) for open-water applications and later extended to the “in behind the hull” condition by adding a hull wake as input the computation (Hoshino 1985). This can be derived from model tests or—nowadays more frequently—from CFD predictions.

QCM allows to model arbitrary propeller geometries beyond the typical limitations of the regular series propellers referred to in Sect. 6.1.2. It combines the advantages of the continuous loading method and discrete loading method in that the loading distribution is assumed to be continuous in chordwise direction and stepwise constant in spanwise direction. Simplicity and flexibility of discrete loading method are also retained.

Comparisons of propeller open-water characteristics calculated by the present method with measured data showed good agreement for a wide variety of propellers including both conventional as well as skewed propeller designs. The method has been established as a standard propeller design and prediction tool in HSVA and other organisations. Today, the code is mostly in use in a coupled mode together with the RANS code FreSCo$^+$ (see Sect. 6.2.4) for numerical propulsion predictions.

HSVA’s QCM code is one example of a larger range of potential flow propeller codes which use different modelling approaches, such as panels, vortex lattice or other discrete models. The HOLISHIP platform over time will integrate different propeller codes either for stand-alone analysis or coupled with RANS codes for the ship propulsion prediction.

6.2.4 Viscous Flow Codes

FreSCo$^+$ (HSVA)

FreSCo$^+$ (Hafermann 2007) is a joint development of Technical University Hamburg-Harburg and HSVA, originating from the Framework 6 project VIRTUE. The code was created as a general-purpose RANS solver with dedicated maritime applications in mind. FreSCo$^+$ solves the incompressible, unsteady Navier–Stokes equations. The transport equations are discretised with the cell-centred finite volume method. Using a face-based approach, the method is applied to fully unstructured grids using arbitrary polyhedral cells. Therefore, the code can use grids from different grid generators like the fully unstructured, automatic grid generator HEXPRESS by Numeca. This reduces the time needed for typical grids from weeks to days. The governing equations are solved in a segregated manner, utilising a volume-specific pressure correction scheme to satisfy the continuity equation. To avoid an odd–even decoupling of pressure and velocity, a third-order pressure smoothing is employed along a route outlined by Rhie and Chow (1983). The fully implicit algorithm is second-order accurate in space and time. The approximation of the integrals is based on the mid-point rule. Diffusion terms are approximated using second-order central differences, whereas advective fluxes are approximated based on blends between high-order upwind-biased schemes (e.g. QUICK), first-order upwind and second-order central differences schemes. The resulting linear equation systems are solved

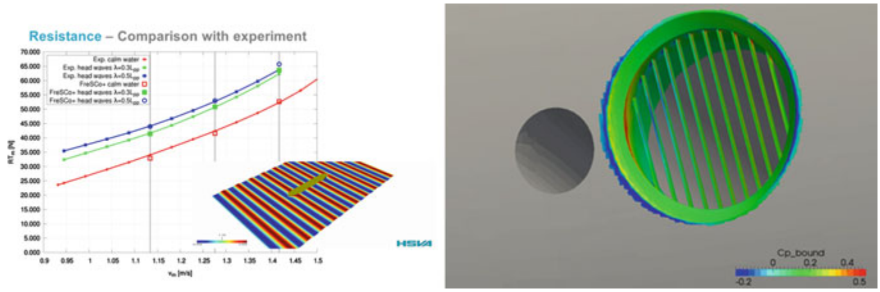


Fig. 6.21 FreSCo$^+$ applications: (left) added resistance in a head waves for a bulk carrier; (right) detail of the flow over a bow thruster opening

iteratively using Krylov subspace methods. The respective solvers are provided by the PETSc library (Balay et al. 2018). The code is efficiently parallelised in space. To account for turbulent flows, additional transport equations are solved for turbulent quantities. Several turbulence models are implemented the code: κ-ε (standard, RNG, Chen), κ- (standard, BSL, SST), Menter's one-equation model and the Spalart–Allmaras turbulence model. To simulate the flow with free surfaces, a volume of fluid approach is used. For complex transient simulations with separation and compound fluid flow topologies, FreSCo$^+$ also employs a DES (detached eddy simulation) model which is used for aerodynamic analyses.

Example of Applications

Being a versatile RANS code specifically developed for maritime applications, FreSCo$^+$ allows addressing a wide range of typical as well as extraordinary maritime flow problems. Standard use cases are of course resistance and propulsion predictions which have been addressed already in Sects. 6.1.1 and 6.1.2. In new ship design, typical applications comprise seakeeping and manoeuvring predictions and a range of detailed flow investigations.

Figure 6.21 shows two examples: on the left, the results of a seakeeping and added resistance prediction are shown for a bulk carrier in head waves. The comparison with experimental data shows very good agreement. The second example on the right shows a detail of the flow (pressure distribution) on a bow thruster opening and the correct orientation of the grille in a full-scale analysis. In this case, it is recommended to perform full-scale predictions as the effect of the boundary layer—although close to the bow—can deteriorate the main orientation of the flow. This will be different in model scale due to the vastly different Reynolds Number. Orientation of the grille and the shape of the thruster edge can influence the resistance.

Using a RANS code to determine options for retrofit solutions can also be a very good option. Two such retrofit applications are shown in Fig. 6.22. On the left, a detailed study for the modification of the bulbous bow of a 6500 TEU container vessel for slow-speed operation analysed in the TARGETS project (Marzi and Mermiris 2012) is indicated. The original design for a speed of 24 kts had to be adapted for slow steaming conditions below 14 kts to fit into new service schedules

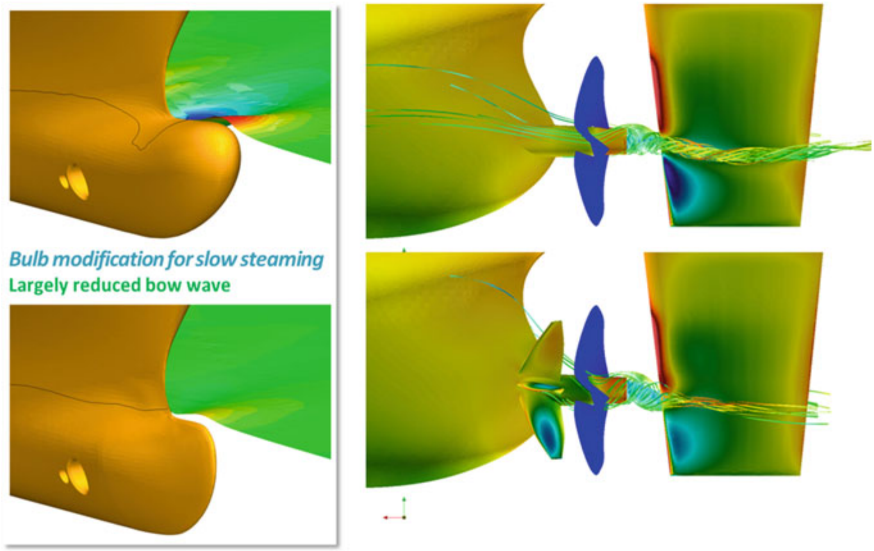


Fig. 6.22 FreSCo$^+$ applications—left: bulbous bow for slow steaming condition; right: effect of energy saving device PSS on bulk carrier propulsion

of the operator. This optimisation resulted in more than 10% power reductions for the new—range—of service speeds compared to the original design. FreSCo$^+$ was applied to confirm initial optimisation results obtained with panel code (ν-Shallo) predictions. The right part shows CFD predictions for a pre-swirl stator (PSS) energy saving device designed for a bulk carrier in the GRIP project (Xing-Kaeding 2015). Figure 6.22 indicates the change of the hub vortex due to the PSS. Full-scale trials with the ship in both conditions later confirmed power saving of up to 6.8% for the trial conditions.

All of the above are important applications which can be utilised during different design stages. As discussed before, huge, time-consuming RANS analyses will hardly be the method of choice in early design stages when a larger number of global design variants need to be considered. However, once the solution space of the overall design problem has been sufficiently narrowed, a detailed look into specific aspects will prove beneficial in any respect as it can help to avoid complex and costly repairs and exchanges of initially rather small components, e.g. the bow thruster, at a later stage. Considering energy saving devices as the PSS shown above, RANS methods are clearly the tools of choice to analyse their effect in a retrofit, especially in later stages of the ship's life cycle.

Xnavis (CNR-INM)

The Xnavis code is a general-purpose unsteady Navier–Stokes equations solver. Numerical discretisation of the RANS equations is achieved in the framework of a finite volume formulation with conservative variables co-located at cell centres.

The computation of the convective fluxes and the surface integral of the velocity in the continuity equation can be done by several approximation schemes available in the code, ranging from the first-order Godunov scheme, the second-order total variation diminishing scheme, the third-order essentially non-oscillatory scheme, the third-order weighted essentially non-oscillatory scheme and the classical fourth-order cantered scheme (for more details see Di Mascio et al. 2001, 2007, 2009). Viscous fluxes are discretised by means of the classical finite volumes second-order formulation. Momentum and mass conservation equations are coupled by a pseudo-time integration that exploits an Euler implicit scheme with approximate factorisation, local pseudo-time step and an efficient multi-grid method are used to accelerate the convergence towards the divergence-free solution. In the solver, several turbulence models have been implemented, namely the one-equation Spalart–Allmaras turbulence model and the two equations κ-ε model; the code is also capable to perform large eddy simulations and detached/delayed detached eddy simulations. The free surface effects are simulated through a fully nonlinear level set single-phase methodology (Di Mascio et al. 2007; Broglia and Durante 2018).

The code is based in a block-structured discretisation of the computational domain; (dynamic) overlapping grid capabilities have been also implemented. In the "chimera" approach, the possibility to let the grids overlap is achieved through a modification of both the boundary conditions and internal point treatment for those zones where overlapping appears: dynamic overlapping grid method allows for easy and accurate handling of complex geometries and multiple bodies in relative motion. Chimera technique requires to locate regions in other blocks from where an approximation of the solution can be extracted; namely, it requires to find "donor" cells. Once the donor is identified, a convex set of eight donor cell centres is searched, and a tri-linear interpolation is used to transfer the solution from one block to the one under analysis. If an overlapped cell is found, the cell is marked as a "hole" only if the donor cell is "smaller" (more refined) than the one under analysis. Differently from standard chimera approaches, however, the cell marked as holes are not removed from the computation; instead, the interpolated solution is enforced on the marked cell point by adding a forcing term to the Navier–Stokes equations, in a "body-force" fashion (for more details see Di Mascio et al. 2006; Zaghi et al. 2015).

High-performance computing capabilities are achieved by an efficient shared and distributed memory parallelisation (Broglia et al. 2014). Propeller effects can be taken into account by either a real geometry representation of the propeller or modelled using an actuator disc model (see Broglia et al. 2013).

The code has been widely applied for several naval hydrodynamic-related problems, for example manoeuvrability of surface vessels and submarines (Broglia et al. 2015a, b; Dubbioso et al. 2016, 2017; Muscari et al. 2017a, b), naval propellers (Muscari et al. 2013; Dubbioso et al. 2013; Broglia et al. 2015a, b) and hydrodynamics of multi-hull vessels (Broglia et al. 2011; Zaghi et al. 2011).

Example of Applications

An example of the high-level capabilities of the Xnavis CFD solver for the prediction of calm water performances of a surface vessel is reported here; the model under

Fig. 6.23 Azimut Benetti *Grande 95RPH*

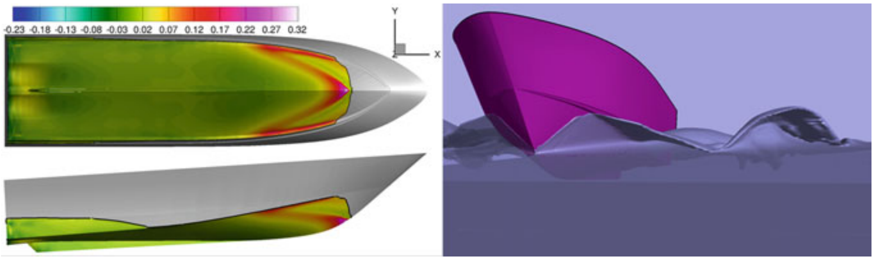


Fig. 6.24 High-speed semi-displacement vessel: left, pressure distribution on the hull surface; right, wave pattern. From Broglia and Durante (2018)

investigation is the *Grande 95RPH* (Fig. 6.23), a luxury yacht of the Azimut Benetti Group.

The calm water analysis is pursued for the semi-displacement vessel in straight-ahead advancement (Broglia and Durante 2018); the vessel is travelling for speeds spanning from 18 to 34 knots (i.e. Froude and Reynolds Numbers in the range [0.6:1.2] and $[1.91 \times 10^8 : 3.60 \times 10^8]$. Computation was performed at full scale without the use of any wall functions; the (block structures, chimera) computational mesh counts for about 18.5 M of control volumes for half ship (simulations consider the longitudinal symmetry).

The flow field is characterised by localised high pressure (see Fig. 6.24) values which give rise to energetic water sheets and, consequently, a rather complex wave pattern. Nevertheless, it is shown that a state-of-the-art hydrodynamic tool is able to correctly reproduce the very complex phenomenon of the formation of the jet, the consequent wave breaking dynamics and the multiple splash ups and ricochets, allowing to an accurate prediction of the resistance, sinkage and trim curves over the entire range of speed.

In Fig. 6.25, the total resistance R_T (non-dimensionalised by the gravitational force mg, m being the displacement mass), the sinkage (i.e. the position of the centre of gravity, positive when the CG moves upward) and the trim (positive when the

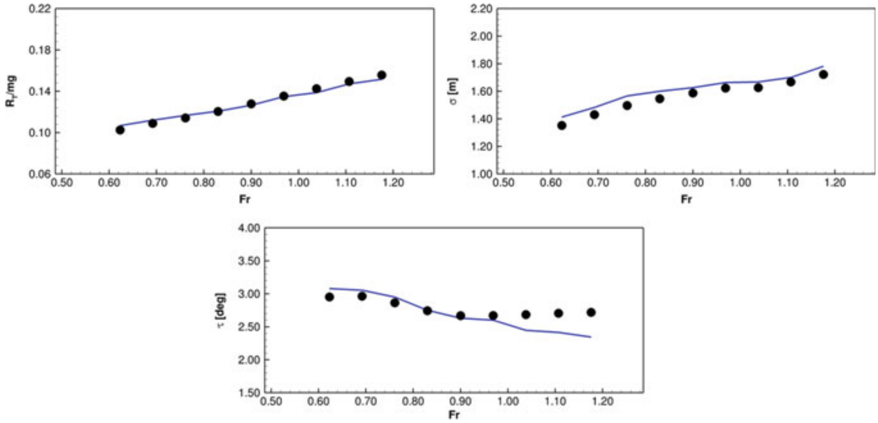


Fig. 6.25 Resistance, sinkage and trim predictions for a high-speed vessel. From Broglia and Durante (2018)

ship rotates bow up) estimations versus Froude Number are shown. Computations (solid line) are reported as long as experiments (symbols). The comparison with experiments is rather satisfactory; resistance is well predicted for the whole speed range (max error is about 6%), as well as for the sink. Trim prediction is rather good at the lower-medium speed. At higher speeds, computational estimations provide a continuously decreasing of the trim, whereas EFD measurements show a kind of plateau.

Another example showing the capabilities of the viscous-based hydrodynamic tools is the prediction of the (free running) evolution manoeuvre of a tanker like vessel; the problem is challenging being two different stern appendage configurations (Fig. 6.26) are compared (see also Broglia et al. 2015a, b; Dubbioso et al. 2016). Due to the unusual configuration, the prediction by simplified mathematical models can provide rather inaccurate results (Dubbioso 2011). Moreover, it has to be highlighted that, especially for tight manoeuvres, the generation of the propeller side force during a manoeuvre can be rather relevant (15–25% of the total lateral force experienced by the fully appended hull); this would require either the inclusion of the rotating propeller in real geometry or the use of propeller models which properly take into account for lateral forces. In the results reported here, since only the global effects of the propeller are relevant for an accurate prediction of the manoeuvring abilities, a suitable propeller model is used (Broglia et al. 2013).

Unsteady RANS simulations here are pursued to predict the trajectory of the ship after the activation of the rudder(s). Similar to classical free running tests, the simulation is performed in two phases: (i) approaching phase where time-accurate three degrees of freedom (DoF) simulation (yaw, sway and roll are retained) is performed to let the ship achieve both the dynamical attitude and the stabilised speed (the propeller working point is given); (ii) evolution phase: once the attitude of the ship has reached a reasonable stable condition, the rudder is rotated with the prescribed

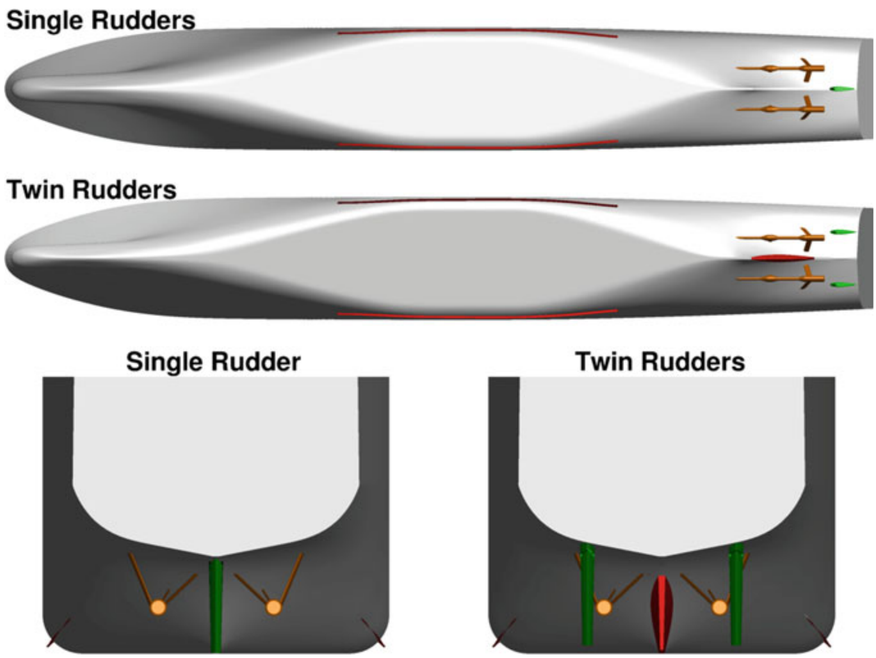


Fig. 6.26 Vessel geometry: single- and twin-rudder configurations

turning rate up to the prescribed deflection angle. During this phase, a time-resolved 6DoF simulation is carried out; the vessel is left free to proceed along the trajectory provided by the integration of the 6DoF equations for rigid motion with the external forces estimated by the CFD.

In Fig. 6.27, the trajectory and the time histories of kinematic parameters (speed drop, drift angle and yaw rate) are shown; results for both configurations are reported. $tU_0/L_{PP} = 0$ is the time at which the rudder starts its rotation; the position of the model at this time is taken as the origin of the earth fixed system of reference. The velocity of the ship is normalised with the velocity at $tU_0/L_{PP} = 0$, i.e. the approaching speed. In Fig. 6.27, the time of the start ($tU_0/L_{PP} = 0$) and the end ($tU_0/L_{PP} = 0.8$) of rudder(s) rotation are indicated with vertical blue dashed lines. As it can be seen, the estimation by the hydrodynamic tool is able to accurately capture both the trajectory and the kinematics.

The agreement between experiments and numerical results is satisfactory; to properly estimate the quality of the numerical simulations, a validation analysis in term of both kinematical and dynamical parameters is reported in Table 6.2. From Table 6.2, it can be clearly seen that the CFD tool is able to provide highly accurate results for both the transient and the stationary phases. The manoeuvring abilities for both configurations are well captured; i.e., contrary to simplified mathematical models, a CFD-based solver is able to correctly predict the manoeuvre of a vessel for both common and uncommon stern configurations, being based on few simplifying hypothe-

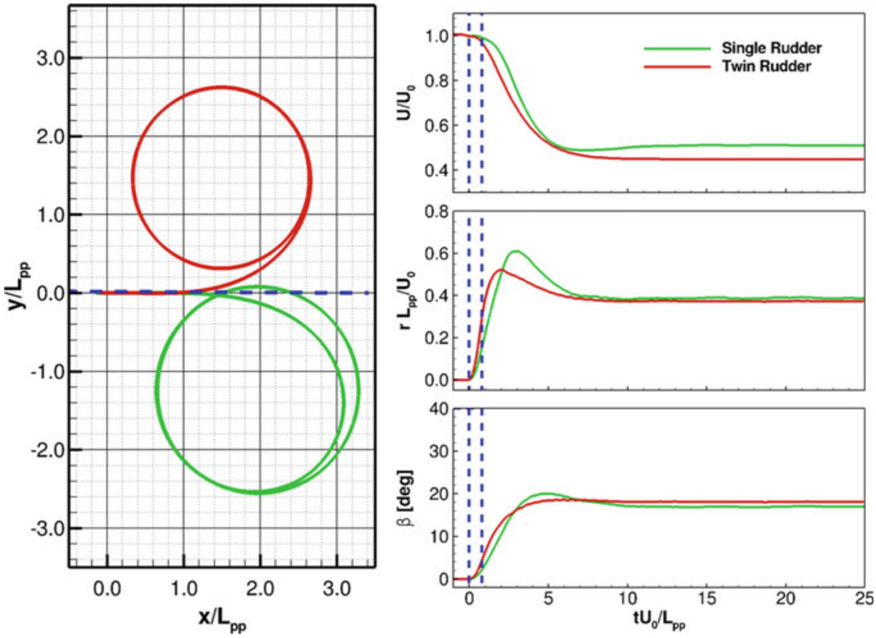


Fig. 6.27 Trajectory and kinematical parameters prediction: single- and twin-rudder configurations

Table 6.2 Single- and twin-rudder results, comparison with experimental measurements (Broglia et al. 2015a, b; Dubbioso et al. 2016)

Parameter	Single rudder		Twin rudders	
	S	ε [$\%D$]	S	ε [$\%D$]
Advance	3.02	3.63	2.59	3.99
Transfer	1.02	0.67	1.06	6.70
Tactical	2.48	5.33	2.56	5.04
Peak yaw rate	0.611	N/A	0.523	N/A
Peak drift	20.01	N/A	18.66	N/A
Turning	2.60	0.13	2.31	7.71
Speed drop	0.51	7.16	0.45	1.65
Yaw rate	0.384	2.52	0.373	0.20
Drift	17.00	6.19	18.15	22.96

ses. In particular, CFD results highlight that the two rudder configuration exhibits a larger efficiency of the manoeuvring appendages, clearly evidenced by the higher slopes of both the yaw rate and drift angle after the rudder actuation, and the smaller advance and turning diameter in the trajectory plot. The larger speed drop (of about 12%) is caused by the faster response of the vessel due to higher rudder efficiency.

6.2.4.1 Propulsion and Propeller Model

It is obvious that the more accurate way to predict the extremely complicated physical phenomena in the propeller region would be achieved by the direct computation of the rotating propellers, but the increase in computational resources would be rather large. Therefore, when the details of the flow are not required, a convenient choice might be the inclusion of simplified semi-empirical models which do not significantly increase the overall complexity and resource demand. In many aeronautics and marine CFD scenarios, the presence of the propeller is taken into account by models based on the actuator disc concept, according to which a field of body forces is distributed over a disc of finite thickness. Distributions of both axial and tangential body forces are utilised in order to simulate the acceleration and the swirl induced flow when passing through the propeller. In the simplest approach, only the mean effects are considered, and therefore, the force fields mimicking the action of the blades on the flow fields are obtained by blade loads averaging in both time and space. Time averages are taken over one period of revolution, whereas space averages are obtained by distributing blade loads in circumferential direction over the whole propeller disc. Body forces depend on the actual velocity field, which in turn depends on the action of the blades. Therefore, any realistic model should take into account their mutual interaction. Moreover, due to the nonlinearity of this interaction, an iterative procedure is required. To show the main differences between the various propeller models utilised in CFD computations, in the following, two models are presented. The first one is based on a prescribed distribution of the circulation on the propeller blades, and their geometry is considered only (at maximum) by main dimensions (such as chord distributions, number of propellers, diameters, etc.). In the second approach, the propeller geometry is considered in its real geometry; propeller loads and the consequent effects on the flow field are estimated by a BEM computation taking into account the effective wake.

Modified Hough and Ordway model

In this model, the propeller loading is computed according to the idea suggested by Hough and Ordway (1965): given the advance, thrust and torque coefficients (J, K_T, K_Q), the (azimuthal averaged) axial, radial and tangential force distributions are computed under the assumption of an optimal distribution for the circulation. A modification of the original model (Broglia et al. 2013) consists to take into account both the axial flow reduction at the propeller disc and the side force developed by the propeller; this improvement has been proved to provide better results when employed in the prediction of free running manoeuvres. Axial flow reduction is accounted for by computing, at each time step, an estimation of the advance coefficient, for the given propeller rate of revolution and using the instantaneous average axial velocity at the propeller disc inflow section. Then, new values of $K_T(J)$ and $K_Q(J)$ are computed from the propeller characteristic curves. Lateral forces due to non-axial-symmetry of the inflow are instead accounted for by means of a simplified model under the assumption of side-forces proportional to a proper drift angle. To this aim, the semi-empirical method of Ribner (1945), which was developed in aeronautics, has been considered. For more details on this approach, including its validation, the reader is referred to Broglia et al. (2013, 2015a, b) and Dubbioso et al. (2016).

Hybrid RANS/BEM approach

The hybrid model is based on the coupling of a boundary integral equation model to solve the propeller loads and a CFD viscous tool for the computation of the flow field around the hull. Here, the methodology is described as it has been implemented in the CFD code Xnavis (Salvatore et al. 2015; Calcagni et al. 2017); several other implementations are available in the literature (as, e.g., for QCM/FreSCo$^+$ solver). The BEM tool used into the hybrid approach described here is the PRO-INS solver, a potential flow-based solver for the analysis of marine propellers in non-cavitating flows and cavitating flows (Salvatore et al. 2011), operating in uniform and non-homogeneous onset flows. A time-marching solution is computed in the frame of reference rotating with the propeller keyblade in terms of the velocity scalar potential over the propeller surface. Under potential flow assumptions, mass and momentum equations reduce, respectively, to the Laplace equation for the velocity potential, $\nabla^2\varphi = 0$, whereas the velocity field is expressed as $\mathbf{U}_p = \nabla\varphi$.

The application of the Green theorem leads to the integral formulation for the scalar potential φ:

$$E(\boldsymbol{x})\varphi(\boldsymbol{x}) = \oint\limits_{S_B} \left(\frac{\partial\varphi}{\partial n}G - \varphi\frac{\partial G}{\partial n}\right)\mathrm{d}S - \int\limits_{S_W} \Delta\varphi\frac{\partial G}{\partial n}\mathrm{d}S \tag{6.13}$$

where S_B denotes the propeller solid surface, S_W is the trailing wake and $\boldsymbol{n}$ is the unit normal to these surfaces. The symbol Δ denotes discontinuity of φ across the wake surface, and G, $\partial G/\partial n$ are unit source and dipoles in the unbounded three-dimensional space. Finally, $E(\boldsymbol{x})$ is a field function defined throughout the fluid domain and characterising the case where $\boldsymbol{x}$ is inside the flow field ($E=1$), on the solid boundary surface ($E=1/2$) or inside the solid body ($E=0$). $\frac{\partial\varphi}{\partial n}$ are determined through boundary conditions on the propeller surface. The pressure distribution is derived from the scalar potential distribution by the application of the Bernoulli's theorem:

$$\frac{\partial\varphi}{\partial t} + \frac{1}{2}|\nabla\varphi + \mathbf{U}_{\boldsymbol{I}}|^2 + \frac{p}{\rho} + gz_0 = \frac{1}{2}|\mathbf{U}_{\boldsymbol{I}}|^2 + \frac{p_0}{\rho} \tag{6.14}$$

where $\mathbf{U}_{\boldsymbol{I}}$ represents the incoming inflow velocity to propeller plane.

Loads are derived from the scalar pressure distribution over the propeller blades with viscosity-induced tangential stress terms corresponding to a flat plate operating in the same turbulent conditions. In the PRO-INS tool, a prescribed shaped propeller trailing wake surface is considered, coaxial to the propeller shaft. The coupling between RANSE/BEM is based on the estimation/exchange of volume force and effective inflow terms. Hydrodynamic forces on propeller blade surface are determined by BEM and distributed as volume forces $\mathbf{Q}$, over the actual position of the propeller blades during rotation. Suitable source terms derived from volume forces

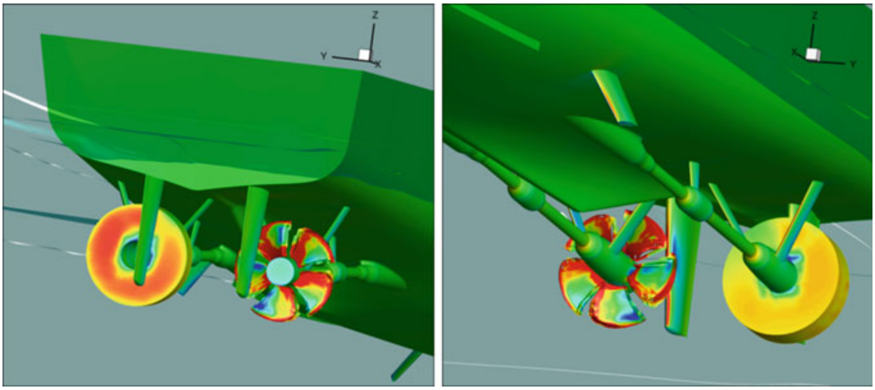


Fig. 6.28 Surface vessel in straight-ahead advancement (self-propulsion test). The solution with the simplified actuator disc model is reported on port side, whereas, on the starboard side, the hybrid (unsteady) RANS/BEM propeller model is shown

are added to the Navier–Stokes momentum equations, allowing for the unsteady solution in presence of the propeller. The velocity distribution by RANSE is then used to determine the total flow at the onset propeller plane. At each time step, the inflow to the propeller representing the ship hull perturbation is calculated by subtracting from the RANSE total velocity the time-accurate propeller induced velocity by BEM, i.e. $\mathbf{U}_R = \mathbf{U} - \nabla\varphi$. The resulting distribution (effective inflow) is used to evaluate boundary conditions for BEM, $\frac{\partial\varphi}{\partial n}$. The procedure is iterated to convergence.

This approach can be used in both steady and unsteady mode; the steady interacting procedure implies azimuthal-averaged distribution of effective inflow $\mathbf{U}_R$ and volume force terms $\mathbf{Q}$.

The different level of accuracy between the two methodologies is shown in Figs. 6.28 and 6.29, where results for a self-propelled computation of a surface vessel in straight-ahead advancement are reported. In the first figure, the different level of accuracy between the two models is shown by the axial velocity on the actuator disc for the simplified model and on the virtual propeller blades for the hybrid RANS/BEM model. As it can be seen, when a simplified (azimuthal averaged) propeller model, the details of the rotating propeller are completely lost, as well as any unsteadiness due to the blade passage (such as unsteady loads on the blade and/or on the rudder, pressure fluctuation on the stern vault, etc.).

On the contrary, using a more accurate propeller model, all the unsteadiness related to the rotating propeller and the blade passage can be taken into consideration, as evidenced in Fig. 6.29, where coherent structures in the propeller wake are visualised using an iso-surface of the Q factor. The more sophisticated model is clearly able to provide rather accurate details about the vortices shed from the tip of the propeller blades, including the possibility to investigate their effects on the rudders and the hull, i.e. allowing an in-depth unsteady investigation of the hull/rudder/propeller interaction. On the other side, the simplified (and azimuthally averaged) model is

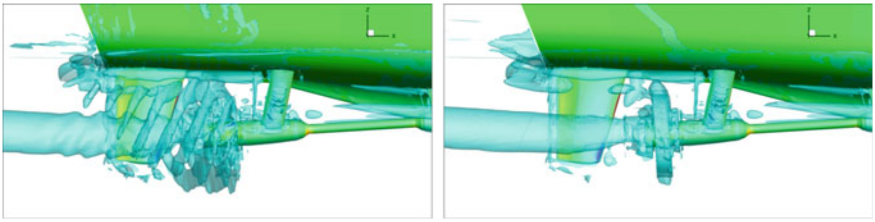


Fig. 6.29 Surface vessel in straight-ahead advancement (self-propulsion test). On the left: hybrid (unsteady) RANS/BEM propeller model; on the right: simplified actuator disc model

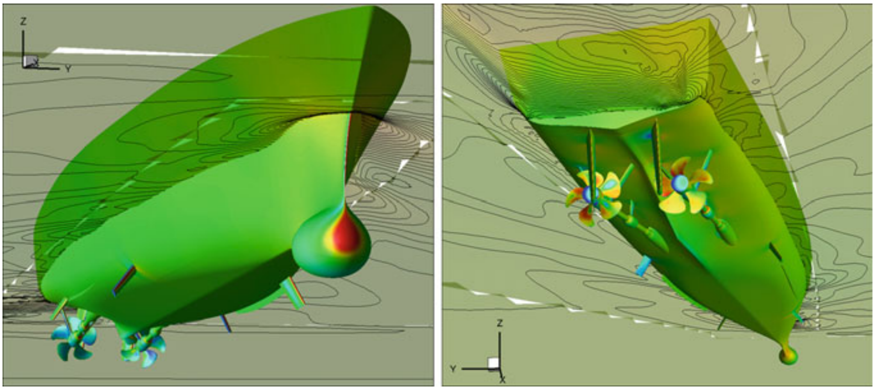


Fig. 6.30 Surface vessel in steady turning manoeuver; full unsteady RANS simulation: pressure contours on the hull and propeller surfaces

only able to provide the acceleration and the swirl (on the average) enforced by the propeller on the flow, any details concerning the tip vortices are lost, as well as any other unsteady effects.

Obviously, the possibility to accurately describe the entire physical phenomenon involved can be obtained with the inclusion of the propeller in real geometry (Fig. 6.30), i.e. by using a fully unsteady RANS approach (see, e.g., Muscari et al. 2013; Dubbioso et al. 2013; Broglia et al. 2015a, b; Carrica et al. 2010; Castro et al. 2011; Mofidi and Carrica 2014, among others), but at computational effort that can be rather high.

6.3 Simulation-Based Design Optimisation and Adaptive Multi-fidelity Metamodelling

In the last decades, the design process of complex ocean engineering systems and in particular ship hulls has experienced a significant improvement, due to the availability of high-performance computing systems (hardware) and accurate physics-based solvers (software). The traditional and expensive build and test procedure (unavoidably associated with a parametric study rather than a real optimisation process) have been replaced by the more advanced and flexible simulation-based design (SBD) approach, which integrates computer simulations, design modification methods, and optimisation algorithms (see, e.g., Campana et al. 2006; Martins et al. 2013).

SBD is usually implemented as an iterative process combining design modification methods, numerical simulations, and optimisation algorithms to identify new optimised designs. In order to achieve accurate final solutions, high-fidelity physics-based solvers (as implemented for CFD, structural analysis, etc.) are needed, resulting in computationally expensive analyses. Furthermore, the integration of these solvers with optimisation algorithms (which may require a large number of function evaluations to converge to the final solution) makes the computational cost very high and the SBD a technological challenge. In order to reduce the computational cost of the SBD process, metamodelling methods have been developed and successfully applied in several engineering fields (see, e.g., Jin et al. 2001). In addition to metamodels, multi-fidelity (or variable-fidelity) approximation methods have been developed with the aim of combining to some extent the accuracy of high-fidelity (HF) solvers with the computational cost of low-fidelity (LF) solvers (Alexandrov et al. 2001). Combining metamodelling methods with multi-fidelity approximations potentially leads to a further reduction of the computational cost. Additive and/or multiplicative correction methods might be used to build multi-fidelity metamodels, using high- and low-fidelity evaluations (Zheng et al. 2013). High- and low-fidelity evaluations may be determined by the physical model, size of the computational grid and/or combination of experimental data with numerical simulations. Multi-fidelity metamodels have been used for both design optimisation (see, e.g., Zhou et al. 2015; Benamara et al. 2017) and uncertainty quantification (see, de Baar et al. 2015; Shah et al. 2015).

6.3.1 Local Hybridisation of Deterministic Derivative-Free Global Algorithms

In SBD, an inverse problem is solved, i.e. the result of the design optimisation is such that to minimises the cost (defined by a suitable objective function), given a set of design specifications (i.e. constraint functions). In general, objective and constraint functions are usually provided by systems of partial differential equations, and therefore, the functions (usually computed by suitable approximated solutions) are likely affected by residuals, and their derivatives are not directly provided. In addition, the existence in the design space of local minima cannot be excluded a priori. For these reasons, derivative-free global optimisation algorithms have been developed, providing a global approximate solution to the design problem (Campana et al. 2009). The robustness and versatility of these methods have allowed for their successful application not only to design optimisation, but also to identification and prediction of complex hydrodynamic systems. When global techniques are used with CPU time expensive solvers (for hydrodynamics, structures, etc.), the optimisation process is computationally expensive and its effectiveness and efficiency remain an algorithmic and technological challenge. Moreover, although global optimisation approaches are a good compromise between exploration and exploitation of the research space, they could still get trapped in local minima and the convergence to the global minimum cannot be proven. If the research region to explore is known a priori, local optimisation approaches can give an accurate approximation of the local minimum. Nevertheless, their convergence may be computationally expensive, and the information is usually not available a priori. For these reasons, the hybridisation of global optimisation algorithms with local search methods has been proven to be an interesting alternative. It is worth noting that a large variety of derivative-free global and local methods available in the literature are probabilistic. These methods make use of random coefficients and have been developed to the aim of sustaining the variety of the search for the optimum. This property implies that statistically significant results can be obtained only through extensive numerical campaigns. Such an approach can be too expensive (often almost unaffordable) in SBD optimisation for industrial applications, when CPU time expensive computer simulations are used directly as analysis tools. For this reason, deterministic approaches have been successfully developed and applied to SBD optimisation, including hydrodynamic problems (Campana et al. 2006; Campana et al. 2010). Here, as an example, four derivative-free global and hybrid global/local optimisation algorithms are briefly recalled and applied to the hydrodynamic hullform optimisation of a USS Arleigh Burke-class destroyer, namely the DTMB 5415 model (see also Serani et al. 2016). Their performance is assessed and compared with that of the original algorithms. Specifically, two algorithms are well-known global optimisation approaches: (i) the DIRECT (DIviding RECTangles Jones et al. 1993) algorithm and (ii) a deterministic version of the particle swarm optimisation (PSO) method (DPSO, Serani et al. 2014). The other two algorithms are hybrid global/local techniques integrated into (i) and (ii), respectively. Specifically, a hybrid DIRECT method is coupled with line search-based derivative-free optimisation (DIRMIN-2, Campana et al. 2015) and a hybrid DPSO coupled with line search-based derivative-free optimisation (LS-DF_PSO, Serani et al. 2015).

Consider the following objective function:

$$f(\boldsymbol{\alpha}) : \mathbb{R}^N \rightarrow \mathbb{R} \tag{6.15}$$

and the global optimisation problem

$$\min_{\boldsymbol{\alpha} \in \mathcal{L}} f(\boldsymbol{\alpha}), \quad \mathcal{L} \subset \mathbb{R}^N \tag{6.16}$$

where $\boldsymbol{\alpha} = \{\alpha_j\}$ is the design variable vector and $\mathcal{L}$ is a closed and bounded subset of $\mathbb{R}^N$, identified here by the lower (l_j) and upper (u_j) bounds of each design variable $\{\alpha_j\}$. The global minimisation of the objective function $f(\boldsymbol{\alpha})$ requires to find a vector $\mathbf{a} \in \mathcal{L}$ so that:

$$\forall \boldsymbol{b} \in \mathcal{L} : f(\mathbf{a}) \leq f(\mathbf{b}) \tag{6.17}$$

Then, $\boldsymbol{\alpha} = \mathbf{a}$ is a global minimum for the function $f(\boldsymbol{\alpha})$ over $\mathcal{L}$. However, the exact identification of a global minimum might be rather complicated; therefore, approximate solutions provided by heuristic procedures are often considered acceptable for practical purposes. The deterministic derivative-free global algorithms (DIRECT and DPSO) and their global/local hybridisations (DIRMIN-2 and LS-DF_PSO) are shown here, for the solution of Eq. (6.16).

The DIRECT algorithm

DIRECT is a sampling deterministic global derivative-free optimisation algorithm and a modification of the Lipschitzian optimisation method (Jones et al. 1993). In this method, the search domain $\mathcal{L}$ of the problem is transformed into the unit hyper-cube $\mathcal{D}$. As first guess, $f(\boldsymbol{\alpha})$ is evaluated at the centre (c) of the unit hyper-cube; the hyper-cube is then partitioned into a set of smaller hyper-rectangles and $f(\boldsymbol{\alpha})$ is evaluated at their centres. At the generic kth iteration of the algorithm, starting from the current partition, the new partition is built by subdividing a set of promising hyper-rectangles of the previous one. The identification of "potentially optimised" hyper-rectangles is based on some measure of the hyper-rectangle itself and on the value of $f(\boldsymbol{\alpha})$ at its centre (c_i). The refinement of the partition continues until a prescribed number of function evaluations have been performed, or another stopping criterion is satisfied. The minimum of $f(\boldsymbol{\alpha})$ over all the centres of the final partition, and the corresponding centres, provide an approximate solution to the problem.

Local hybridisation of the DIRECT algorithm: DIRMIN-2

DIRMIN-2 is a global/local hybridisation of the DIRECT algorithm and a variant of DIRMIN (Lucidi and Sciandrone 2002; Campana et al. 2015). Differently from DIRMIN that performs as many local searches as the number of identified potentially optimised hyper-rectangles, DIRMIN-2 performs a single derivative-free local minimisation per iteration, starting from the best point produced by dividing the potentially optimised hyper-rectangles. DIRMIN-2's local minimisation is used when the number of function evaluations reaches the activation trigger $\gamma \in (0, 1)$, a ratio of the maximum number of function evaluations ($N_{f_{max}}$). The local minimisation proceeds until either the number of function evaluations exceeds $N_{f_{max}}$ or the step size falls below a given tolerance.

The DPSO algorithm

As it is well known, particle swarm optimisation was originally introduced in Kennedy and Eberhart (1995a, b). PSO belongs to the class of heuristic algorithms for single-objective evolutionary derivative-free global optimisation. In order to make PSO more efficient for use within SBD, a deterministic version of the algorithm (DPSO) was formulated in Campana et al. (2009) as:

$$\begin{cases} \boldsymbol{v}_i^{n+1} = \chi\left[\boldsymbol{v}_i^n + c_1\left(\boldsymbol{p}_i - \boldsymbol{x}_i^n\right) + c_2\left(\boldsymbol{g} - \boldsymbol{x}_i^n\right)\right] \\ \boldsymbol{x}_i^{n+1} = \boldsymbol{x}_i^n + \boldsymbol{v}_i^{n+1} \end{cases} \tag{6.18}$$

The above equations update velocity $\boldsymbol{v}_i^n$ and position $\boldsymbol{x}_i^n$ of the ith particle at the kth iteration, where χ is the constriction factor, c_1 and c_2 are the cognitive and social learning rate; $\boldsymbol{p}_i$ and $\boldsymbol{g}$ are the cognitive and social attractor (defined in the variable space). Specifically, $\boldsymbol{p}_i$ is best position found by the ith particle, whereas $\boldsymbol{g}$ is the best position ever found by the whole swarm. The set-up suggested in Serani et al. (2014) is used: number of particles (N_p) equal to $4N$, initialised using a Hammersley sequence sampling over variable domain and boundary with non-null initial velocity. The coefficients are set as proposed by Clerc (2018), with $\chi = 0.721$ and $c_1 = c_2 = 1.655$.

Local hybridisation of the DPSO algorithm: LS-DF_PSO

Global convergence properties of a modified PSO scheme may be obtained by properly combining PSO with a line search-based derivative-free method, so that convergence to stationary points can be forced at a reasonable cost. Serani et al. (2015) provides a robust method to force the convergence of a subsequence of points towards a stationary point, which satisfies first-order optimality conditions for the objective function. The method LS-DF_PSO starts by coupling the DPSO scheme with a line search-based method. Specifically, a positively spanning set is used, where the set of search directions ($D_\oplus$) is defined by the unit vectors $\pm e_i = 1, \ldots, N$, as shown in the following equation (i.e. $N = 2$):

$$D_\oplus = \left\{ \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \begin{pmatrix} -1 \\ 0 \end{pmatrix}, \begin{pmatrix} 0 \\ -1 \end{pmatrix}, \begin{pmatrix} 1 \\ 0 \end{pmatrix} \right\} \tag{6.19}$$

After each DPSO iteration, the local search is performed if the swarm has not found a new global minimum. The initial step size (ς^k) for the local search is set equal to 0.25 times the variable domain range, and it is reduced by $\vartheta = 0.5$ at each local search iteration. Local searches continue in each direction until the step size is greater than $\mu = 10^{-3}$. If the local search stops without providing a new global minimum, the actual global minimum is declared as a stationary point. The line search method is not allowed to violate the box constraints.

The SBD application shown here as an example is the hydrodynamic hullform optimisation of the DTMB 5415 model (Fig. 6.10). Here, a single-speed single-objective optimisation is aimed at the reduction of the total resistance in calm water at 18 kn, corresponding to a Froude Number $F_N = 0.25$. The ship is free to sink and trim. An expansion of orthogonal basis functions is used for the modification of the hullform and the sonar dome. Geometric constraints include fixed length between perpendicular (LBP) and fixed displacement (Δ), with beam (B) and draft (T) varying between $\pm 5\%$ of the original hull. Fixed LBP and Δ are satisfied by automatic geometric scaling, while constraints for B and T are handled using a linear penalty function method. The shape modification δ_s is defined using $N = 6$ orthonormal basis functions of curvilinear coordinates ξ and η over the demi-hull:

$$\delta_s(\xi, \eta) = \sum_{j=1}^{N} \alpha_j \psi_j(\xi, \eta) \tag{6.20}$$

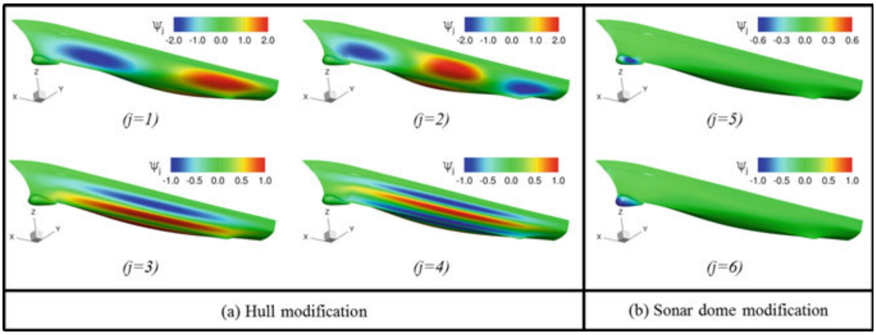


Fig. 6.31 Orthonormal functions $\psi_j(\xi, \eta)$

where $\alpha_j \in \mathbb{R}(j = 1, \ldots, N)$ are the design variables, and with:

$$\psi_j(\xi, \eta) : S = \left[0, L_\xi\right] x \left[0, L_\eta\right] \in \mathbb{R}^2 \to \mathbb{R}^3, \quad j = 1, \ldots, N$$
$$\iint \psi_i(\xi, \eta) \cdot \psi_j(\xi, \eta) \mathrm{d}\xi \mathrm{d}\eta = \delta_{ij} \tag{6.21}$$

Four functions and design variables are used for the hull, whereas two functions/variables are used for the sonar dome. The corresponding basis functions are shown in Fig. 6.31.

Simulations are conducted using the WARP, hydrodynamic tool (see Sect. 6.2.3.1). For the hullform optimisation process, a limit to the number of function evaluations is set equal to 1536, i.e. 256N. The optimisation exercise has been conducted for: (i) low number of function evaluations (192) (which corresponds to 32N, one-eighth of the full budget) and (ii) for the full budget of 1536 function evaluations (which corresponds to 256N). For the case (i), the optimisation procedure achieves a resistance reduction of 13.7 and 15.5% using DIRECT and DIRMIN-2, respectively, and a reduction of 13.5 and 16.0% using DPSO and LS-DF_PSO, respectively. The two global/local hybrid algorithms outperform their global version. In particular, LS-DF_PSO is found to be the most efficient algorithm for the present SBD problem, achieving the best design with the fastest convergence rate. For the case (ii), the optimisation procedure achieves a resistance reduction of 16.0 and 16.2% using DIRECT and DIRMIN-2, respectively, and a reduction of 16.2% using both DPSO and LS-DF_PSO.

The convergence history of the objective function towards the minimum is shown in Fig. 6.32, confirming the efficiency and robustness of the two hybrid global/local approaches DIRMIN-2 and LS-DF_PSO. More in detail, LS-DF_PSO achieves the most significant reduction of the objective function overall, although all the solutions are very close to each other. Figure 6.33 presents the values of the corresponding optimised design variables and shows the optimised shapes compared to the original.

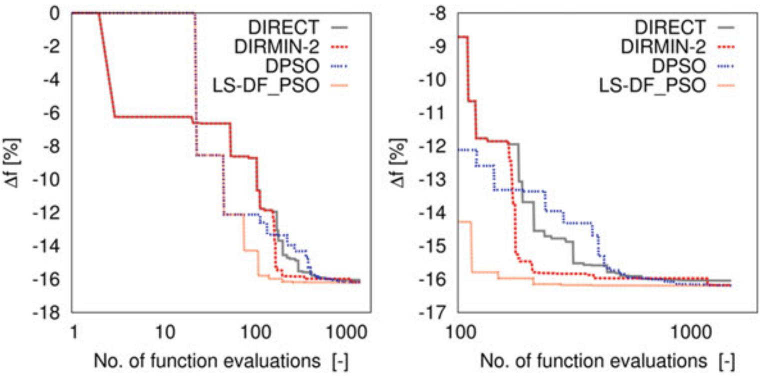


Fig. 6.32 Objective function convergence history (left) and detail after the first 100 function evaluations (right)

The close agreement of the solutions obtained by the different algorithms indicates that the global minimum region has been likely achieved. The reduction of the wave elevation pattern of the final shape, both in terms of transverse and diverging stern waves, is visible in Fig. 6.34.

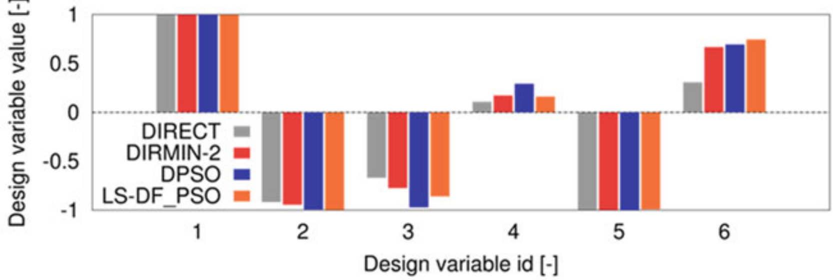
6.3.2 Adaptive Multi-fidelity Metamodelling

In the adaptive multi-fidelity metamodel, the multi-fidelity approximation is built as the sum of a low-fidelity-trained metamodel and the metamodel of the difference (error) between high- and low-fidelity simulations, i.e. the high-fidelity model is used to improve the accuracy of the low-fidelity prediction (Pellegrini et al. 2016). The use of a metamodel allows both reducing the low- and/or high-fidelity estimations and providing the required uncertainty assessment which guides the need to a new low- or high-fidelity element of the training set.

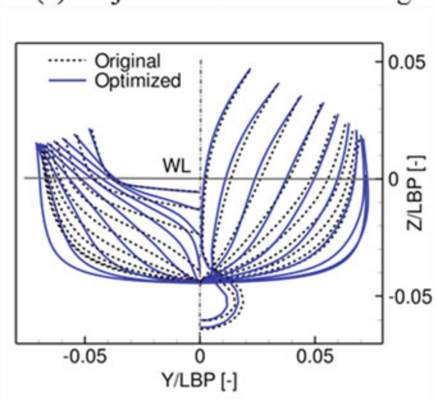
Consider an objective function $f(\boldsymbol{x})$, where $\boldsymbol{x} \in \mathcal{R}^N$ is the design variable vector. The associated multi-fidelity metamodel $\hat{f}(\boldsymbol{x})$ is defined as:

$$\begin{aligned} \hat{f}(\boldsymbol{x}) &= \hat{f}_L(\boldsymbol{x}) + \tilde{\varepsilon}(\boldsymbol{x}) \\ \varepsilon(\boldsymbol{x}) &= f_H(\boldsymbol{x}) - f_L(\boldsymbol{x}) \end{aligned} \tag{6.22}$$

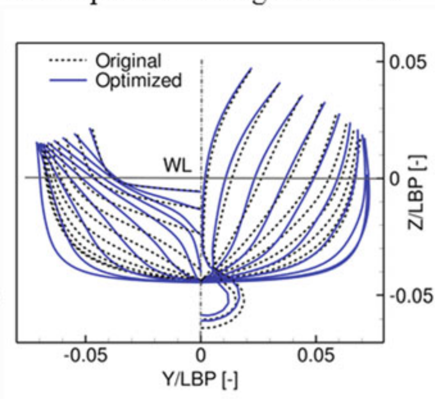
where superscript $(\tilde{\cdot})$ denotes the prediction by a suitable metamodel, such as for example the stochastic radial basis function, and $\varepsilon(\boldsymbol{x})$ is the difference (error) between high- and low-fidelity simulations (f_L and f_H, respectively). The training set for $\tilde{f}_L$ is denoted by $\mathcal{L}$, whereas the training set for $\tilde{\varepsilon}$ is denoted by ε. Note that by definition of $\tilde{\varepsilon}$, it is $\mathcal{E} \subseteq \mathcal{L}$. Denoting with $U_{\tilde{f}_L}$ and $U_{\tilde{\varepsilon}}$ the prediction uncertainty of $\tilde{f}_L$ and $\tilde{\varepsilon}$, respectively, under the assumption of uncorrelated uncertainties, the uncertainty



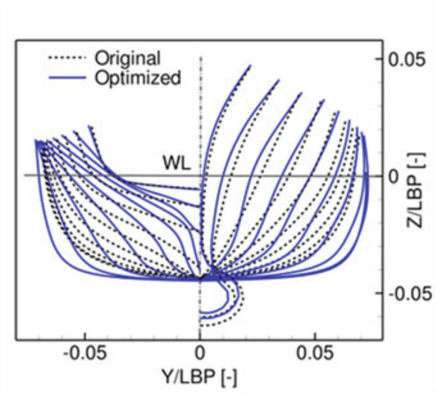
(a) Objective function convergence of optimised design variables



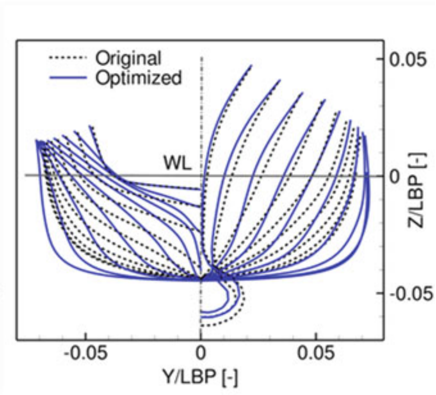
(b) DIRECT



(c) DIRMIN-2



(d) DPSO



(e) LS-PS_PSO

Fig. 6.33 Optimisation result after 1536 function evaluations

associated with $\hat{f}(\boldsymbol{x})$ is $U_{\hat{f}} = \sqrt{U^2_{\hat{f}_L} + U^2_{\tilde{\varepsilon}}}$. New evaluations are then added to the training set based on the following maximisation problem of $U_{\hat{f}}$:

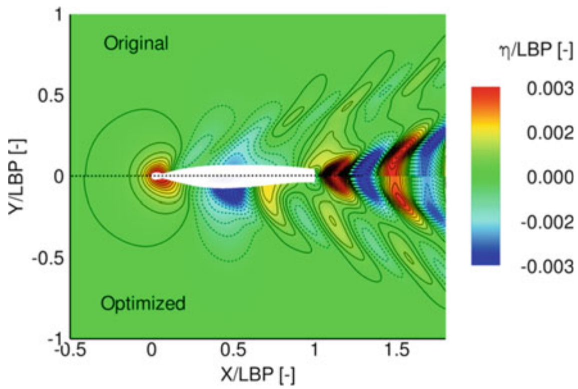


Fig. 6.34 Optimisation result after 1536 function evaluations, optimised hull forms at F_N=0.25 compared with original: wave patterns

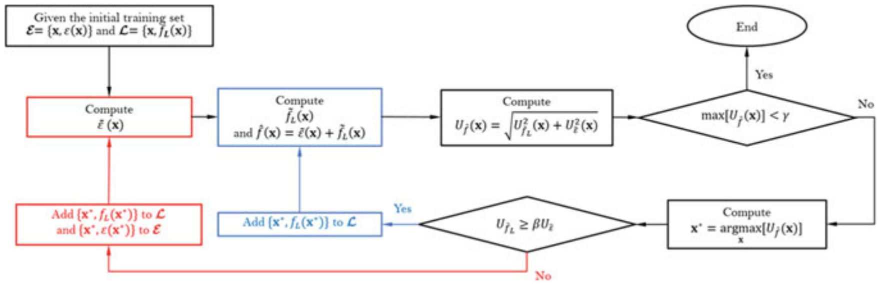


Fig. 6.35 Multi-fidelity metamodel, adaptive sampling procedure

$$\boldsymbol{x}^* = \arg\max_{\boldsymbol{x}} \left[U_{\hat{f}}(\boldsymbol{x}) \right] \tag{6.23}$$

Once $\boldsymbol{x}^*$ is found, the training sets $\mathcal{L}$ and/or $\mathcal{E}$ are updated as

$$\begin{cases} \text{If} \quad U_{\tilde{f}_L}(\boldsymbol{x}^*) \geq \beta U_{\tilde{\varepsilon}}(\boldsymbol{x}^*) & \text{add}\left\{\boldsymbol{x}^*,\ \tilde{f}_L(\boldsymbol{x}^*)\right\} \text{ to } \mathcal{L} \\ \text{else} & \text{add}\{\boldsymbol{x}^*,\ f_L(\boldsymbol{x}^*)\} \text{ to } \mathcal{L} \text{ and } \{\boldsymbol{x}^*,\ \varepsilon(\boldsymbol{x}^*)\} \text{ to } \varepsilon \end{cases} \tag{6.24}$$

where $\beta \in [0, 1]$ is an arbitrary tuning parameter which takes into account the computation cost ratio between the low- and the high-fidelity estimation. To be noted that, a HF estimation is required only in the second case. The sketch of the sampling procedure is reported in Fig. 6.35.

A hybrid global/local formulation of the multi-objective deterministic PSO combined with a derivative-free line search-type local algorithm (see Sect. 6.3.1) is used for the final multi-objective optimisation [i.e. solution of Eq. (6.23)]. The multi-objective deterministic global/local hybrid algorithm (MODHA, Pellegrini et al.

2017b) combines a multi-objective deterministic PSO (MODPSO, Pellegrini et al. 2017a) formulation and a line search-type derivative-free multi-objective (DFMO, Liuzzi et al. 2016) local optimisation algorithm.

The MODPSO formulation reads:

$$\begin{cases} \boldsymbol{v}_i^{n+1} = \chi\left[\boldsymbol{v}_i^n + c_1\left(\boldsymbol{p}_i - \boldsymbol{x}_i^n\right) + c_2\left(\boldsymbol{g}_i - \boldsymbol{x}_i^n\right)\right] \\ \boldsymbol{x}_i^{n+1} = \boldsymbol{x}_i^n + \boldsymbol{v}_i^{n+1} \end{cases} \tag{6.25}$$

where $\boldsymbol{p}_i$ is the personal minimiser of the aggregated objective function $F(\boldsymbol{x}_i) = \sum_{m=1}^{M} f_m(\boldsymbol{x}_i)$ and $\boldsymbol{g}_i$ is the closest point to the ith particle of the non-dominated solution set $\mathcal{S}$ at the nth iteration ($\mathcal{S}^n$). DFMO is a derivative-free algorithm for constrained non-smooth multi-objective problems; it embeds a line search approach that takes into account the presence of multiple objectives. At each iteration, the fitness of $\mathcal{S}^n$ is assessed in terms of convergence and clusterisation of $\boldsymbol{s} \in \mathcal{S}^n$ through the hypervolume metric (Diez et al. 2015). The local search starts if the hypervolume value at the nth iteration is not improved by a factor ϑ from the previous iteration. DFMO is started from all the points of $\mathcal{S}^n$, with a budget of ηN_p evaluations. The number of particles for MODPSO is set to 8 MN, initialised using a Hammersley sequence sampling over variable domain and boundary with non-null initial velocity. The MODPSO coefficients are set as for the DPSO. The MODHA parameters are set as $\vartheta = 1.0$ and $\eta = 10$. The number of problem evaluations, where one problem evaluation involves one evaluation of each objective function, is set equal to 2000 MN.

As an example of the algorithm described above, the hullform optimisation of a small waterplane area twin hull (SWATH, Fig. 6.13 left) for resistance reduction and payload increase is reported here (see also Pellegrini et al. 2018). The adaptive multi-fidelity metamodel considers the Xnavis RANSE tool (Sect. 6.2.4) and the WARP (Sect. 6.2.3.1) potential flow solver as the high- and the low-fidelity solvers, respectively. The parametric geometry of the SWATH is produced with the computer-aided design (CAD) environment integrated into the CAESES® software, developed by FRIENDSHIP SYSTEMS (Fig. 6.13 right). Twenty-seven design variables have been used; significant geometric parameters controlled by the design variables are the overall length, the struts clearance, the curvature of the torpedo nose and the torpedo diameter. The inter-axis distance is kept constant. In the present work, the Sobol engine available in CAESES® has been used for producing pseudo-random variations of the 27 geometric parameters, providing a uniform distribution of the parameters of the original design space.

A design space dimensionality reduction of the parametric model is performed by Karhunen–Loève expansion (KLE, Diez et al. 2015). A number of $S = 3000$ random designs are produced assuming a uniform distribution. Figure 6.36 shows the KLE results in terms of design variability associated with a reduced-dimensionality space of dimension N for $S = 1000$, 2000 and 3000 samples. The results are convergent versus S. The number of design variables is reduced to $N = 2$, retaining the 85% of the original variability. The corresponding KLE modes are shown in Fig. 6.37 by x, y and z components. It is worth noting that each row in the figure represents

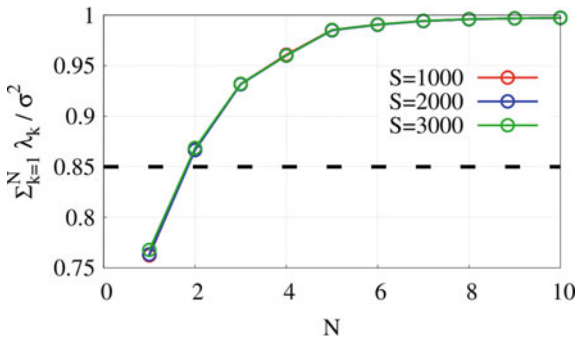


Fig. 6.36 Normalised variance resolved by a reduced dimensionality space of dimension N (KLE values cumulative sum)

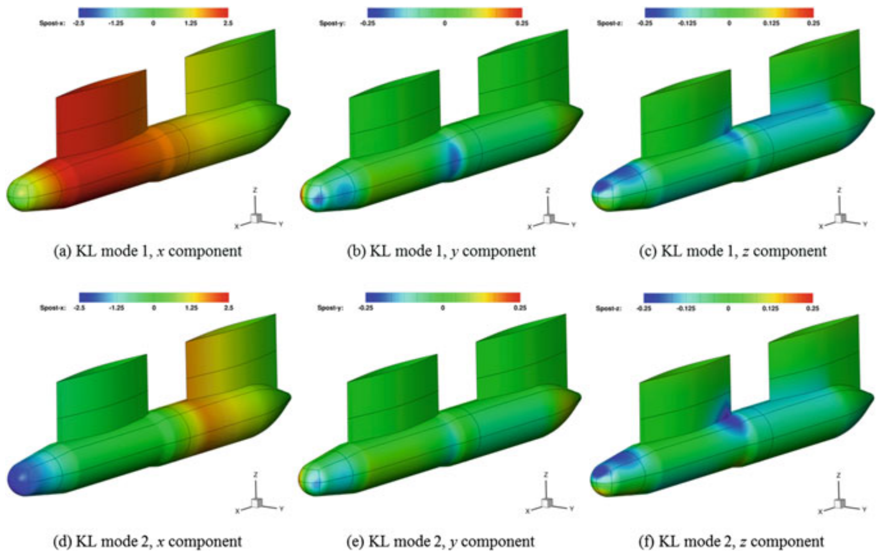


Fig. 6.37 First two KLE modes shown by x, y and z components of SWATH

simultaneous shape modifications by one (new) design variable. Both modes are dominated by the x component of the shape modification vector.

Hybrid global/local multi-objective deterministic algorithm described previously is used for the final multi-objective optimisation. The optimisation problem addresses the minimisation of the hydrodynamic resistance and the maximisation of the displacement (payload) at service speed, corresponding to $F_N = 0.489$. The optimisation is formulated by two (alternative) problems. Problem 1 addresses the minimisation of the hydrodynamic resistance (R_T) and the maximisation of the displacement (Δ), subject to a constraint for the minimum waterplane area, i.e.

$$
\begin{aligned}
&\text{minimize } \{\Delta R_{\mathrm{T}}(\boldsymbol{x}), -\Delta\nabla(\boldsymbol{x})\}^{\mathrm{T}} \text{ with } \boldsymbol{x} \in \mathcal{D} \subset \mathbb{R}^N \\
&\text{subject to } \frac{L_{OA}(\boldsymbol{x})}{L_{OA,}\text{max}} - 1 \leq 0 \\
&\text{and to } \quad -\Delta A_{\mathrm{WP}}(\boldsymbol{x}) \leq 0 \\
&\text{and to } \quad \boldsymbol{x}_l \leq \boldsymbol{x} \leq \boldsymbol{x}_u
\end{aligned}
\tag{6.26}
$$

Problem 2 addresses the minimisation of the hydrodynamic resistance and the maximisation of the waterplane area, subject to a constraint for the minimum displacement, i.e.

$$
\begin{aligned}
&\text{minimize } \{\Delta R_{\mathrm{T}}(\boldsymbol{x}), -\Delta A_{\mathrm{WP}}(\boldsymbol{x})\}^{\mathrm{T}} \text{ with } \boldsymbol{x} \in \mathcal{D} \subset \mathbb{R}^N \\
&\text{subject to } \frac{L_{OA}(\boldsymbol{x})}{L_{OA,}\text{max}} - 1 \leq 0 \\
&\text{and to } \quad -\Delta\nabla(\boldsymbol{x}) \leq 0 \\
&\text{and to } \quad \boldsymbol{x}_l \leq \boldsymbol{x} \leq \boldsymbol{x}_u
\end{aligned}
\tag{6.27}
$$

where $\Delta(\cdot)$ indicates the variation versus the original hull and $L_{\mathrm{OA,max}}$ is the maximum length overall allowed.

The metamodel training is based on the hydrodynamic resistance computation only. A subset of sensitivity analysis values is used as initial training set for the AMFM, resulting in five high- and five low-fidelity evaluations. A convergence value (γ) for the maximum prediction uncertainty (max$\left[U_{\widetilde{\Delta R_T}}\right]$ set equal to 5% of the function range computed at the initial iteration. A maximum number of 20 iterations is used for the adaptive sampling procedure.

Figure 6.38 shows the convergence of max$\left[U_{\widetilde{\Delta R_T}}\right]$ as well as the HF and LF evaluations, versus the AMFM iteration number. It is worth noting that for the first four iterations, the LF evaluations are able to reduce significantly the maximum uncertainty. At the 12th iteration, the maximum uncertainty increases because the HF evaluation significantly changes the metamodel training and associated prediction. Finally, the AMFM is trained by 14 HF and 25 LF evaluations. After 20 iterations, the maximum overall uncertainty is less than 6%, close to the desired value of 5%.

Figure 6.39 (left) shows the non-dominated solution set of problem 1. This reduces to a single point, showing that the two objectives are concurrent. The solution is referred hereafter as solution **A**. Figure 6.39 (right) shows the non-dominated solution set of problem 2. In order to identify a good candidate solution for the verification of the metamodel prediction, solution **B** is selected.

Table 6.3 summarises the comparison of metamodel prediction and actual RaNSE evaluation of the ΔR_{T}, showing a remarkable agreement.

Figures 6.40 and 6.41 show the comparison of the original hull with **A** and **B**, respectively. The free surface elevation of **A** and **B** is slightly lower than the original. Both **A** and **B** show lower pressure gradient on the hull than the original and a higher pressure on the leading edge of the front. The figures also show a geometrical comparison of **A** and **B** with the original hull, respectively. Both optimised hulls are

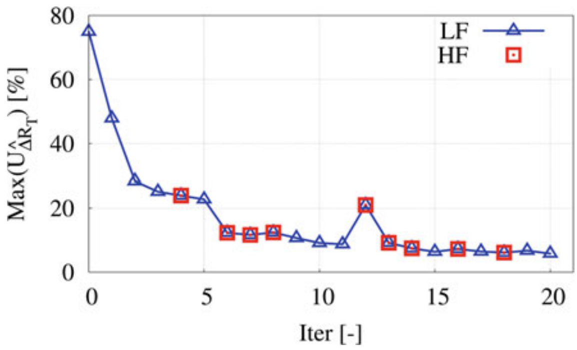


Fig. 6.38 Maximum overall uncertainty versus iteration number

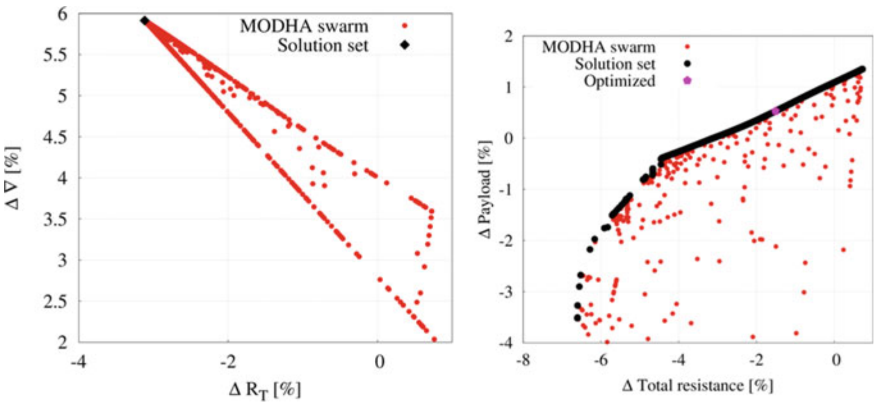
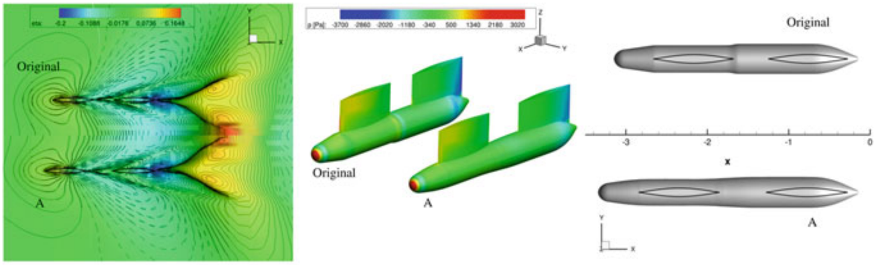


Fig. 6.39 Non-dominated solution set for problems 1 and 2

Table 6.3 Comparison between metamodel prediction and actual HF evaluation

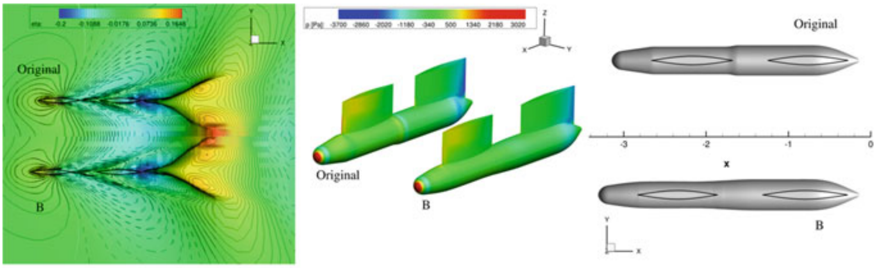
Solution	AMFM	HF	Geometric constrains			KLE variables value	
	ΔR_T (%)	ΔR_T (%)	$\Delta\nabla$	ΔA_{WP} (%)	ΔL_{OA} (%)	x_1	x_1
A	−3.12	−3.21	5.92%	0.00	−1.57	0.00	0.493
B	−1.51	−1.61	4.945	0.55	−2.56	0.00	0.290

longer than the original. Furthermore, **B** shows a longer rear strut, which produces the increase of A_{WP}. Finally, Fig. 6.42 highlights the difference between **A** and **B**. **B** has a shorter torpedo nose than **A**, whereas the rear strut is longer. It is worth noting that the difference between the two hulls is only due to the second KLE mode.



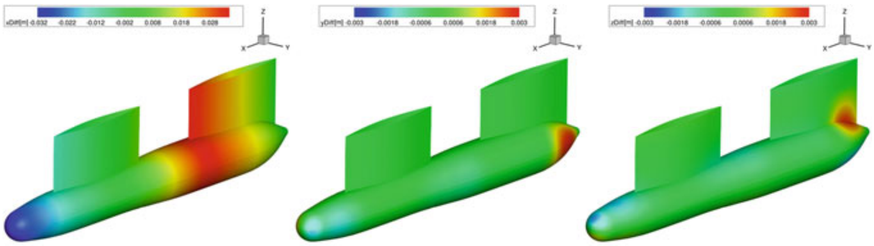
(a) Free surface comparison (b) Hull pressure distribution (c) Hull comparison

Fig. 6.40 Hull comparison for problem 1 of SWATH



(a) Free surface comparison (b) Hull pressure distribution (c) Hull comparison

Fig. 6.41 Hull comparison for problem 2 of SWATH



(a) **A-B**, *x* component (b) **A-B**, *y* component (c) **A-B**, *z* component

Fig. 6.42 Hull comparison between solution **A** and **B** of SWATH

6.4 The HOLISHIP Integration Concept (for CFD Codes): Hydrodynamic Optimisation of a RoPAX Ferry

The HOLISHIP integration platform based on Friendship Systems' CAESES environment allows to include almost any new or existing CFD code in the overall process flow which is typically made up from (geometry) hullform definition and optimisation, (pre-processing) CFD grid generation, (computation) CFD prediction and post-processing of results, typically in form of flow visualisations and graphs. Examples

Table 6.4 FINCANTIERI RoPAX vessel, main characteristics

Length between perpendiculars	162.85 m
Beam	27.6 m
Subdivision draught	7.10 m
Height of bulkhead deck	9.80 m
Gross tonnage (GT)	≈36,000
Deadweight (DWT)	5000 t

for global optimisations using the HOLISHIP platform were presented by Harries et al. (2017), Marzi et al. (2018) for global optimisations of a RoPAX ferry. Both papers describe a holistic optimisation of a RoPAX ferry which is also highlighted in Chap. 8 later in this volume. Starting form a given design provided by project partner FINCANTIERI in the context of an earlier research project, the aim of the collaborative work described was an optimisation of the vessel design with respect to different disciplines. These include besides hydrodynamic performance: ship stability, energy simulation and a cost assessment.

While the papers and the preceding descriptions in Chap. 8 focus on the overall optimisation for different disciplines, more emphasis is placed on hydrodynamics in the following; the example presented in this chapter highlights the different steps associated with the hydrodynamic optimisation of a ship hull at an early design stage using a potential flow method.

The main characteristics of this vessel are given in Table 6.4. The operational profile of the RoPAX ferry features two distinct speeds resulting from day and night sailing between its destinations. The vessel operates at two different speeds, namely 21 and 27 kts, which correspond to Froude Numbers $F_{N1} = 0.270$ and $F_{N2} = 0.347$, respectively; a comparison with the length considerations given in Sect. 6.2.1 indicates that none of these is an implicitly favourable length. However, to attain favourable Froude Numbers for the two speed points to correspond to $F_{N1} = 0.252$ and $F_{N2} = 0.325$) would require to increase the ship length by 23.2–186 m (L_{PP}). This is obviously not an option, and hence, more sophisticated solutions based on local form variations and a proper shaping of the bulbous bow must be sought to obtain an optimal form.

6.4.1 Hydrodynamics

The hydrodynamic performance of a ship determines to a large extent the energy efficiency and—together with stability—a major part of its safety. The required propulsive power for a specified speed is a key contractual item for any new vessel as it determines fuel consumption and hence cost and emissions. Low resistance and high propulsive efficiency are fundamental prerequisites, and optimising the hullform and the propeller/propulsor performance using different specific CFD tools

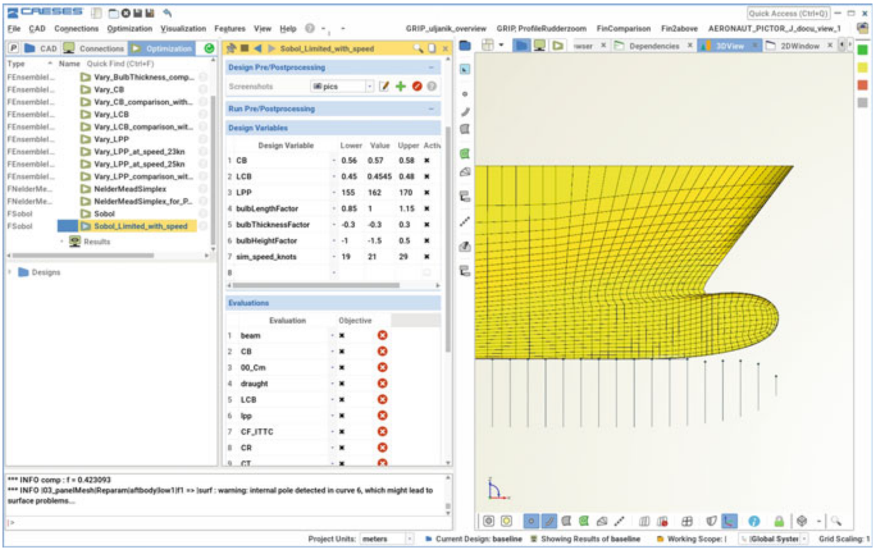


Fig. 6.43 Design optimisation: form parameters in CAESES

is mandatory. A variety of further analysis tools for seakeeping performance added resistance in seaways and due to wind, manoeuvring or the effects of hull appendages and energy saving devices up to the prediction of the effect of increased frictional resistance due to hull fouling form the basis for a complete hydrodynamic analysis.

The range of simulations applied to a specific design is adapted to its particular requirements. CFD predictions typically require substantial computational effort which is barely tolerable during an actual design optimisation process. Such analyses are successively implemented and generate response surfaces (surrogate models) which can be used during design and optimisation.

Although for the initial design stages a simple speed—resistance—power prediction will typically be the first step to determine main properties of the hull, the power requirement is usually of foremost interest. Hence, a combination of potential flow and RANS predictions is needed. Figure 6.43 describes how this is done using the HOLISHIP design environment.

6.4.2 Hullform

The starting point for the optimisation is the appropriate description of the hullform from a CAD system. Typically, CFD codes and their mesh generators allow for a variety of different three-dimensional geometry exchange formats, e.g. IGES, STEP, stl or other. As flexible as they are, these all have an imminent disadvantage in form of the fixed geometry. Form optimisation, however, implies that the geometry

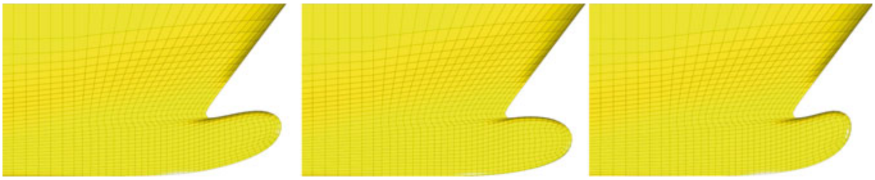


Fig. 6.44 Effect of form parameter "bulb length"

of the hull must be change in order to find an optimum for the given objective function (see also Sect. 6.3.1). This means that a parametric hullform model is needed which allows modifying the hull geometry or parts of it which are deemed necessary during the optimisation process. The geometry kernel in CAESES forming the core of the HOLISHIP platform allows to generate parametric hullform models with great flexibility so that overall parameters such as length, breadth, draft and block coefficient can be controlled as well as local parameters. In the RoPAX example, these include three further parameters controlling the shape of the bulbous bow: length, height and a thickness factor. Figure 6.43 shows the parametric set-up in CAESES.

The bulb parameters have been chosen to attain maximum effect during the optimisation with rather narrow limits. Figure 6.44 shows the effect of a variation of the bulb length parameter indicated in the upper central panel in Fig. 6.43 specifically on the bow shape.

The hydrodynamic tool used for the shape optimisation is ν-SHALLO which has been introduced already in Sect. 6.2.3. Using CAESES' software connector, the integration of the code which only uses ASCII inputs in form of panel mesh and control files is straightforward, Fig. 6.45 (see also Chap. 8).

6.4.3 Organising Computations

Traditionally hullform optimisation has been run as a stand-alone task during the design process. This is of course still a possibility, but the real benefit of working in an integrated and holistic design environment will only be obtained when using the full potential of the holistic approach unleashed in the HOLISHIP platform. Rather than developing complex analyses to determine the effect of a large number of design parameters, the platform provides a customisable environment which can be adapted to all individual evaluation needs.

Although potential flow computations are fast compared to the more complex RANS predictions, they do take time and when a large number of design variants are analysed the direct integration of such predictions may be too cumbersome. To overcome such problems, the HOLISHIP platform/CAESES provides methods to pre-compute data for later usage and store them in response surfaces: the surrogate

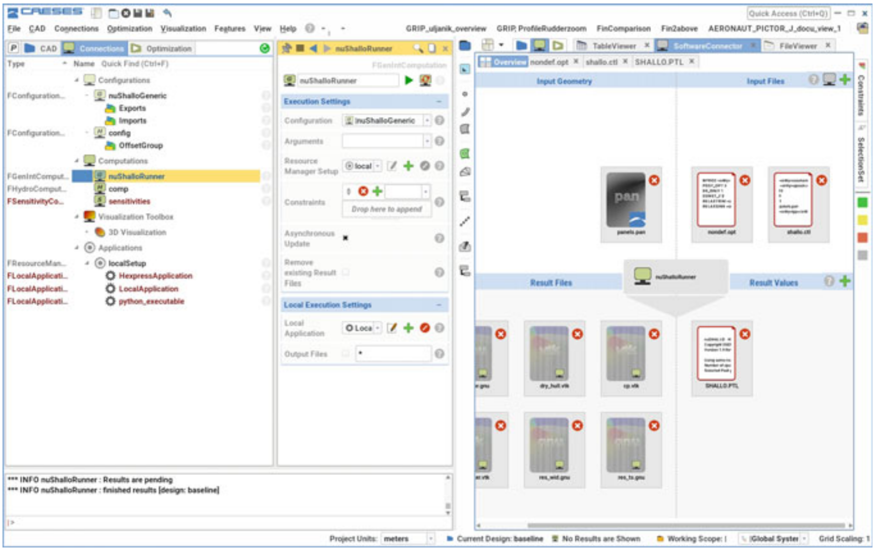


Fig. 6.45 ν-SHALLO integration using the CASES software connector

model. A design of experiment is undertaken for a chosen set of free design variables, which form a task-specific—i.e. hull hydrodynamics—subset of the total design space of interest to build the surrogate model. Further details on this aspect are provided in Chap. 8.

For the present RoPAX design example, two response surfaces for delivered power were established, one for the ferry's lower speed of 21kts and the other for the top speed of 27 kts. Two design of experiments (Sobol) were run with ν-Shallo, each comprising 360 design variants. Combining both ν-Shallo and FreSCo$^+$ results to estimate power demand for all ferry variants during an optimisation, the response surface approach described before was applied. Artificial neural networks were employed within CAESES, and their accuracy was checked by comparing additional variants that were not contained in the training set with the corresponding results from direct simulations. A typical deviation of about 1% was found.

6.4.4 Results

The optimisation yields a large amount of output data. Typically, several hundred design variants are analysed during an automated process, and the sheer amount of data will hardly allow to inspect every detail. However, before relying solely on integral results and judging the outcome of the optimisation process on the basis of resistance data depending on form parameters chosen, an inspection of the overall quality of results is advisable. For a selected, small number of cases detailed results

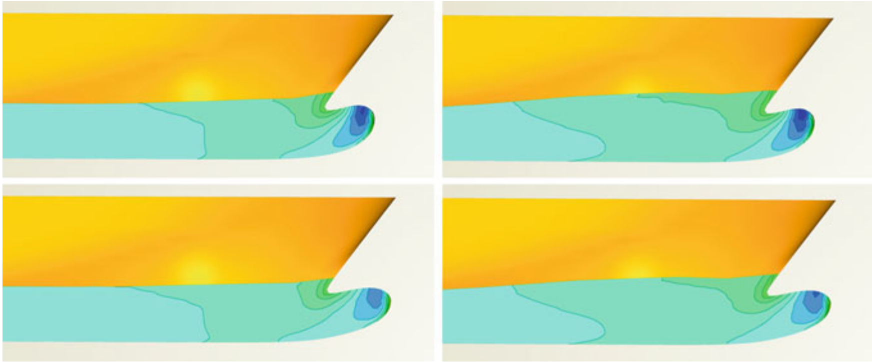


Fig. 6.46 Bow optimisation: surface pressure: Form 1 (top row) and Form 2 (bottom row). Speeds 21 kts (left column) and 27 kts (right column)

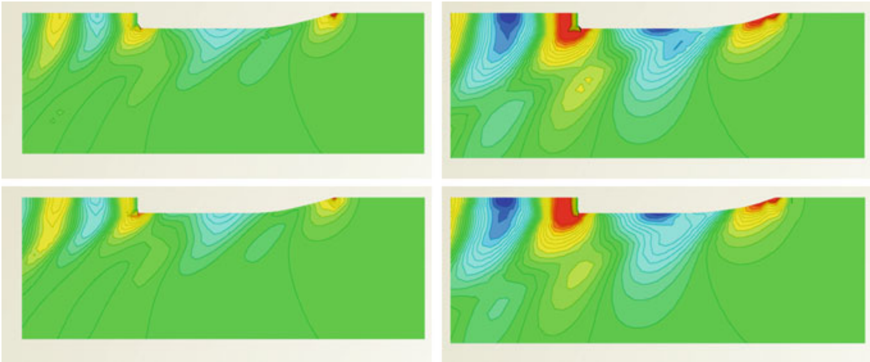


Fig. 6.47 Bow optimisation: wave patterns: Form 1 (top row) and Form 2 (bottom row). Speeds 21 kts (left column) and 27 kts (right column)

should be visualised and checked. For a panel computation, hull pressure distribution and wave pattern are good indicators for the quality/feasibility of the predictions. In any case, it is advisable to check the results for those solutions which appear optimal to assure that they are not the result of any numerical error occurring in the CFD-optimisation process. This may arise in certain cases when parametric form variations lead to an extremely deformed surface discretisation/panelisation which would violate numerical boundary conditions and yield unrealistic data.

Figures 6.46 and 6.47 show a valid example of hullform variants obtained during the optimisation of the RoPAX ferry. The first set of figures indicates the pressure distribution on the bow of two design variants for the two speeds, 21 and 27 kts, whereas the second set of pictures shows the wave patterns.

The pressure distribution and the elevation of the free surface are plausible and realistic. The relatively short bulbous bow of the first design variant considered here shows a strong low-pressure area (dark blue patch) on its side where the flow is

Table 6.5 Predicted resistance, comparison between Form 1 and Form 2

Form	v_s=21.0 kts (kN)	v_s=27.0 kts (kN)
1	542.66	1121.43
2	513.99	1056.81

accelerated. Further downstream a steeper rise of the pressure leads to a prominent bow wave at the stem which is even more emphasised for the higher speed. This result indicates that a longer bulb should give improved results. The second form variant selected for this visual comparison sports a longer and slightly thinner bulb. The results indicate a slightly smoother pressure drop towards the side and a less pronounced rise further downstream which leads to a reduced bow wave.

The wave pattern for all four cases indicate a distinct primary wave system, i.e. bow and stern wave and wave trough in the mid-ship part of the hull. This is more pronounced for the higher speed. The higher bow wave of the first variant can be clearly seen at both speeds.

Predicted Resistance

Comparing the predicted resistance indicates that the considerations made above comply with the numerical data, reported in Table 6.5.

For both speeds, the second version yields an improvement: 5.2% for the slower speed and 5.75% for the higher speed.

Global results

Having gained confidence in the detailed results during the previous check, global optimisation results can be inspected. During the automated optimisation performed using the CAESES-based HOLISHIP platform, several hundred of design variants were evaluated. Given the prime design parameters length, breadth, draft and block coefficient, as well as the parameters determining the bulb shape, different analyses can be performed. The following scatter diagrams show the dependency of the ship's total resistance on the length, for both 21 and 27 kts. Not surprisingly, the plots indicate a different behaviour. For the lower speed, frictional resistance becomes more important. This scales with the wetted surface and hence will be better for a shorter vessel as shown in the left part of Figs. 6.48 and 6.49. Although less pronounced, the relationship is turning round for the higher speed. Here, pressure effects and a better wave resistance become more important. Consequently, a longer, more slender ship appears to be favourable.

For the bulb length, a more uniform behaviour can be seen. In both speed cases, a longer bulb appears to be superior. This is related to an improved interference of the wave generated by the bulb itself with the hull bow wave in both cases.

Validation and extension of results using a viscous flow code

As outlined in the previous sections, potential flow computations can only attain a reasonable level of accuracy. Due to the lack of viscous effects being considered in the model, there will always be a discrepancy between the result from a panel code

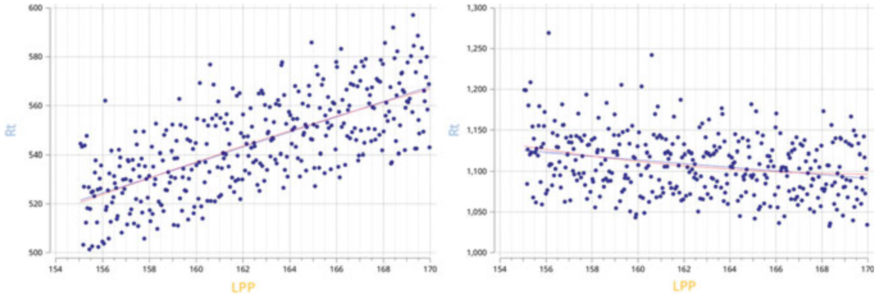


Fig. 6.48 Dependency of resistance on length (L_{PP}) for 21 and 27 kts

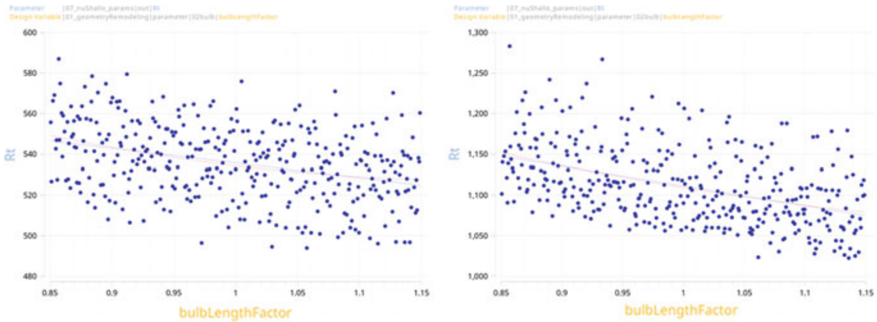


Fig. 6.49 Dependency of resistance on bulb length factor for 21 and 27 kts

prediction and the real vessel performance. In addition, potential flow codes will be limited to the prediction of the resistance of a hullform. What is, however, needed in design is the power requirement to attain a certain speed, i.e. P_D for the design speed or range of speeds. While in the past several empirical models have been introduced to assess the various propeller efficiencies related to the condition behind the ship hull, a more adequate way would be to perform viscous flow predictions using a RANS code to assess the performance of the complete ship-propeller system. As the viscous predictions are generally more time-consuming and costly, a practical approach is to run a limited number of viscous flow predictions and use them to scale the panel code results for the entire design space generated before. This also helps to validate and confirm the earlier predictions.

Figure 6.50 shows the comparison of the predicted wave pattern for 21 kts. The bottom half presents the panel code results as shown before, and the top part represents the corresponding RANS predictions for the same hullform. While the overall wave pattern complies very well between the two predictions, a closer look reveals differences in the details. Starting from the bow, the RANS prediction indicates a slight forward shift of the bow wave. Further downstream the shoulder wave which is only vaguely indicated in the panel prediction appears much more pronounced in the viscous prediction. Both effects can be related to a relatively coarse meshing of

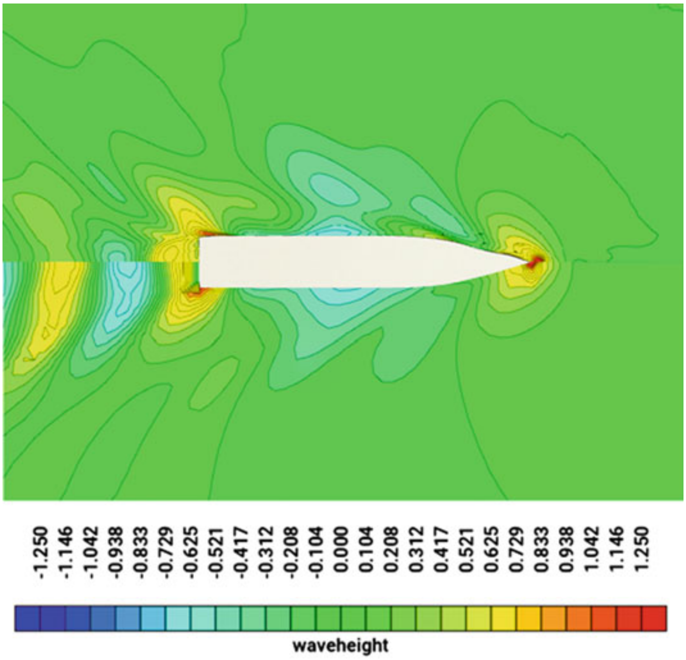


Fig. 6.50 Comparison of predicted wave pattern: potential flow (top) and RANS (bottom)

the free surface in the potential flow predictions. Another difference appears at the stern: while the RANS computation indicates a slightly wetted transom, the potential flow model is not able to capture this effect. Instead, the clear transom is the result of a kinematic boundary condition applied at this place in lack of an—a priori unknown—pressure condition.

These differences between viscous and inviscid predictions indicate that the results obtained in the response surfaces created using the panel code should not be used directly to predict the power requirements. Instead, calibration factors should be established from a limited number of RANS predictions to scale the potential flow results for the resistance and finally add the effect of the propeller which is included in the current viscous flow prediction using a propeller model.

The power curve for the baseline design vessel is shown in Fig. 6.51. Together with the predicted resistance, it is straightforward to determine a calibration factor for the panel code resistance and the power requirement.

This can later be used to scale the entire data set, i.e. the response surface which was produced from panel code results for actual power requirement P_D. Depending on the type of hullform modifications applied in the form optimisation process, a number of “anchor points” must be set using RANS predictions. If the form modifications comprise significant changes to the aft body of the ship, including topological changes or significant variations of the floating condition, i.e. a transom stern either wetted or

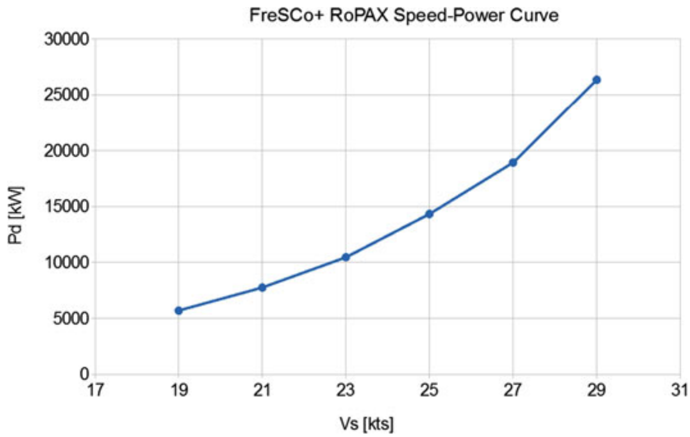


Fig. 6.51 Speed–power curve for the RoPAX baseline design (FreSCo^{+})

clear, it will be necessary to run several RANS predictions to support such conditions. In case only smaller changes are applied and they are confined mainly to the forebody of the vessel, a limited number of supporting RANS predictions will be sufficient.

6.4.5 Discussion

The previous subsections describe necessary steps to analyse and optimise the calm water performance of a ferry hull during an overall ship optimisation process. The result of such optimisation is obvious: the vessel with the least power requirement will be the preferred solution. This optimisation strategy has been a standard since powerful CFD methods have been introduced in the ship design process almost two decades ago. In most cases, a design condition has been given in form of speed and displacement and the optimisation yielded a hullform for this condition. The present example already indicates that optimal performance at more than one design point is required for the vessel's regular operation. This requires the inclusion of a dedicated objective function for the optimisation which relates the importance of the two conditions to each other. This can be a simple linear combination of the relative endurance of the two speed points, but it might also be a much more complex condition which includes also the manoeuvring performance during port approaches. In addition, the performance at actual operating conditions needs to be considered. So far, only calm water resistance and propulsion have been taken into account for the optimisation. The real ship will operate in a natural seaway which implies ship motions and, most importantly, added resistance and power requirements in a seaway. Such predictions have been performed by NTUA in (Harries et al. 2017), and an excerpt of the results is shown in Table 6.6.

Table 6.6 Added resistance results for two speeds and a range of headings for a JONSWAP spectrum ($H_s = 3$ m, $T_P = 6.7$ s)

Original design		Optimum @ 21 kts		Optimum @ 27 kts	
Heading	Added resistance [kN]	Added resistance [kN]	Difference [%]	Added resistance [kN]	Difference [%]
135	245.7	232.4	−5.4	211.2	−14.0
150	208.2	205.2	−1.4	193.4	−7.1
165	149.3	146.6	−1.8	127.0	−14.9
180	128.8	110.0	−14.6	99.1	−23.1

For a complete optimisation, it will be required to (i) analyse the environmental conditions for the expected operational area, (ii) to consider additional loading conditions (e.g. ballast condition, trim, depending on ship type) and (iii) perform analyses for these conditions for the entire set of form variants which have been generated earlier during the calm water analysis. This will require a large number of predictions which even when using a fast potential flow code will be rather time-consuming and costly. Hence, in such cases, the use of response surfaces similar to those applied before is recommended.

For the final assessment during an optimisation, such results need to be placed in context. So far, purely hydrodynamic aspects were considered. In the following chapters, a number of other design requirements will be highlighted. Often, they will show some conflicting behaviour, and the quest for the hydrodynamically optimal ship will likely yield a different result than the one with cheapest building costs or optimal solutions for other design parameters such as stability, energy, loading capacity, lane meters in case of the RoPAX.

The design optimisation must consider all relevant aspects for the specific design in question and bring them together in a holistic optimisation process and environment. The present chapter focuses on selected individual aspects which need to be considered when looking at the hydrodynamic performance of a ship and its optimisation. This alone calls for a considerable amount of analysis work to be included in the optimisation process. However, the overall ship design optimisation will require consideration of many more disciplines, and all need to be introduced and considered in the optimisation process. The following chapters will introduce further design disciplines and provide examples of how they can be integrated into the holistic environment that HOLISHIP provides.

6.5 Conclusions

Ship hydrodynamics are at the core of any ship design process. On one hand, they play a key role in the overall quest for improved energy efficiency in ship design.

Ship resistance and propulsion on average account for almost 85% consumption of all useable energy of a merchant vessel, and even for complex ships such as cruise vessels, they are still responsible for about 50% of the consumption of available energy on board. On the other hand, they determine, to a large extent, the safety and survivability of a ship in adverse conditions. Such fundamental requirements have always called for a thorough hydrodynamic analysis starting already during the early stages of the design of a new ship. In the past, such analyses have been cumbersome and very time-consuming and large parts could only be done using model testing, often at later design stages. Over the past decades, a large variety of CFD tools have been developed and further improved and validated which by now has led to high quality, validated methods and tools with good performance which are ready to use in integrated design processes from the beginning. Other than traditional empirical methods, these allow to consider the actual geometry of a ship hull and its details when performing a large variety of predictions. This in turn paves the way for a real optimisation of the ship hull, its shape and hydrodynamic properties in many respects.

Today, the range of available CFD tools spans from simple and fast potential flow panel codes for wave resistance predictions or propeller flows to more complex methods for transient behaviour, working in time or frequency domains up to rather complex viscous methods for accurate predictions of either steady-state or transient problems. The huge integration effort performed in the HOLISHIP project assures that all these methods are readily available to ship designers and ship design at various stages of the design process.

Given today's ever-increasing range of design requirements, considering the entire projected life cycle of a new vessel calls for significantly increased hydrodynamic performance not only for a single point of operation but for an entire regime of possible operational conditions. This in turn requires flexible, fast and accurate CFD prediction tools in a streamlined holistic design process. The HOLISHIP project delivers such an environment that assures a complete and consistent design process and the tools necessary to optimise and prove the hydrodynamic properties of a new design.

In the present chapter, a variety of CFD tools with different levels of complexity and fidelity have been presented; these tools can be used in the HOLISHIP design platform to achieve optimal designs. This includes resistance and propulsion predictions required at an early design stage as well as more complex flow codes for seakeeping, manoeuvring or dedicated special predictions resulting from special requirements for a new design. Most of the methods have their own, often lengthy, development history and have been applied in the past as stand-alone tools for special analyses. Integrating them into the novel HOLISHIP design platforms unleashes the full potential inherent to the methods during the design process.

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Chapter 7
Parametric Optimisation in Concept and Pre-contract Ship Design Stage

George Zaraphonitis, Timoleon Plessas, Andreas Kraus, Hans Gudenschwager and Gregor Schellenberger

Contents

Abstract The design of a ship is a delicate compromise between conflicting requirements and constraints imposed by the shipowner and all involved stakeholders. A ship needs to be optimised for cost-effectiveness, operational efficiency, safety and comfort of passengers and crew and, nowadays, for minimum environmental impact. Ship design is considered to comprise both art and science, highly dependent on the creativity, ingenuity and experience of accomplished naval architects, with good background in many fundamental and specialised scientific and engineering subjects. Parametric models could be a valuable tool for the experienced naval architect, especially if they can be used as the core of a formal optimisation procedure, facilitating the rational exploration of the design space and the identification of a series of 'optimal' or 'near-optimal' design solutions, while at the same time fulfilling a given set of design constraints. The implementation of such a design procedure, along with parametric models specifically developed for the concept and pre-contract design of a medium-size RoPAX, is presented and discussed in the present chapter.

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7.1 Introduction

Employing the so-called parametric design procedure, the design and optimisation of a mechanical engineering system, component or object may be 'automated' by elaboration of sets of design parameters defined by the designer or an optimisation algorithm. In case of large integrated systems, such as an aircraft or a ship, the implementation of a parametric model is a quite complicated and demanding task, requiring particular attention and significant effort in order to ensure its integrity, accuracy, robustness and functionality. The parametric model should be flexible and generic, so that it is applicable to as many design alternatives as possible, detailed enough to depict all the essential characteristics of the design, and at the same time as simple as possible to avoid any unnecessary complexities and implications during the development and/or integration of the corresponding software tools. These requirements are particularly important for parametric models intended to be used for the design of ships during the pre-contract or contract design stage. In these stages of ship design, a parametric model needs to be more sophisticated and detailed than in concept stage, while at the same time the required assessment tools need to be of advanced accuracy and hence computationally demanding. At this stage, design work would be based on the results obtained before during the concept design and associated optimisation.

Parametric models, if available, could be used as the core of a formal optimisation procedure, facilitating the rational exploration of the design space and the identification of a series of 'optimal' or 'near-optimal' design solutions, according to a suitable set of design criteria (the so-called objective functions or merit functions), while at the same time fulfilling a given set of design constraints. Inherent to ship design optimisation are conflicting requirements, resulting from design constraints and optimisation criteria, reflecting the interests of various stakeholders: ship owners and operators, shipbuilders, classification societies, administrations, regulators, insurers, cargo owners/forwarders, port operators, etc. A ship needs to be optimised for cost-effectiveness, operational efficiency, adequate safety and comfort of passengers and crew, and, last but not least, for minimum environmental impact (minimisation of risk of accidental oil outflow, greenhouse gas emissions, etc.). The use of optimisation methods in ship design is by no means a new development. As a matter of fact, such methods can be traced in pioneering works presented during the sixties (e.g. Evans and Khoushy (1963), Leopold (1965), Mandel and Leopold (1966), Mandel and Chryssostomidis (1972) and Nowacki et al. (1970)). A thorough review of the introduction of optimisation methods coupled with the evolvement of Computer-Aided Ship Design is given by Nowacki (2010).

The development of parametric models for the hull form and internal layout of a series of ship types along with appropriate assessment tools and their interconnection with optimisation algorithms, in order to come up with integrated optimisation platforms, is the key objective of the HOLISHIP project. A series of Application Cases[1] are foreseen in the project for the validation and demonstration of the potential of the design and optimisation procedures and tools currently under development. In the meanwhile, an additional Application Case (the optimisation of the design of a medium-size RoPAX vessel) has been selected in order to be used as the 'testbed' for development and testing of the employed procedures and tools, both for the concept and for the pre-contract ship design stage. In the following, along with a brief discussion of the employed procedures and tools, selected results obtained from this particular optimisation study will be presented and discussed.

7.2 Parametric Concept Design Optimisation

In the early concept phase, the designer's first 'guess' has to fulfil a number of conditions and constraints simultaneously. The first concept in ship design is usually based on designer's experience and purposeful modifications of existing similar vessels. There are two main challenges when trying to support this process with a computer-based design platform:

1. The set-up for answering a specific enquiry must be simple, robust and fast.
2. The optimisation system—even at the very early stage of the ship design process—gets complex, consists of many equations and inequality constraints, and is difficult to solve.

The following approach may be selected to face these challenges:

1. A compiler could be introduced to rewrite a set of design equations/functions/software applications (apps) into an optimisation problem. The advantage of this approach is that the designer can write a set of design equations or constraints in a—to him or her—familiar way. Such a compiler is described by Gudenschwager (1988).
2. The optimisation problem could be solved by repeated linearisation and application of a modified Simplex algorithm (Söding 1983). The advantage of this algorithm is an extremely fast and robust way to solve the problem in a reasonably accurate way, giving a result good enough at this early stage of design, when most of the parameters and methods used are still estimates.

[1] i.e. a large RoPAX ship, a double-ended ferry, an offshore support vessel, a research vessel, a cruise ship, a multi-purpose ocean ship, a merchant vessel, two large cargo vessels and an offshore platform.

7.2.1 Optimisation Approach

Any optimisation system has to be defined in the following steps:

1. Formulation of equations/inequality constraints referring to all aspects of the examined design problem in the form of
   a. Simple equations/inequalities and
   b. Functions, software applications (apps).
2. Definition of optimisation objectives.
3. Selection of the design parameters.
4. Classification of the parameters used in the equations/inequalities:
   a. Parameters that have defined or given values ('Constants').
   b. Parameters that have to be determined by calculation ('unknowns', 'variables').
5. Check of the defined system regarding its sufficiency for a well-posed optimisation problem: Does the number of variables exceed the number of available equations?

After the definition of the system, the optimisation problem can be coded in a readable way by an extended programming language. The extended program code is the source for the following compilation process. As a first step, a compiler like the DELPHI compiler (Gudenschwager 1988) translates the extended syntax to a standard code preparing the defined optimisation system for the use with an optimisation tool, like the modified OPT optimisation algorithm (Söding 1983).

The solution is sought by solving the corresponding nonlinear optimisation problem with equality and inequality constraints. When using the modified OPT algorithm, the algorithm is searching numerically for a valid optimum in the design space described by the limits of the variables. The algorithm is solving the problem by adapting the method of linear optimisation by continuous linearisation of the nonlinear system. A solution is valid when the result is found within a predefined tolerance. The result could be any local or global optimum within the area of observation. The results have to be checked for consistency. In case of non-solvable systems, the user has to check the constraints and the definitions as well as the objective of the optimisation system. Building an optimisation system should start from simple systems to more complex ones. Used functions have to be carefully checked according to their calculation behaviour.

Table 7.1 Requirements and limitations

Project-specific information	Shipyard-specific information
Limitations in draught, beam, length, height	Restrictions in size or weight, due to capacity of docks, cranes, etc.
Cargo unit weights/dimensions	Estimates for weight components
Number of passengers	Cost per ton of steel weight
Number/size of cabins	
Size of public spaces	
Service speed	
Range, operational profile	
Cargo capacity	
Minimum free height of decks	
Geometric requirements for ramps	
Rules, regulations, etc.	

7.2.2 Formulation of Early Concept Design Problem

7.2.2.1 Variables and Parameters

The number of variables and the complexity of the used design tools vary significantly, depending on the level of concept design. In the very beginning, the designer is looking for main dimensions and first ideas for arrangement, weight and propulsion power. Rough estimation formulas on this level have to be based on few available data, resulting from owner requirements and other project-specific information as well as shipyard-specific information; see Table 7.1.

The sought-after main parameters can be introduced as design variables, like length, beam, draught, depth, displacement or block coefficient, centre of gravity. Even in a first simple approach, numerous additional variables will occur in the calculation process (resistance, propeller diameter, wake fraction, weight of steel, machinery, equipment, deadweight, etc.). These could be ‘hidden’ within the calculation routines, but formulation of the optimisation problem might get easier for the designer by introducing additional variables. At the start of the concept design process, calculations requiring a detailed form definition are out of question. Only rough estimations are required—and possible—but even at this stage the number of variables as well as the number of equations and inequality constraints might add up to 30 and more.

7.2.2.2 Equality and Inequality Constraints

The vessel has to satisfy simultaneously the so-called owner (or mission) requirements, a set of fundamental naval architectural principles and regulatory requirements. All these requirements have to be expressed as equality or inequality constraints such as:

- Freeboard ≥ required value (International Load Line Convention);
- Areas for passengers and crew ≥ required value (Owner);
- Cargo capacity/Lane lengths ≥ required value (Owner);
- Gross tonnage in the required range (Owner);
- Ship weight = weight of displaced water (Archimedes);
- Vertical centre of gravity ≤ required value (intact and damage stability);
- Longitudinal centre of gravity = longitudinal centre of buoyancy (for zero trim);
- Resistance = thrust minus thrust deduction;
- Installed power ≥ propulsion power for given speed plus auxiliary power;
- Tank capacities ≥ fuel for range, freshwater, grey and black water for endurance, ballast water volume for stability or minimum draught;
- EEDI ≤ required value (IMO-MEPC regulation).

7.2.2.3 Objectives

Reasonable objectives (objective functions) in early concept design could be propulsion power, installed power, fuel consumption, steel weight, lightship weight, building cost, operational expenditures, required freight rate (RFR) or daily cost, net present value (NPV), environmental footprint. For the evaluation of objectives as well as for checking constraints, a series of calculations are required. As mentioned earlier, the complexity of calculations and of the employed tools should correspond to the design level. Calculation methods in early design have to be less complex, due to limited information and time available. To evaluate the objective functions and constraints, a series of design attributes have to be addressed by estimation formulas, some of which are listed in the following:

- Hull geometry, transport capacity;
- Weight, structural scantlings;
- Power, machinery;
- Freeboard and load line;
- Stability;
- Cost and financing;
- Life cycle and key performance indicators.

Examples for the treatment of different topics and different levels of calculation will follow in Sect. 7.2.3.

7.2.3 *Adaptation of Tools*

Adaption of tools for concept design optimisation is herein presented for steel weight, power estimation and stability. Stability is discussed in more detail, to exemplify different approaches to different design levels.

7.2.3.1 Steel Weight Estimation

Estimation of the real weight of a ship is a difficult task with many uncertainties due to the complexity of a vessel; even in the detailed design phase, when more detailed information is available, this task remains very demanding. Still today, the accurate weight of the ship is determined after ship's launching by performing a draught survey of the readily built ship. In early design, however, many details of the ship are unknown, and it is impossible to predict the weight exactly. It is common practice to split the weight into separate groups, like structure, machinery, equipment and outfitting, and estimate these parts separately.

There are various approaches to estimate the steel weight of a ship, based on:

- Main dimensions and parameters;
- Volumes and areas;
- Midship section and some longitudinal information;
- Structural layout of several sections and some longitudinal information;
- Layout of the full structure;
- Surrogate models.

In very early concept design, steel weight can be calculated from estimation formulas based on ship's main dimensions (Schneekluth 1980; Papanikolaou 2014). A better estimate of the weight may be achieved by looking at horizontal layers of the ship, while each layer is defined by length, beam and height of the respective deck. The weight per volume of such a layer can be estimated from similar ships. Even if it is not the weight per real volume, this procedure gives reasonable results, as long as the weight per volume factor from the similar vessel is calculated in the same way. If a parametric geometry model is available, the estimations can rely on real deck areas and volumes.

In a later stage of concept design, a common approach is to define the structure of the midship section and to calculate the weight per metre of longitudinal steel structure quite precisely for this part of the ship. Transverse frames and bulkheads have to be added. The number, position and area of bulkheads should be available at this stage. The weight per metre towards the ends of the ship may be calculated by taking into account changes of the section area and correction factors for changes of the structure. The main challenge for this approach within an optimisation routine is the structural layout of the midship section. It has to be performed in an automated way, which requires a parametric structural model, adapted to the design in progress.

One way to set up a parametric structural model is the combination of NAPA Steel® with Poseidon (DNV GL software for the strength assessment of ship hull structures) for a first check of the layout (see, e.g. Papanikolaou et al. 2010). Another approach is explained in Chap. 9 of this book. With such a model in hand, it would take little extra effort to consider more than one sections, or even a complete model of the ship. Setting up and checking the parametric model of a design variant might take too long for early design, so again, for early concept design it should be sufficient to work with surrogate models.

7.2.3.2 Power Estimation

As a first estimate of the required propulsion power P, the British Admiralty formula is still in use in early concept design. It relates the propulsive power P_0, displacement Δ_0 and speed v_0 of a similar vessel of comparable size and speed to the corresponding values of the new design.

$$P_{\text{new}} = \left(\frac{v_{\text{new}}}{v_0}\right)^3 \cdot \left(\frac{\Delta_{\text{new}}}{\Delta_0}\right)^{\frac{2}{3}} \cdot P_0 \tag{7.1}$$

This simplified approach is not suitable for an optimisation, because the power for a given speed is herein only a function of displacement.

A better approach would be here the use of an empirical method, like that of Holtrop (1984) or Hollenbach (1997). The above methods use ship's main dimensions and hull form coefficients to estimate the total resistance, as well as the thrust deduction and wake coefficients. Propulsive efficiency values can be found from data of standard propeller series, like Wageningen B (Oosterveld and van Oossanen 1975). These methods are fast enough for optimisation purposes, while their accuracy is generally sufficient in the early design stage, in particular when the methods are calibrated with (sea trial of model test) results of similar vessels.

Another approach is nowadays the use of Computational Fluid Dynamics (CFD) methods. The drawback of this approach is that even potential flow calculations take too long for optimisation in the early concept design, while they require a full definition of the hull geometry, which is generally not available at this early stage. If a parametric model from a similar ship is available, the geometry could be retrieved in a fast and efficient way from the main dimensions, but the problem of computation time remains. Here, surrogate models might offer a reasonable solution for concept design too. The set-up and use of such surrogate models are explained in Sects. 7.2.3.3 and 7.3.3.

CFD methods—potential flow as well as RANSE—still require some experience in proper use and in order to give reliable results, as shown in recent benchmark studies (Ponkratov 2016). If these methods are adapted to a certain ship type and size, it might be possible for a less experienced user to get reasonable results, but then the setting up and adapting of the procedures have to be carried out by an expert in CFD. If a surrogate model of sufficient accuracy is available, the use and implementation of this model in an optimisation could be possible without any deep

CFD knowledge, but still the designer has to be well aware of the expected accuracy and limits of the methods behind the numerical simulation model.

7.2.3.3 Stability Estimation

Since stability of passenger vessels concerns a highly critical safety issue, one of the most important steps in the ship design process is the verification of the ship's intact and damage stability behaviour. The following regulatory framework defines minimum standards for intact and damage stability, which are mandatory or came recently into force for RoPAX vessels engaged in international voyages:

- Intact Stability Code (IMO 2008);
- SOLAS Ch. II-1, Reg. 6, 7 and 8 (IMO 2014);
- MSC Circ. 421(98), Reg. 6, 7 and 8, (SOLAS 2020, IMO 2017);
- Directive 2003/25/EC (Stockholm Agreement, European Commission 2003).

For the early design phases when, apart from the main dimensions, information on the hull form and compartmentation is not available, the assessment of stability can only be performed with empirical formulas based on a very limited number of input parameters. As a means of assessment of the ship's intact and damage stability, the initial stability GM is widely recommended for application in the early design phase (cf. Lamb 1969; Schneekluth 1980; Papanikolaou 2014). Therefore, from a stability point of view the following equation has to be fulfilled:

$$\mathrm{GM}_{\mathrm{attained}} \geq \mathrm{GM}_{\mathrm{required}} \tag{7.2}$$

Typical values of required initial stability $\mathrm{GM}_{\mathrm{required}}$ are either suggested empirical values, which are based on absolute GM values for certain ship types (e.g. for passenger vessels: $\mathrm{GM} = 1.5{-}2.2\,\mathrm{m}$, Schneekluth 1980), or in relation to the ship's beam (e.g. for ferries: $\frac{\mathrm{GM}}{B} = 0.09{-}0.102$, Lamb 1969). It has to be noted that these data and empirical formulas for $\mathrm{GM}_{\mathrm{required}}$ correspond to hull forms and regulations in use about five decades ago, and thus, they may lead to unrealistic results in some cases.

The attained initial stability $\mathrm{GM}_{\mathrm{attained}}$ can be calculated as the difference of the height of metacentre above keel KM and the centre of gravity above keel KG:

$$\mathrm{GM}_{\mathrm{attained}} = \mathrm{KM} - \mathrm{KG} \tag{7.3}$$

KM can be estimated by empirical formulas in total or as the sum of its components, the height of centre of buoyancy above keel KB and the transverse metacentric radius BM. KG can be determined based on empirical formulas for the weight of ship's mass and centres of gravity of lightweight and deadweight components for the laden ship. This approach is very rough and only suitable for the very early steps of the concept design phase. Therefore, in order to generate more reliable results

Table 7.2 Intact stability criteria for passenger vessels (IMO 2008)

Criterion	Requirement
Min. intact stability GM	$GM \geq 0.15\,m$
Max. righting lever GZ	$GZ_{max} \geq 0.20\,m$
Position of max. righting lever	$\varphi_{GZ_{max}} \geq 25°$
Area(s) under GZ curve	$A_{30°} \geq 0.055\,mrad$
	$A_{40°} \geq 0.090\,mrad$
	$A_{30°-40°} \geq 0.030\,mrad$
Weather criterion	$b \geq a$
Max. heel due to wind moment	$\varphi_0 \leq 16°$
Max. heel due to passenger crowding	$\varphi_{Pax} \leq 10°$
Max. heel due to turning at speed	$\varphi_{Turn} \leq 10°$

concerning compliance with intact and damage stability, a new method for the concept design phase is adopted: to ensure compliance with the stability requirements during the optimisation, a maximum permissible KG is proposed, which can be directly compared with the results of the centre of gravity calculation without need of elaboration of the hydrostatic data:

$$KG_{max} \leq KM - GM_{required} \tag{7.4}$$

$$KG \leq KG_{max} \tag{7.5}$$

$GM_{required}$ corresponds to the minimum GM which is required to fulfil the stability requirements under consideration.

Intact Stability

The currently in force Intact Stability Code (Res. MSC.267(85), IMO 2008) was adopted in 2008, aiming to provide in a single document the necessary information about the minimum stability requirements based on existing IMO instruments for a number of different types of vessels and marine floating structures. The code contains mandatory stability criteria for all vessels and recommendatory stability criteria for certain vessel types. The mandatory requirements for RoPAX vessels are listed in Table 7.2. As can be seen from Table 7.2, only one criterion uses solely the initial stability value GM as a requirement. All other criteria depend on the properties of the heeling arm lever curve GZ and a comparison of the attained values to the required ones, e.g. for the attained area under the GZ curve versus the required one. Therefore, for a more accurate consideration of the intact stability in the concept phase, it will not be enough to define a fixed or beam-dependent minimum GM value as requirement. For rule compliant intact stability calculations of a RoPAX vessel, the following information must be available:

- Hull form including water-/weathertight superstructure;
- Location of unprotected openings;

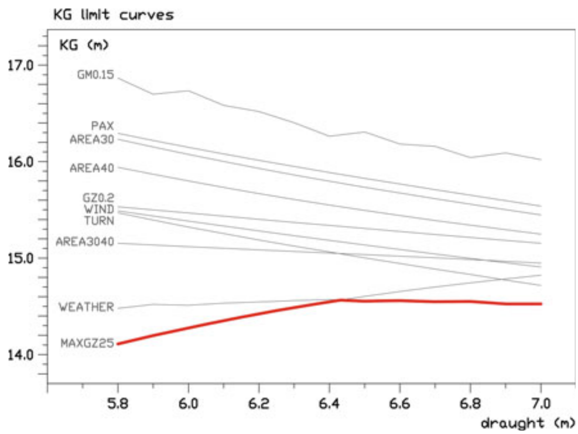

Fig. 7.1 Maximum KG curves versus ship's draught for each intact stability criterion and envelope curve (red)

- Wind profile, bilge keel areas, skeg and rudder area(s);
- Number of passengers;
- Service speed.

To overcome the problem of missing information in the early concept phase, an approach using a parametric description of the hull form of a similar vessel is proposed. This model should be suitable to adjust the global parameters L_{pp}, B, T, D and C_B. Based on this model, a number of hull variants are generated and stability analyses are performed. Additional information required to perform the stability analyses are taken as absolute or relative values from the parent design. As a result, curves of maximum KG to fulfil all intact stability criteria as defined by the IS code (IMO 2008) are generated (see Fig. 7.1). For the concept design phase, it is sufficient to generate a single maximum KG at design draught and compare it with the attained KG in the design loading condition. Nevertheless, all information is available to derive KG_{max} values at any draught within the limits. The results can be transferred to a surrogate model (response surface, regression formulas) which allows a more precise prediction of the influences of variations in the main particulars of a ship design with respect to intact stability requirements.

As an example, a RoPAX vessel developed by FINCANTIERI S.p.A. (herein denoted as the 'baseline' design) for the EU project GOALDS[2] was used as a parent design. A parametric description of the hull form in CAESES developed by Friendship Systems with 25 parameters was used. A process chain for an automatic stability analysis was set up within CAESES. The hull form is transferred to NAPA in IGES format. Within NAPA, a stability hull is generated and the required settings to perform stability calculations are initialised. As a result, a text file with information on the maximum KG values for the considered draughts is returned via text file. Design space exploration methods (e.g. Sobol) can be applied to create designs with the

[2]GOALDS (2009–2012): Goal-based Damage Stability, project funded by the European Commission, FP7-DG Research, Grant Agreement 233876.

Table 7.3 Hull form parameters of the FINCANTIERI RoPAX (baseline) and parameter limits for the design variants

Parameter	Unit	Lower boundary	Upper boundary	Baseline
L_{pp}	(m)	150.00	180.00	162.845
B	(m)	27.60	30.60	27.600
T[a]	(m)	6.00	7.10	7.000
C_B	(–)	0.54	0.60	0.570
LCB	($\%L_{pp}$)	0.4545		0.4545
D	(m)	15.40		15.40

[a]Draught T represents herein the maximum draught. For this study—since the differences in draughts for RoPAX vessels are small—it was assumed that the design draught, maximum draught and deepest subdivision draught according to SOLAS are the same

best possible coverage of the set limits (e.g. due to the limitations of the parametric model). For the stability analyses in the concept design phase, four global parameters were varied within the limits presented in Table 7.3.

A nonlinear regression analysis with a sample of 110 design variants was performed to deduce a prediction formula for a maximum KG at design draught based on a very limited number of ship design parameters:

$$\begin{aligned} KG_{max} &= 47.083 - 12.685 \cdot \frac{B}{T} + 5.485 \cdot B - 0.0537 \cdot B^2 \\ &\quad - 19.88 \cdot T + 0.904 \cdot T^2 + 2.486 \cdot C_B \end{aligned} \tag{7.6}$$

For the assessment of the prediction accuracy, the exact maximum KG values resulting from stability calculations can be compared with the predicted values from the regression formula. As can be seen from Fig. 7.2, the results are within limits of less than 15 cm or 1% of KG_{max}.

The influence of single parameters on the maximum permissible KG values can be seen from the graphs in Fig. 7.3. In these graphs, selected parameters (see Table 7.3) were varied within the limits of the regression analysis (solid line) and beyond them as extrapolations (dashed lines). As can be seen from these plots, the KG_{max} values are independent from the ship length and show little influence on changes of the block coefficient and the draught. The main driver for KG_{max} is ship's beam, which is in accordance with well-known laws of ship theory.

Hydrostatic information can also be derived from the design space exploration and can be expressed by nonlinear regression formulas applied to data of the design variants. As an example, the height of transverse metacentre above keel (KMT) as function of main ship design parameters at draught d_s was derived as:

$$\begin{aligned} KMT &= -24.155 + 5.832 \cdot \frac{B}{T} - 1.102 \cdot B + 0.01964 \cdot B^2 \\ &\quad + 7.79 \cdot T - 0.385 \cdot T^2 - 6.126 \cdot C_B \end{aligned} \tag{7.7}$$

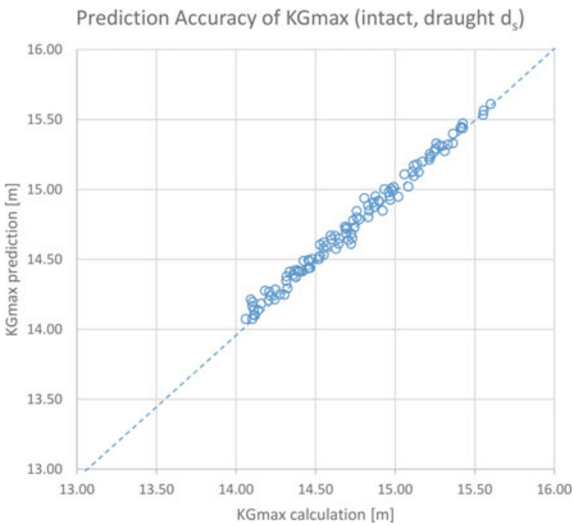

Fig. 7.2 Comparison of exact and predicted (by regression) values for KG_{max} to fulfil intact stability requirements

Predicted values based on this formula showed good agreement with exact calculation results (see Fig. 7.4).

Damage Stability

Damage stability calculations for RoPAX vessels have to be performed in accordance with SOLAS requirements. In addition, water on deck calculations according to Directive 2003/25/EC known as 'Stockholm Agreement' (European Commission 2003) may be required for RoPAX vessels on international routes in European waters. More stringent damage stability requirements have been introduced recently by IMO Resolution MSC.421(98) which will come into force in 2020 and will replace the existing SOLAS regulations known as SOLAS 2009. The new stability requirements provide an updated formulation of the Required Subdivision Index R, leading to an increase of the survivability level especially for smaller and medium-size passenger vessels; they further introduce a modified formula for the survivability index s of RoPAX vessels in case of damage to a RoRo space. SOLAS Chapter II-1 for both SOLAS 2009 and SOLAS 2020 is structured with respect to damage stability calculations as follows:

- Regulation 6: Required Subdivision Index *R;*
- Regulation 7: Attained Subdivision Index *A* (probabilistic);
- Regulation 8: Minor Damages (deterministic);
- Regulation 9: Bottom Damages (deterministic).

In this study, we focus on the probabilistic part of the damage stability regulations. Minor damages are for this type and size of vessel typically not a critical issue. Bottom damages are to be analysed in case an untypical bottom arrangement is selected. For the baseline design, this is the case due to the partial double hull arrangement.

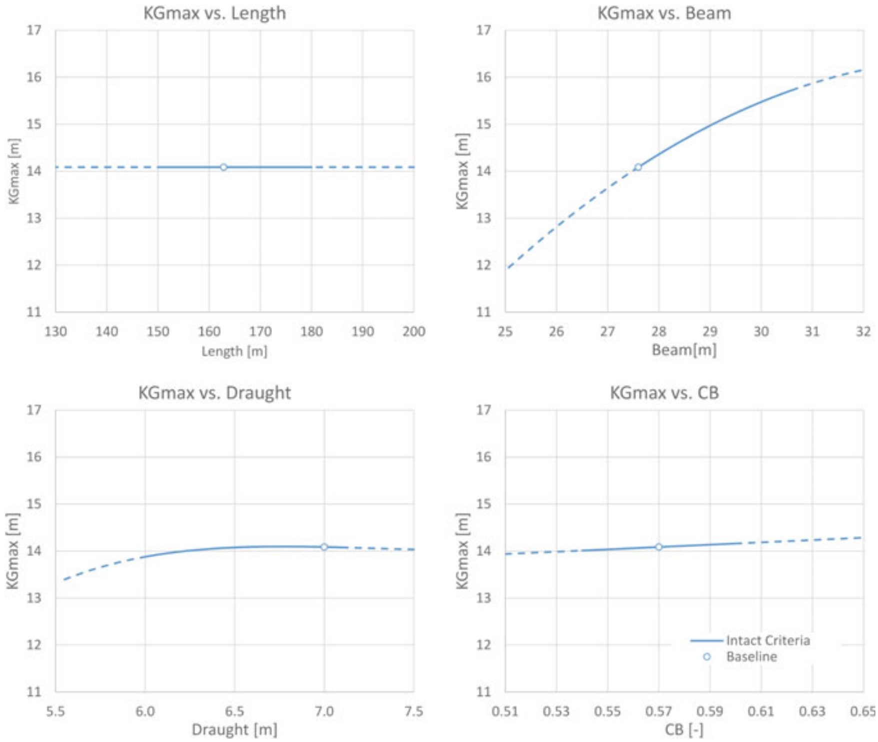

Fig. 7.3 Influence of ship design parameter variations on the maximum permissible KG with respect to intact stability

However, regulation 9 is assumed not to be decisive compared to the requirements for KG_{max} established by the probabilistic damage stability requirements.

The subdivision of a ship with respect to the probabilistic damage stability requirements is considered sufficient, if the Attained Subdivision Index A, calculated as the weighted average of the partial indices A_s, A_p, A_l at the three draughts d_s, d_p, d_l (deepest subdivision, partial and light service draught, respectively), is not less than the Required Subdivision Index R:

$$A = 0.4 \cdot A_s + 0.4 \cdot A_p + 0.2 \cdot A_l \geq R \tag{7.8}$$

In addition, the partial subdivision indices for passenger vessels have to fulfil the following requirement:

$$A_i \geq 0.9 \cdot R \tag{7.9}$$

where A_i denotes the partial subdivision indices on draughts d_s, d_p, d_l. The deepest subdivision draught d_s, the partial subdivision draught d_p and the light service draught

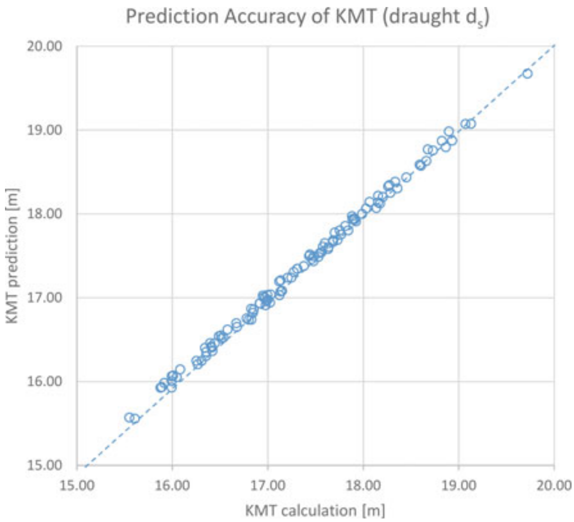

Fig. 7.4 Comparison of exact and predicted values for KMT

d_l are defined in SOLAS and are supposed to represent typical loading conditions over the draught range. Each partial index is a summation of contributions (i.e. damage cases which are survived) from all damage cases taken into consideration:

$$A = \sum p_i \cdot s_i \tag{7.10}$$

where i represents each compartment or group of compartments under consideration, p_i accounts for the probability that only the compartment or group of compartments under consideration may be flooded, disregarding any horizontal subdivision, and s_i accounts for the probability of survival after flooding the compartment or group of compartments under consideration and includes the effect of any horizontal subdivision (SOLAS 2009).

The results of damage stability calculations are mainly influenced by the initial floating condition (i.e. draught, trim and initial metacentric height), by the internal compartmentation (i.e. number and location of bulkheads and decks) and by the location of openings. Furthermore, A-class bulkheads, escape routes and cross-flooding arrangements require further considerations in damage stability analyses. For passenger vessels, additional heeling moments due to wind, passenger crowding and launching of survival craft have to be considered.

In early concept design phase, this detailed information is not available. Therefore, to consider a typical internal arrangement in the damage stability calculations, a parametric model of a similar vessel (parent design) is used. As an example, a parametric model of the internal compartmentation of the baseline design (FINCANTIERI RoPAX) provided by NTUA was used for a damage stability analysis in accordance with SOLAS 2020. For the derivation of the results presented in the following, the position of transverse and longitudinal bulkheads as well as decks is scaled in accordance with the main dimensions. However, the height of the main vehicle deck (Deck 3) was kept constant, to consider the height of fixed and movable ramps at the loading terminals. Nevertheless, since the height of the main vehicle deck (i.e. the bulkhead deck) has a huge impact on damage stability, it could also be treated as a free variable in further studies.

Calculations were performed to evaluate the maximum permissible KG values to reach an A-Index on the respective draught of 90, 95, 100 and 102.5% of the required index R. For the deepest subdivision draught d_s, the results of the nonlinear regression analysis show the following relations:

$$\mathrm{KG}_{\max}^{A=0.90R} = -52.71 + 7.042 \cdot \frac{B}{T} - 1.01 \cdot B + 0.0124 \cdot B^2 + 14.528 \cdot T - 0.859 \cdot T^2 - 4.878 \cdot C_\mathrm{B} \tag{7.11}$$

$$\mathrm{KG}_{\max}^{A=0.95R} = -76.71 + 7.568 \cdot \frac{B}{T} - 0.3794 \cdot B + 18.366 \cdot T - 1.1432 \cdot T^2 - 3.968 \cdot C_\mathrm{B} \tag{7.12}$$

$$\mathrm{KG}_{\max}^{A=1.00R} = -92.325 + 5.114 \cdot \frac{B}{T} + 24.999 \cdot T - 1.833 \cdot T^2 - 2.072 \cdot C_\mathrm{B} \tag{7.13}$$

$$\mathrm{KG}_{\max}^{A=1.025R} = -129.196 + 5.049 \cdot \frac{B}{T} + 36.788 \cdot T - 2.8076 \cdot T^2 \tag{7.14}$$

A parameter study based on the above formulas shows little influence of length and block coefficient on the maximum permissible KG, while on the other hand, the influence of beam and draught is quite strong. While an increase in beam has a strong positive impact on the maximum permissible KG, the opposite is true for an increase in draught (Fig. 7.5).

The maximum permissible KG to fulfil the damage stability requirement at draughts d_p and d_l as required by SOLAS was derived as described for the deepest subdivision draught d_s:

$$d_p\text{: } \mathrm{KG}_{\max}^{A=1.00R} = -75.911 + 6.236 \cdot \frac{B}{T} - 0.142 \cdot B + 18.619 \cdot T - 1.24 \cdot T^2 - 2.45 \cdot C_\mathrm{B} \tag{7.15}$$

$$d_l\text{: } \mathrm{KG}_{\max}^{A=1.00R} = -64.187 + 5.741 \cdot \frac{B}{T} + 14.173 \cdot T - 0.8892 \cdot T^2 - 0.412 \cdot C_\mathrm{B} \tag{7.16}$$

The analysis of the prediction accuracy shows similar good results for all three draughts. The maximum prediction error based on 110 design variants was less than 8 cm (see Fig. 7.6). The influence of beam and draught on intact and damage stability requirements is presented in Fig. 7.7.

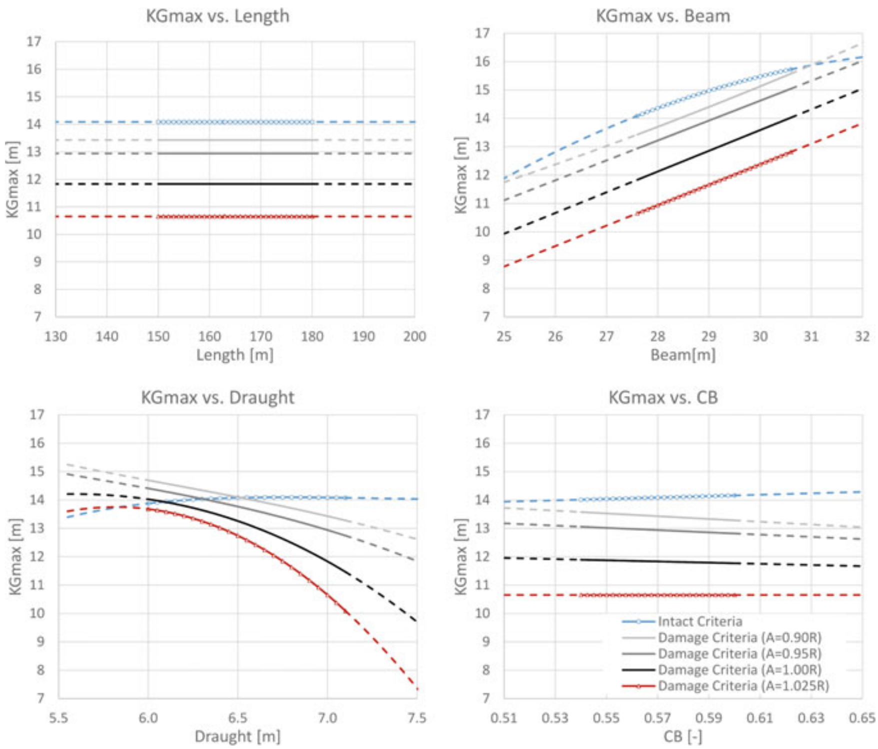

Fig. 7.5 Influence of main ship design parameter variations on KG_{max}

Table 7.4 Calculation formulas for required index R (MSC Circ.421(98))

Persons on board	R
$N < 400$	$R = 0.722$
$400 \leq N \leq 1350$	$R = N/7580 + 0.66923$
$1350 < N \leq 6000$	$R = 0.0369 \times \text{Ln}\,(N + 89.048) + 0.579$
$N > 6000$	$R = 1 - (852.5 + 0.03875 \times N)/(N + 5000)$

The maximum permissible KG at deepest subdivision draught depends on the required index R, which according to MSC Circ.421(98) for passenger ships is only dependent on the total number of persons on board (Table 7.4).

To allow for a prediction of KG_{max} values if the persons on board vary based on owner requirements, an analysis was performed to establish KG_{max} values in relation to the required index R. The analysis of results shows that for the baseline design the KG_{max} values as function of the relation A-Index to R-index follow a quasi-quadratic form. Based on the KG_{max} values at $A = 1.00R$, $A = 0.95R$ and at $A = 0.90R$, the following quadratic function was derived for draught d_s based on a regression analysis of the 110 design variants:

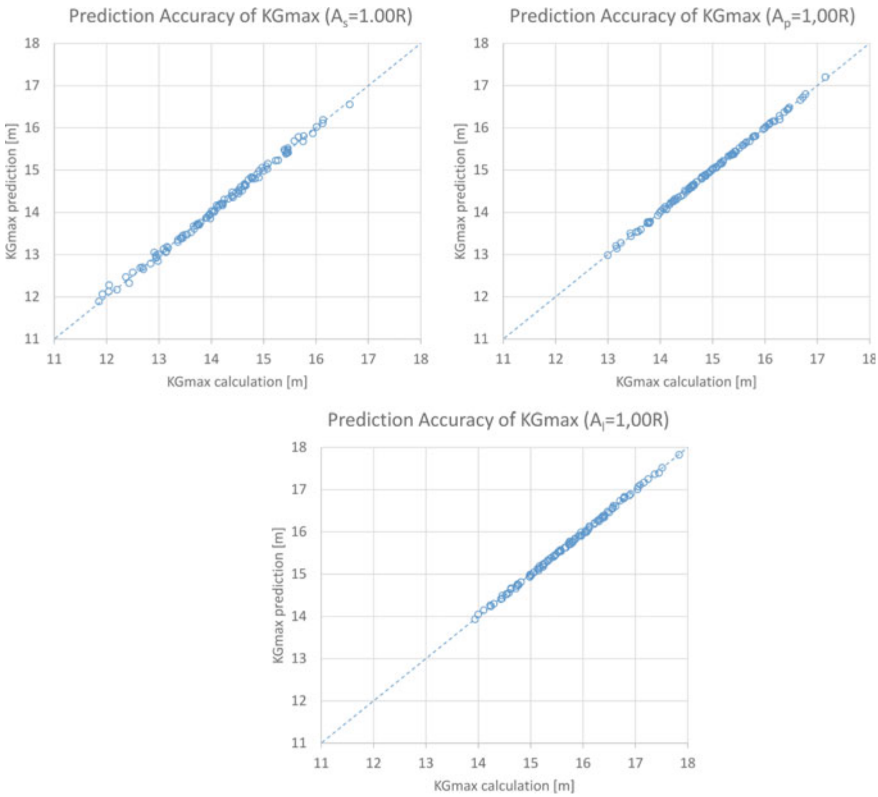

Fig. 7.6 Prediction accuracy of KG_{max} values for draughts d_s, d_p, d_l

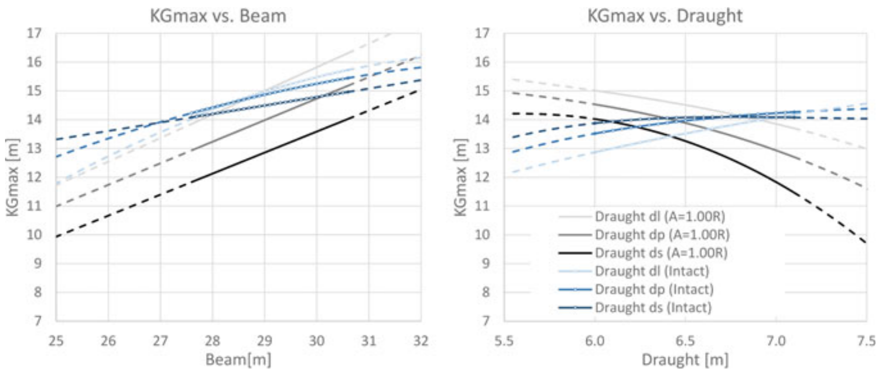

Fig. 7.7 Parameter study for intact and damage stability requirements for draughts d_s, d_p, d_l

$$KG_{max} = \left(a \cdot \delta A^2 + b \cdot \delta A + 1\right) \cdot KG_{max}^{A=1.00R} \tag{7.17}$$

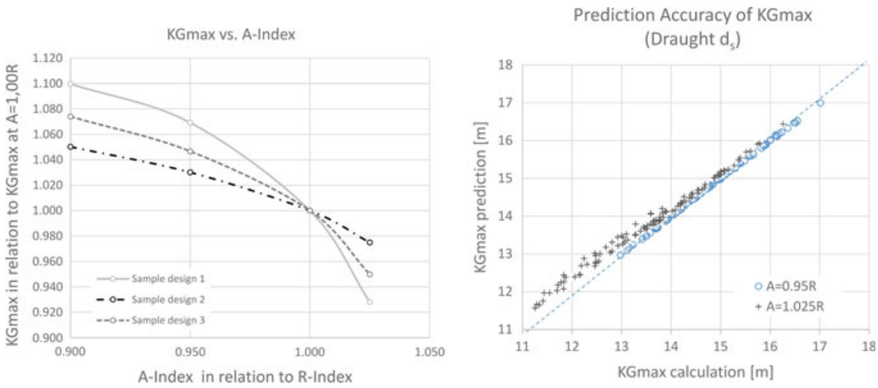

Fig. 7.8 Typical curves of KG_{max} versus A-Index (left) and prediction accuracy based on quadratic approximation formula for draught d_s (right)

with:

$$\delta A = \frac{A - R}{R} \tag{7.18}$$

$$a = -95.7249 \cdot \frac{KG_{max}^{A=0.90R}}{KG_{max}^{A=1.00R}} + 98.5138 \tag{7.19}$$

$$b = -19.5725 \cdot \frac{KG_{max}^{A=0.90R}}{KG_{max}^{A=1.00R}} + 19.8514 \tag{7.20}$$

The prediction accuracy shows good results with errors in the prediction of less than 6 cm at $A = 0.95R$ for the 110 samples. For $A = 1.025R$, the accuracy is not sufficient (see Fig. 7.8, grey crosses). However, it can be assumed that the above formula shows acceptable results in the range $0.90R \leq A \leq 1.01R$.

Combined KG_{max} values for intact and damage stability

Based on the formulas derived above, the maximum permissible KG can be calculated and compared with the results for ship's weight and centre of gravity in the respective loading condition:

$$KG_{max} = \min\left(KG_{max}^{Intact}; KG_{max}^{Damage}\right) - \text{Margin} \tag{7.20}$$

A suitable margin to account for inaccuracies in the calculation model as well as in the prediction formulas should be considered. For the early concept phase, it is usually sufficient to only consider the full load condition at draught d_s. An accuracy analysis for two example cases is presented in Table 7.5. The results show good prediction accuracy for the permissible KG*s* at all draughts with maximum errors of about 1.1% of KG.

Table 7.5 Accuracy analysis for two example cases

	Parameter	Baseline			Example 1		
	L	162.850			165.000		
	B	27.600			28.500		
	T	7.100			7.000		
	D	15.400			15.400		
	C_B	0.5680			0.5600		
	LCB	0.4545			0.4545		
		Predict. (m)	NAPA (m)	Error (m)	Predict. (m)	NAPA (m)	Error (m)
d_s	KMT	15.483	15.414	0.069	16.370	16.344	0.026
	KG_{max} (intact)	14.086	14.038	0.048	14.670	14.647	0.023
	KG_{max} ($A = 0.90R$)	13.310	13.290	0.020	14.121	14.117	0.004
	KG_{max} ($A = 1.00R$)	11.469	11.346	0.123	12.512	12.417	0.095
	KG_{max} (total)	11.469	11.346	0.123	12.512	12.417	0.095
d_p	KMT	–	15.556	–	–	16.528	–
	KG_{max} (intact)	14.261	14.042	0.219	14.624	14.662	−0.038
	KG_{max} ($A = 1.00R$)	12.706	12.612	0.094	13.632	13.641	−0.009
	KG_{max} (total)	12.706	12.612	0.094	13.632	13.641	−0.009
d_l	KMT	–	15.976	–	–	17.027	–
	KG_{max} (intact)	14.172	13.949	0.223	14.300	14.256	0.044
	KG_{max} ($A = 1.00R$)	13.700	13.719	−0.019	14.597	14.609	−0.012
	KG_{max} (total)	13.700	13.719	−0.019	14.300	14.256	0.044

7.2.4 Application Example

For a first illustration of the HOLISHIP developments, a realistic design example was chosen at the start of the project to serve as both a testbed and a showcase. An idealised route of 175 nm was selected which would, for instance, correspond to a ferry service between Piraeus (close to Athens) and Heraklion (on the island of Crete), in which a daytime trip would take about 6.5 h at 27 kn, while a return trip during the night would require around 8.3 h at 21 kn. Taking into account port time for manoeuvring, bunkering and loading, the round trip could be realised within 24 h. Such a vessel could serve also in many other sea routes connecting European ports, such as from Naples to Palermo (170 nm), from Genoa to Ajaccio (185 nm), from Marseille to Ajaccio (189 nm), or from Kiel to Gothenburg (230 nm).

The most important owner's requirements with regard to transport capacity are presented in Table 7.6. As the starting point of this study, a typical RoPAX ship, designed for short international voyages, was used. This design was initially developed by FINCANTIERI S.p.A. in the context of the EU project GOALDS to be used in an optimisation study aiming to explore the potential of cost-efficiently raising

Table 7.6 Owner's requirements

Number of passengers	≥2080	Lane length	≥1950 m
Passenger cabins	>300	Payload	≥3500 t

Table 7.7 Main characteristics of the baseline design

Length BP	162.85 m	Deadweight	5000 t
Breadth	27.6 m	Passengers	2080
Subdivision draught	7.10 m	Lane metres	1950 m

the safety level of passenger ships in damaged condition (Zaraphonitis et al. 2012). It is a twin-screw vessel with mechanical propulsion, featuring two diesel engines per shaft coupled to a gearbox with clutch couplings, fitted with three trailer decks, namely the main and upper trailer deck (deck 4 and deck 5) and a garage below the main deck (deck 1). The vessel's main characteristics are given in Table 7.7. Results from this study have been already presented or have been accepted for publication in a series of international conferences (Harries et al. 2017; Marzi et al. 2018a, b; Zaraphonitis et al. 2018).

Calculations for the RoPAX ferry, based on the owner's requirements and optimised with respect to building cost, lead to main dimensions close to those of the baseline. However, optimisation with respect to propulsion power (PD) resulted, not surprisingly, in a longer and more slender vessel. In Fig. 7.9, the optimal length between perpendiculars (L_{PP}) for minimum propulsion power, minimum building cost and minimum operational expenditures is presented as a function of design speed. The results apparently converge towards minimum length and, hence, the smallest vessel, for all speeds. Figure 7.10 shows optimal L_{PP} for minimum daily cost, combining operational cost and capital cost. Different operational profiles were considered, assuming different distributions of operational speed, with different percentages of operation at 21 and 27 kn. Results again show a higher length for higher speed. The range of the results is limited, and due to considering operational cost, it is above the value for optimisation of building cost. The example demonstrates that it is possible to get a first idea of main dimensions in a fast and effective way, as a starting point for further optimisations. Here, the point of view—shipyard, owner, operator, society—has an influence on the optimisation outcome.

7.3 Parametric Ship Design and Optimisation in the Pre-contract Stage

In the course of the HOLISHIP project, a series of parametric models for various types of ships, including RoPAX ships, double-ended ferries, OSVs, bulk carriers and containerships using appropriate Computer-Aided Ship Design (CASD) software tools

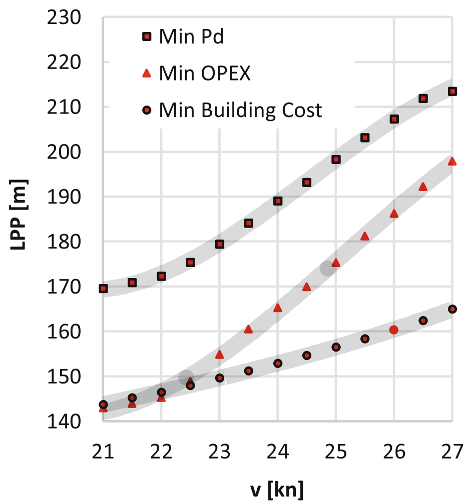

Fig. 7.9 Optimal length BP as function of speed for different objectives

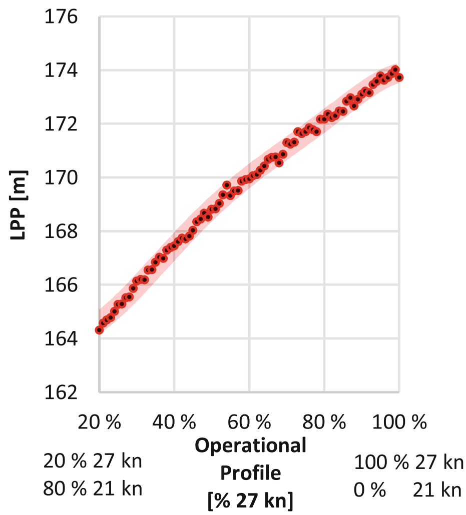

Fig. 7.10 Optimal length BP for minimum daily cost as function of operational profile

are under development or ready to use. Some of them are developed entirely in the CAESES software by Friendship Framework. In other cases, the hull form is created in CAESES and subsequently is transferred to NAPA, where the detailed parametric model of their internal arrangement is elaborated and a series of calculations are carried out. A series of software tools, enabling the assessment of each alternative design (e.g. potential flow or viscous flow solvers for the assessment of hydrodynamic performance of alternative hull forms, NAPA macros for the evaluation of compliance with intact and damaged stability requirements), are already integrated with CAESES. Other types of tools for the assessment and optimisation of the steel structure, for the modelling and simulation of machinery, equipment and control systems, or for the life cycle assessment of a ship are currently under development and will be integrated with CAESES in the course of the project. The development of parametric models in CAESES and NAPA and the integration of the required assessment tools will provide the designer with a powerful design platform, enabling the elaboration and evaluation of a large number of designs with minimum effort. More importantly, such a design platform is inherently suitable to be used in the framework of an optimisation campaign, aiming to identify the most promising design solutions, subject to selected design objectives and constraints. As a matter of fact, one of the more important advantages of using CAESES in the present studies, apart from a large series of powerful tools for the parametric modelling of complex geometries and the ease of integration of external software codes, is the multitude of optimisation algorithms offered, enabling the development of fully integrated parametric design and optimisation platforms, each one specifically adopted for the corresponding ship type and size at hand and the design stage considered.

The medium-size RoPAX vessel used in the present study should have a transport capacity of approximately 2000 passengers and 2000 m lanes length for the carriage of trailers. The main characteristics of this vessel are listed in Table 7.7. In the following, the design platform developed and applied for the optimisation of a ship with the above transport capacity, according to a prescribed operational scenario, will be outlined and selected optimisation results will be presented.

7.3.1 Parametric Modelling of Hull Form and Watertight Subdivision

A parametric model for the hull form of typical twin-screw, single-skeg RoPAX ships has been developed in CAESES by Friendship Systems and was made available for use by the HOLISHIP partners. The size and the hull form details of each design are controlled by a series of design parameters, enabling the user to specify among others:

- The ship's main characteristics (length BP, beam, design draught, depth);
- The block coefficient (C_B) and the midship section coefficient (C_M) at design draught and the corresponding longitudinal centre of buoyancy (LCB);
- The length of entrance and run;
- Local hull form details, e.g. the size and shape of the bulbous bow, the shape of the ship's stern (height and shape of transom) and the details of the skeg.

A typical example of a hull form created by the above parametric model is presented in Fig. 7.11. The hull serves as input to a series of software tools, which have been already integrated with CAESES and are used for the assessment of each design alternative. As already mentioned, the detailed definition of the ship's watertight subdivision is carried out in NAPA, using a series of specifically developed macros. The hull is exported from CAESES in the form of an IGES file, which is then imported in NAPA. As an alternative means of transferring the geometry, the definition of a

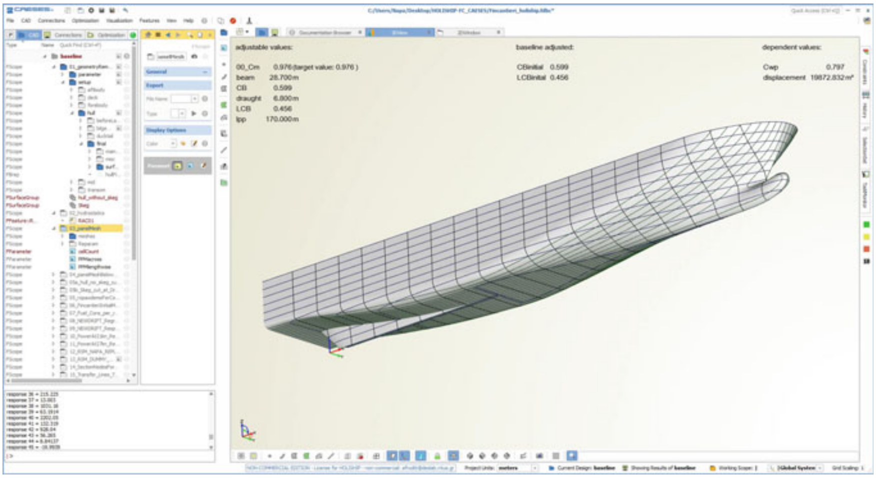

Fig. 7.11 Screenshot of the parametric model for the hull form

series of curves can also be extracted from CAESES, to be used as input for the elaboration of a NAPA hull, accurately resembling the original geometry developed in CAESES. The parametric model for the watertight subdivision is developed on the basis of a detailed NAPA model of the baseline design, already available from the GOALDS project (Zaraphonitis et al. 2012). This model was parameterized by NTUA, so that it automatically adjusts when the main particulars of the hull (length, beam, draft, block coefficient prismatic coefficient, length of entrance and run) or any shape details are modified.

The parametric model enables the user (or the optimisation algorithm) to control the position of the main transverse bulkheads and consequently the length of watertight zones, to specify the deck heights, or to uniformly increase or decrease the distance of longitudinal bulkheads, tanks and other compartments from the ship's centre-plane. However, in the current form of the parametric model, the topology of the watertight compartmentation remains unchanged. All watertight compartments up to deck 5, including all types and sizes of tanks, are automatically created and used for the development of the so-called Ship Model in NAPA. In addition, all openings and cross-connections are automatically created, to be used during the damaged stability calculations for each design alternative, according to the probabilistic principle (SOLAS 2009, as updated). The set-up drawing of the watertight subdivision of a typical design alternative, created by the parametric model in NAPA, is illustrated in Fig. 7.12. As soon as the definition of the three car decks is completed, their transport capacity in terms of lanes length and the maximum number of transported trailers is calculated by a specifically developed NAPA macro. Then, a series of loading conditions are automatically created, providing the basis for the intact and damaged stability calculations.

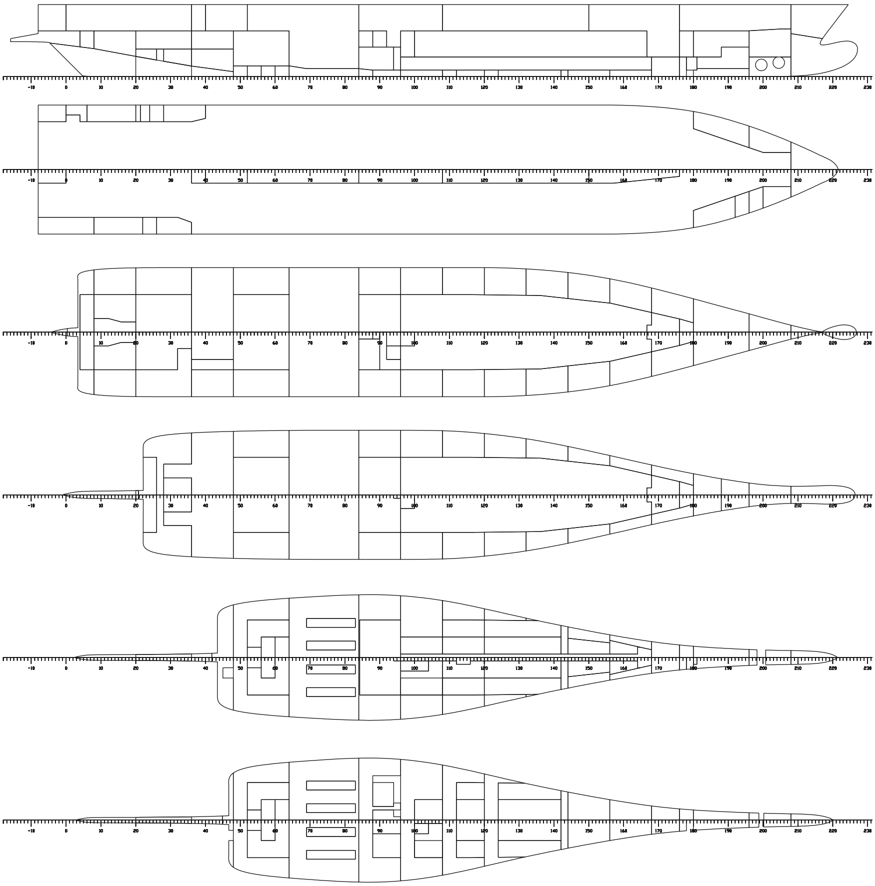

Fig. 7.12 Watertight subdivision of a design alternative, created by the corresponding parametric model in NAPA

7.3.2 Assessment Tools

The aim of the HOLISHIP project is to develop, extend and refine a sequence of software tools of adequate complexity and precision, enabling the evaluation of each design alternative in every important aspect. Some of these tools are developed for use in the concept design stage, while others are suitable for the contract design. The development and integration within CAESES of several of these tools have been already completed. Since, however, the project is still in a comparatively early stage of its elaboration, other tools are still under development.

Already available and coupled with CAESES are a series of hydrodynamic tools, both potential and viscous flow solvers. These tools can be readily used for the calculation of calm water resistance and propulsion power of the bare hull or the appended ship, the evaluation of responses of the ship in a seaway and of its added resistance. For the calm water analysis, the results presented herein are based on a combination of HSVA's in-house tools, i.e. the panel code for wave resistance ν-Shallo and the RANSE code FreSCo+ (Gatchell et al. 2000; Hafermann 2007). For the prediction of added resistance in waves, NTUA's NEWDRIFT+ code is employed. This is a three-dimensional panel code based on Green's functions to evaluate the velocity potential and eventually motions, wave loads and mean second-order forces in the frequency domain. The code is a further development of the original NEWDRIFT code by adding software tools for the calculation of added resistance in waves based on the far-field method, with empirical corrections for the short waves regime (Liu and Papanikolaou 2016). In addition, a series of NAPA macros is already available for the assessment of intact and damaged stability. Intact stability assessment is based on the requirements specified by the IMO Intact Stability Code (2008), while for the damaged stability the requirements of SOLAS 2009, as amended, and those of the Stockholm Agreement are applied. The integration of these tools in the design platform is described in more detail in Harries et al. (2017) and Marzi et al. (2018a).

On the other hand, a series of software tools for the structural analysis of the ship, the modelling and simulation of the installed propulsion plant and auxiliary machinery and the lifetime assessment of each design alternative are still under development. Until these tools are available, simpler tools, specifically developed for the Application Case presented here are used, aiming to close the design loop and to enable the demonstration of the potential of the adopted design procedure and of the developed optimisation platform. Simplified procedures, proposed by FINCANTIERI during the elaboration of the GOALDS project, are used for the estimation of the resulting variations of the lightship weight, the weight centroid and building cost of each design alternative in comparison with the baseline design. For the evaluation of the economic potential of each design alternative, the difference of its NPV in comparison with the baseline design is calculated. All these simplified calculations are performed by specifically developed NAPA macros.

7.3.3 Surrogate Models

Several of the above-described assessment tools require considerable computer resources. For example, only for the calculation of the Attained Subdivision Index of a ship with the size and complexity of the one studied here, approximately 40 min would be required on a typical workstation (20 min if the calculations are limited to one side only). To save time and speed up calculations during optimisation, CAESES provides methods to pre-compute data for later usage. Based on these pre-computed results, surrogate models are developed, enabling the sufficiently accurate estimation of the quantities of interest in practically zero computing time. Apart from dramatically reducing the required calculation time, the use of surrogate models increases considerably the robustness of the whole process and at the same time resolves possible IPR issues by avoiding the need of remote computing in the (quite usual) case

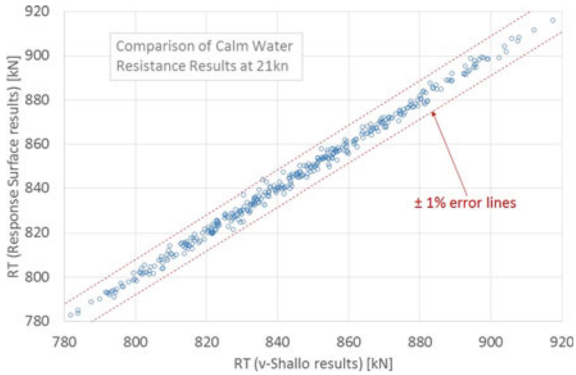

Fig. 7.13 Comparison of calm water resistance predictions at 21 kn

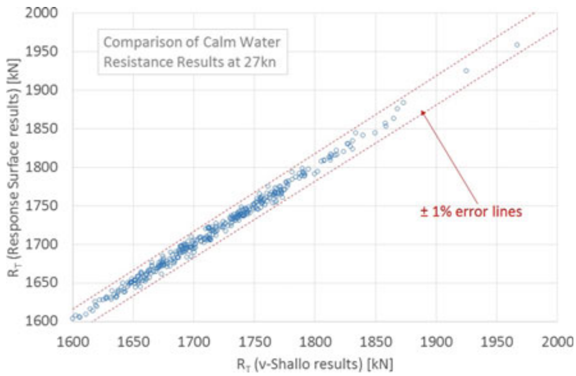

Fig. 7.14 Comparison of calm water resistance predictions at 27 kn

that all software tools are not available on the same computer, or even by the same partner.

For the optimisation studies presented herein, three different types of surrogate models have been used. The first one is used for the evaluation of the calm water resistance and subsequently of the required propulsion power. To this end, systematic calculations were carried out in HSVA using ν-Shallo, both at 21 and 27 kn, for a series of hull forms developed by the parametric model in CAESES. These hull forms were obtained by performing a Design of Experiment (DoE), varying selected design variables within a specified range of variation. Selected cases have been tested using FreSCo+, and the obtained results were used in order to calibrate the potential flow predictions. Based on the obtained results, response surfaces were developed in CAESES for the prediction of total resistance in calm water. Comparisons of the results obtained by these response surfaces with the results of the CFD codes are illustrated in Fig. 7.13 (at a speed of 21 kn) and in Fig. 7.14 (at 27 kn). As may be observed from these figures, the estimations obtained by the response surfaces are in a very good correlation with the CFD results, with their difference being less than $\pm 1\%$ in all cases.

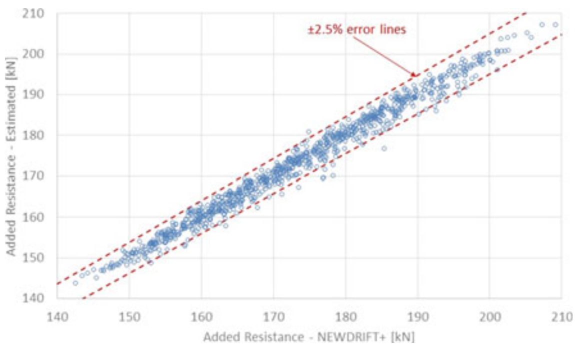

Fig. 7.15 Comparison of added resistance in head seas at 27 kn calculated by NEWDRIFT+ and estimated by a response surface

Surrogate models were also used for the prediction of added resistance in waves. In this case, systematic calculations were carried out in NTUA using NEWDRIFT+ for a JONSWAP spectrum with $h_S = 3$ m and $T_P = 7$ s (head seas). Again, a series of hull forms were developed by the parametric model in CAESES using the same design variables within the same range of variation as for the calm water resistance calculations. The obtained results were used to create a response surface in CAESES, as well as a linear regression in MATLAB. A comparison of the estimations obtained by the response surface and those obtained by NEWDRIFT+ is presented in Fig. 7.15. As may be observed from this figure, the estimations obtained by the response surface are in a very good correlation with the CFD results, with their difference being less than $\pm 2.5\%$ in almost all cases. A similar conclusion was derived from the comparison of the results obtained by the linear regression.

Finally, nonlinear regression was used to provide an estimation for the Attained Subdivision Index of each design alternative. Since damaged stability assessment according to the probabilistic concept is quite time-consuming, in order to speed up calculations during an optimisation campaign, the integrated models developed in CAESES and NAPA were used to carry out a series of preparatory calculations, to provide adequate data for the development of surrogate models for fast yet reasonably accurate estimation of the A-Index and the corresponding partial A-Indices at the three draughts specified by SOLAS 2009 (subdivision, partial and light service draught). A comparison of the actual A-Index calculated according to SOLAS 2009, as amended, and the estimated A-Index obtained using the response model is presented in Fig. 7.16.

7.3.4 Formulation of a Sample Optimisation Problem

Starting with the baseline design and the results of the concept design optimisation, an optimisation study was carried out to identify optimal RoPAX designs, fulfilling the owner's requirements and the specified constraints. More specifically, the objective of this study was to identify the optimum combination of main particulars (length BP,

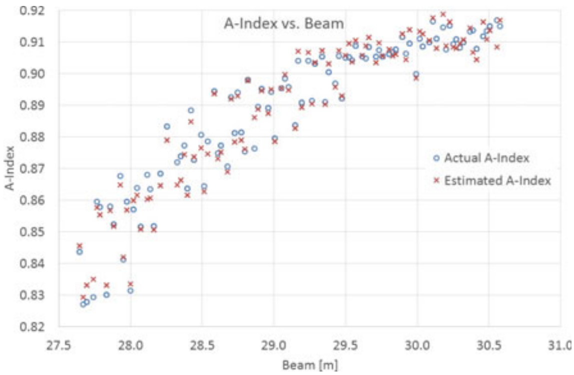

Fig. 7.16 Actual and estimated *A*-Indices versus beam

beam and design draught), maximising the vessel's economic potential expressed by its NPV and at the same time minimising its environmental footprint.

Once again, a route of 175 nm was selected which would, for instance, correspond to a ferry service between Piraeus (close to Athens) and Heraklion (on the island of Crete). A daytime trip would take about 6.5 h at 27 kn while a return trip during the night would require around 8.3 h at 21 kn. The most important owner's requirements with regard to transport capacity are listed in Table 7.6. The ship will be operated year-round, considering a high season of seven weeks with seven round trips per week, a medium season of twenty-four weeks with five round trips per week and a low season of twenty-two weeks with three round trips per week resulting in 235 round trips per year. Appropriate occupancy rates for passengers, cars and trucks for each of these three periods have been assumed for the calculation of annual revenues. Since there are always limits in the demand for transport work, a gradual reduction of the occupancy rates for ships with larger transport capacity is assumed. For example, for a 10% (resp. 20% or more) increase of transport capacity in comparison with the baseline design, the assumed increase of annually transported passengers or vehicles is limited to 7.5% (resp. 10%).

An obvious choice for an appropriate optimisation criterion, reflecting the economic potential of a vessel, is the maximisation of its NPV for a selected operational scenario. However, pending the completion of the detailed Life cycle Analysis Tools currently under development in the HOLISHIP project and in view of the inherent uncertainty of financial data, NPV is herein replaced by a more tractable variant, herein denoted as Delta NPV, corresponding to the difference of the NPV of each design variant in comparison with the baseline design. An additional optimisation criterion was also introduced, aiming to minimise fuel consumption per round trip. It is acknowledged that the minimisation of fuel consumption is inherently related to the first objective (i.e. the maximisation of Delta NPV). However, it was decided to include this second objective in the optimisation to boost our search for designs of enhanced economic competitiveness and at the same time of minimal environmental footprint.

Table 7.8 Free variables and range of variation

Free variable	Lower bound	Baseline	Upper bound
Length BP (m)	155.0	162.0	170.0
Beam (m)	27.6	27.6	30.6
Design draught (m)	6.5	7.1	7.1

A series of constraints were introduced so as to identify feasible and infeasible designs. The most important constraint required compliance with the intact and damaged stability requirements specified by the IMO Intact Stability Code (2008) as well as with SOLAS 2009 Part B, Reg. 6 and 7, as amended by the IMO Resolution MSC.421(98). As a temporary safeguard against possible inaccuracies in the surrogate model for the damaged stability assessment and in the KG estimation, suitable safety margins were introduced: The intact stability requirements should be met with a GM margin of 0.20 m, meaning that the actual GM in all loading conditions tested ought to be greater by at least 0.20 m than the one required by the intact stability criteria. For the A-Index and the three partial indices, a safety margin of 0.02 was introduced; i.e. all feasible designs need to meet the following inequality constraints:

$$A - R \geq 0.02 \tag{7.22}$$

$$A_i - 0.9R \geq 0.02 \tag{7.23}$$

where A_i is the partial A-Index at subdivision, partial and light service draught. Additional constraints were introduced to ensure adequate transport capacity in terms of lane length and DWT for each feasible design variant. It should be stressed at this point that the baseline design was developed in 2012 according to the SOLAS 2009 regulations, which were in force at that time. In the meanwhile, important revisions of the regulatory requirement, significantly increasing the level of safety of RoPAX ships in damaged condition, have been adopted by IMO. Any new design should comply with the considerably more stringent damage stability requirements introduced by the IMO Resolution MSC.421(98), adopted in June 2017. It was therefore anticipated that although sharing the same topology with the baseline, the outcome of the optimisation should be a significantly different design. In other words, the baseline, although being a valid RoPAX ferry when developed several years ago, would now have to be considered an infeasible design and, consequently, the design space was extended towards vessels of wider beam as can be seen in Table 7.8.

As discussed in previous sections, resource-intensive simulations were first performed upfront (and at different sites) and afterwards replaced by dedicated surrogate models. Using these fast yet sufficiently accurate surrogate models, approximately 200 designs could be studied per hour on a standard desktop computer. For comparison, about one hour per design variant would have been needed if the simulations had to be performed using CFD tools for the hydrodynamic assessment and NAPA for damaged stability calculations.

7.3.5 Results and Discussion

Utilising the established synthesis model, the optimisation was conducted in two stages: first, a design space exploration was undertaken in which 500 variants were generated within CAESES by means of a Design of Experiment (Sobol). The hull forms were transferred to NAPA in order to create their watertight subdivisions, and afterwards, they were evaluated using the tools and procedures described above. Subsequently, a multi-disciplinary and multi-objective optimisation was carried out in which, as mentioned already, the Delta NPV of the design alternatives was to be maximised while the fuel consumption per round trip was to be minimised. The genetic algorithm Non-dominated Sorting GA II (NSGA II), available within CAESES, was used, resulting in 1130 feasible and 799 infeasible designs.

Selected results are presented in the following in a series of scatter diagrams (for more clarity, only feasible designs are shown). Figures 7.17 and 7.18 present scatter diagrams of the NPV difference of each alternative design in comparison with the baseline (denoted as Delta NPV) versus the ship's length BP and beam, respectively. It should be reminded at this point that the baseline design is infeasible, since it fails to comply with the new damaged stability requirements. These diagrams indicate that Delta NPV generally increases with length BP and decreases with beam. This is due to the impact of length and beam variations on the propulsion power, and eventually on the fuel consumption. A constraint was introduced in this study, according to which all feasible designs should have positive Delta NPV. Because of this constraint, as shown in Fig. 7.17, all feasible designs have a length BP above 167.8 m. The A-Index margin (i.e. the difference between the Attained and Required Subdivision Indices) is plotted in Fig. 7.19 as a function of beam. All feasible designs have a significantly increased beam (at least 1.1 m larger than that of the baseline). Not surprisingly, this is due to the new damaged stability requirement (which the baseline had not had to comply with). A diagram of the A-Index versus beam is presented in Fig. 7.20. In order to provide more insight into the impact of beam on damaged survivability, both feasible and infeasible designs are included in this figure. The feasible designs are marked by full blue circles and can be clearly seen surrounded by a 'cloud' of infeasible designs. The diagram in Fig. 7.21 presents the relationship between DWT and the fuel used for the vessel's propulsion per round trip, excluding any other fuel consumption either at sea or in the port. Scatter diagrams illustrating the relationship between Delta NPV and fuel consumption for propulsion per round trip, DWT and CAPEX (i.e. the corresponding increase of building cost in comparison with the baseline) are presented in Figs. 7.22, 7.23 and 7.24.

The most promising design, selected for further study, was the one maximising Delta NPV. This design has a length between perpendiculars of 170 m, which is the maximum length considered, a beam of 28.7 m, i.e. the minimum beam for which the damaged stability requirement was fulfilled, and a design draught of 6.8 m. Its propulsion power at 21 kts and at 27 kts is equal to 14.7 and 40.3 MW, respectively, and its NPV and building cost are increased by 2.964 m€ and 8.814 m€, respectively, in comparison with the baseline.

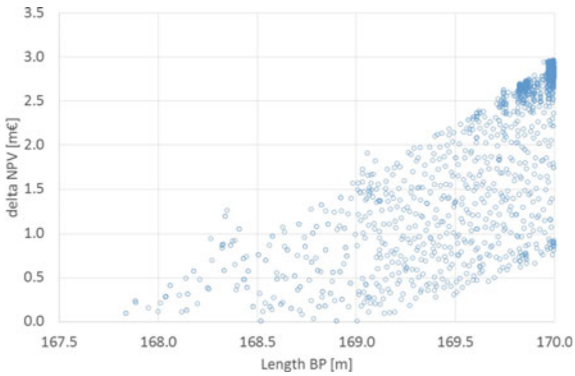

Fig. 7.17 Delta net present value versus length BP

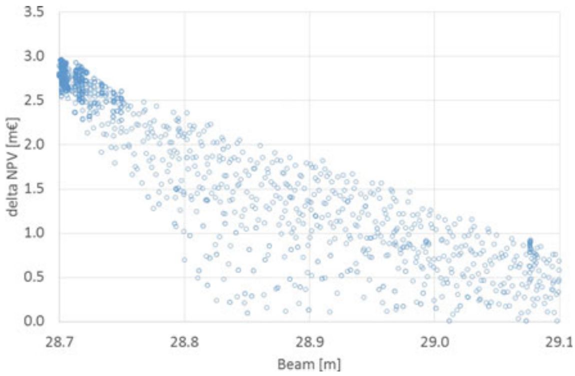

Fig. 7.18 Delta net present value versus beam

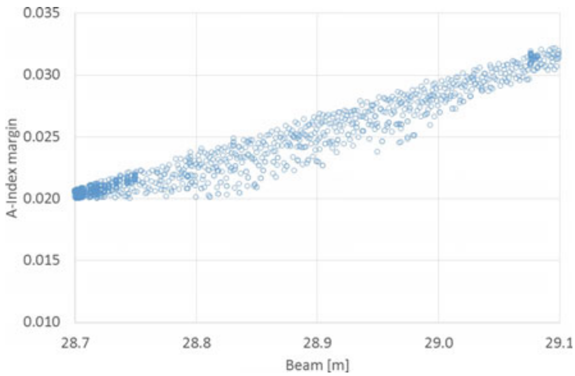

Fig. 7.19 A-Index margin versus beam

This design has been re-assessed by the panel codes ν-Shallo and NEWDRIFT+ for the calm water resistance and added resistance in waves and NAPA for the probabilistic damaged stability, and the results were compared with the predictions obtained by the surrogate models. The error in the results of the surrogate models for the total resistance in comparison with those obtained by the CFD tools

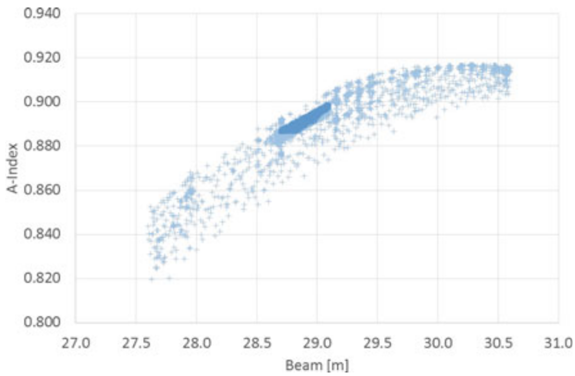

Fig. 7.20 A-Index versus beam

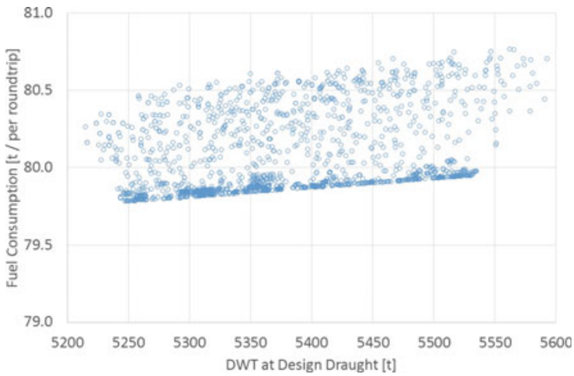

Fig. 7.21 Fuel consumption/round trip (only for propulsion) versus DWT

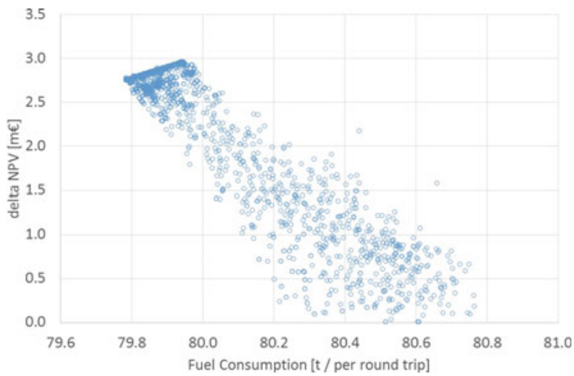

Fig. 7.22 Delta NPV versus fuel consumption/round trip

is −0.64% at 21 kn and 2.6% at 27 kn (see Fig. 7.25). The calculated Attained Subdivision Index is equal to 0.88078, which is 0.64% lower than the approximated value (0.8865). The Required Subdivision Index is equal to 0.86637, allowing for a reasonable safety margin.

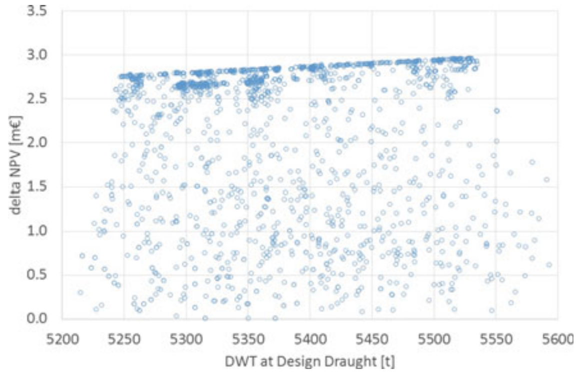

Fig. 7.23 Delta NPV versus DWT

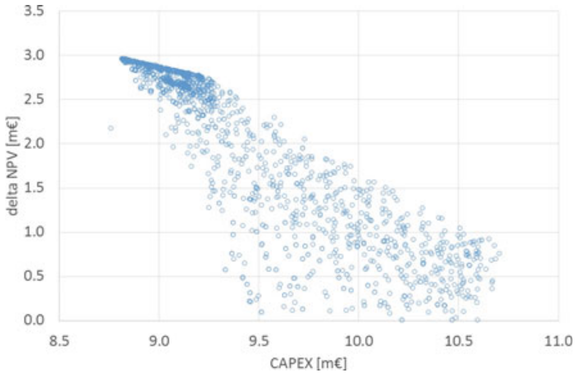

Fig. 7.24 Delta NPV versus CAPEX

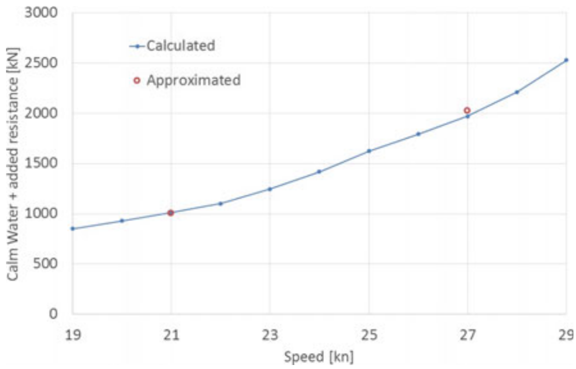

Fig. 7.25 Comparison of total resistance obtained by CFD tools and surrogate models for the optimum design

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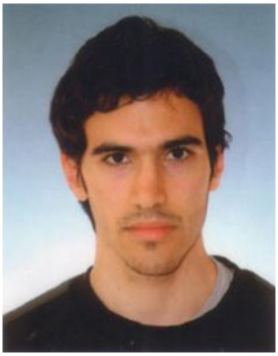

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Gregor Schellenberger studied Naval Architecture and Ocean Engineering at the Technical University of Hamburg-Harburg (Dipl.-Ing.) and at the University of Michigan (MSE). After graduation, he worked for more than 10 years in the ship theory and project department of Nordseewerke, Emden (later ThyssenKrupp Marine Systems). In his position as a team leader, he was responsible for the design of civil and military projects, mainly special craft (SWATH, OPV, LPD). In 2011, he joined the University of Applied Sciences Bremen as a professor for ship hydrostatics, stability and design of special craft. Since then, he has been involved in several smaller projects, mostly in close cooperation with maritime industry.

Chapter 8
CAESES—The HOLISHIP Platform for Process Integration and Design Optimization

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Contents

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Abstract This chapter focuses on the approach taken within the European R&D project HOLISHIP to flexibly integrate and utilize software tools and systems of tools for the design, analysis, and optimization of maritime assets, primarily of ships. The tools and systems come from different developers, companies, and research institutes and, consequently, have been mostly used as stand-alone applications. The purpose of integration is to create (software) synthesis models that comprise many, if not all, key aspects that ought to be considered when working on a specific ship design task. Rather than proposing an all-encompassing single (monolithic) design system in a top-down approach, the idea pursued within HOLISHIP is to support bottom-up approaches, namely the ad hoc assembly of dedicated models that are fit for a specific purpose under the umbrella of a state-of-the-art computer-aided engineering (CAE) system, namely CAESES®. This CAE system will be elaborated in the present book chapter. The approach of tool integration will be discussed, and it will be shown how to replace time-consuming simulations by means of surrogate models. Examples taken from the design and optimization of a RoPAX ferry and of an offshore supply vessel will be given for illustration.

Keywords Process integration and design optimization (PIDO)
Computer-aided engineering (CAE) · Simulation-driven design (SDD)
Synthesis model · Surrogate model · Parametric model · Tool coupling

8.1 Introduction and Motivation

Design and optimization are closely connected. As soon as a team of engineers has realized a feasible design, i.e., something that works and fulfills all requirements, somebody starts thinking of how to come up with an improvement. Improvements are looked for because of competitive markets but also because people inherently strive to do things better (Nowacki in Birk and Harries 2003).

Maritime assets such as ships and offshore structures are very complex systems that operate in harsh environments. They are run by people, they shelter people, and they are meant to serve people. Consequently, many systems, sub-systems, and components need to be brought together in order to reach a design that is uncompromisingly safe, economically attractive, and environmentally friendly.

Most systems and sub-systems are very closely connected and typically need to be in a state of balance. The single most important (and most obvious) balance for a floating object is that its overall weight may not be larger than the weight of the water it displaces at its desired draft. Another balance needs to be established between the propulsion system, including engines and power supply, and the energy it takes to operate the asset in all possible scenarios.

Due to the complexity of maritime assets, a great deal of experience is called for, and still many analyses are typically made one after another as idealized via the classical design spiral: A team of designers and engineers makes reasonable assumptions, undertakes analyses based on them, and subsequently corrects and refines the design. This is repeated until a single design or a small set of potential designs has been found, essentially constituting a sequential and iterative process. Since expert knowledge may not be internally available for all disciplines, external suppliers are regularly involved to support the design effort.

This traditional approach is particularly successful if an earlier project is at hand that is close to the new design task. It also leads toward substantial progress, at least incrementally and over time. For increasingly demanding and shifting markets, for completely new missions and for design challenges for which only little experience is (at least locally) available, however, this is often too slow and too cumbersome.

A different approach is therefore proposed in which many, if not all, important disciplines for designing a maritime asset are taken into account concurrently. This can only be achieved if many dedicated systems and tools for design, analysis, and simulation, as disparate as they may be, are closely combined to form an overarching computer-aided engineering (CAE) environment that

- holds, converts, and shares data
- controls interactions and logical dependencies, and
- supports the swift creation of variants both manually and automatically.

The European R&D project HOLISHIP sets out to establish such a CAE environment, the so-called HOLISHIP platform(s), by bringing together systems and tools as well as the expertise from different institutions and sites, typical of the many stakeholders in the maritime industry and their heterogeneous CAx solutions.

Instead of proposing an all-encompassing "super system," a rather moderate approach was taken, namely the flexible combination of legacy systems and tools as needed to solve a number of interesting application cases (AC) along with the possibility to add further tools quickly and efficiently, also beyond the original partners of the HOLISHIP consortium.

This chapter explains how process integration and design optimization are realized, what methods are provided, and how to benefit from the approach.[1]

[1]Naturally, it is hoped that this will add value to the creative and excellent design work that has been done over all the years since human beings have put to sea. In no way is the intention of this chapter to suggest that process integration and design optimization are the only ways to achieve further improvements.

8.2 Process Integration and Design Optimization

8.2.1 Overview

Quite a few commercial software systems for process integration and design optimization (PIDO) are available today. Typically, they are generic systems that provide several of the following techniques:

- Multi-tool integration
- Process automation
- Process capturing and reuse
- Design space exploration/design of experiments (DoE)
- Exploitation/deterministic and stochastic optimization
- Multi-objective and multi-disciplinary optimization (Pareto frontiers)
- Robust optimization and sensitivity analyses
- Visual data analytics
- Data mining
- Surrogate modeling
- Multi-fidelity and multi-physics modeling
- Simulation data management and
- Product life-cycle management

Walsh (2018) summarized the available systems under the general term of design space exploration. Several of the methods, for instance DoE and surrogate models, are considered by Bostrom (2014) to belong to the wider field of artificial intelligence (AI). One overarching theme of PIDO is that of enabling the efficient generation and systematic assessment of large sets of prototypes as discussed by Schrage (2000).

For the integration of systems and tools within HOLISHIP, CAESES® was chosen. This is because CAESES® offers, in addition to many of the PIDO techniques specified above, a comprehensive computer-aided design (CAD) package with which to model but also to convert geometry as needed to feed the various analysis and simulation systems. In this sense, CAESES® is a computer-aided engineering (CAE) environment that tightly combines PIDO and CAD.

8.2.2 Background

CAESES® has been developed and licensed by FRIENDSHIP SYSTEMS AG with its headquarter in Berlin/Potsdam, Germany. The company is a spin-off from the Technical University of Berlin, established in 2001, and provides systems and consultancy for simulation-driven design (SDD).

Ideas of CAESES®, particularly with respect to parametric modeling of hull forms, go back to R&D projects undertaken in the 1990s (Harries 1998), but the actual code has been developed from scratch, starting in 2004. A first release of CAESES® was launched in 2007 (then named *FRIENDSHIP-Framework*). The description and the screenshots given here are based on CAESES 4.3 as released in 2018.

CAESES 4.3 comprises around 1,000,000 lines of written and more than 6,000,000 lines of generated code. It is mainly developed in C++, uses Qt for its cross-platform GUI (www.qt.io), combines a legacy CAD kernel by FRIENDSHIP SYSTEMS with several commercial CAD kernels, most notably the SMlib by Solid Modeling Solutions (www.smlib.com), links with DAKOTA by Sandia National Laboratories (dakota.sandia.gov) as an optimization kit and, furthermore, incorporates more than 20 open-source libraries. CAESES® can be run on both Windows® or Linux™. Furthermore, it allows the execution of software located remotely and in cross-platform environments.

8.2.3 *Overview of Intrinsic CAESES Functionality*

CAESES® takes a different approach than other PIDO environments. It not only provides various coupling mechanisms and a wide range of optimization strategies but also offers parametric CAD for robust models of variable geometry. The overall functionality is summarized in Fig. 8.1 (green boxes with blue components).

Originally, CAESES® was developed for the simulation-driven design of functional shapes that serve a fluid-dynamics purpose such as hull forms, propellers and energy-saving devices for ships as well as impellers, volutes, diffusers and manifolds for turbomachinery, and combustion engines. In a typical design and optimization

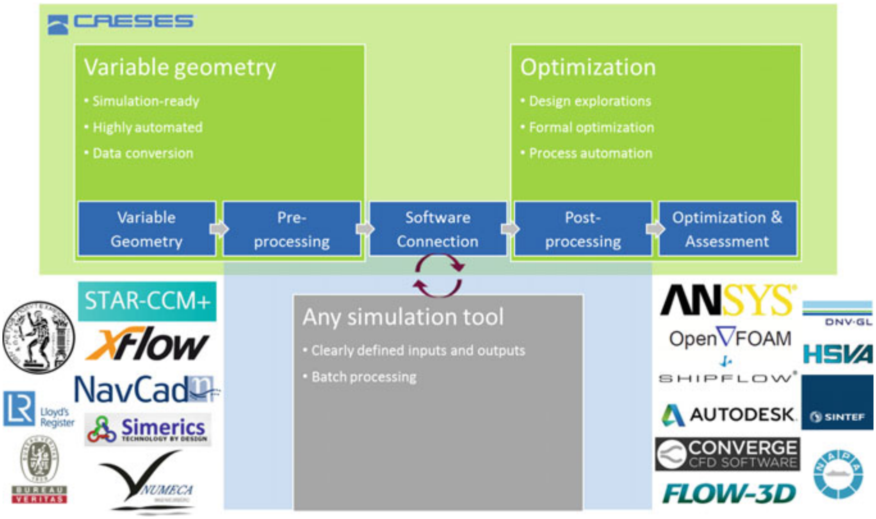


Fig. 8.1 Overview of CAESES® functionality along with a selection of software systems frequently coupled and providers of tools and systems from the HOLISHIP consortium

process, several components (the so-called big five of CAESES® as shown in Fig. 8.1) are brought together:

1. Variable geometry: A parametric model is developed, and a shape variant is created as an instance of the chosen parameter set.
2. Pre-processing: The variant is pre-processed to enable the simulation(s) to take place.
3. Simulation(s): For all variants of interest, one or several simulations are undertaken.
4. Post-processing: Variants and their data are post-processed (e.g., visualizing flow fields for comparison).
5. Optimization and assessment: Variants are produced and assessed in accordance to the selected optimization strategy (e.g., Sobol, MOGA), repeating the sequence from variable geometry to post-processing again and again.

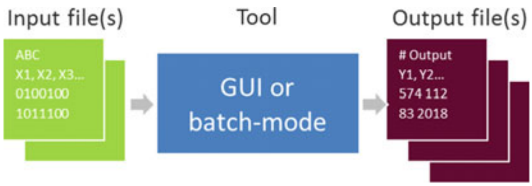
With its various CAD kernels, CAESES® provides both boundary representation (BRep) and constructive solid geometry (CSG) techniques as needed to build sophisticated parametric models (Harries et al. 2015a). This also supports the conversion of geometric data from one format to another, feeding different tools with their required inputs. CAESES' heritage being simulation-driven design on the basis of computational fluid dynamics (CFD), the system also allows the generation of watertight tri-meshes as needed for grid generators, see Harries (2014) for an overview and Albert et al. (2016) for a detailed example.

Finally, CAESES® offers a comprehensive feature technology to script additional analyses, for instance, a comparison of required versus attained EEDI, and to encapsulate higher-level objects, for instance, a Wageningen B-series propeller as elaborated in Harries et al. (2018). Features can access all objects available within CAESES®. They are interpreted code and can be reused, but also adapted, in different projects. Features can contain (internal) optimizations and even be nested. For convenient feature development, CAESES® allows both the interactive creation from chosen (geometric) models and writing code line by line while offering compiler functionality such as auto-completion of entities, error checks, and break points.

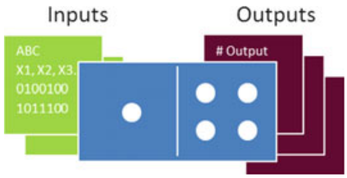
8.2.4 Integration Approach Taken in HOLISHIP on the Basis of CAESES

Practically all tools for analysis and simulation can be run in batch mode. Often they support setting up calculations interactively within a dedicated graphical user interface (GUI). Typically, all input data needed are either readily stored or can be recorded in a set of input files, commonly comprising configurations and geometry. While the actual calculations take place and/or when they are finished, both intermediate and final results are stored in one or several output files.

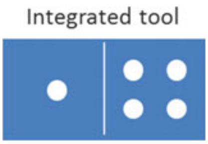
Usually, these calculations can be repeated subsequently by running the tool in batch mode. Using the same input data, the very same output data are generated.



(A) Standard tool execution: Tool is run interactively (GUI) or in batch-mode



(B) Tool can be run in batch-mode on the basis of interactive work (e.g. using recorded input)



(C) Integrated tool with input file(s) and output files(s) encapsulated (i.e., inputs and outputs are taken care of by CAESES®)

Fig. 8.2 Tool wrapping via its input and output files in CAESES®

However, if the input data are changed, for instance by providing a new geometry to be analyzed, different output data are produced. The input and output of data along with their encapsulation are shown in Fig. 8.2.

Within CAESES®, every tool that can be executed in batch mode can be readily coupled via its inputs and outputs. Any data item in the input file(s) can be tagged and, if wanted, replaced with a different value. Alternatively, a file can be replaced completely with a new version. This is often done for geometry files since very many data items change, e.g., all vertex positions of a NURBS representation in an iges file. Furthermore, any data item in an output file can be identified and read for further usage.

In order to establish the integration, all input file(s) and output file(s) are made known to CAESES®. They are used as templates, meaning that only a small number of data items are to be replaced and retrieved, respectively, while most data items are just kept as given, making the integrations light and flexible. Unaltered data items constitute input to and background information for the analysis and are considered constant for a particular design task. It should be noted that only those data items

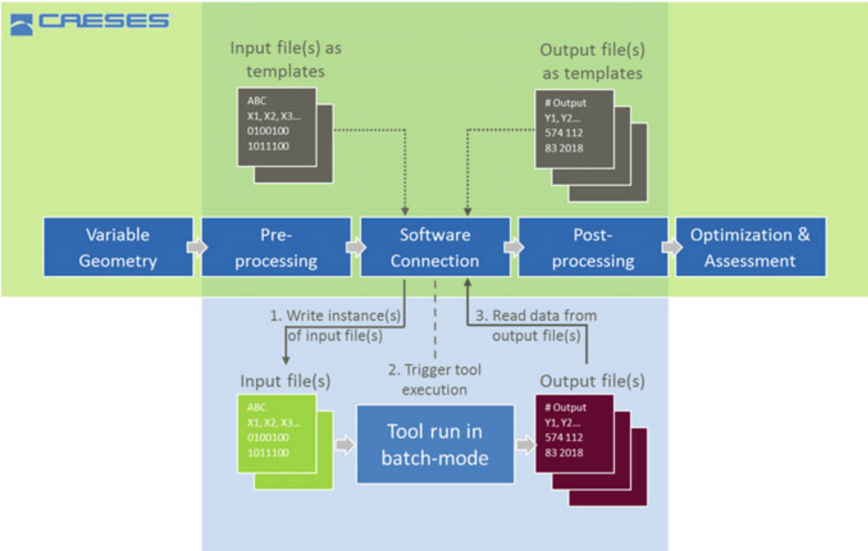


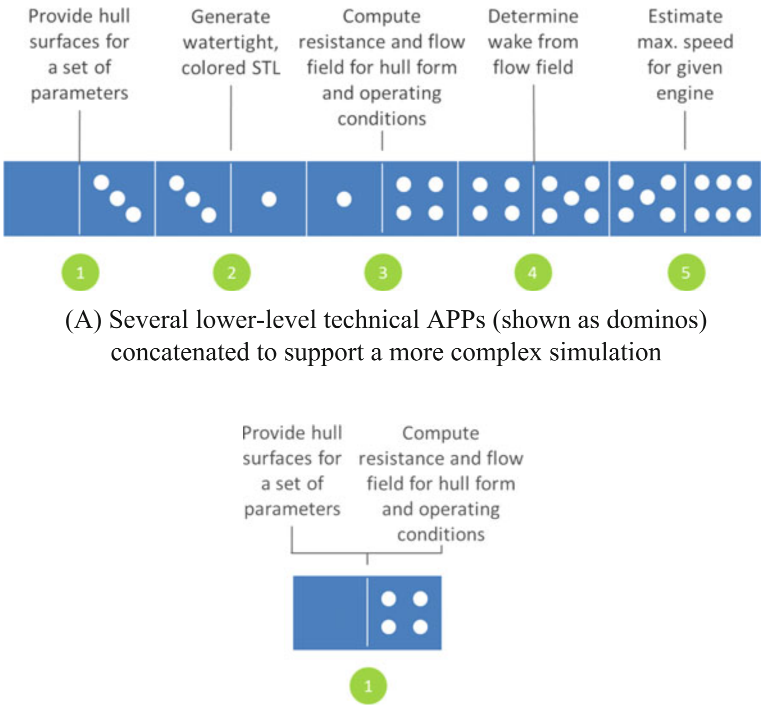
Fig. 8.3 Connecting tools within CAESES® via template files as part of a process chain

that shall be changed, that are needed for the design itself and/or that shall be passed on to another tool are managed. Figure 8.3 illustrates the usage of templates and the flow of data. See also Figs. 8.16a and Fig. 8.17 in Sect. 8.4 for data dependencies and data storage, respectively. Further details on how to set up a tool integration are given in Sect. 8.5.

8.2.5 *Encapsulating Tools*

Integrating a tool in CAESES® via templates is not a very difficult or lengthy undertaking. Nevertheless, it naturally requires knowledge of both CAESES® and the tool to be coupled. A team of designers and engineers may be very interested in utilizing certain tools within their design work but would probably want to leave the specifics of how to set them up and how to make them accessible to others. Consequently, encapsulating tools for easy handling will increase the community of happy users that benefit from the caring experts. In this sense, an encapsulating tool can be interpreted as a technical APP or “domino” as suggested in Fig. 8.2c.

Depending on the complexity of the task that is encapsulated, a single domino may either solve just a small task or concatenate several tasks in order to realize a bigger “job.” As an illustrating example, five dominos are shown in Fig. 8.4a which together shall provide an estimate of the speed attained for a given set of parameters that describe a hull form, an operational profile, and an engine. Clearly, every domino



(A) Several lower-level technical APPs (shown as dominos) concatenated to support a more complex simulation

(B) Higher-level technical APP combining parts of a complex simulation

Fig. 8.4 Technical APPs which wrap functionality for ease of use

in the sequence solves a small (sub) task. Several dominos, namely dominos 1–3 from Fig. 8.4a, could also be combined as depicted in Fig. 8.4b.

The provider of a domino (a technical APP) needs to compromise between ease of use and flexibility. Lower-level dominos may be more generic and can be further combined. Higher-level dominos may turn out to be more convenient if they offer the complete functionality as needed.

Furthermore, it is important to ask at what level a tool can or should be integrated. On one side of the spectrum, you can integrate a tool such that every possible command and workflow is supported within CAESES®. SHIPFLOW by Flowtech is a prominent example of such a tight integration, the actual GUI of SHIPFLOW being built on (a subset of) CAESES® (www.flowtech.se). On the other side of the spectrum, you can very loosely couple a tool if you only want to execute it for a clearly defined task, say, as part of a more comprehensive optimization. Somewhere in the middle of the spectrum are tool integrations that are task-specific yet generic enough so that a suitable range of analyses can be undertaken.

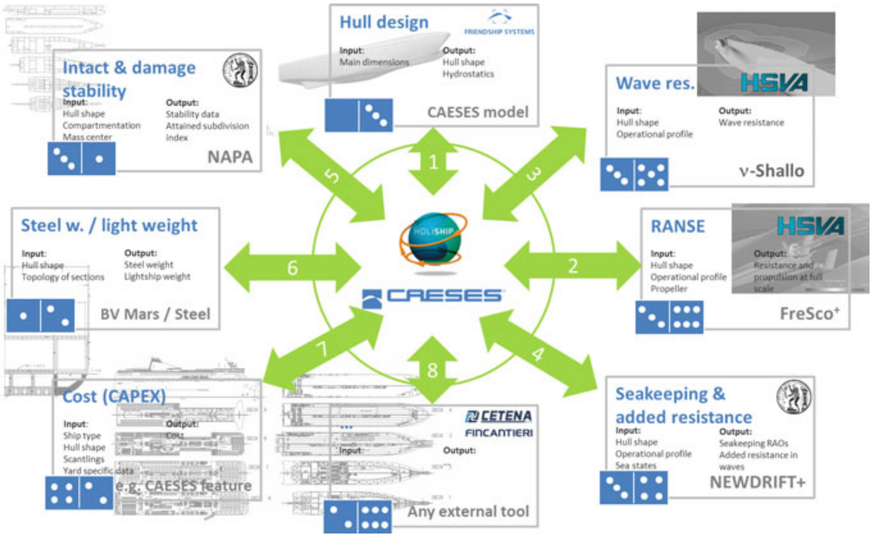


Fig. 8.5 HOLISHIP synthesis model based on CAESES® for the design and optimization of a RoPAX ferry

Within HOLISHIP, the integrations are chosen to be task-specific, see also Sect. 8.4. This is because any integration can start loosely and then grow step-by-step as the complexity demands. Very importantly, too, many tools are pretty powerful and are continuously developed further. Consequently, it would just not be practical to aim at an all-encompassing super system. Rather, the idea is to provide the functionality needed to address any new design challenge by bringing in additional tools and/or by extending the integration of tools that have already been coupled.

Figure 8.5 presents the synthesis model of a RoPAX ferry as an illustrating example of task-specific integrations, utilized for design and optimization (Harries et al. 2017). Several tools are combined so as to investigate the performance of the ferry with regard to resistance and propulsion, seakeeping, intact and damage stability along with estimates for weights, lane meters, costs, and the EEDI.

Specifically, the parametric CAD functionality within CAESES® is used to create a hull form (item 1 in Fig. 8.5). A watertight tri-mesh of the hull is then handed over to *FreSco*+ by HSVA for viscous flow simulation of the baseline (item 2), using an stl file. This is followed by potential flow analyses of calm-water resistance for a large set of variants with ν-Shallo by HSVA (item 3) for which CAESES® provides the discretized input via a dedicated panel file. Seakeeping behavior and added resistance in waves are then determined with NEWDRIFT+ by NTUA (item 4). Again, CAESES® delivers the necessary geometry input, here panels distributed up to the waterline written to a different panel file. For intact and damage stability, NAPA by NAPA Oy is run in batch mode (item 5). For this, CAESES® hands over the geometry of each variant as an iges file which NAPA imports and subsequently processes.

Additional analyses are made through external tools and features written within CAESES® that combine and/or post-process output from the various simulations (items 6 and 7). The extendibility of the synthesis model is illustrated by item 8.

In the synthesis model of Fig. 8.5, several dominos are shown, too. They serve to elucidate that various tools are combined at a certain level of abstraction, the number of points on either side of a domino giving an appreciation of input received and output delivered. Let us take the hull geometry from the parametric model as an example: The geometry is symbolized by three points, see also Fig. 8.4a. The geometry shows as output from the parametric model (item 1) and as input to the various simulation tools (items 2–4) even though different data and file formats are employed for the actual data transfer which is being taken care of by CAESES®. For geometry data that are used to feed the various tools, see also Fig. 8.18 in Sect. 8.4.

8.3 Variable Geometry

8.3.1 Geometric Modeling

In the design and optimization of maritime assets, geometry often plays a central role. Different to land-based facilities and plants, the geometry of ships and offshore platforms determines key performance aspects such as load-carrying capacity but also energy consumption, seakeeping behavior, comfort, and survivability. As a consequence, complex three-dimensionally curved shapes, featuring compound curvature, constitute the norm rather than the exception.

In principle, any CAD tool for geometric modeling that can be run in batch mode, even an instance of CAESES® itself, could be coupled to CAESES® so as to form part of the design synthesis model. However, since CAESES® already provides a comprehensive CAD functionality dedicated to the parametric modeling of hull forms, propulsors, appendages, etc., allowing the export of geometry data in both standard (e.g., iges , STEP files)[2] and tailored formats (e.g., panel and offset files), CAESES® can be utilized as both the platform for integration and the primary CAD engine.

For design and optimization, it is particularly important that geometry can be varied efficiently and at high quality. Efficiency relates to the effort needed to create a variant. Ideally, an update of geometry when producing a variant for design assessment takes only a few (split) seconds and not hours of manual work as would be the situation in a purely interactive modeling environment. High quality means

[2]The following standards are supported by CAESES®: Import formats: iges, iges (deprecated), SAT (ACIS), STEP, PARASOLID, stl, DXF (subset), Offsets (NAPA/SHIPFLOW), PFF (propeller free format); Export formats: iges, iges (deprecated), iges (STAR-CCM+), SAT (ACIS), STEP, STEP (STAR-CCM+), PARASOLID, TETIN, stl, stl (color), stl (multi body), stl (extract colors), stl (OpenFOAM), stl (STAR-CCM+), GridPro, Convergence, Wavefront (Obj), VTK Format, Offsets, Plot3D (panel mesh), PFF, GeomTurbo (NUMECA), DXF (subset), FSC (CAESES script).

that a small set of parameters already controls the geometry and that each variant produced is fair and potentially feasible so that any subsequent and time-consuming simulation becomes meaningful to launch.

There are two distinctive approaches which CAESES® supports both separately and in combination (yielding hybrid models):

- Fully parametric modeling (FPM) and
- Partially parametric modeling (PPM).

The former applies a hierarchical model built from scratch in which any variant constitutes an instance related to the chosen parameter values while the latter takes an existing CAD model and (only) modifies it parametrically.

The more powerful of the two approaches is fully parametric modeling since it may comprise and combine mathematical expressions, if-then clauses, cascading dependencies, all possible curve and surface entities, internal optimizations (e.g., to capture equality constraints), Boolean operations, etc. It is typically more demanding and time-consuming to build but can be applied at various stages, from early design to fine-tuning, by addressing different parameters within the same model. For example, at an early stage, the main dimensions may be subject to change. Later, as soon as the main dimensions are fixed, local parameters may be further adjusted, say parameters controlling the bulbous bow or the region around the propeller.

Partially parametric modeling is easier and faster to realize. An existing baseline, i.e., a CAD model that would often be called a “dead” geometry and that may stem from any CAD tool, is taken as a starting point. A number of transformations are subsequently imposed on the baseline, leading toward variants that feature new geometry for the initial topology. Scaling would be the most trivial yet very consequential PPM transformation. A prominent method with roots in animation and gaming is free-form deformation (FFD). In naval architecture, the Lackenby shift is a popular representative of PPM in which a concerted swinging of sections allows in- and decreasing as well as shifting of a vessel’s displacement volume. Partially parametric modifications can be confined to certain parts of the geometry, and, importantly, within CAESES® several transformations can be concatenated. Yet, the essence and topology of the baseline always remain.

A detailed discussion of both fully parametric and partially parametric modeling along with further references can be found in Harries et al. (2015a). For further reading, see Harries (2010) which covers the FPM of a mega-yacht and MacPherson et al. (2016) which discusses the PPM of a patrol craft.

In the sections to come, two examples taken from the HOLISHIP project shall serve to illustrate FPM and PPM, along with hybrid modeling, so as to gain an appreciation of their role in design synthesis.

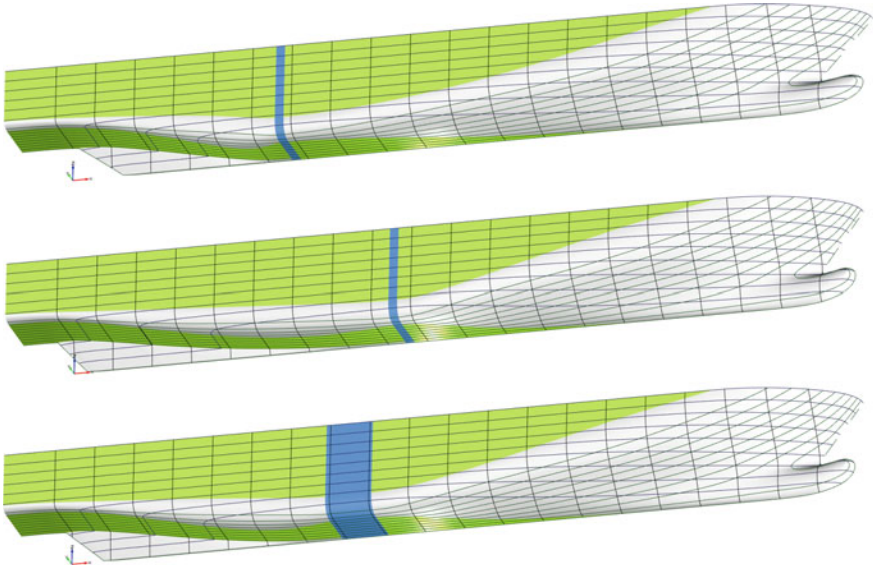


Fig. 8.6 Change in position and length of parallel mid-body

8.3.2 A RoPAX Ferry as an Example of Fully Parametric Modeling

A RoPAX ferry was used as a showcase for the integration of various tools as shown in Fig. 8.5 and discussed thoroughly in Harries et al. (2017) as well as in Marzi et al. (2018). A FPM was built within CAESES®, utilizing a design by Fincantieri as a reference.

The hull, stemming from a former R&D project, was made available as an iges file that contained numerous small surface patches. Instead of taking this CAD geometry as input to a PPM, a FPM was developed that followed the design idea without aiming at replicating the exact geometry.

To begin with, prominent shape characteristics were extracted from the initial design. All flat and developable surfaces were remodeled based on a dedicated CAESES® feature (as introduced in Sect. 8.2.3) that would identify the "rails" of such surfaces from the given hull. These curves were approximated using B-spline curves which were suitably parameterized. The main dimensions of the hull were introduced as global parameters, linking all control points to the overall size of the hull. Furthermore, relative measures were introduced so that any change in main dimensions yields a new shape that is still feasible and fair.

Figure 8.6 illustrates different shapes that stem from a variation of the relative position of the parallel mid-ship and its length. The ruled surfaces shown in green can be seen to follow the change of the parallel mid-body marked in blue.

While the ruled surfaces require only two parametric rails each, the remaining hull surfaces are somewhat more complex in shape. The bilge region in the aft body as well as the surfaces in the fore body, both shown in silver-gray in Fig. 8.6, are modeled using so-called Meta Surfaces.

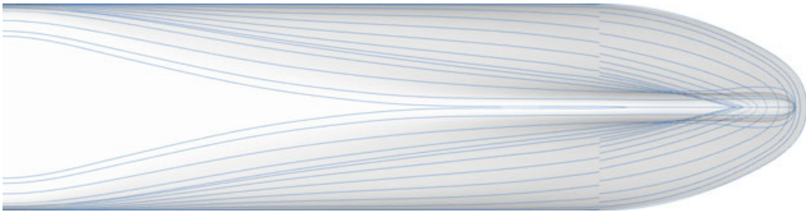
Meta Surfaces are powerful entities within CAESES®, specifically developed for the fully parametric modeling of three-dimensionally curved shapes. The idea of this type of surface is to sweep a certain building pattern, here a parametric section, along a dominant direction, here the hull's longitudinal axis. Importantly, the parameters that serve as input to the building pattern at each longitudinal position are not given as discrete values but are provided as parametrically controlled curves, too. This smoothly defines the gradual change as the section is swept, see also Harries et al. (2015a).

In the case of the RoPAX ferry, those (longitudinal) curves were again extracted from the given Fincantieri design, see Fig. 8.7a. Additional parameters were then introduced to achieve further variability to the model. Waterlines as derived from the Meta Surfaces are depicted in Fig. 8.7b, c for different parameter values. Differences in the resulting shapes can best be seen close to the flat-of-bottom.

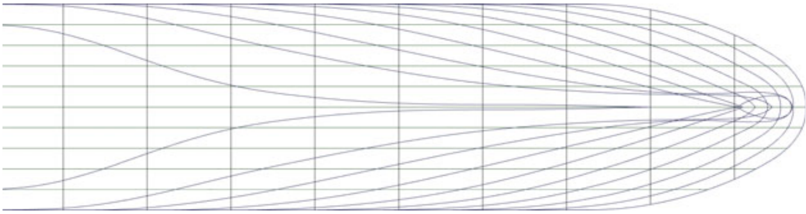
A substantial set of parameters make up the model in order to support a wide variety of global and local shape variations. Besides changing the main dimensions such as length, beam, height, design draft, position, and length of the parallel mid-body, it is also possible to modify shape details such as the bulbous bow's height, its length, volume, center of displacement, and inclination. Figure 8.8 shows a change of shape due to the modification of a single bulb parameter. Finally, a fully parametric skeg supports the setting of position, taper, etc., as illustrated in Fig. 8.9, while further parameters control the aft body.

The parametric rails of the ruled surfaces and the longitudinal curves used as input to the metasurfaces influence the hull shape directly while some parameters are not readily accessible yet that would typically be of interest to the naval architect. Primarily, that would be displacement volume and the longitudinal center of buoyancy. In principle, a sectional area curve could be utilized as input to the Meta Surface as shown by Harries (1998, 2010). Nevertheless, here a slightly more robust approach was taken: First, the "natural" hull shape that follows the rails and inputs to the Meta Surfaces is generated. Its associated displacement and center of buoyancy are then computed. If they do not meet the desired values, a Lackenby shift is undertaken, tweaking the hull shape to comply with the target displacement (or prismatic coefficient for given main dimensions) and center of buoyancy. Within CAESES® the Lackenby shift performs an internal optimization, actually hidden from the user, which ensures smooth transitions at either end when swinging the sections (Abt and Harries 2007b).

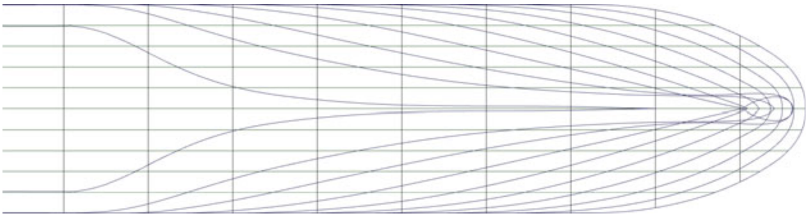
In addition, CAESES® allows further (nested) optimizations within a parametric model, purposely introduced by the user within a feature, in order to control certain parameters. For instance, in the RoPAX model at hand a one-dimensional search algorithm, here the so-called Brent, is employed to meet a given mid-ship coefficient. To this end, the bilge radius is used as an internal variable to attain the desired mid-ship coefficient while, within each iteration, the Lackenby shift is automatically



(A) Curves extracted from iges-file, serving as input to the Meta Surfaces



(B) Resulting surfaces with waterlines



(C) Resulting surfaces with waterlines for pronounced elongation of parallel mid-body

Fig. 8.7 Elements of a parametric model and resulting shapes

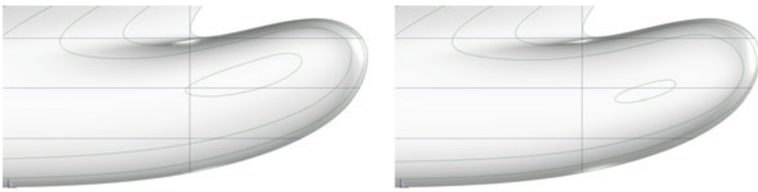


Fig. 8.8 Parametric modification of the center of displacement of the bulb

adjusted to ensure that the other settings are kept. Figure 8.10 depicts two hull forms for different mid-ship coefficients with all other parameters held constant.

The modeling techniques described above already constitute a very powerful FPM. Its user, be it a human being or an optimization algorithm, can address both global and local parameters with high efficacy. The direct control of global parameters allows the wide scanning of the design space (exploration) while local fine-tuning

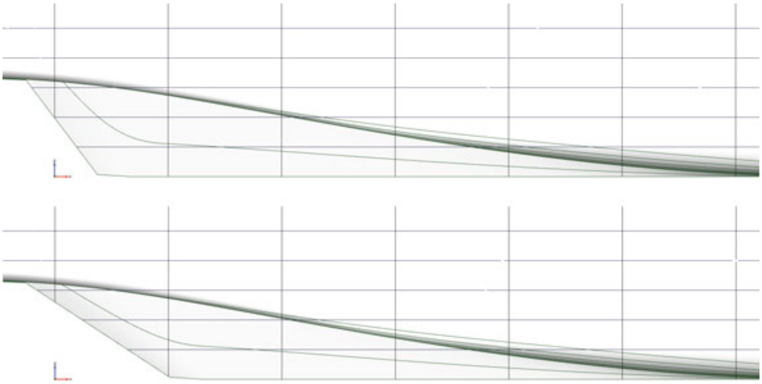
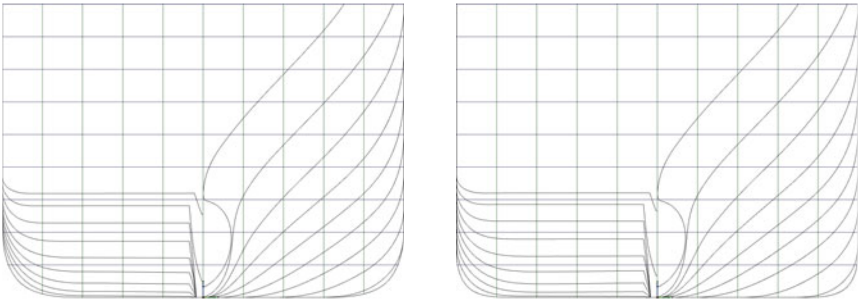


Fig. 8.9 Parametric modification of the skeg angle close to the transom



(A) Smaller mid-ship coefficient ($C_M = 0.965$), resulting in a larger bilge radius

(B) Larger mid-ship coefficient ($C_M = 0.985$), resulting in a smaller bilge radius

Fig. 8.10 Example of two different settings for the mid-ship coefficient with all other free variables kept constant

in critical areas such as the aft body and the bulbous bow are nicely supported, too (exploitation).

Finally, in the context of applying a parametric model within an automated optimization, it should be noted that the model may be built on dozens if not hundreds of parameters. Naturally, they are not all subject to change during a single optimization campaign. Rather, most parameters are set for a specific design task and then kept constant while only a few parameters, often not more than 10 to 20, are chosen for variation. These parameters are then treated as free variables, see also Sects. 8.4 and 8.6.

8.3.3 An OSV as an Example of Partially Parametric Modeling

PPM is often used in day-to-day work for quickly adapting a given geometry or conveniently investigating variants that do not deviate too much from an existing baseline. To this end, independent of the format in which a geometry has been imported (e.g., B-spline surfaces from an iges file or tri-meshes from an stl file), CAESES® offers a broad range of methods to evoke partially parametric changes to a geometry that was previously built within another CAD system (so-called dead geometry). The more prominent of the available PPM methods are

- Free-form deformation (FFD)
- Cartesian shifts
- Radial basis functions (RBF) and
- Morphing

For a detailed discussion of partially parametric modeling and further references, see Harries et al. (2015a).

In naval architecture typical modifications include scaling, change of both displacement and center of buoyancy as well as transformations confined to certain regions, for instance, modifying the bulbous bow to accommodate alterations in the operating profile. Within CAESES® a number of dedicated feature-based templates have been made available that provide the designer control over key parameters without the need of understanding the underlying mathematics.

A template project contains a predefined setup of features for analysis of an imported hull form and for the transformations acting on an image of the original shape. The process for generating a variant usually comprises four steps:

- Import of the baseline geometry from an iges file or similar
- Selection of the design draft for analysis
- Initialization, and finally
- Modification of the free variables.

Figure 8.11 depicts the hull form of an offshore supply vessel (OSV) for which such a template was used. Here, the baseline geometry came from NAPA and comprised a set of B-spline surfaces that were post-processed with CAESES® (e.g., to form a watertight definition, the deck being deliberately left out in the display). Important shape characteristics were identified and are shown in different colors.

It should be noted that the import of the baseline geometry is not a trivial step in the process. Exchanging mathematical representations of geometry, even though standards are utilized, bears the potential of errors due to misinterpretations between the sending and the receiving software tools. While B-spline curves and surfaces are exact representations of the shape, trimming operations are approximations[3] that depend on tolerances and the actual algorithms utilized. Boundary representations (BRep) form the basis of handling topological relationships between the geometric

[3] With the exception of iso-parametric trim curves in the domain of the parent surface.

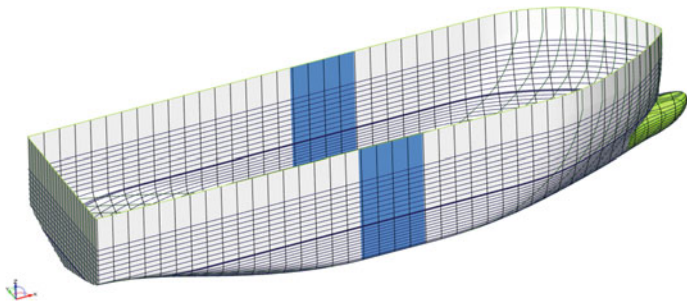


Fig. 8.11 Baseline imported from an iges file, comprising a set of B-spline surfaces

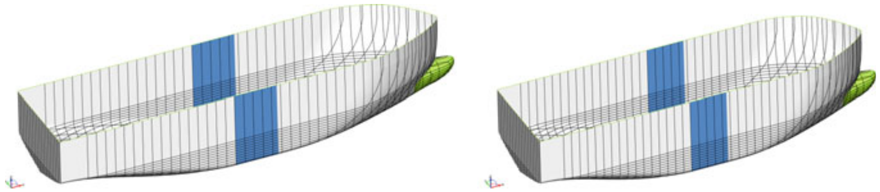


Fig. 8.12 Lengthened and shortened version of an imported OSV

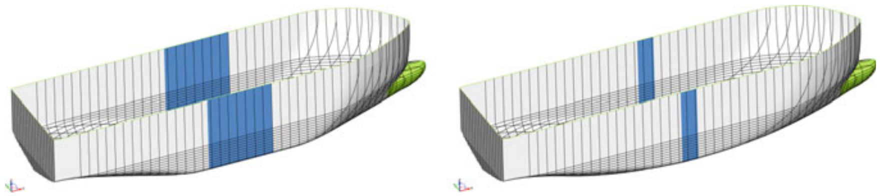


Fig. 8.13 Two hull forms with lengthened and shortened parallel mid-body (shown in blue) but identical displacement and longitudinal centers of buoyancy

entities, such as trimming and Boolean operations. The outcome of such operations, unfortunately, varies in different CAD systems. Sometimes deviations are small but occasionally operations cannot be successfully executed at all.

In hull form design shapes are often transferred as a pure patchwork of B-spline or NURBS surfaces (e.g., when using an iges export from NAPA) and sometimes as just one single surface (e.g., from MARIN's CAD tool GMS). CAESES® offers dedicated functions to repair and refine imported CAD models so as to prepare them for subsequent tasks.

In the example given, main dimensions are changed, see Fig. 8.12, and minor modifications of displacement volume and longitudinal center of buoyancy are undertaken, see Fig. 8.13. The latter two are realized by a Lackenby transformation, see Sects. 8.3.1 and 8.3.2, for a reference draft chosen by the user.

From the given input, baseline geometry and design draft, the variables are initialized, in particular, the main dimensions of the vessel. Complementary modifiers

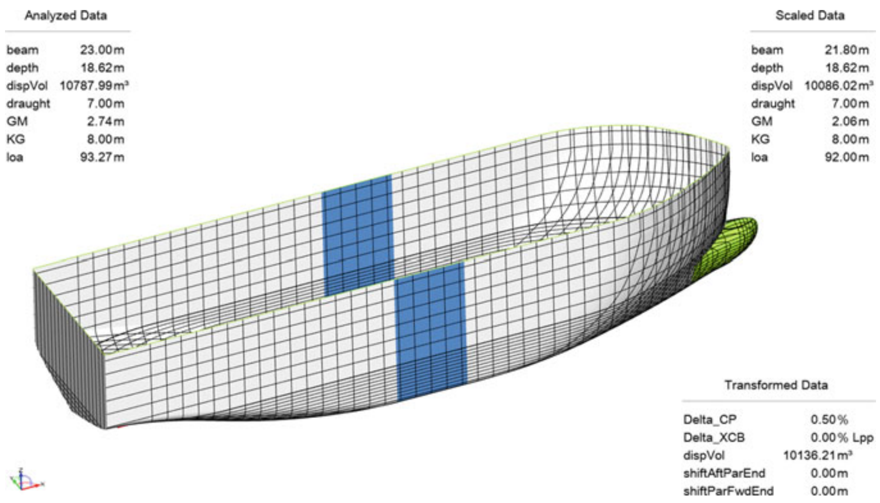


Fig. 8.14 Modified hull and control monitors for interactive shape adjustment

are set to zero at the start. These free variables allow controlling the bulbous bow and the location of the parallel mid-body. While Fig. 8.11 depicts the imported baseline, Fig. 8.14 shows a modified version along with the information displayed for interactive control of relevant parameters.

The partially parametric template discussed here forms the basis of a design space exploration in which various combinations of main dimensions were investigated. For given main dimensions, complementary parameters, in particular for the mid-body and the bulb, are (again) adjusted within an inner optimization loop. These nested optimizations are undertaken to come up with very competitive shapes for calm-water hydrodynamics for any current set of main dimensions. Further details are given by de Jongh et al. (2018). Figure 8.15 shows possible modifications of the bulbous bow shape.

8.4 Data Management

8.4.1 Hierarchical Models

CAESES® takes an object-oriented view toward modeling and data management (Abt and Harries 2007a). CAESES® objects can be asked for their attributes, values, and status, using *get* commands. Vice versa all objects can be assigned values, using *set* commands. The system allows introducing parameters and free variables without restraint. Parameters are mostly real or integer values that are either assigned a specific value, derived from other objects (e.g., output values from simulations) or computed

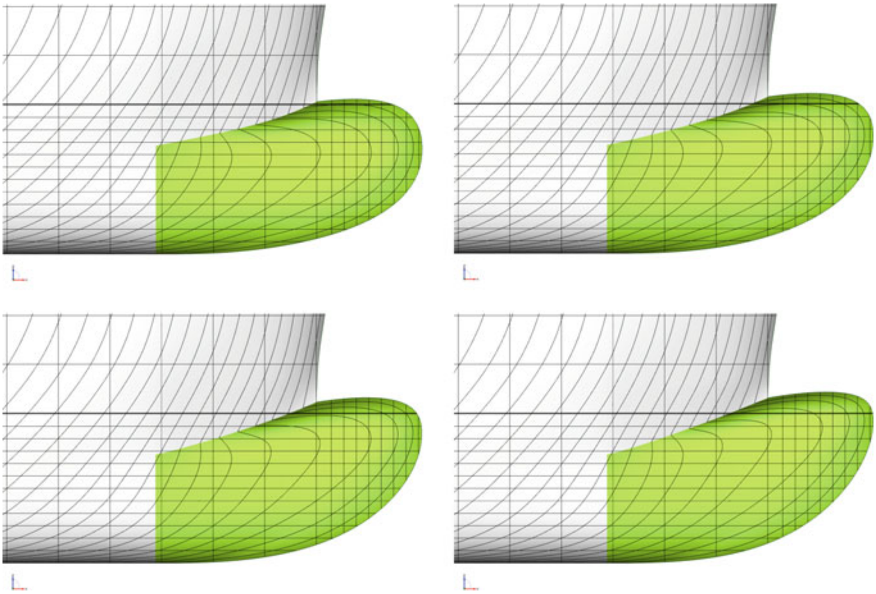


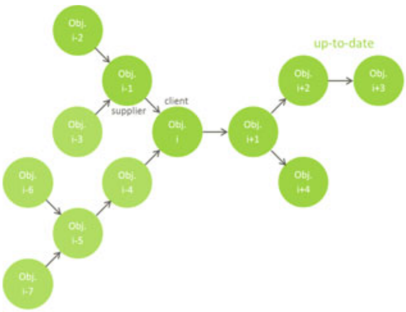
Fig. 8.15 Variation of bulb shape changing a single design variable

from mathematical expressions (often involving other parameters). Parameters form entries at the lowest level of a hierarchical model if they do not depend on any other object. A parameter at the lowest level of the model can be used as a free variable within an optimization, see also Sect. 8.4.2.

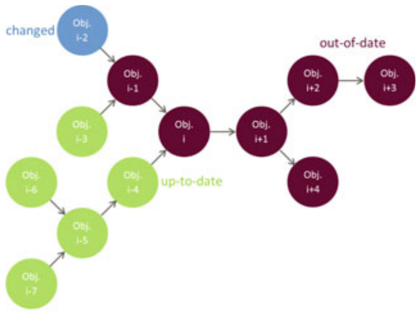
Figure 8.16 illustrates a hierarchical model (in abstract form) with a number of objects (here just 12 for simplicity). In principle, each object has one to several (lower level) suppliers and, vice versa, serves as a supplier to one or several (higher level) objects. When an object receives data, it is considered to be a "client." When it provides data, it acts as a "supplier."

In Fig. 8.16a, object i (called Obj. i) has two direct suppliers while it acts as supplier to just one following object (for simplicity), namely object i+1 (called Obj. i+1). Figure 8.16a shows a status in which all data are "up-to-date," meaning no changes have taken place since a complete update has been cascaded throughout the entire model. As soon as a single part of the model changes, all objects depending on it change their status to "out-of-date," see Fig. 8.16b. CAESES® would not necessarily update the model since, potentially, this may require considerable resources, for instance, if a CFD simulation is involved. Rather, the system waits for a request that an object needs to deliver data and then updates the model as need be. This so-called lazy evaluation (also known as lazy fetching) is depicted in Fig. 8.16c and d.

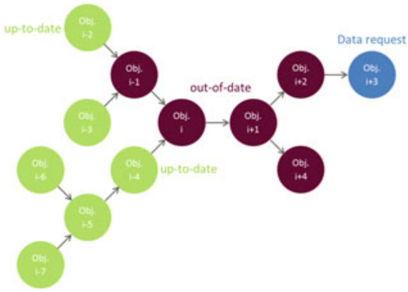
Objects and parameters can be flexibly introduced, erased, copied, renamed, and moved within the hierarchy as long as no circulate dependency is established. This



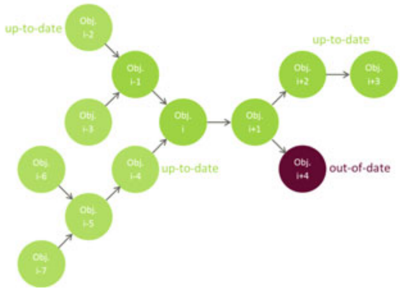
(A) Hierarchical model: All objects are up-to-date (indicated by objects shown in green)



(B) Objects that are out-of-date are not updated unless requested (here, objects that have gone out-of-date are shown in red while the one object that was changed is shown in blue)



(C) Object “Obj. i+3” (shown in blue) is requested to deliver data



(D) Object “Obj. i+3” is again up-to-date while “Obj. i+4” is still out-of-date since it has not been asked to deliver any data

Fig. 8.16 Lazy evaluation within CAESES®: Objects are only updated when they are needed (by another object or an action such as graphical display)

situation, however, is checked and excluded by CAESES® at the time of setting up a relationship between objects.

Importantly, an object may depend on an external simulation. This means that if the object is asked for its data, for instance, a parameter whose value is the resistance of a vessel at a specific draft and speed, it checks its current state. If it is up-to-date (e.g., none of the inputs to the flow simulation, in particular not the hull form itself, have changed), it can readily provide the requested piece(s) of information. However, if out-of-date (e.g., since a change in draft was made), it starts the necessary analysis. For the example of ship resistance, this may cause a full-fledged CFD simulation to be undertaken, unless deliberately suppressed, but may also just trigger the call of a surrogate model (see also Sect. 8.7).

8.4.2 Parameters Versus Free Variables

CAESES® allows defining parameters and free variables flexibly while working on a design and optimization project. Free variables within CAESES® differ from parameters as follows: A parameter can be any mathematical expression, a value taken from a simulation or just a number. Free variables, however, can only be numbers (or specific instances from a selection set). This is because they are controlled by the design engine during an optimization, i.e., they are varied by the strategy chosen for exploration (e.g., Sobol) or exploitation (e.g., MOGA). Hence, they need to be at the very start of any hierarchical model (as shown at the left end of Fig. 8.16).

Any parameter can be converted into a free variable and vice versa. In the latter case, this is straightforward since a free variable never has any suppliers to begin with. In the former case, however, it may cause the relationship to any suppliers, if given, to be cut since only the value itself can be associated with the free variable. This does not create any major problems but needs to be considered.

8.4.3 Bottom-Up Approach for Integration

It should be noted that the integration approach taken does not aim at holding all data items of a synthesis model that define a certain design task. Rather, tool specific data that neither are required to be shared nor are of interest to the design team are deliberately left out of the common database even though they form part of the wider repository.

For instance, a viscous flow code may allow setting a relaxation factor which an expert has tuned for a certain type of analysis. While this is certainly of importance to the CFD analysist, it may not be of major concern to the designer as long as the simulation converges and the quality of the results is ensured.

Figure 8.17 graphically depicts a synthesis model (in abstract form) in which three external tools are combined. Just a subset of all data is held within CAESES®. This subset will usually be larger than the sum of all individual intersections as illustrated by the white hexagon which comprises the data held centrally.

The reason for not sharing all possible data items is to support efficient—and possibly ad hoc—coupling of tools without having to first undertake lengthy data definitions. Naturally, there are advantages and drawbacks to this. An advantage of this so-called bottom-up approach is that the data to be shared can grow as the project advances. It has been found that defining data abstractly and completely ahead of a sophisticated project is not only time-consuming but also pretty difficult with many different tools and disciplines involved. A disadvantage of a bottom-up approach certainly is that databases cannot be readily recycled from one project to the next as

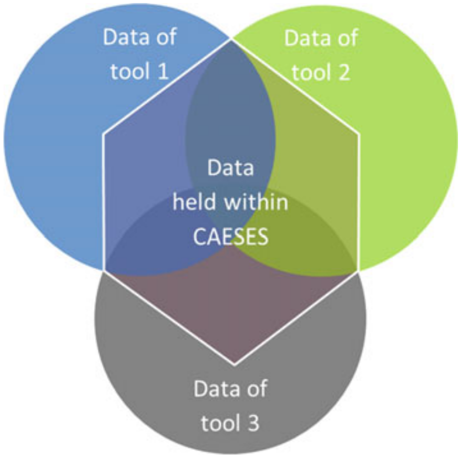


Fig. 8.17 Data storage within CAESES® illustrated for a setup with three external tools

that would ideally be possible in a comprehensive top-down approach.[4] Nevertheless, they can still be copied and, subsequently, amended and adapted.

8.4.4 Conversion and Enrichment of Data

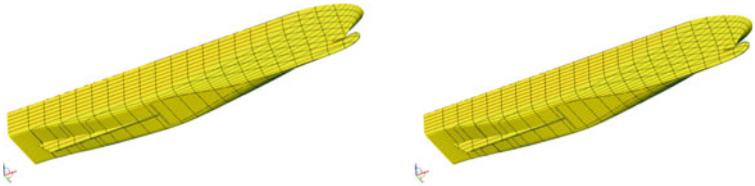
Data items from various tools can be brought together by means of expressions associated with a parameter or, if additional calculations or more comprehensive processing are needed, within CAESES' advanced feature technology, see Sect. 8.2.3.

When combining tools often the formats in which data are exchanged differ. For instance, hull forms sometimes need to be delivered as an iges files for one tool and as a watertight stl file for another tool while a third tool asks for a specific panel file or for a ASCII file with offset points, see Fig. 8.18. CAESES® may then act as a go-between, converting data to the format that suits each tool to be fed.

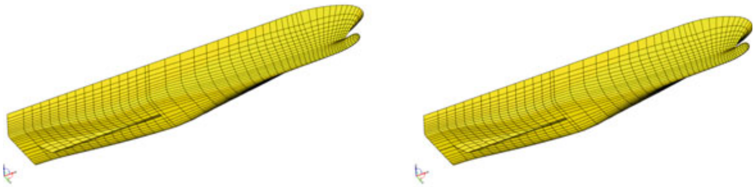
Figure 8.18 depicts various outputs for two different hulls, one being a long and slim variant and the other being a bit shorter and a little beamer design of the RoPAX ferry as introduced in Sect. 8.3.2. Figure 8.18a–e give the hulls' geometry, two different panel meshes, pure sectional data, and a wireframe model. Here, all these outputs form an integral part of the parametric model.

Furthermore, CAESES® can also be used to generate data that would otherwise be lacking. For instance, suppose that a baseline was available as offset data only. CAESES® could then be utilized to make the best fit of the points, yielding a set of fair curves that are subsequently skinned to provide a surface definition. From these enriched data new representations, say a watertight tri-mesh, would then be derived as needed.

[4]However, the vast range of maritime assets and different design scenarios would call for an extraordinarily large effort of defining a unifying data set.



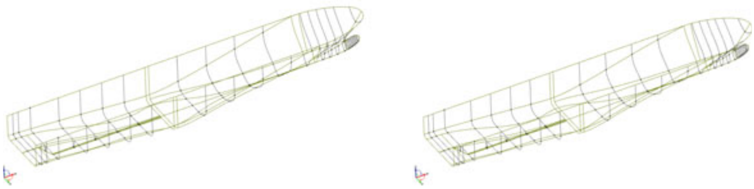
(A) Hull geometry for two variants (long and slender vs. shorter and beamer)



(B) Panel meshes for calm-water resistance analysis (input to ν-Shallo)

(C) Panel meshes for seakeeping analysis (input to NEWDRIFT+)

(D) Sectional data for structural analysis (input to MARS/STEEL)



(E) Wireframe model of surface patches for safety assessment (input to NAPA)

Fig. 8.18 Different data sets used to feed various simulation tools (shown for two instances of a RoPAX ferry)

8.5 Software Connection

8.5.1 Software Connector

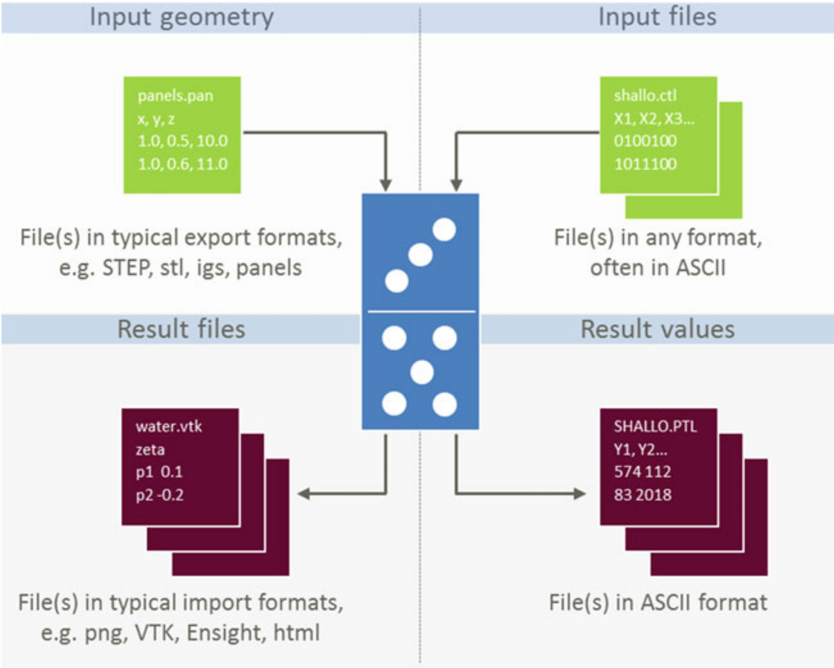
In order to prepare a tool to be connected to CAESES® a person familiar with the tool would first run it as a stand-alone application. He or she would provide all input and output file(s) that a batch mode execution requires, see also Fig. 8.3 of Sect. 8.2.4. These files are then loaded into CAESES® and used as templates as described in Sect. 8.2.5.

Figure 8.19 shows the so-called SoftwareConnector within CAESES® in both abstract and concrete form, using HSVA's wave resistance code ν-Shallo as an example. The SoftwareConnector provides four quadrants, two of which are for different types of input files while two of which are for different types of output files, supporting both binary and ASCII formats.

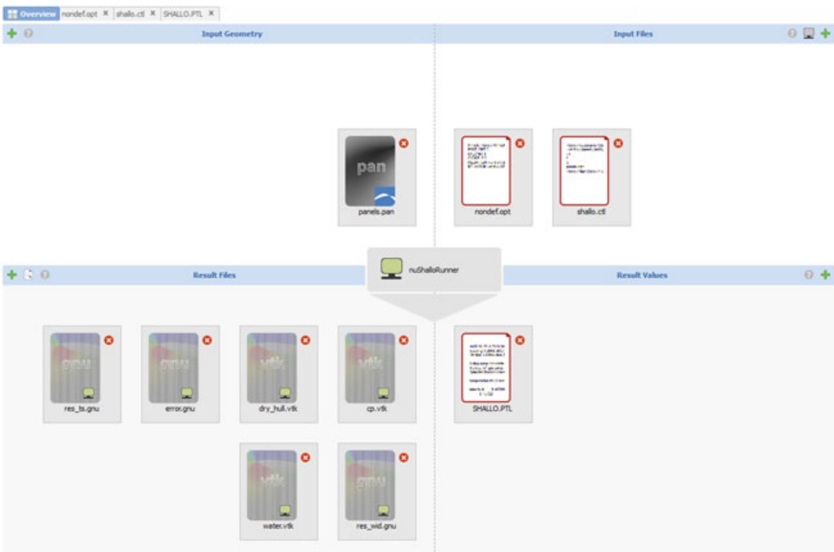
Certain types of input files can be handled directly, namely those which relate to the export formats readily supported by CAESES®, e.g., STEP, stl, igs, panel meshes. Likewise, for certain types of files that are output from the tool to be integrated, CAESES® provides interpreters, e.g., png, VTK, Ensight, Tecplot, and html. Furthermore, any data item in an input file can be tagged to be replaced by a parameter or free variable from the entire synthesis model. Similarly, any output file in ASCII format can be parsed by CAESES®. For flexibility, all sorts of identifiers can be utilized within a template, see also Sect. 8.2.4. Typical identifiers are characteristic names (so-called anchor strings), line and column numbers (also as offsets to anchor strings), relative position of a data item within a file (e.g., first or last occurrence).

Within the SoftwareConnector also the path to the executable of the tool to be integrated is specified. A tool can be run either locally or as a remote computation on a different computer or HPC cluster, be it internally via a company's intranet or externally via the Internet, for instance in the Cloud (see Albert et al. 2016). CAESES® allows for command line arguments and logical constraints. The latter would suppress tool execution if important prerequisites have not been met, for example, the quality of the mesh falls below a certain threshold, and hence, a lengthy CFD simulation may not be worthwhile to run.

For a discussion about further ways of connecting tools to CAESES® see Abt et al. (2009).



(A) Abstract view of SoftwareConnector



(B) SoftwareConnector for ν-Shallo within CAESES®

Fig. 8.19 Tool integration via templates

8.5.2 *Integration of a Single Tool*

Figure 8.20 illustrates the extraction of data from a ν-Shallo output file. Once the flow solver is executed, an ASCII file, here SHALLO.PTL, is written. The CAESES® parser extracts several important simulation results from the file which are shown in the left lower part of Fig. 8.20. The highlighted row in the right part of Fig. 8.20 depicts that a certain anchor string is searched for, namely CR (for residual resistance coefficient), and the value next to it is read. Since the number of iterations needed for a flow simulation to converge would typically not be known beforehand here the last occurrence of the anchor string is searched for, see upper left part of Fig. 8.20, and a parameter, here nuShallo_CR, is assigned to the value found for CR. This way the results are made known to the platform and become available for further processing within the synthesis model.

For an elaborate treatment of single tool integration, see also Harries et al. (2015b) and MacPherson et al. (2016).

8.5.3 *Integration of Several Tools*

For each tool to be integrated, a dedicated SoftwareConnector has to be set up within CAESES®. This is frequently done ad hoc whenever a new tool comes into play. A

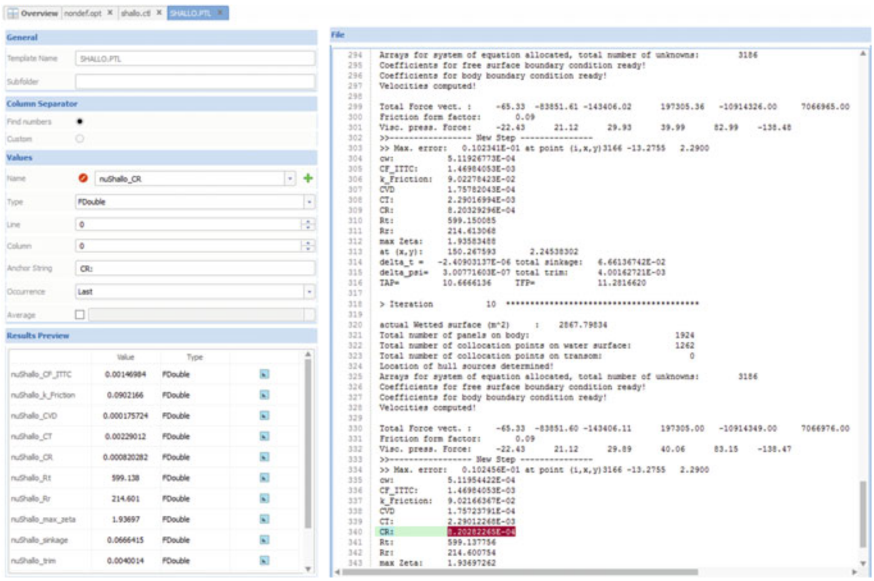


Fig. 8.20 Output file from ν-Shallo used as a template to identify data for extraction by the SoftwareConnector

SoftwareConnector, however, can also be imported from a previous project so that, quite often, only a few adjustments are called for.

Some tools are fairly sleek to connect while others may involve the handling of a lot of files. NAPA is an example for a tool that just needs a single script, and if hull variants are studied, an iges file for the current geometry. OpenFOAM is an example for a system that uses many input files, namely a watertight stl file for the geometry and quite a few control files. Still, the principle of integration stays the same independent of the number of input and output file(s).

In principle, a CAESES® project may comprise as many SoftwareConnectors as need be, readily allowing the flexible combination of several tools either to streamline a process that encompasses several tools to be run consecutively or to establish synthesis models of tools as introduced in Fig. 8.5. If the tools are independent of each other, they can be run in parallel by CAESES® (asynchronous update). Quite often, however, one tool requires input from another, and hence, a predefined sequence of execution has to be observed (synchronized update). This can be realized by making (parts of) the output of one tool (parts of) the input to another, i.e., by establishing a supplier-client relationship. As illustrated in Fig. 8.16, objects know the status they are in, namely up-to-date or out-of-date. If one tool, say tool A, requires input from another, say tool B, and that input is still up-to-date, then tool B does not have to be executed, but its data can be readily utilized. However, if tool B is out-of-date (or has not been run so far at all), then tool B would be triggered before tool A. If again tool B depends on yet another tool, say tool C, that would then be the first to be run, cascading through the hierarchical model until the first object is found that is up-to-date.

A further elaboration is given in Harries et al. (2017) regarding the synthesis model shown in Fig. 8.16 while an example of combining tools to establish a process chain for CFD, bringing mesh generation and flow analysis together is presented in Albert et al. (2016).

8.5.4 Connection with Other Frameworks

The integration of tools does not stop at connecting one or several stand-alone tools, but any other framework to which tools have been coupled can be connected as well. The prerequisites are that those additional frameworks themselves can be run in batch mode and that they allow setting parameters, launching encapsulated applications and providing result files. Since CAESES® can be easily run in batch mode and allows setting and getting of data, a straightforward scenario is to run a CAESES® project, a domino in the sense of Sect. 8.2.5, out of another CAESES® project. Nesting several CAESES® projects within one combining project would constitute a meta-project as further discussed in Sect. 8.9.1.

Alternatively, other frameworks, say a generic PIDO environment (like modeFRONTIER by Esteco or OPTIMUS by Noesis) or a CAE system (such as the ANSYS workbench), may be utilized to establish further levels of integration. A

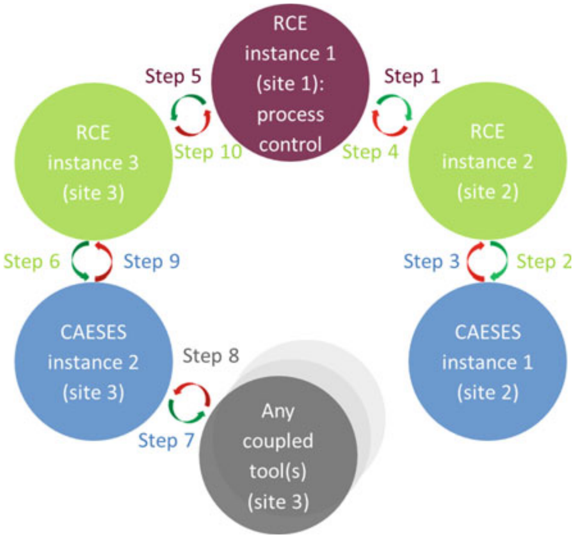


Fig. 8.21 Connection between RCE, CAESES® and additional tool(s)

pretty common application is that CAESES® acts as a pure geometry engine for parametric modeling. A more sophisticated scenario is that a framework calls one or several tools that are provided through CAESES®. This is illustrated in Fig. 8.21. Here the remote component environment (RCE) by DLR, the German Aerospace Center (DLR) being part of the HOLISHIP consortium, takes care of combining tools. Within the RCE, safe data transfer can be realized via the Internet between different sites and/or companies.

As shown in Fig. 8.21, a first RCE instance, being available at site 1 (e.g., in Hamburg, Germany) would take care of process control. It is connected with a second RCE instance that executes CAESES®, say as a geometry engine. This could be made available at any party connected to the Internet, say at site 2 (e.g., in Berlin/Potsdam, Germany). The first RCE instance gathers data from the second RCE instance and then transfers these data to a third RCE instance at yet another site (e.g., in Wageningen, The Netherlands). That third RCE could be connected to another instance of CAESES® which would make available additional tools already embedded. The sequence of data transfer is illustrated by the numbers associated with each step shown in Fig. 8.21. Once data have been produced, processed, and moved between RCE instance 2 and RCE instance 3 (steps 1–10), RCE instance 1 could trigger a new sequence, starting again with step 1. Naturally, this simple setup can be extended to further tools which could be either integrated within the RCE environment directly or, again, indirectly via CAESES®. If suitably and steadily extended that could form the basis of a powerful engineering ecosystem related to the Internet of Things (IoT), see also Sect. 8.9.2.

8.6 Optimization

8.6.1 Overview

Once synthesis models are set up they can be utilized interactively by a designer or run automatically at large scale. A designer will most likely investigate just a handful of variants manually, be it to get an appreciation of system behavior or to check if all tools work together smoothly. Studies with hundreds and even thousands of variants are carried out within formalized optimization campaigns, mostly during the night, the weekends or, if time-consuming direct simulations are involved, even over the course of several days. Utilizing surrogate models, see Sect. 8.7, moves the effort of heavyset computations upfront, enabling a tremendous speed up for the actual optimization phase which can then be realized within a timeframe of minutes to hours.

Mathematically speaking, optimization is finding the extremum (minimum or maximum) for one or several objectives under a set of (inequality and equality) constraints. All elements in the synthesis model that are under control of the design team and which are consciously selected for modification constitute the set of free variables, see also Sect. 8.4.2. It is the design team that then decides on the lower and upper bounds of these free variables, i.e., the range within which each free variable is permitted to change.

If a multi-objective design problem is posed, as is the typical situation in engineering, there typically is no solitary optimum but a set of solutions that are non-dominated (Pareto frontier), i.e., for which no single objective can be further improved without impairing one or several of the other objectives. From all feasible solutions, in particular from the Pareto optimal solutions, the team finally suggests the most favorable design according to the client's preferences.

In general, two major types of optimization strategies can be distinguished (Harries 2014):

- Design space exploration and
- Exploitation

In general, optimization strategies aim at scanning the design space (exploration) or improving the objective(s) (exploitation) with as few costly evaluations (simulations) as possible. If many evaluations are affordable—for instance, by employing surrogate models as discussed in Sect. 8.7—some strategies (e.g., genetic algorithms as a hybrid between exploration and exploitation) try to establish not only a local but also a global view. For an in-depth discussion of strategies that have been successfully applied to the optimization of maritime assets see, for instance, Birk and Harries (2003).

Inherently, a multi-dimensional design space, often of order 10 regarding the number of free variable but sometimes even of order 100, requires the evaluation of a lot of variants to establish a thorough understanding. This means that very quickly many hundreds or even thousands of designs have to be generated and assessed.

Looking at so many variants might, at first glance, seem to be a rather brute force method. Nevertheless, besides finding better (and possibly even the best) solutions there are many important benefits to gain:

- Seeing cause and effect relationships (for example between free variables and objectives)
- Understanding trade-offs between opposing objectives (in a multi-objective design scenario)
- Settling on what should be selected as an objective and what ought to be treated as a constraint (which sometimes is far from trivial)
- Producing a tangible number of feasible variants (in particular for a heavily constrained design problem)
- Identifying constraints that are particularly difficult to meet (and which could possibly be relaxed)
- Getting an appreciation of the overall potential for improvements
- Gaining a feeling for the design task and, furthermore
- Mitigating the risk associated with taking a design decision.

It should be noted that the strategies of exploration and exploitation as discussed here are usually based on handling floating-point numbers. Usually, the topology of the product is kept constant during a single optimization run. Different configurations, for instance, a single-screw versus a twin-screw vessel or a direct-drive shaft line with a diesel engine versus a diesel electric Azimuth thruster, are usually treated consecutively within separate optimizations. As soon as many variants for a small number of different topologies have then been investigated, the various design clusters are compared from which the best topology and the most favorable overall design can finally be identified.

Naturally, there are limits to this practical approach, for example, if the number, material, and type of stiffeners should be optimized within a structural optimization. Discrete changes like these would formally be captured via Boolean, string and/or integer variables. Unfortunately, this quickly sparks a combinatorial explosion.

Therefore, as a work-around topology-defining variables are sometimes simply treated as floating-point numbers, too. A standard optimization strategy for real variables would then be employed in which a roundoff to the closest integer value takes place or a look-up table is employed that relates the real variables to discrete entries (Zeitz et al. 2014).

8.6.2 Exploration

Before starting to push for improvements, it is often advisable to develop an understanding of the design space, i.e., to answer, at least by and large, the following questions:

- Which of the free variables are particularly influential and which may not be so important after all and could possibly be left out of further investigations?

- Are there many isolated regions in which good designs are found (which would be an indication of many local extrema) or are the objectives and constraints quite smooth with respect to the free variables?
- Do better variants lie rather in the middle of the design space or toward the chosen bounds?
- Which of the constraints are often active, i.e., violated, and which are actually not creating any problems at all and could be taken out of the investigation?

The group of strategies that spread variants in the design space either systematically or randomly are called design of experiments (DoE), see Siebertz et al. (2010) for an elaboration. Only if the number of free variables n is small, a fully populated matrix of variants can be investigated since the grid scales with g^n, with g being the number of (regular) grid points in each direction of the n-dimensional design space. For example, three variants per axis ($g = 3$) in an eight-dimensional space ($n = 8$) already call for 6561 variants. Hence, there are more sophisticated exploration strategies which try to produce as much insight with as few variants as possible.[5]

A popular DoE is the so-called Sobol algorithm as developed by Sobol (1976). It is a quasi-random approach that mimics the behavior of people at a beach: Unless they know each other, they tend to lie down at the spot that is furthest away from all other people so as to maintain utmost privacy. Every newly arriving person or group of persons would intuitively identify the region in which the free space is still the largest. Figure 8.22 illustrates the Sobol for a two-dimensional problem (first five variants).

The beauty of the Sobol procedure is that it produces the same spread in design space when repeated and that it can just be extended if further variants are desirable (Harries 2014). For instance, if the above questions cannot be answered reasonably well by the initially chosen number of variants, it is straightforward to complement the exploration with further variants that readily blend in. Finally, explorations like the Sobol are typically used to produce the data sets required to build surrogate models as explained in Sect. 8.7. The reason is that there is no unintended bias in the variants produced.

8.6.3 Exploitation

As soon as an exploration has led to a set of designs that, admittedly by chance, perform really well, a true optimization can be started. This means that a conscious push toward better solutions is made. To this end, the good or best designs found within a DoE, possibly along with the baseline, are so to say "exploited" by iteratively improving one or several objectives. There are numerous strategies to select from,

[5]The following strategies for exploration are provided internally by CAESES®: Sobol, exhaustive search, ensemble investigation, design assembler (externally defined matrix of variants), design lab (interactive variant creation). Furthermore, a range of complementary strategies are made available via DAKOTA by Sandia National Laboratories, e.g., Latin Hypercube and sensitivity analysis.

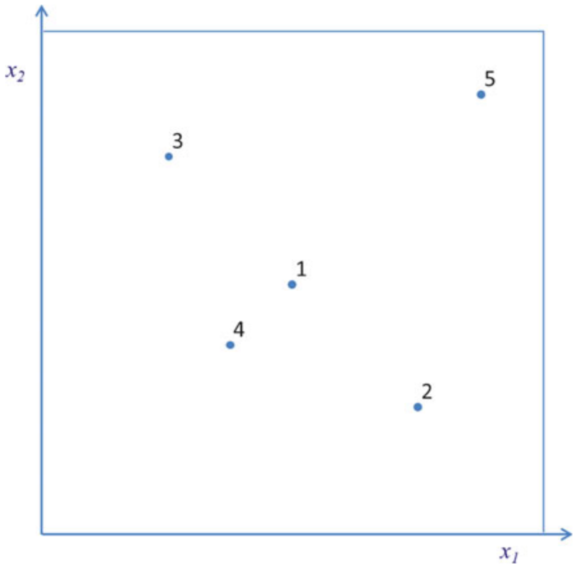


Fig. 8.22 Sobol sequence for five variants in a two-dimensional design space

and it is important to note that, unfortunately, there is no single strategy that would be best for all optimization problems. Thus, CAESES® offers a range of exploitation strategies.[6] Some strategies search locally, mostly (deterministic) search strategies, while others act more globally, like genetic algorithms, adding robustness albeit at the cost of considerable effort. Details and references are given in Birk and Harries (2003).

The principle idea of a deterministic search strategy is that of a blindfolded person in the mountains trying to find the nearest valley (minimization). The person would probe into the first direction, using a meaningful delta of the first free variable. If an improvement was found, a step forward would be made. Otherwise the opposite direction would be taken unless there is no improvement found there either. This is followed by a similar step into the second direction of the design space and so on. The search typically ends in a local minimum (or close to it). It is fairly quick but depends on the starting point(s). Inequality constraints are often handled during a search by means of an external penalty functions (sometimes by means of a barrier) unless a strategy already comes with an internal mechanism (e.g., the T-Search). The idea is rather simple: Whenever a constraint is violated the objective(s) are artificially worsened so that the search has no incentive to remain in the infeasible domain (or to leave the feasible domain in the first place). There are, not surprisingly, many search strategies around, some of which use objective values only while others make use of gradient information, too.

[6]The following strategies for exploitation are provided internally by CAESES®: Nelder–Mead Simplex, T-Search, Newton–Raphson, Brent (1d), NSGA II, MOSA. Furthermore, a large range of advanced strategies are made available via DAKOTA by Sandia National Laboratories, e.g., local optimization (multi-start), global optimization on response surface.

The principle idea of a genetic algorithm is that the objective(s) are interpreted as a fitness measure that determines an individual's chance of survival and of having children. A genetic algorithm commences with an initial population, possibly taken from a preceding DoE. The best individuals of that generation are selected to produce children. Similar to nature's standard approach, two individuals are paired, leading to a swap of parts of their free variables (their DNA) and randomly receiving (smaller or larger) mutations. This creates new individuals that belong to the next generation. The objective(s) and constraints are computed for this new generation, and infeasible individuals (designs) would be excluded as eligible parents. The best candidates are again selected for reproduction, leading to the third generation and so forth. Again, many different strategies and variations to the theme have been proposed and are in use.

8.6.4 Assessments

Once an exploration and/or exploitation has been run, CAESES® as the HOLISHIP platform for design and optimization allows scanning through the results by means table views, correlation diagrams, and a design viewer for direct comparison of variants. Figures 8.23, 8.24, and 8.25 show some of these assessment tools for the RoPAX ferry as discussed more thoroughly by Harries et al. (2017) and Marzi et al. (2018).

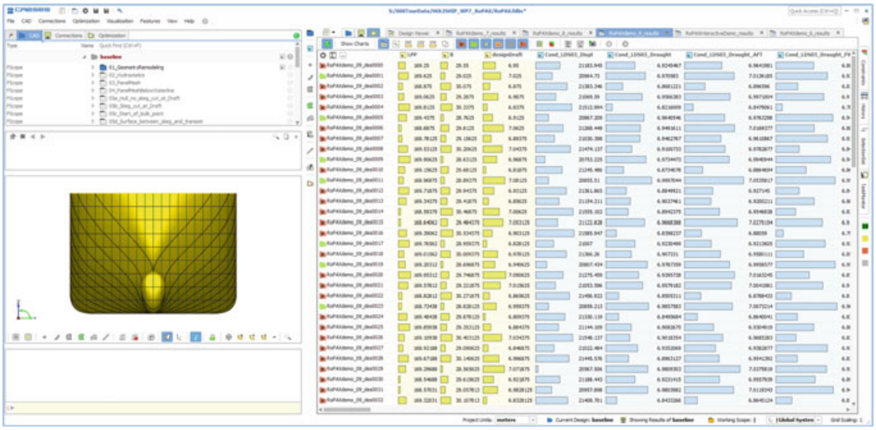


Fig. 8.23 Design table for free variables, objectives constraints, and further parameters of interest

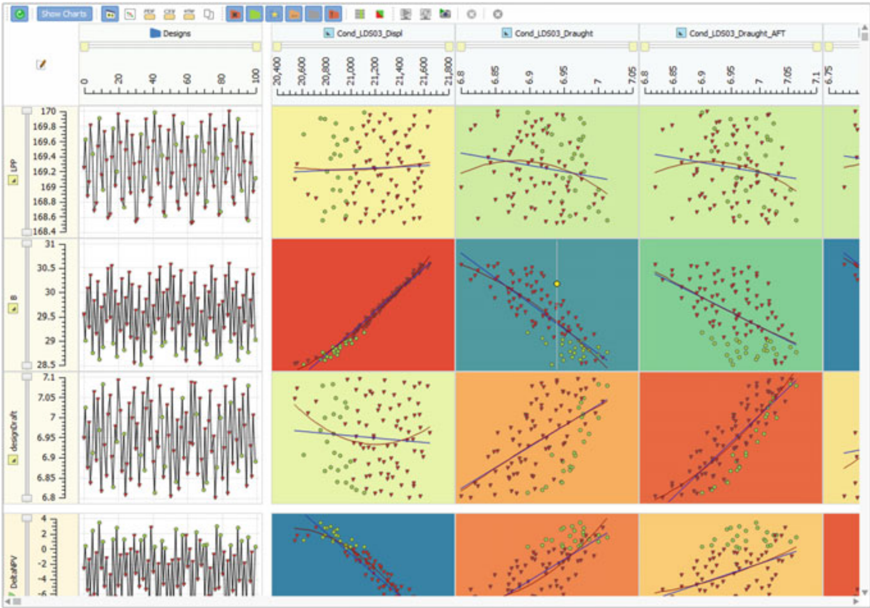


Fig. 8.24 Charts correlating objective and constraints with free variables

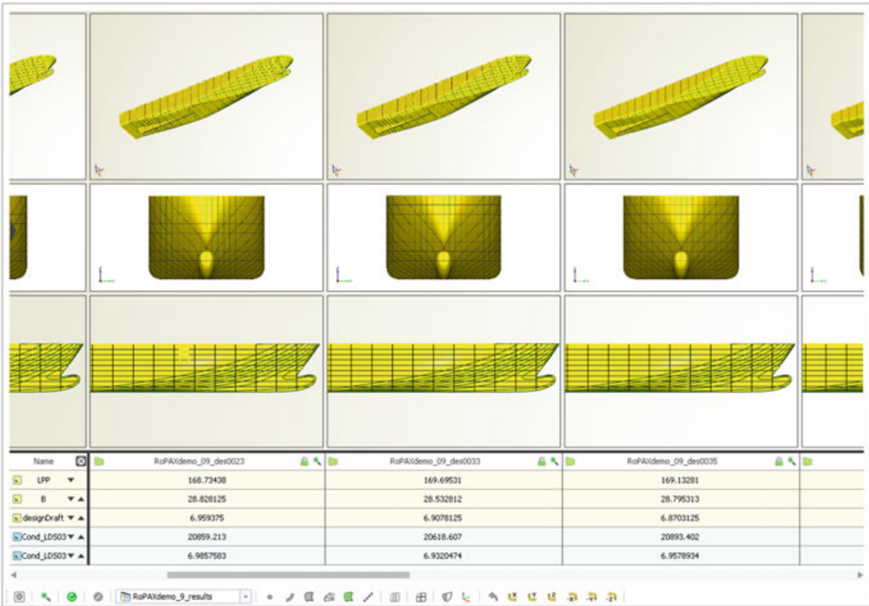


Fig. 8.25 CAESES® design viewer for graphical comparison of variants (excerpt from hundreds of variants)

8.7 Direct Simulation Versus Surrogate Models

8.7.1 Idea of Surrogate Modeling

Simulations vary in effort and resources from just a few CPU seconds to hours and even days of number crunching. Frequently, they require expert knowledge that is neither available at all times nor in every design team. Furthermore, resource-intensive simulations such as viscous CFD and damage stability assessment generally require special hardware, possibly even an HPC environment, and associated licenses.

A possible solution to this predicament is to replace direct simulations by so-called surrogate models, also known as meta-models or response surfaces. The concept is as follows: A sufficient set of simulations is undertaken upfront before the actual design work takes place. These simulations are then utilized to build an approximation, the surrogate model, which later on replaces the direct simulations within an acceptable level of accuracy. As can be readily seen, the effort of undertaking direct simulations cannot be avoided. However, it is shifted in time and to the right people.

Naturally, the variants for which the direct simulations are to be performed need to relate to the free variables that shall be subsequently used in the design task and/or the optimization campaign. Otherwise, the surrogate model will not depend on these free variables and cannot be utilized meaningfully. As a consequence, the important questions to ask are if it is actually required to engage in surrogate modeling and, if yes, how to do it properly. Table 8.1 gives some recommendations.

Table 8.1 Recommendations for replacing direct simulation with surrogate models

Resources needed for analysis per variant	Smooth behavior of response to be captured	Licenses and/or tool know-how locally available	Direct simulation	Surrogate model
Low	Yes	Yes	+	–
	Yes	No	–	++
	No	Required	++	–
Medium	Yes	Yes	+	+
	Yes	No	–	++
	No	Required	++	–
Large	Yes	Yes	+	++
	Yes	No	–	++
	No	Required	+	–

Low Less than one minute on a standard computer (PC or workstation)
Medium A few minutes to half an hour
Large Several hours to several days (possibly on a cluster or an HPC)
– Unsuitable
+ Recommended
++ Highly recommended

8.7.2 Typical Surrogate Models

The easiest surrogate model is that of a linear regression of a data set that depends on only one free variable as illustrated in Fig. 8.26. This is often done for experimental and empirical data. A line is fitted through the data points such that the square sum of the errors between the actual values and their approximations is minimized. Quadratic and even higher-order polynomials are also regularly used, in one-dimensional but also in n-dimensional regressions, n again denoting the number of free variables.

The input required to produce a meaningful surrogate model quickly scales up with n. The number of coefficients L needed for a (fully populated) n-linear response surface is $L = ½ (n \cdot (n + 1)) + 1$. Hence, as a rule of thumb, about n^2 independent data points are required if the response to be captured is well behaved and shall be replaced with more than just an n-linear model. Well behaved means that the response is rather smooth, i.e., that it does not oscillate (or jump) with regard to any of the free variables.

As can be readily imagined the number of free variables has to be sufficiently small if the simulations take a lot of resources. For example, if you need one hour of CPU time for the simulation of every variant, ten free variables already call for 100 h (more than four days) of number crunching. Cutting down to five free variables means that about 25 variants could be sufficient which could then be processed within a little more than a day.

The distribution of variants in the n-dimensional design space is clearly of importance, too. If the variants from which to derive the surrogate model were unfavorably placed, say all of them were aligned with regard to one of the free variables, clearly the model would not be able to capture any other dependencies. Two strategies of design space exploration are often employed to spread the variants in design space intelligently, the Sobol and the Latin Hypercube as elaborated in Sect. 8.6.1 on design of experiments.

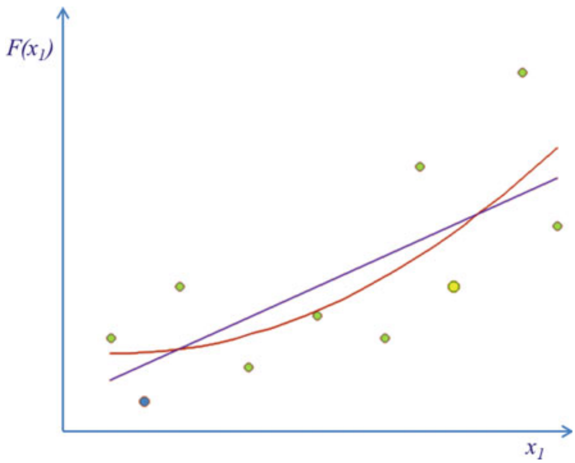


Fig. 8.26 Linear (shown in blue) and quadratic (shown in red) surrogate models for a set of data points

Popular surrogate models that are more sophisticated than polynomial regressions are artificial neural networks (ANN), Kriging and hybrid models that combine various surrogate models to increase the coefficient of prognosis, i.e., the accuracy of predicting system behavior.

ANNs are particularly suitable for responses that are not necessarily smooth and for which large data sets are available. In principle, ANNs mimic the human brain that, if fed continuously with input of a certain kind, learns to predict system behavior by suitably connecting neurons. For example, a goalkeeper after hundreds of hours of parrying practice has learned to predict the trajectory of an approaching ball. In many situations the prediction is good enough, leading to a save, while sometimes something unforeseen happens, causing a slightly different system behavior and, eventually, a goal. In order to build an ANN, the data set of the response to be captured is subdivided into a training set and an independent set for validation. For a thorough introduction to ANNs, used in maritime applications, see for instance Mesbahi in Birk and Harries (2003).

Kriging is a method that interpolates the training set while weighting the responses of various data points to predict system behavior at intermediate points. It was introduced by Danie G. Krig, a South African mining engineer, who wanted to predict the most likely distribution of gold based on samples from just a few boreholes, see for instance Press et al. (2007).

CAESES® supports quite many surrogate models by means of the DAKOTA software package from Sandia National Laboratories. Which of the surrogate models yields the best behavior and accuracy for a particular application is subject to testing. This does not create any major bottlenecks since the database for both training and validation can be run once and then utilized time and again.

For further elaborations see Myers and Montgomery (2009).

8.7.3 Using Surrogate Models

Once a surrogate model has been tested and found to be sufficiently accurate and reliable, it can be employed to replace the actual simulation. The advantage of speed is tremendous since a surrogate model would typically yield a result within seconds (if not split seconds) instead of minutes, hours, or even days of simulation time.

Figure 8.27 shows the replacement of several direct simulations within the synthesis model of the RoPAX ferry as given in Fig. 8.5 and discussed by Harries et al. (2017). Specifically, the wave resistance and seakeeping analyses by means of potential flow theory were replaced along with the laborious computations of damage stability. These types of analyses would typically require several minutes per variant, adding up to 15–30 min of overall simulation time for each design of interest. With the heavy number crunching replaced, however, the investigation only

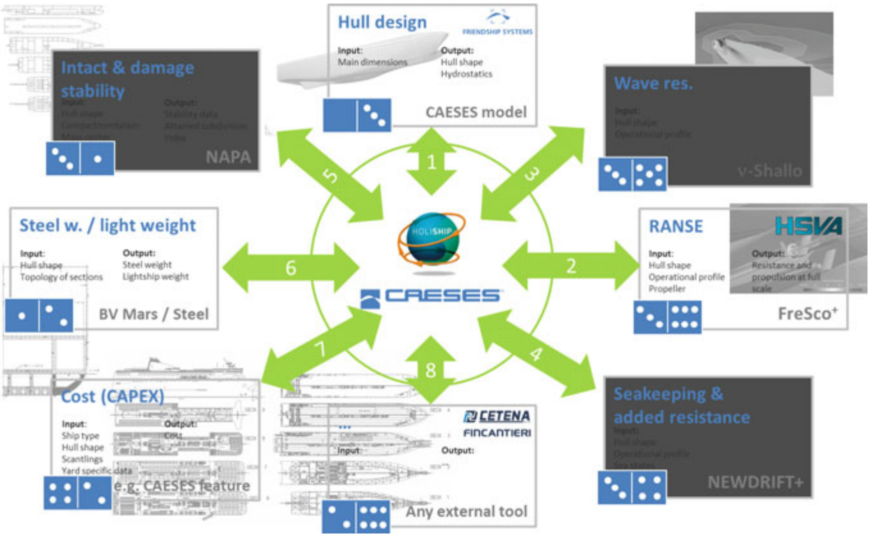


Fig. 8.27 HOLISHIP synthesis model based on CAESES® including surrogate models for the design and optimization of a RoPAX ferry

takes a fraction of a minute.[7] Hundreds of designs can thus be run within one to two hours, and thousands of designs can be studied over the course of a night (Harries et al. 2017). As a consequence, the designer gets a lot of insight into potentials and trade-offs along with an appreciation of dependencies and critical regions. Furthermore, it allows asking what-if questions and reacting to ad hoc modifications of the design requirements.

Figure 8.28 gives a comparison of the results from a surrogate model and data for the calm-water resistance prediction with ν-Shallo. The data from the surrogate model are plotted over the actual simulation data. If the surrogate model was perfect, all points would line up on a straight line with unit slope. This is not the case, yet the accuracy lies within the ±1% error lines which would be within the repeat accuracy typically associated with model tests.[8]

[7]One may wonder why the much more cumbersome RANSE simulation was not replaced by a surrogate model in the example given. This is because for the sake of reducing the overall computational burden the calm-water performance of the RoPAX ferry was first computed with FreSco+ as a viscous free-surface flow solver by HSVA, yielding the total resistance and propulsive efficiency of the appended baseline. Subsequently, a potential flow analysis of the non-linear wave resistance of the baseline's bare hull was run with ν-Shallo, the non-linear potential flow code by HSVA. The performance of each variant was then determined by means of the difference between the baseline's wave resistance and each variant's wave resistance computed with the same panel code, utilizing a comparable discretization.

[8]This does not mean, as should be well noted, that the accuracy of the CFD simulation itself is within ±1% of experimental data.

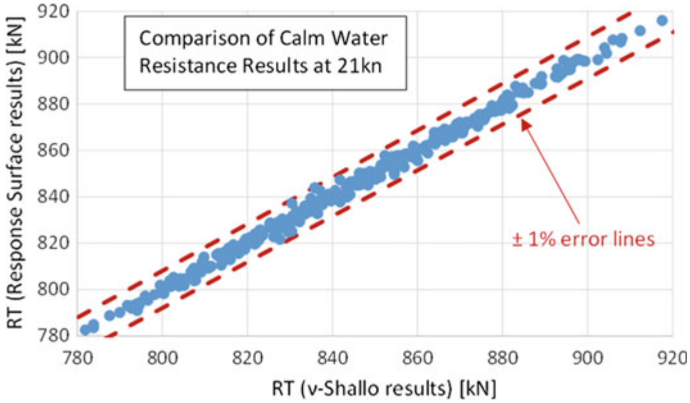


Fig. 8.28 Comparison between simulation data and surrogate model for calm-water resistance of a RoPAX ferry

Whether or not this accuracy level is sufficient needs to be decided on the basis of the design task for which the surrogate model shall be used. For finding the right dimensions of the ferry within a multi-disciplinary optimization, it seems to be perfectly acceptable while for fine-tuning a hull with respect to its hydrodynamics it may not yet be reliable enough. For further usage of surrogate models see, for instance, Harries (2010).

8.8 Scenarios of Application

8.8.1 Manual Versus Automated Design

In principle, CAESES®—and, hence, the HOLISHIP platform—supports different modes of operation, namely

- Manual (interactive) work
- Automated (formal) optimization and
- Batch mode execution.

Unless CAESES® is integrated itself, as discussed in Sect. 8.5.4, the two common scenarios are manual and automated design. Naturally, both manual and automated design work can be done at early stages, for instance, to identify main dimensions, and at later stages, for instance, to fine-tune the design to maximum energy efficiency.

When running an exploration or exploitation in an automated process, each variant that is produced receives a unique identifier under which all data associated with that design are stored. A folder for each design is created in the project directory, and all input and output file(s) along with additional files like screenshots are kept unless explicitly tagged to be temporary. In this way, every variant can be studied afterward either within CAESES® or externally as if the design team had executed all simulations one by one and by hand. Hence, all data are open and accessible.

When doing manual design work, there are two convenient ways to use the system. Naturally, one can change settings and values for the baseline itself. This is quite common when building the hierarchical model and connecting to simulation codes. However, as soon as the synthesis model is established and a good starting point has been reached it may be of interest to keep that status as reference. In this situation, one can manually derive variants from the baseline for which all free variables and, possibly, any other parameter and/or relationship can be changed. The advantage is that the baseline is not touched, and hence, the design team is able to try out promising variants and use the baseline, or any of the variants, for comparisons. It should be noted that, in order to keep the storage requirements low, for each variant, only the changes to the baseline are stored within a CAESES® project. When doing automated optimization studies, the exploration and exploitation strategies discussed in Sect. 8.6 are put to use.

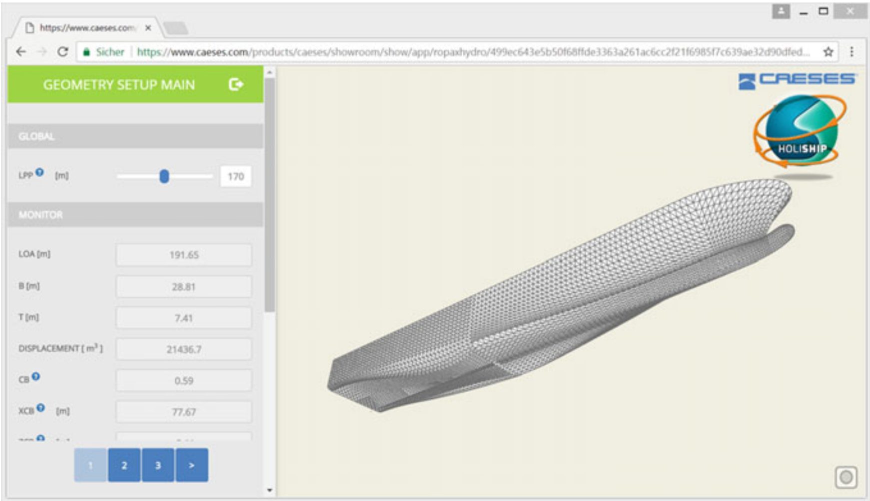
8.8.2 Offers via WebApps

In principle, any functionality that CAESES® offers and any tool that has been coupled to CAESES® can be made available as a technical application via the Web. These so-called WebApps, as discussed in Harries (2017) and Harries et al. (2018), enable access of sophisticated models and simulations through a Web browser. The aim of WebApps is to define meaningful workflows, configured in advance by an expert, that are easy to use by a designer. In that sense, a WebApp constitute a domino as introduced in Sect. 8.2.5.

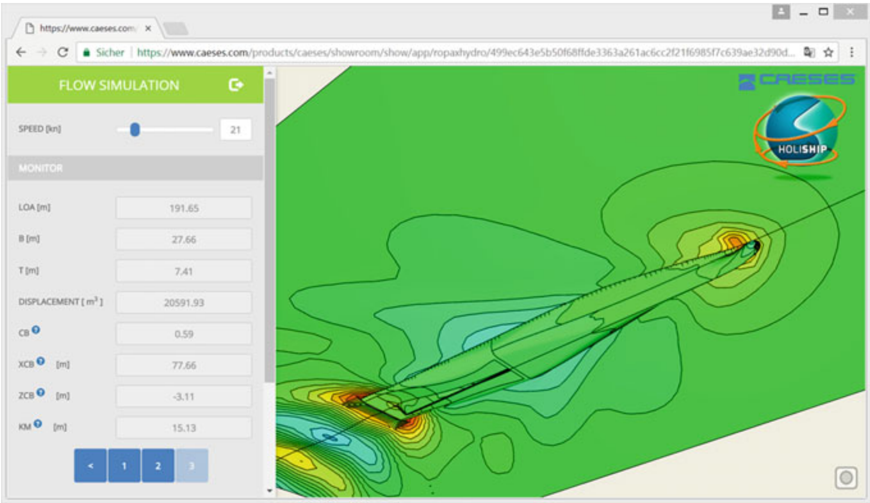
Naturally, the use case of a technical app is, by definition, somewhat confined. Essentially, the user shall be relieved from specialist knowledge associated with a certain tool but shall be put into the position of quickly producing reliable results for a specific task within given guard rails.

Of course, this is quite different to building and running synthesis models within a holistic approach that supports a range of workflows. However, the idea is that dedicated tools can be spread more widely and that, potentially, a future market place for a range of tools and associated services would help connecting designers, tool providers, and consultants. A number of technical apps could then form the basis for solving a more complex task.

Figure 8.29 illustrates a WebApp in which HSVA's non-linear potential flow code, ν-Shallo, is made available for analyzing a RoPAX ferry with regard to its wave resistance at various speeds. The topology of the hull—here a classic monohull as introduced in Sect. 8.3.1 with bulbous bow, transom stern, center skeg, and twin-screw arrangement—is static while the main dimensions and several local parameters can be changed within predefined bounds. Upon setting the accessible parameters as shown in Fig. 8.29a, CAESES® generates the geometry along with a suitable panel



(A) First page of the webApp, allowing the modification of the parametric model



(B) Third page of the webApp, allowing to choose vessel speed and launch ν-Shallo

Fig. 8.29 Resistance analysis of a RoPAX ferry via a WebApp (http://www.holiship.eu/approach)

mesh. As soon as the shape has been finalized a flow simulation can be triggered, yielding the resistance, the pressure distribution and the wave field as shown in Fig. 8.29b.

It should be noted that a standard browser acts as a front-end, replacing the detailed GUIs of CAESES® and the integrated code(s). For the Web-based application depicted in Fig. 8.29, the computations are run on a remote server. Alternatively, a local setup can be provided, for instance, to assist less experienced members of staff with ready-to-go solutions prepared by a specialist within the team or by an external consultant.

8.9 Outlook

8.9.1 Meta-Projects

As can be imagined the complexity of projects that address the design of maritime assets holistically is high. For each simulation code that is integrated many parameters are involved, quite a few data items need to be provided and a lot of data are produced.

By using surrogate models the complexity can readily be reduced since a limited number of inputs typically lead to a small number of outputs as elaborated in Sect. 8.7. In addition, current development work for CAESES® aims at a plug-and-play approach in which projects can become part of an encompassing larger project, a so-called meta-project. Using one or several CAESES® instances in batch mode out of a CAESES® project that subsequently acts as the controlling platform is already possible as discussed in Sect. 8.5.4. Yet, an effort is made to further simplify the registration, execution, and data exchange between CAESES® projects, paving the path for providing, using and exchanging dominos conveniently and quickly.

8.9.2 Community of Providers, Consultants and Users

Taking a longer perspective, tool providers, consultants, and users are all believed to benefit from an open and flexible integration platform. Naturally, a certain market place would need to be created on top of the technical integration. While this is not part of the developments within HOLISHIP itself, the R&D project may serve to provide a critical mass of interested parties.

A market place would have to ensure that

- tools and services are made available
- can be booked and rendered as well as
- paid while
- intellectual property rights (IPR) are observed.

Furthermore, access rights and bidding techniques would have to be considered. This could democratize the access to tools, help the formation of temporary design teams across company boundaries and, as a consequence, lead to a growing network of stakeholders that may work together more swiftly and concurrently.

As an example, if a design team is interested in developing a new vessel for which they do not have reliable hydrodynamics data at their disposal, they could acquire an existing surrogate model for the ship type in question, if available, or solicit for a consultant to build a model on their behalf. Similarly, consultants could anticipate a certain market demand and offer numerical hull series proactively. As another example, tool providers, be it companies or academic institutions, could offer their solutions more flexibly, reducing the threshold for non-expert users, and thereby increasing their group of potential clients and beneficiaries.

8.10 Conclusions

The European R&D project HOLISHIP addresses the integration and utilization of simulation tools from all disciplines relevant for the design of maritime assets. The tools come from different providers, use their own licensing schemes, and typically run either under Windows® or Linux™. Most tools have been developed over many years and are continuously worked on. In order to benefit from this vast pool of resources and expertise, a flexible and extendable integration approach has been favored. Consequently, CAESES® as a generic process integration and design optimization environment was chosen for the coupling of tools and the ad hoc definition of synthesis models.

A bottom-up approach is taken in which data are stored and exchanged only as actually needed for the design task at hand. Different to deploying a single legacy system this means that new tools and additional data can be quickly introduced and (re)combined, either by the tool providers or by the users themselves, as design tasks evolve and/or change. The integration requires that a tool can be run in batch mode. Input and output files are utilized as templates and only those data items that need to be varied, read, exchanged, or stored are addressed. Data that are used by just one single tool and that are not needed for design and optimization are not stored centrally but only kept and managed locally.

CAESES® acts as both a PIDO environment and a CAD system. The CAD technology within CAESES® aims at variable geometry for design and engineering as opposed to CAD for production. The system fully supports the definition of parametric models and of hierarchies. Dependencies between tools can be established so as to trigger automatic updates, ensuring consistency throughout both manual and automatic studies.

Within CAESES® a parametric model and a set of integrated tools constitute a synthesis model. Synthesis models are dedicated to scenarios within a certain scope such as the design of a twin-screw RoPAX ferry or the development of an offshore supply vessel for safe crane operations under DP. It can be run either interactively or automatically. Tools are triggered in parallel or, if one tool requires input from another tool, in the sequence of their dependencies. Furthermore, CAESES® supports the substitution of time-consuming and/or expensive simulations by means of surrogate models. Within acceptable accuracy levels, this enables a team of designers to run large investigations (several thousands of variants) both conveniently (even if not all tools are locally available) and quickly (within just a few hours).

Very importantly, CAESES® readily supports formal optimization campaigns. To this end, it provides a range of strategies for both exploration (e.g., Sobol) and exploitation (e.g., MOGA), triggers the execution of external simulation tools, collects results, manages the variants, and offers advanced methods of design assessment.

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Chapter 9
Structural Design Optimization—Tools and Methodologies

Philippe Rigo, Jean-David Caprace, Zbigniew Sekulski, Abbas Bayatfar and Sara Echeverry

Contents

Abstract This chapter focuses on methodologies to perform ship structure optimization, decreasing steel weight and keeping the production cost at an acceptable level. Ship performance is always an important concern when a design is started, and should always be considered for new designs. This is in line with the evolution of ship

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classes and size. For this reason, several aspects are important to be taken into account within the optimization procedure, and therefore, multi-objective optimization is the common route. This chapter outlines actual trends in optimization methodologies, comments on the quality assessment of the obtained Pareto solutions and describes modern tools used in/by the maritime industry (with focus on the LBR-5, BESST and HOLISHIP projects). The importance of consideration of risk assessment in the structural design optimization procedure (e.g. of a ship collision with an offshore structure) is also elaborated with a highlight on the response surface method and its use in combination with optimization algorithms for ship and offshore structures in early design stages.

Keywords Holistic ship structural design · Multi-objective optimization
Pareto optimal dominance · Optimization algorithms · Integration sets
Quality assessment

9.1 Introduction

The achievement of improved performance, including several aspects related to ship's structure, is fundamental to the evolution of ship classes and size for different types of cargo and services. Examples of structural performance contribution to overall ship engineering and economic performance include the following:

1. Higher-performance structures in terms of reduced weight with higher degrees of safety and reliability;
2. Lower fabrication costs;
3. Better economic performance through a lower lightship weight, and hence, larger payload fractions;
4. Reduced structural maintenance costs over the life cycle;
5. Recognition of social responsibility in terms of environmental protection, collision/damage tolerance, reduced risk of failure, etc.
6. High returns on investment.

The desire to take into account all the above-mentioned aspects means that real ship structural design or ship structural decision-making problems involve the simultaneous optimization of *multiple conflicting objectives*. Single-objective problems in practice are rare, and they are in most cases the idealization and simplification of multi-objective problems. This is one of the ways to simplify and/or speed up the calculations.

A multi-objective optimization problem is defined as such when the goal is to simultaneously minimize or maximize several objective functions with one objective often conflicting with another (e.g. high structural strength and reliability vs. low structural weight, high structural strength and reliability vs. low production costs combining material and labour). In case of ship structural design, such problems may be subject to constraints, all related functions may be nonlinear, and design

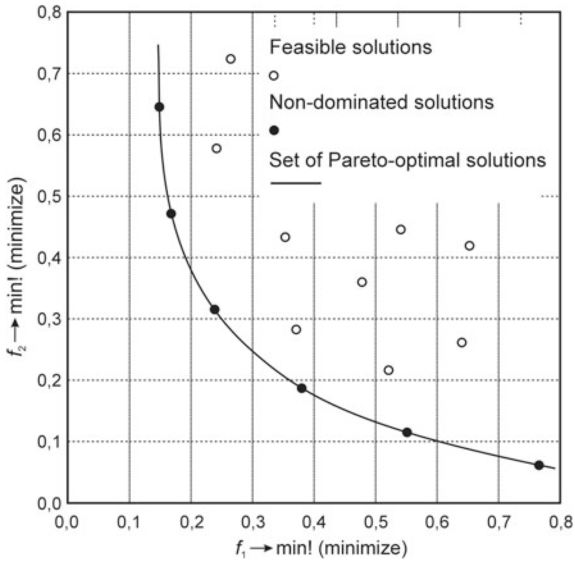


Fig. 9.1 Graphical illustration of a set of Pareto optimal solutions

variables may be discrete. In such cases, the same optimum values of design variables are unlikely to result in the best optimal values for all the objectives. Hence, some trade-offs between the objectives are needed to ensure a satisfactory design.

Because ship structure efficiency indices may differ (and be mutually contradictory), it is reasonable to use the multi-objective approach to optimize the overall ship structural efficiency (e.g. weight, costs, deflection, reliability). This can be done mathematically correctly only if a principle of optimality is used, for instance, a Pareto optimality concept (Pareto 1896). The solution to the multi-objective optimization problem is considered Pareto optimal if no other better solution satisfies all the objectives simultaneously. In other words, there may be other solutions that better satisfy one or several objectives, but they must be less satisfactory than the Pareto optimal solution in satisfying the remaining objectives. In that case, the result of the multi-objective optimization problem is finding a full set of Pareto optimal solutions; see Fig. 9.1.

As a rule, because of cost as well as time resources, it is impossible to find a full, numerous or even infinite, set of Pareto optimal solutions for particular real-life ship structural problem. Therefore, the aim of a ship structural multi-objective optimization problem is to determine a finite subset of objectives-distinguishable Pareto optimal solutions. A task of the multi-objective optimization is thus the appropriate identification of the set of "best possible compromises" or the single "best possible solution".

If we focus on the ship structure itself, we can say that a primary target of the ship structural optimization is to find the optimal space localization (*topology optimization*), shapes (*shape optimization*) as well as scantlings of structural elements (*scantling optimization*) for an objective function subject to constraints. Formally, selection of structural material (*material optimization*) can also be treated as a part of the optimization process; nevertheless, selection of the structural material is usually not an explicit optimization task, but it is rather done according to the experience and capability of a shipyard. Systematic optimization procedures for the selection of structural material are applied directly only in rare cases.

Due to the following practical problems,

(1) Lack of information about the actual localization of non-dominated solutions set and
(2) Necessity to deploy significant computational resources to solve the multi-objective optimization problem; the main effort in the practical multi-objective optimization of ship structures is directed at determining the acceptable approximation of Pareto set instead of accurate composition of this set. With regard to this, it can be assumed that in practice the result of a ship structural multi-objective optimization process is a set of non-dominated solutions called shortly the approximation of Pareto set and not the exact Pareto optimal solutions set. Practical formulation of ship structural multi-objective optimization problem and of attained results should follow this guideline.

9.2 Trends in Optimization Methodologies

Considering dimensioning of ship structural components,[1] the bases for the structural optimization are either requirements of classification societies published as classification rules or more rational approach based directly and fully on the structural mechanics for capacity assessment of designed structures. Regardless of occasionally formulated criticism of the classification rules, as a tool not meeting the designers' expectations, in case of designing innovative concepts, their application in case of conventional ships is fully satisfactory. From practical point of view, estimation of dimensions of structural components determined only according to the requirements of a classification society enables quick and automatic dimensioning of many structural variants by an optimization algorithm. It is also possible to use more complex, rational methods, e.g. finite element methods; this entails however a considerable computational effort for analysing all generated test solutions.

In general, the methods used for the solving of multi-objective optimization tasks may be divided into two basic groups:

1. *Classical methods* based mainly on a conversion of the original problem with multiple-objective into a single-objective optimization problem; this is called a scalarized problem;
2. *Heuristic algorithms*, often inspired by natural systems (e.g. genetic algorithms, evolutionary strategy, Tabu search, simulated annealing, ant algorithm).

[1]By structural dimensioning of ship structure, we refer to the process of determining loads and loads combination on a structure, the material properties, scantling of structural components and their effects on structure, with the goal of ensuring a safe ship structure.

Classical methods use advanced mathematical methods for accurate solution of formulated optimization tasks; very often, it is necessary to simplify the task (e.g. linearization, continuity). These methods based on an aggregation of the vector objective function have been used in wide-ranging applications also in heuristic methods of multi-objective optimization.

The aggregation methods have been found promising again with the hope to developing simple and intuitive algorithms for problems with a large number of the optimization objectives. Fundamental disadvantages of methods from this group are:

- Seeking only a single point on the non-dominated solutions front and resulting necessity to make numerous calculation runs for the single optimization task;
- Sensitivity of some solutions to the shape of non-dominated solutions front.
- The fact that expert's or decision-maker's knowledge is required at the beginning to specify the weight coefficients used for component optimization objectives.[2]

Heuristic algorithms are designed to solve problems in a faster and more efficient fashion than traditional methods by sacrificing optimality, accuracy, precision, or completeness. In these problems, there is no known efficient way to find a solution quickly and accurately although solutions can be verified when given. Heuristic algorithms can produce a solution individually or be used to provide a good baseline and are supplemented with classical optimization algorithms. They usually do not require advanced mathematical procedures and the necessary simplifications. Heuristic algorithms are most often employed when approximate solutions are sufficient and exact solutions are necessarily computationally expensive.

In a group of heuristics algorithms, there are evolutionary algorithms: a class of stochastic optimization methods that simulate the process of natural evolution. Until today, several evolutionary optimization algorithms have been proposed, mainly genetic algorithms, evolutionary programming and evolution strategies. Methods based on aggregation of the objective function are also used in a many evolutionary multi-objective algorithms.

Methods based on aggregation of the objective function are considered less effective in the evolutionary multi-objective optimization. Nevertheless, the researchers have reported for several years that if the number of the optimization criteria is greater than 3, the methods based on the domination relation turn to be ineffective, since together with the increase in the number of optimization criteria, the number of non-dominated variants decreases reducing the effectiveness of the selection operator (e.g. Hughes 2003; Purshouse and Fleming 2003; Jaszkiewicz 2004; Hughes 2005).

The aggregation methods have been found promising again with the hope to:

(1) Develop more simple and intuitive algorithms than algorithms based on the domination relation, obtaining expertise on the multi-objective ship structural optimization.
(2) Develop effective algorithms for problems with a large number of the optimization objectives.

[2]Classical scalar algorithms with random weighting coefficients are also used.

Attempts to ship structural multi-objective optimization are not numerous. Initially, the concept of Pareto dominance was not used and systematic exploration of solution space was not performing to obtain a set of non-dominated solutions. Moe and Lund (1968) presented a two-objective optimization of the cost and weight of the oil tanker hull structure. The results of the calculations were graphs showing changes in the optimization criteria for decision variables. Rahman (1992) and Rahman and Caldwell (1995) presented results of cost and weight optimization of inland waterway ship structure. Jang and Shin (1997) used an evolutionary strategy for multi-objective optimization of tanker structure in terms of weight and cost. Applying an evolutionary strategy to multi-objective optimization has allowed finding a set of non-dominated solutions. Jang and Shin (1997) is probably the first publication showing the results of a search for a set of non-dominated solutions in the task of multi-objective optimization of ship hull structure. Yang and Hwang (2002) used a genetic algorithm to optimize the shape of the corrugated bulkhead in terms of weight and cost of structure, but did not look for a set of non-dominated solutions. Klanac and Kujala (2004) used a genetic algorithm to optimize naval sandwich panels in terms of weight and cost. Shin et al. (2006) used an evolutionary strategy for multi-objective optimization of tanker structure in terms of weight and cost. Klanac and Jelovica (2007) used a genetic algorithm for optimization of the structure of a high-speed passenger–car ferry in terms of weight and height centre of gravity. Jelovica and Klanac (2009) used a genetic algorithm to optimize the structure of a chemical tanker. Caprace et al. (2010) presented results of optimization of LNG tanker structure. For optimization, they used the deterministic linearization method of the nonlinear optimization task and the aggregation of the optimization objectives with suitably choosing weighting factors. More recently, Sekulski (2014) used various strategies of a multi-objective genetic algorithm to optimize the structure of fast passenger–car ferry.

The multi-objective evolution-based (heuristic) optimization algorithms have been tested on simple problems of ship structural multi-objective optimization (e.g. Okada and Neki (1992)—genetic algorithm, Jang and Shin (1997)—evolutionary strategy, Hutchinson et al. 1998—genetic algorithm, Kitamura et al. (2000)—genetic algorithm, Klanac et al. (2009)—genetic algorithm, Sekulski (2010)—genetic algorithm, Cui et al. (2012)—multi-objective particle swarm optimization and the multi-objective genetic algorithm, Cui and Wang (2013)—multi-island genetic algorithm, Ehlers and Kujala (2013), Pedersen et al. (2014)—particle swarm optimization, Na and Karr (2016)—genetic algorithm, Fu et al. (2012)—adaptive simulated annealing, Sekulski (2014)—multi-objective genetic algorithm with combined fitness function.). As no systematic research into the suitability of these algorithms for the solving of optimization problems involved in the design of ship structures has been carried out so far, then the application of a particular method should be preceded by systematic investigations into its effectiveness in the problems involved in the design of such structures.

As it appears from the review presented by Colette et al. (2015), the majority of the works are concerned with the use of randomized algorithms to ship structural multi-objective optimization. As it comes to works focusing on multi-objective optimization, most authors report the use of genetic algorithms. Much less teams reported that they had used a particle swarm optimization algorithm or a simulated annealing algorithm.

There are various criteria that can be used for assessment of the effects of optimization in designing ship structures. An optimally shaped structure can be compared to a design made by an experienced designer. However, certain difficulties are to be expected here. Thus, for certain typical simple structures, the optimization effects amount to a few percentage points, whereas for more complex and untypical structures, such effects may amount to a dozen or so per cent.

Because running an optimization process would extend the design stage's duration and increase its cost, the conclusion is that optimization is only meaningful in the case of manufacturing series of structures or their elements in which even a slight percentage unit profit will yield large-scale global savings and in the case of untypical costly structures, for which substantial unit savings will thus be secured (Colette et al. 2015).

Summarizing, it can be concluded that the successful search for approximation sets of ship structures, without being simplification necessary for application of an advanced mathematical procedures to solving problems formulated, enabled only the use of evolutionary multi-objective optimization algorithms in the end of the twentieth century and that in most discussed ship structure optimization cases, two optimization criteria were adopted—weight and production cost of structures.

9.3 Optimization Tools

Calculation tools used for solving multi-objective optimization problems may be divided into three groups:

1. In-home computer codes developed by researchers for his own use only;
2. Universal commercial codes designed to solve problems in many areas that can be adapted to solve ship structural multi-objective optimization problems (e.g. PTC Mathcad, MathLab, modeFRONTIER);
3. Computer codes specially developed for solving ship structural multi-objective optimization problems (e.g. LBR-5, MAESTRO, OCTOPUS, CONSTRUCT).

Codes belonging to the last group can be characterized as follows:

- LBR-5—for optimization of ship structures at the conceptual design stage in terms of cost, weight and stiffness (e.g. Rigo and Fleury 2001; Rigo 2001a, b, 2003).
- MAESTRO—the software combines rapid ship-oriented structural modelling, large-scale global and fine mesh finite element (FE) analysis structural failure evaluation; scantlings and topology optimization.
- OCTOPUS—for simplified finite element method (FEM) response calculations at concept design phase, ultimate strength and system reliability evaluations combined with a set of optimization solvers (e.g. Zanic et al. 2002, 2013a, b; Zanic and Prebeg 2004; Stone and McNatt 2017).

- CONSTRUCT—for structural assessment and optimization of ship structures in the early design stage of ships; the software applies the coupled beams method for evaluation of the structural response and the fundamental failure criteria (e.g. Klanac and Jelovica 2007; Klanac et al. 2009).

9.4 Quality Assessment of the Pareto Solutions

We already know that algorithms used in practice to ship structural multi-objective optimization usually generate a finite set of non-dominated, in the Pareto sense, solutions approximating the true Pareto frontier of the formulated task. Consequently, a method is needed that will effectively enable the assessment of quality and comparative studies of such approximation sets.

In case of a multi-objective optimization problem, the primary purpose of the decision-maker is to generate a set that approximates Pareto front. In final, the decision-maker will choose from the approximation set assumed as the best one, a single solution that best suits his or her preferences, the so-called *best compromise*. For this purpose, it is necessary to use information relating the quality of non-dominated solutions and not included directly in the optimization algorithm. This selection may be supported by interactive procedures. Parsons and Scott (2004) discussed a methodology to help design teams select the best solution from a set of excellent Pareto solutions with a minor additional computation cost.

The decision-maker's preferences relating to the quality of the approximation sets are not known prior to starting to formulate and solve a ship structure multi-objective optimization problem. It is not known, for example, how many non-dominated solutions can be expected in a good quality approximation set. The decision-maker may have more freedom to explore the solution space, but only when assumptions from the use of heuristic algorithms to generate approximation sets can be justified by the lack of formulated preferences.

It can be seen that the complexity of the solved problems, complex models and the large computational effort usually result in satisfaction of the authors to obtain any approximating set, considering such a solution as satisfactory. Caprace et al. (2010), Rigo and Caprace (2011), Richir et al. (2007) and Shin et al. (2006) presented a single approximation set, while Liu and Collette (2015), Cui et al. (2012), Klanac et al. (2009), Na and Karr (2016), Jelovica and Klanac (2009) and Sekulski (2014) presented more than single approximation sets. However, they did not discuss their quality.

The most natural method of comparing the quality of sets of Pareto optimal solutions is to use the concept of *Pareto dominance*; see Fig. 9.2. This concept forms the foundation for the concept of Pareto optimality and the most commonly used calculation algorithms. Using this concept, Hansen and Jaszkiewicz (1998) formulated the different variants of outperformance relations. These relations allow formulation of the conclusion that one approximation set is better than the other in terms of the relation of Pareto dominance. These relationships, however, do not assess the degree

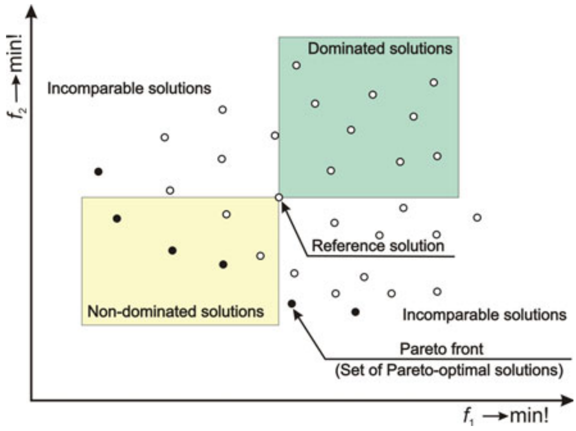


Fig. 9.2 Graphical illustration of possible relations between solutions in the 2D objective space according to Sekulski (2010); the solutions dominated by a reference solution and the solutions dominating it are highlighted; solutions non-dominated by any other ones belonging to the set constitute a set of Pareto optimal solutions

of outperformance and cannot be applied to any pair of approximation sets. Using the above assumptions, it can be stated that the approximation *A* (meaning approximation set *A*) outperforms (is better than) approximation *B*, if for some possible preferences expressed by the decision-maker, he or she can find a better compromise in *A* than can be found in *B*, and for other possible preferences, the solutions found in *A* will be no worse than those found in *B*.

The size as well as internal structure of the approximation set depends on the settings used to run the optimization algorithm. More detailed information regarding the importance of using good quality metrics to evaluate approximation sets may be found in dedicated literature (Knowles and Corne 2002; Zitzleret al. 2002; Bosman and Thierens 2003; Jaszkiewicz 2004; Zitzler et al. 2008). As explained by Knowles and Corne (2002) and Zitzler et al. (2003), no single quality metric can simultaneously evaluate different aspects of an approximation set. The quality metric used should therefore be tailored to the appropriate quality required in the investigation.

Zitzler et al. (2000) listed the following quality attributes of approximation sets (see Fig. 9.3):

1. *Convergence* of the solutions to the true Pareto front;
2. *Diversity* of non-dominated solutions crossing the trade-off surface in the objective space;
3. Their *spread* in the objective space.

According to Sayin (2000), there are three aspects of interest for evaluating a discrete representation of the approximation set: (1) *coverage*, (2) *uniformity* and (3) *cardinality*. These quality attributes may be interrelated in practice. At this point, we mention that finding a "good" set of solutions to a multi-objective optimization of ship structure problem consisting of *k* objectives can be more accurately thought of as an optimization scenario with $k+q$ objectives. These $k+q$ objectives are divided into *k* ship structure-specific objectives and *q* general objectives related to the quality of

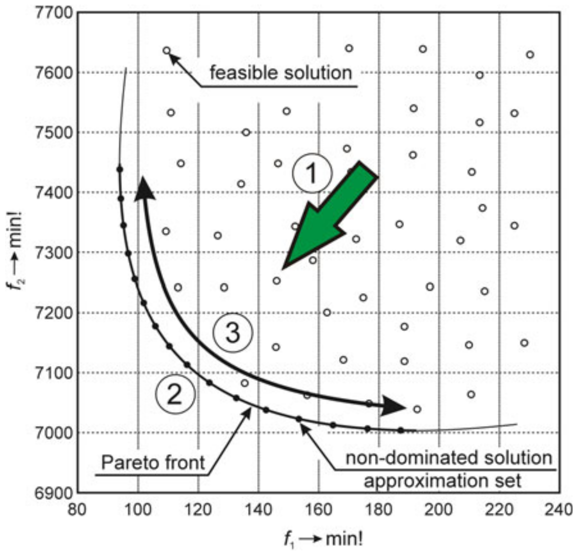


Fig. 9.3 Graphical presentation of quality attributes of approximation sets according to Zitzler et al. (2000): ① convergence, ② diversity, ③ spread

an approximation set ($q = 3$ for both Zitzler et al. (2000) and Sayin (2000) proposals, for example).

The existence of the objective preferences and priorities, and their incorporation in the multi-objective optimal ship structure search process has not been used in practice so far. Nevertheless, one thing remains consistent: the *convergence* criterion is usually prioritized over the *diversity* criterion. As a result, diversity promotion is usually deployed as a secondary consideration to proximity promotion in most multi-objective optimization algorithms. This is well justified since, as stated by Bosman and Thierens (2003): "… the goal is to preserve diversity along an approximation set that is as close as possible to the Pareto optimal front, rather than to preserve diversity in general; the exploitation of diversity should not precede the exploitation of proximity".

In most cases, multi-objective optimization problems in ship structures design are solved in two steps: (1) determining a set of compromises/trade-offs (Pareto optimum); approximating set; (2) selection of the preferred solutions/variants/candidates from the set of compromises. Such an approach corresponds with the Pareto supported decision-making (PSD) strategy. An example of such a methodology is presented in Fig. 9.4.

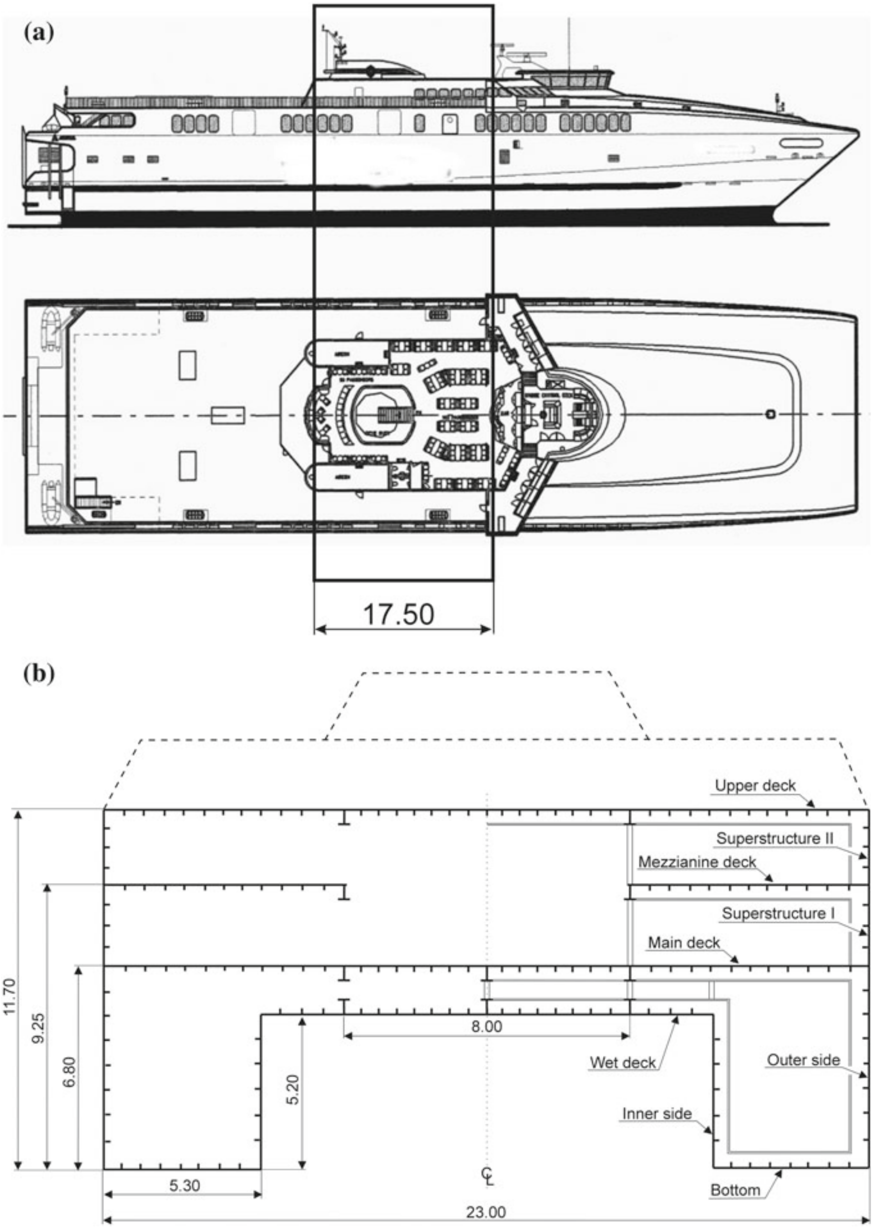


Fig. 9.4 Multi-objective optimization of ship hull structure: **a** longitudinal section of a case ship; **b** mid-ship section model; **c** approximation sets containing the non-dominated variants of the ship hull structure produced in six computer simulations sym1-1, sym1-2,…, sym2-3; **d** set of non-dominated solutions in the unit of approximation sets; **e** detailed specification of the reference set as a solution of multi-objective optimization task; set of compromises/alternatives/variants as a result of ship hull structural multi-objective optimization; according to data from Sekulski (2014)

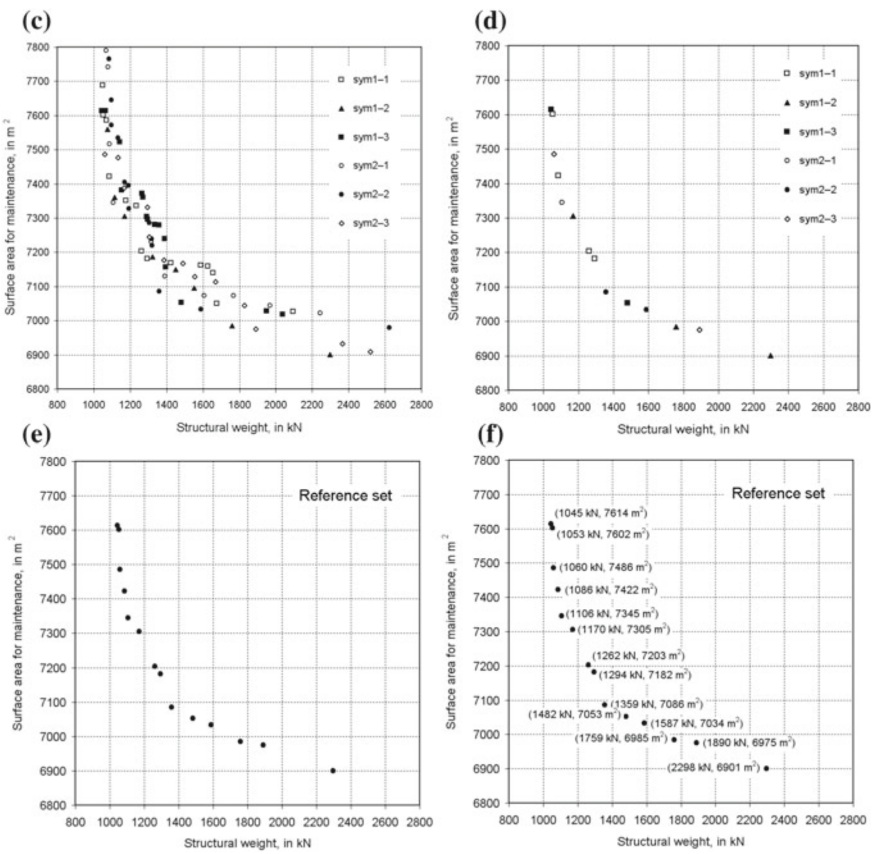


Fig. 9.4 (continued)

9.5 LBR-5: A Least Cost Structural Optimization Method

To be attractive to shipyards, scantling optimization has to be performed at the preliminary design stage. It is indeed the most relevant period to assess the construction cost, to compare fabrication sequences and to find the best frame/stiffener spacing's and most suitable scantlings to minimize ships life cycle cost. However, at this stage of the project, few parameters (dimensions) have been definitively fixed and standard FEM is often unusable, particularly to design offices and modest-sized shipyards. Therefore, an optimization tool at this design stage can provide precious help.

This is precisely the purpose of the LBR-5 optimization software, Rigo (2001b) and Rigo and Fleury (2001). The structural analysis is performed on a model based on an extrusion of the cross section of the structure (2D+) solving the stiffened plate differential equations with Fourier series expansions, Rigo (2003).

The LBR-5 structural optimization model is composed of several modules and is made up of three key modules (objective function, optimization algorithm and structural constraints, as shown in Fig. 9.5), which forms the framework of the

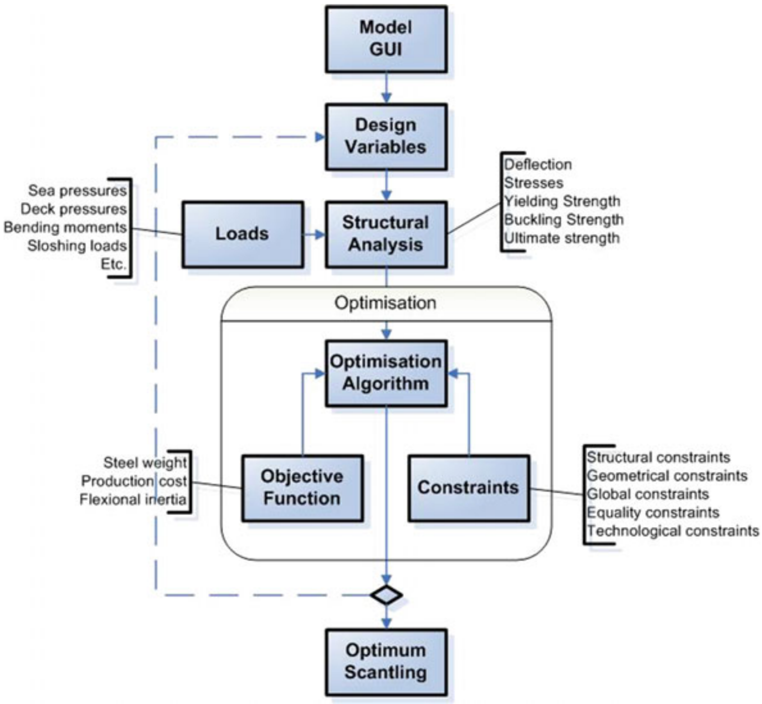


Fig. 9.5 Flow chart of the LBR-5 optimization software Rigo (2001b, 2003)

optimization tool. Around the objective function and constraints modules, there are a large number of submodules. Each of these submodules is specific to a type of constraint. An example of an optimization of a cruise ship is presented by Rigo et al. (2017).

9.6 BESST Project

9.6.1 Motivation

Shipbuilding and shipping market along with the society have been increasingly facing conflicting needs and requirements such as safety improvement, reducing environmental impact, flexible use for varying operational conditions, decreasing/improving life cycle cost/performance. This is while such a significant growing demand must be fulfilled in a very high competitive level. This calls for an efficient–effective multidisciplinary and multi-objective design optimization platform to be launched in early design stage of traditional ship design process.

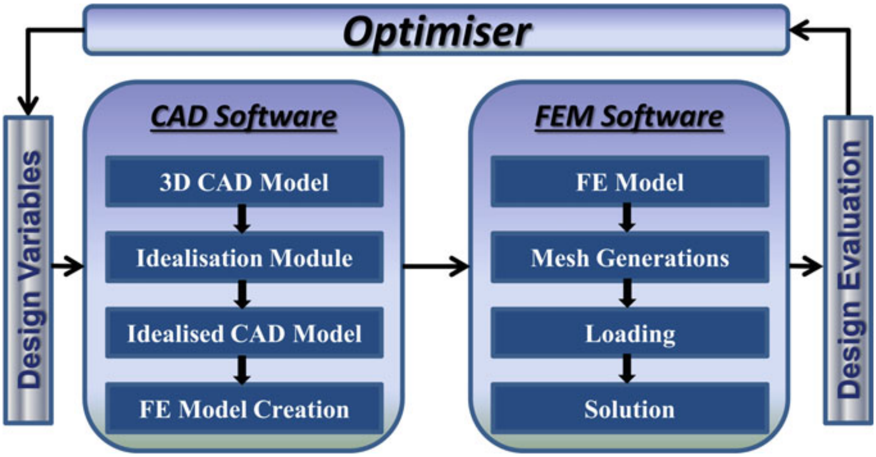


Fig. 9.6 Schematic of optimization workflow (Bayatfar et al. (2013); rebuilt version)

This chapter presents a development which was initiated in the framework of European project BESST.[3] "Breakthrough in European Ship and Shipbuilding Technologies" (BESST) is one of the main early European projects that initiated a contribution to the subject area. It concerns advanced structural assessment-optimization supported by CAD/FEM for early structural design purposes.

University of Liege (Bayatfar et al. 2013) assessed the feasibility of an integration of AVEVA Marine® 12.0.SP6.39[4] as CAD software, ANSYS® Classic 14.0[5] as FEM software and modeFRONTIER® 4.4.2[6] as an optimization tool to obtain a full automatic optimization package of the scantling spacing of ship structure in component level.

As it is schematically shown in Fig. 9.6, a 3D CAD model is first transferred from the CAD software to an idealization module. Then, the idealization module generates a simplified geometry taking into account the FEM needs. After that, the idealized CAD model is transferred to the FEM software to create its FE structural model including required boundary conditions and loads. The FE analysis is performed, and its obtained results (i.e. stress, weight) are transferred to the optimization tool. The optimizer evaluates the values of the objective function and the constraints previously defined and modifies the design variables (i.e. plate thickness, stiffener scantling, stiffener spacing) to create a new structural model going to the next iteration of optimization loop. This process continues until a convergence is attained, and a set of best solutions will be available for designer/yard to decide the most suitable one.

[3] http://www.besst.it.

[4] http://www.aveva.com.

[5] https://www.ansys.com.

[6] http://www.esteco.com.

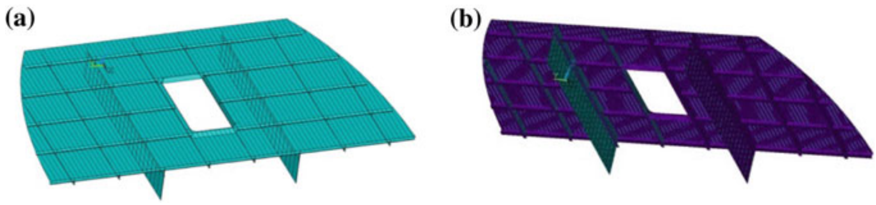


Fig. 9.7 **a** Deck structure model. **b** Typical mesh generation (Bayatfar et al. 2013)

9.6.2 Model for Study

A typical deck structure was taken into consideration to evaluate the iterative process within the workflow using AVEVA Marine, ANSYS and modeFRONTIER. The deck structure model built in AVEVA Marine (Fig. 9.7a) was constituted a deck plate, longitudinal girders, transversal frames, longitudinal stiffeners placed between girders and two longitudinal walls along with its stiffeners. The longitudinal stiffeners placed between girders and the stiffeners placed on two longitudinal walls were taken into consideration as beam members.

The deck structure was made of mild steel having Young's modulus, Poisson ratio and yield strength equal to 206, 0.3 and 235 GPa, respectively. Figure 9.7b shows a typical mesh generation done by ANSYS in which SHELL63 and Beam 44 were selected to, respectively, discretize the plate and beam members. The boundary conditions were assumed to suppress the displacements along x-, y- and z-directions at fore and aft sides. The FE analyses were made based on a lateral pressure that acts on deck plate, with the value of 0.02 MPa.

9.6.3 Optimization Workflow Description

The design variables used in the optimization loop along with their lower and upper bounds are given in Table 9.1.

- A typical set of geometrical constraints such as given below was implemented in the optimization workflow (Fig. 9.8—ellipse outline). Web thickness of stiffeners to be less than the double of the deck plate thickness.
- The deck plate thickness to be less than the double of web thickness of stiffeners.
- Web height of frames to be greater than the web height of stiffeners.

Figure 9.8 describes more details concerning the optimization workflow. As it is shown in red outline, AVEVA Marine is first launched to create FEM model and to export it to ANSYS Classic input file (APDL file). Then, the automatic loading tool shown in orange outline combines the provided APDL file with the file included mesh generation, boundary and loading conditions, in order to be read by ANSYS Classic.

Table 9.1 Design variable limits

Member	Design variable	Min (mm)	Max (mm)
Deck	Plate thickness	5	40
	Long stiffener profile	HP80x6	HP430x20
	Numbers of stiffeners (between girders)	5	15
Transversal frame	Web height	200	1000
	Web thickness	5	40
	Flange breadth	50	500
	Flange thickness	5	40
Longitudinal girder	Web height	200	1000
	Web thickness	5	40
	Flange breadth	50	500
	Flange thickness	5	40
Longitudinal wall	Plate thickness	5	40
	Stiffener profile	HP80x6	HP430x20

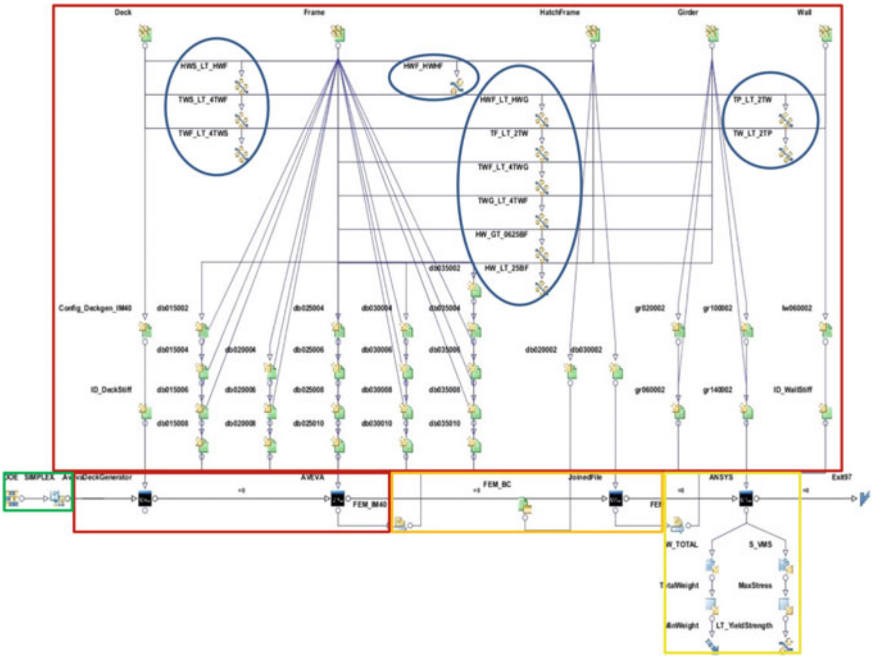


Fig. 9.8 Optimization workflow (Bayatfar et al. 2013)

After that, the FE analysis is done and the required results are provided in the result extraction module shown in yellow outline. In this module, the weight of the structure was defined as objective function to be minimized. And, as a structural constraint, maximum von Mises stress was imposed to be less than the yield strength of the material.

Finally, the obtained results for the objective function and the constraints previously defined are transferred to the optimizer tool (shown in green outline) to be evaluated, in order to modify the design variables and to create a new structural model going to the next iteration of optimization loop. This process continues until a convergence is attained, and a set of best solutions will be available for designer/yard to decide the most suitable one.

9.6.4 Results and Discussion

The optimization workflow was launched using a SIMPLEX algorithm. The communication between all integrated software and tools was successfully tested, fully in an automatic iterative process. The convergence of the solution was obtained after 246 iterations. The total calculation time per run, using the machine with Intel® Core ™ i7 CPU 860 @2.80 GHz and RAM 12.0 Go., was about one minute. The total run took about 4 h.

Figure 9.9 shows the convergence histories of the objective function (i.e. the total weight of the structure) and the structural constraint (i.e. the maximum von Mises stress) by a multi-history chart. The optimum is reached after 209 iterations.

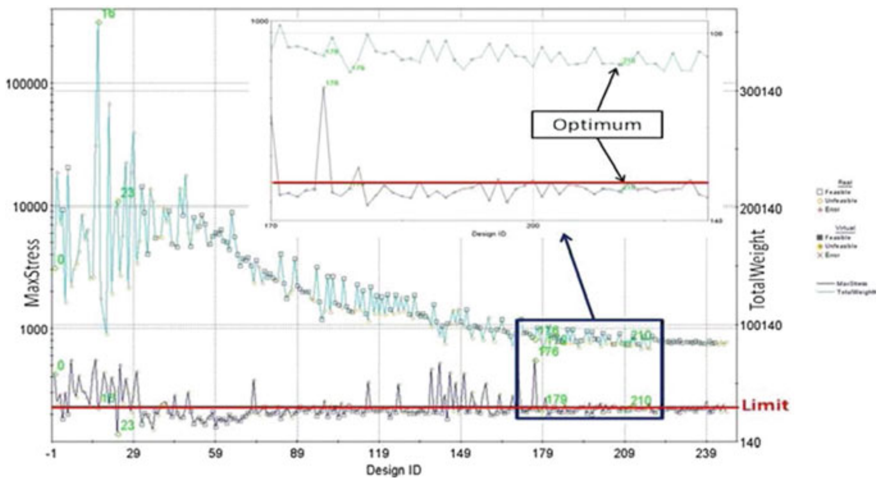


Fig. 9.9 Convergence histories of the objective function and the maximum von Mises stress (Bayatfar et al. 2013)

In other words, the optimum solution is achieved at the iteration 210 in which the total weight of the structure is 83661.9 kg, and the maximum value of the von Mises stress is 220.4 MPa. The total weight of the structure and the maximum value of the von Mises stress, respectively, decrease up to 44 and 49%, compared with the original configuration. This can be seen more clearly in Table 9.2 through which the optimization results are given in detail for some iterations, i.e. 0, 16, 23, 176, 179 and 210.

- 16 (at which the total weight of the structure is at the highest level);
- 23 (at which the maximum value of the von Mises stress is at the lowest level);
- 176 (at which the maximum value of the von Mises stress is at the highest level);
- 179 (at which one geometrical constraint is not respected, although the total weight of the structure is lower than the optimum solution and the maximum value of the von Mises stress is less than the limit);
- 210 (at which the optimum solution is reached).

9.7 HOLISHIP Project

9.7.1 Presentation

This section concerns advanced structural assessment-optimization methodology in the early stage of ship design process, which has been developing within the framework of EU project HOLISHIP.

Structural and functional assessment-optimization of ship/maritime structures is targeted to reduce the design cycle time and to promote the use of hybrid structures within integrated design loops for producibility and reduced life cycle cost (LCC), particularly throughout the initial and contract design phases. A number of methods and tools are aimed to be developed so that they can:

- Comprehensively and systematically fit to the owner's and shipyard requirements;
- Have a thorough capability of integration within ship/maritime product design optimization software platforms (HOLISHIP), to serve structural/functional assessment-optimization of the application cases (ACs) described in matrix depicted in Fig. 9.10.

In what follows, the basic methodology of "structure" optimization—in the early stage of design process—is mainly presented. More details regarding the "functional" assessment/optimization will be provided in Volume II of the HOLISHIP book, dealing with application studies (to appear in 2020).

Table 9.2 Optimization results in detail for AVEVA marine case study

Id		Original configuration	16	23	176	179	210
Deck	Plate thickness	22	39	19	9	7	9
	Long stiffener profile	HP80x11.5	HP430x20	HP320x13	HP80x7	HP80x6	HP80x6
	Numbers of stiffeners (between girders)	5	14	9	11	13	11
Transversal frame	Web height	345	275	305	390	325	335
	Web thickness	17	18	36	18	17	17
	Flange breadth	375	165	275	225	210	225
	Flange thickness	11	33	27	31	33	30
Longitudinal girder	Web height	440	205	760	945	860	855
	Web thickness	34	34	26	11	10	11
	Flange breadth	255	125	445	495	500	480
	Flange thickness	14	8	25	18	20	19
Longitudinal wall	Plate thickness	14	15	27	10	12	8
	Stiffener profile	HP280x10.5	HP180x11.5	HP320x11.5	HP200x12	HP180x11.5	HP200x11
Geometrical constraint: (TW) F-2xTp		−27	−60	−2	0	*3*	−1
Structural constraint: Maximum Stress		*430.1*	231.4	140	*555.2*	226.2	220.4
Total weight		148,808.3	359,144.5	205,599.6	88,160.5	79,589.2	83,661.9

(The unit used for dimension, weight and stress are, respectively, mm, kg and MPa)

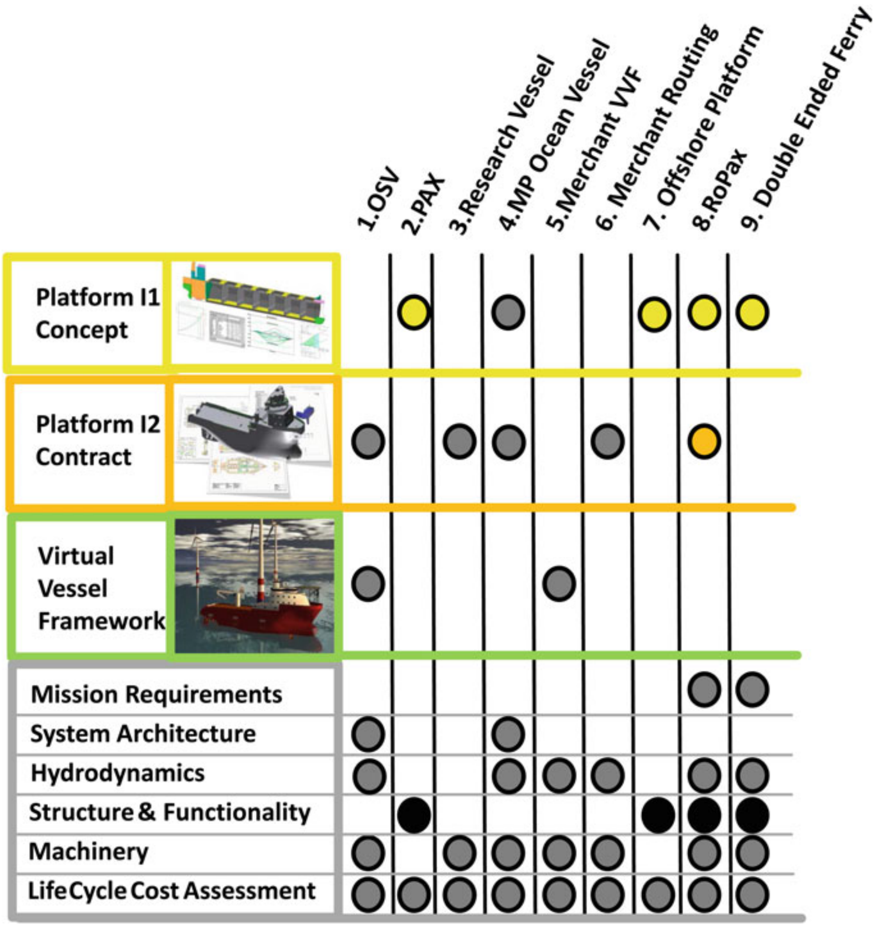


Fig. 9.10 HOLISHIP project: application cases using structural design optimization tools

9.7.2 Methodology

In order to develop, in a comprehensive and systematic manner, structural/functional design-oriented methodologies/tools for initial and contract design phases, a top-down approach is adopted as a basis. Information regarding technical requirements and challenges as well as associated objectives are identified and collected from HOLISHIP relevant ACs, i.e. ACs which require the use of structural and functional methods/tools, within their design process. Afterwards, structural/functional simulation methods/tools are set up and evaluated towards efficient, best-fit and bottom-up service of relevant ACs through HOLISHIP design software integration platforms.

Recent feedback from ACs leaders of RoPax and DE ferry indicates that lightweight reduction is one of the main needs within their design process-concept/contract phase. To fulfil this demand, in an efficient and effective manner, integrated innovative/advanced methods and tools are required to be provided.

9.7.3 Concept Design Phase

In concept design phase, where rule-based, simplified assessment methods/tools are necessary, we proceed as outlined in Fig. 9.11.

The prime objective is herein to perform a structural optimization of ship's midship section for effective least steel weight. To this end, BV's structural design tools (i.e. MARS® and STEEL®)[7] and a "weight and centre of gravity" estimator are integrated in an optimization workflow, which is steered by modeFRONTIER® as optimizer tool.

The approach is to use MARS® tool for the structural strength assessment of plating and longitudinal stiffeners, and STEEL® tool for the structural strength assessment of primary supporting members. The integration of these tools along with a "weight and centre of gravity" estimator intends to be capable of portraying the changes in structural design parameters (i.e. plate thickness, stiffener scantling, stiffener spacing and frame scantling/spacing) and perform the structural strength analyses for appropriate rule-based load cases (e.g. hull bending moment, pressures on hull), as well as compute the weight of the steel structure along with its centre of gravity.

For the optimization purpose, MARS® and STEEL® tools together with the "weight and centre of gravity" estimator intend to automatically communicate with each other within modeFRONTIER® environment. In this way, the obtained values of the objective function (steel weight) and the constraints (e.g. yield strength) in each iteration are evaluated by modeFRONTIER®. This iteration process continues to reach a set of suitable alternative structural designs.

9.7.4 Contract Design Phase

In this phase, two approaches are adopted. One approach is an extension of what is done in concept phase, while considering the weight of a number of transverse sections along ship's length. In the other approach, which is associated with the use of advanced assessment methods/tools, a structural design optimization of ship's mid-body space is targeted, with the aim to conclude on effective least steel weight. This will be demonstrated for a RoPax ship in the HOLISHIP project.

To this end, an extended optimization workflow, which was originally initiated in the EU project BESST (see the preceding section), has been established

[7]https://www.veristar.com/portal/veristarinfo/detail/generalinfo/giRulesRegulations/bvRules/bvRules.

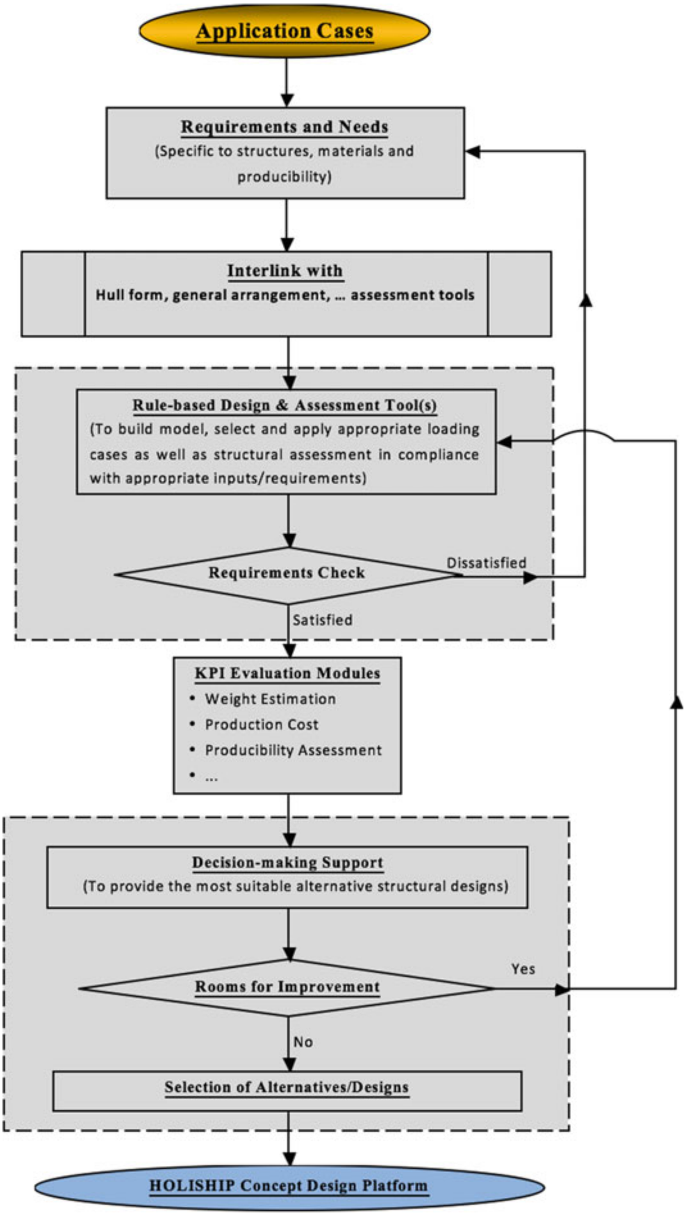


Fig. 9.11 Structural and functional assessment-optimization in concept design phase

in which AVEVA Marine® (as CAD tool), ANSYS® Classic (as FEM software) and modeFRONTIER® (as optimization platform), as well as a number of additionally required tools, are integrated in a fully automated process (without any manual intervention on GUI). All of these tools intend to be capable of portraying the changes in structural design parameters (i.e. plate thickness, stiffener scantling, stiffener spacing and frame scantling/spacing) and perform the structural strength analyses for required actual load cases (e.g. hull bending moment, pressures on hull), as well as compute the weight of the structure along with its centre of gravity.

The approach (as it can be seen from Fig. 9.12) is to build 3D AVEVA idealized parametric model of RoPax cargo hold (fulfilling FE structural requirements) and export it to ANSYS® Classic. To feed FEA procedure, the model is meshed by an appropriate tool. Then, the intention is to have an implemented tool(s) in optimization workflow, capable of assessing/receiving direct loads and boundary conditions fro hull form, stability and hydrodynamic assessment tool(s) and automatically implement/apply it in ANSYS® FE model. After that, using a macro, the required structural FEA is performed. By a post-processing module, the desired results (stress, displacement, weight, centre of gravity, etc.) are extracted to be submitted for evaluation process using modeFRONTIER®. During this evaluation process, the proposed structural designs—for effective least steel weight—must meet the requirements in the constraint module(s) implemented in optimization workflow. This workflow is automatically processed until a set of suitable alternative structural designs is achieved.

9.8 Efficient Tools for Ship and Offshore Structure Optimization in Collision Scenarios

9.8.1 Summary

Offshore structures are subjected to a very harsh environment; therefore, they require a regular monitoring and maintenance, which is done with offshore supply vessels (OSVs) normally. This is one of the reasons the collision risk increases, as well as the construction of offshore structures closer to the traffic lanes. As consequences, loss of human lives upon the collapse of offshore wind turbine on the ship and ecological damage may happen. Risk collision analysis could be therefore an important part of optimization for both ships and offshore structures, since risk analysis is required in the predesign stage in order to identify the collision scenarios having the greatest probabilities of occurrence, to estimate the consequences of such events and to ensure safe operations through the offshore structures' service life.

This section focuses on response surface method (RSM) for ship structure optimization and analytical methods to assess the crashworthiness of offshore wind turbine structures. Such methodologies are very useful when an optimization tool is intended to be implemented in an early design stage, for instance with a huge amount of design parameters and crushing scenarios, looking for the best structural resistance or less damage caused. These methodologies are still in development phase, but in the future they would be a good tool(s) to introduce in the optimization procedure.

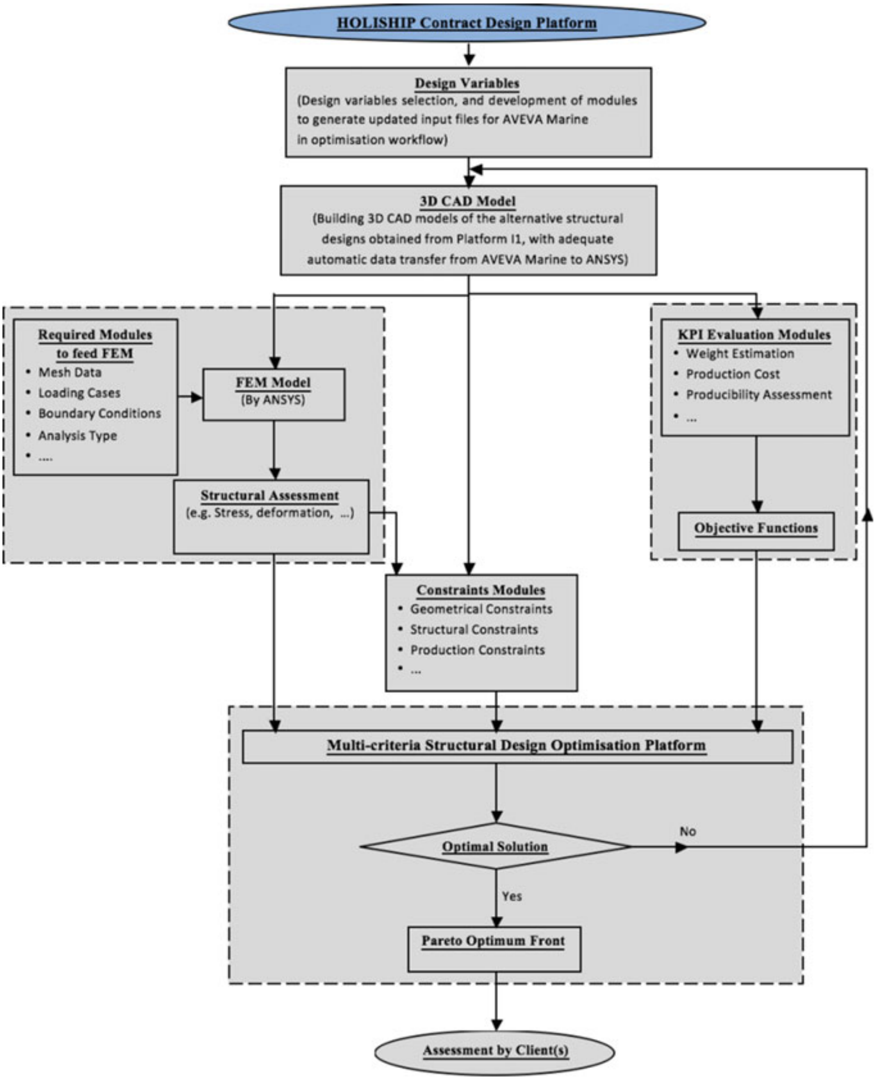


Fig. 9.12 Structural and functional assessment-optimization in contract design phase

9.8.2 Response Surface Method (RSM)

RSM is a statistical method that explores a variety of explanatory variables in order to search for one or more response variables (e.g., the dynamic response of a structure). The objective is to determine an approximate functional relation (typically a polynomial) between input variables and targeted calculation responses, but RSM presents some prediction errors for highly nonlinear systems. If a functional relation

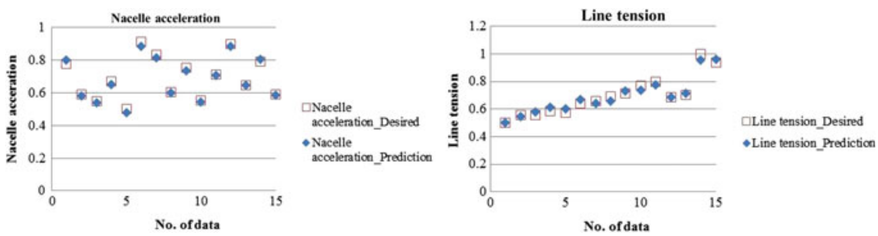


Fig. 9.13 Accuracy of generated response surface (Lee et al. 2015)

exists and fits the data with user-defined accuracy, it could be used instead of the time-consuming numerical computations.

The two main steps of the RSM are:

1. Design of experiment: selection of the number of points for the sample and its arrangement within the domain;
2. Estimator calculation: calculation of the approximation functions usually by a polynomial fit and statistical verification of fitness. This can be done with methods like polynomial regression using least squared method, Kriging method, radial basis functions.

Some attempts have already been done in the ship design industry for the accurate application of RSM. Arai et al. (2000) performed the optimization of the transverse bulkhead structure of a crude oil tanker as an example of the application of RSM. Also, Kong et al. (2006) combined genetic algorithms, Tabu search and RSM for improving the convergent speed. The purpose of their study was low vibrations of ship structures. In more advanced developments, Gorshy et al. (2009) used an approach combining RSM and particle swarm optimization to ship multidisciplinary design and optimization. This method was validated through the study of a bulk carrier.

In more recent studies, Lee et al. (2015) have confirmed the applicability of the proposed neuro-response surface method for multi-objective side-constraint optimization problems through case studies of marine systems and ship structure. The first objective was to find optimal TLP-type (tension leg platform) while considering hydrodynamic performance. In Fig. 9.13 we can see how accurate is the result obtained by Lee et al. (2015) using their proposed method with respect to the simulation tool AQWA; the error values are less than 0.05 for the nacelle acceleration and line tension.. The second study was the optimization of bulk carrier bottom stiffened panels while considering structural performance (ultimate strength and steel weight); here, they register an error value less than 0.15.

Another possible application of the RSM is as a complementary tool to predict the crashworthiness of a monopile offshore wind turbine (MOWT) when collided by a ship. Such study has been done using finite element simulations by Bela et al. (2017), and RSM would be complementary to this. This method can be used to rapidly assess the structural consequences of collision events by finding an approximate functional relation between input variables and the required responses, based on a series of numerical simulations. For example, in order to study the influence of the impact velocity of the striking ship on the structural behaviour of the MOWT, some numerical simulations are performed for three values of the impact velocity (e.g. 1, 3 and 5 m/s). Based on the results (responses) obtained from these numerical simulations, by using RSM, we could determine the responses for impact velocities of 2 and 4 m/s. This application of RSM is currently under study, and accuracy of the results depends on the design of experiment chosen (full factorial, cubic, face-centred central composite design, etc.).

9.8.3 Analytical Method

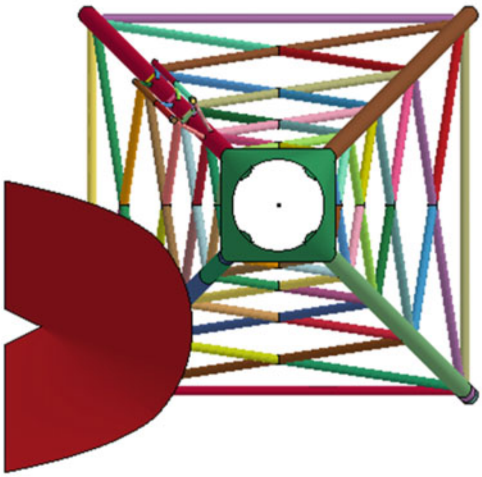
New simplified analytical methods, based on the so-called upper-bound theorem, are being developed in order to compute the crashworthiness of offshore wind turbine structures collided by a ship in a faster way. The method, widely explained by Jones (1997) in case of impacts, simply expresses that the external power is equal to the internal power during the whole collision process. These methods have not been applied to optimization schemes because they are still in development phase.

In order to compute the internal power, a kinematically admissible displacement field has to be assumed. This assumption can be based on the analytical results or thanks to real tests in a laboratory.

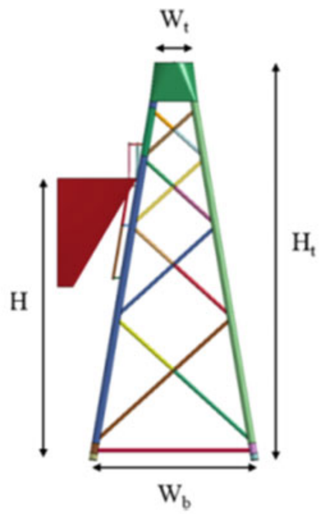
Numerical analysis of ship collision with monopile foundations is presented by Bela et al. (2017). Their study intends to understand the crushing behaviour and the nacelle dynamics of a MOWT when impacted by a ship. The influence of various parameters (ship impact velocity and location, wind direction, soil stiffness and deformability of the striking ship) was also investigated. The analysis was carried out by means of nonlinear numerical simulations of ship–MOWT collisions.

Currently, similar analyses are carried out simulating ship-FOWT collisions. For this type of structure, it is important to study the mooring system response to high loads and displacements, as well as fluid–structure interaction for the submerged platform and the influence of wind loads on the tower (and turbine).

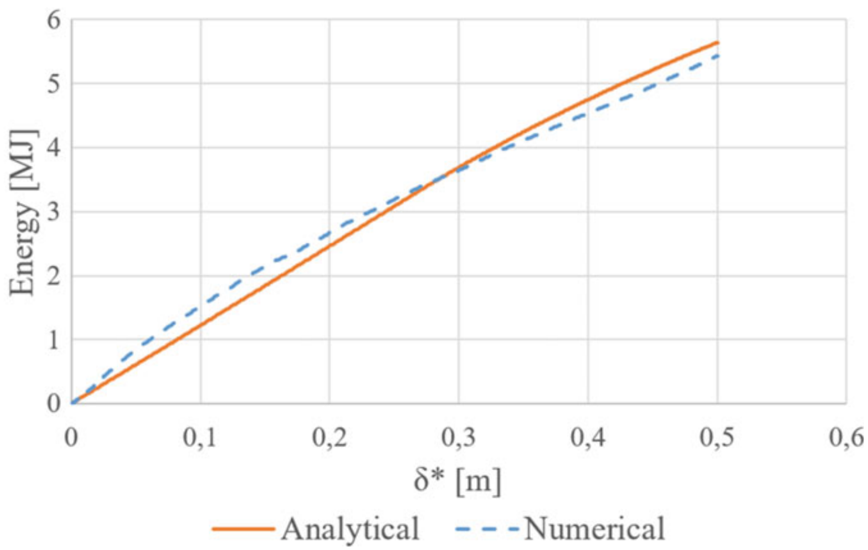
For jacket structures, a new simplified tool was developed based on the work of Paik and Thayamballi (2003) and Soreide et al. (1993) for analysing the local crushing of impacted structural elements (stiffened panels and tubular offshore structures). Plastic limit analysis is used to assess the local crushing resistance of the members of a wind turbine jacket for different deformation modes (i.e. leg punching and leg foot buckling). Some of the results are presented by Buldgen et al. (2014) and Le Sourne et al. (2015, 2016) and Pire et al. (2017). In Fig. 9.14, the collision scenario is shown from lateral and top views, and it depicts the comparison between a numerical simulation and the analytical method developed by Pire et al. (2017) for the assessment of energy dissipated after ship collision at the base of an offshore wind turbine jacket structure. $\delta*$ represents the displacement of the structure with respect to the initial position (the star represents the studied area, which is the base of the jacket). H_T is the total height of the jacket, 55 m. W_b is the width at the bottom, 25 m. W_t is the width at the top, 6.4 m. H is the ship height, 43 m.



(a) Top view



(b) Side view



(c) Analytical method vs Numerical simulation of the energy dissipated by the base of the jacket structure.

Fig. 9.14 Collision scenario and energy dissipation results comparing analytical method and numerical simulation Pire et al. (2017)

9.8.4 *Future Scope for Optimization Tools*

Ship and offshore structures are in trend, and every day more and more structures of various types are built in our oceans. Analytical methods under development could be a very useful appendage for the optimization tools, thanks to the fast and reliable results which would be very important in an early design stage.

RSM proved to be useful for ship design (and optimization), which means that there is the possibility to use it in the offshore design field as well, as an alternative to analytical methods when it is necessary. In the risk assessment for offshore wind turbine structures, these methods could look as an objective function, for example the structural loads, damage equivalent load or extreme loads. In this regard, the method is currently under study at ULiege.

9.9 Conclusions

In the ship industry, several parameters take an important place when referring to an optimal design. Therefore, optimization methodologies are evolving in order to fulfil all the needs for a better performance of ships. Because ship structure efficiency indicators may differ, it is reasonable to use the multi-objective approach to optimize the overall ship structural efficiency (e.g. weight, costs, deflection, reliability).

The demonstration of the development described in the BESST procedure indicates that early structural design assessment-optimization supported by CAD/FEM is feasible, at least at component level. Further demonstration is indeed needed considering more complex case studies with larger structural extent (e.g. mid-body of ship structure), along with realistic loading cases and constraints, as well as more objective functions (e.g. production cost) implemented in the optimization workflow. One of the main challenges will be the computational effort, which must be kept at a practical level.

Holistic optimization of ship design and operation for life cycle[8] (HOLISHIP), an European project, is a promising continuation of former European projects, such as IMPROVE and BESST, while encompassing all design disciplines.

To make a significant breakthrough in fulfilling conflicting-growing demand in maritime industries, HOLISHIP is targeting innovative holistic design optimization methodology in which all relevant main disciplines of maritime product design must be included under the umbrella of advanced parametric modelling tools and integrated software platforms, enabling the parametric, multi-objective and multidisciplinary optimization of maritime products.

The future challenge in ship structure optimization will not concern the optimization algorithm itself, but the development of some specific modules and their integration into design software platforms (Rigo et al. 2017), such as development

[8] http://www.holiship.eu.

of fast and reliable modules to assess structural constraints like fatigue and loads, at the early design stage.

Another challenge could be to develop interfaces and/or open platforms, such as CAESES, for an easy plug and play (integration) of external modules, and to integrate optimization tools in design chains with direct links to the major CAD/CAM tools and FE software to avoid data retyping and time-consuming re-meshing. In parallel, the implementation of multi stakeholders and multi-objective approaches to better converge towards reliable industrial solutions is also required.

Finally, integrating life cycle cost and particularly the maintenance and operation costs within the global cost assessment for the entire life of the ship should be addressed. In that case, optimization will be a supportive design tool towards the "Design for Maintenance" and "Design for Operation".

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Chapter 10
Design for Modularity

Stein Ove Erikstad

Contents

Abstract *Design for modularity* refers to decisions taken at the design stage of the ship lifecycle, addressing how we can decompose and encapsulate ship system elements to both improve design and manufacturing process efficiency and ship operational performance. At the design stage, modularity can concurrently support both standardization and diversification using a product platform strategy and thus lay the foundation for a configuration-based design process. In the production phase, modularity is relevant in supply chain design, modular production, early outfitting and outsourcing. In the operation phase, modularity implies flexibility, providing opportunities for adapting the vessels to changing markets, technologies, regulations and customer needs.

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Keywords Modular design · Modular adaptable ships
Configuration-based design

10.1 Introduction to Design for Modularity

By "design for modularity", we refer to explicit actions towards subdividing the ship into well-defined parts and components that can later be recombined according to given rules and procedures. There might be various motivations for modularity that are relevant for different phases of the ship lifecycle. For example, in the ship design and acquisition phase, modularity may support an efficient ship configuration process towards specific customer needs based on a ship product platform. In the ship production phase, a modularization strategy can support distributed production with turnkey suppliers, enabling a high degree of pre-outfitting. In the operation phase, modularity supports flexibility towards missions, markets, and technical and regulatory changes.

This chapter will provide an overview of the many aspects related to ship design for modularity. First, the concept of modularity is more precisely defined and placed in a wider context by relating it to adjacent topics such as product platforms, product architectures and configuration-based design. This is followed by a review of design for modularity for each of the three main phases of the ship lifecycle—-modularity in the design phase aimed at providing a ship design and configuration platform, followed by modularity in production, and finally on modularity in operation for providing flexibility and handling uncertainty. For each of these, the benefits and challenges are discussed, models and methods are reviewed, and industrial applications are presented.

10.2 Defining and Delimiting Modularity

From a systems perspective, modularity is basically a strategic approach to handle complexity, whether this complexity is structural, behaviorial, contextual, perceptual or temporal (Gaspar et al. 2012). This is achieved by dividing a system into manageable and self-contained parts. Modularity as a concept is used widely in different fields such as biology, computer science, languages, mathematics and engineering. Even though there are significant variations in the way modularity is both understood and implemented between these different fields, there are some basic characteristics that can be summarized as follows:

1. The division of a larger system into smaller parts or components
2. The principle of (relative) self-sufficiency of the individual parts
3. The recombination of the parts into multiple end products, according to a set of "rules" given by an overall systems architecture.

These aspects are also captured in Schilling (2000), where modularity is defined as "*A general systems concept: it is a continuum describing the degree to which a system's components can be separated and recombined*".

Intrinsically, modularization involves both *decomposition* and *encapsulation*. Decomposition typically follows hierarchical structures of the system, for instance functional breakdown structures or assembly/part structures, denoted by Simon (1962) as a primary strategy for architecting complex systems. Encapsulation involves an effort to hide the complexity of each part behind well-defined interfaces, thus controlling complex interactions. This relates to the axiomatic design theory (Suh 1990), where the *independence axiom* states the preference of one-to-one mappings between functional requirements and design parameters.

The definition of modularity implies that simply splitting up a product for later assembly is not necessarily termed a modular approach, such as for instance in section- and block-oriented ship production strategies. There needs to be a certain level of flexibility in the way that the parts are recombined, such as for the Sigma Modular Ships or the Littoral Combat Ship. This will be discussed in more detail later, related to modular production strategies.

However, in literature we can find more expansive definitions for the term "modular", and in some sources it is also used for all types of assembly and packaging of systems and elements. In an early reference on this topic from 1974, the following definition is used (Jolliff 1974):

> Pre-Packaging a collection of equipment (systems or components) for the purpose of their assembly and check-out prior to delivery to the ship for installation and for ease of installation and removal of the package (module)

This definition also captures the division of the ship into blocks, sections and modules as part of the ship production process. Here, the purpose is not "mass customization", but rather a "divide-and-conquer" strategy for a division into chunks that are fit for the production facilities (weight and size of crane, docks, halls, ports, production equipment, etc.) and the production process (planning units, parallel production, procurement units, material management, etc.).

10.2.1 A Modular or an Integral Product Architecture?

The product architecture defines "the scheme by which the functions of a product are allocated to physical components" (Ulrich and Tung 1991). Thus, the product architecture describes the structure of a system, in defining the main function and entities of the system and how these are related to each other.

The basic choice of product architecture needs to be determined at the outset of the design process. In a simplistic world, we have to choose between an *integral* or a *modular* architecture.

This can be illustrated using a very simple example. Consider two basic functions for a seaborne transport vessel:

F1: Provide cargo support
F2: Provide thrust through water.

In a traditional design, these two functions are, at a high level, allocated to a single ship "chunk", as illustrated in Fig. 10.1. To the extent that this overall chunk can be separated into a hull module and a machinery and propulsion module, the interaction between these modules are complex and not well defined. For instance, an increase in speed would typically require a larger and heavier propulsion system that in the next step would require an increase in hull displacement. Thus, these two modules have a high degree of dependency, which is a typical characteristic for *integral architectures*. From an axiomatic design perspective (Suh 1990), we have a coupled design, that is not in adherence to the *independence axiom* requiring a (close to) one-to-one mapping between a function and the corresponding form element.

In general, *integral architectures* are characterized by the following properties (Ulrich 2008):

- Product functions are implemented using more than one chunk or module
- A single chunk or module implements many product functions
- There is a high degree of (complex) interaction between the product modules.

The opposite of an integral architecture is a *modular architecture*. Here, the different functions of the product are, to the extent possible, allocated to separate product modules, and the interaction between these modules is small or non-existent.

For the seaborne transport example, a more modular architecture could be achieved by separating the system into a cargo unit, such as a barge, and a propulsion unit, such as a tug (Fig. 10.2). In this case, an increase in speed would only require a

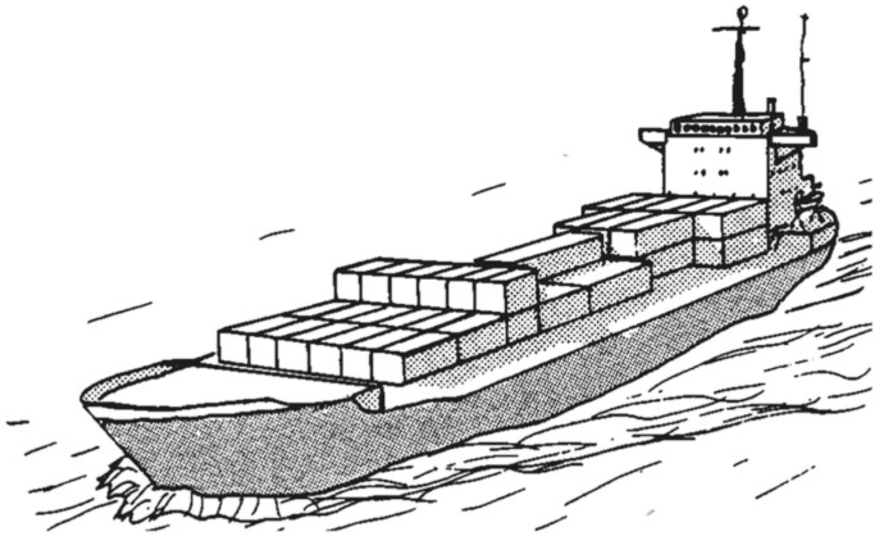

Fig. 10.1 A traditional monohull ship is an example of an integral architecture (Erichsen 1989)

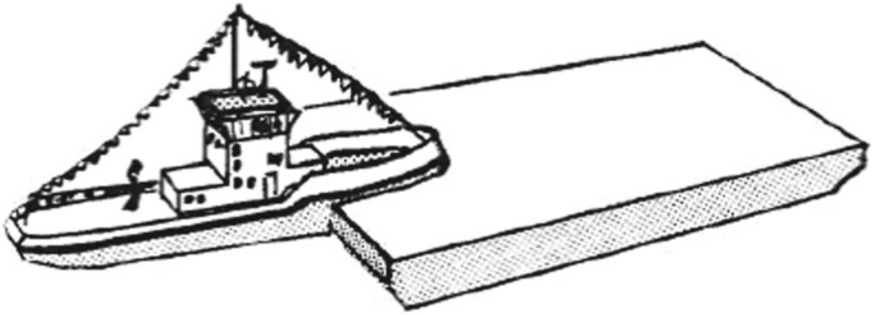

Fig. 10.2 Assigning the cargo support and thrust provision function to separate modules provides a more modular architecture (Erichsen 1989)

change in the "tug module", and not per se influence the "barge module". (However, this functional independence does not hold the opposite way).

From a business perspective, modularity has many benefits, primarily related to cost savings, in all phases of the ship lifecycle, as will be exemplified later in this chapter. However, full modularity is not always possible to achieve from a technical perspective, typically due to weight and size constraints (Hölttä-Otto and de Weck 2007).

10.2.2 Related Concepts

Modularization is closely related to several other systems concepts and technologies that have received considerable attention lately. Modules provide the basic elements in a product platform. They also provide the building blocks in a configuration-based design strategy, in which customized products can be derived by scaling and combining standardized modules towards specific end-user needs, i.e. "mass customization". The relations between these concepts are illustrated in Fig. 10.3.

10.2.3 Modularity Types

It is common to distinguish different types of modularity based on how the modules are interconnected, as well as how they are attached to a common platform. In Salvador et al. (2002), four main types are identified, as illustrated in Fig. 10.4.

In *component swapping modularity*, which is a sub-type of slot modularity (Ulrich 2008), the interfaces are specific to the module type. An example can be seen in Fig. 10.5 showing a US Navy concept that allows for different configurations and rapid refits, but with a predefined location for each equipment type where the

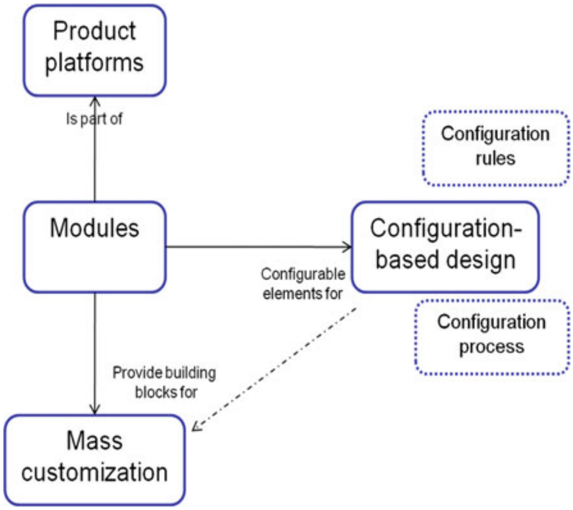

Fig. 10.3 Core concepts related to modularity and their interrelations (Erikstad 2009)

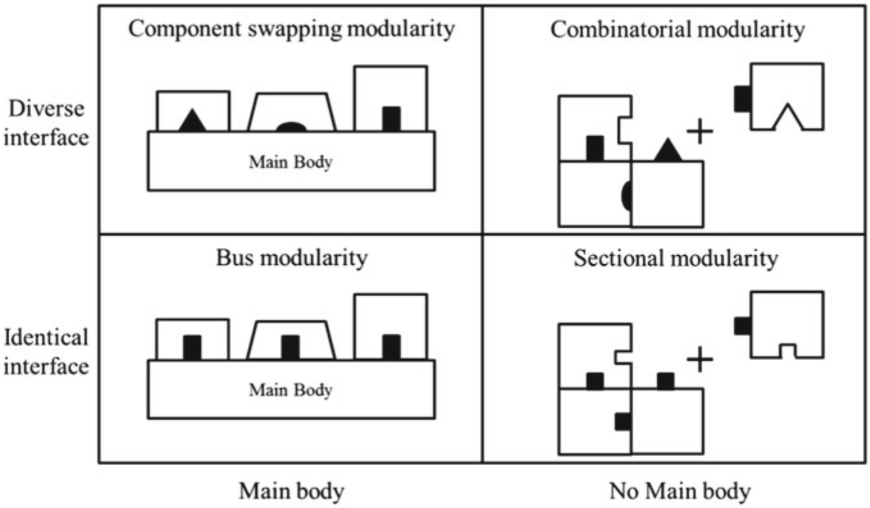

Fig. 10.4 Different types of modularity (Salvador et al. 2002)

appropriate interface slot is available. A variant of this is the combinatorial modularity, also with a diverse set of interfaces, but without a main body.

In *bus modularity,* the interface is standardized across several module types. This type of modularity is required when different selections and combinations of (equipment) modules are used to customize the product towards different purposes. One example is the US Navy Littoral Combat Ship, see Fig. 10.6, where containerized mission modules can be replaced in operation.

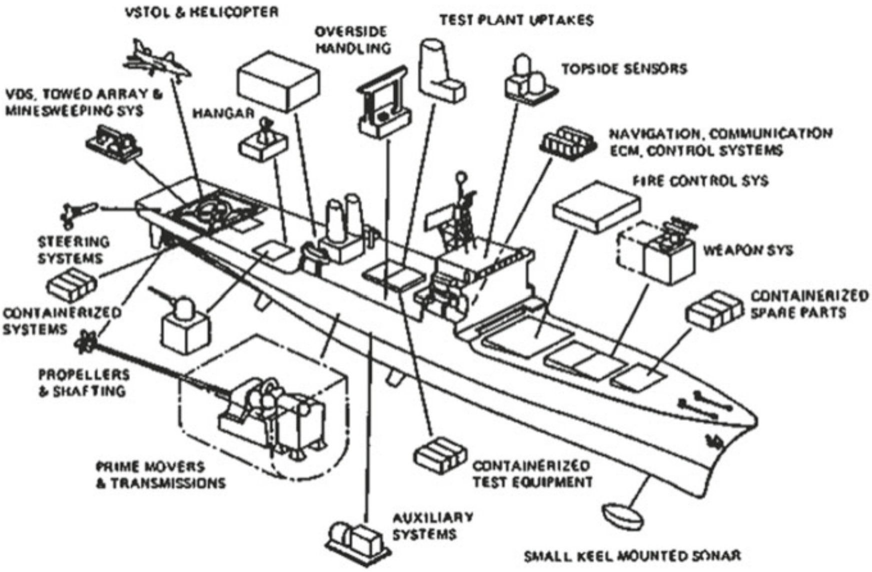

Fig. 10.5 Component swapping modularity in US Navy TES concept (Jolliff 1974)

Fig. 10.6 Littoral Combat Ship is an example of bus modularity, where different mission modules, packaged as containers, can be plugged into a standard interface to provide a wide array of different mission capabilities (AOC 2018)

In *sectional modularity,* there is no "platform" module in which the other modules attach. Rather, all modules have one or a few common interfaces, which typically allow a larger variety in the physical layout of the product. On a ship, piping and HVAC systems typically exhibit sectional modularity. We have also seen this on a ship level, for instance with the SIGMA modular ship, where standardized hull sections are arranged according to specific needs and mission requirements (Fig. 10.7).

Fig. 10.7 Ship piping system, illustrating sectional modularity (Erikstad 2009)

10.3 Modularity in the Design Phase

In the design phase, modularity is important for:

- Enabling both standardization and diversification/customization using a product platform strategy
- A more efficient design process through a configuration-based design process
- Supporting innovation by exploring the design space through modular re-combinations.

In general, modularity in design enables ship designers to reuse earlier designs and makes structural complexity manageable with simplified representation due to the hidden interactions within modules. This simplification is necessary for holistic approaches to ship design because ship designers have to deal with a large number of subsystems and the conflicting requirements of multiple stakeholders (Papanikolaou 2010).

10.3.1 Supporting a Product Platform Strategy

During recent years many industries have moved from designing individual, "one-of-a-kind" products towards developing *product platforms*. A "product platform" can be defined as "*a structured, coherent collection of resources, including systems and template hierarchies, textual components, variants, rules and interface definitions, from which a range of customized product definitions can be derived*".

There are numerous cases from diverse industries on how this technology has improved the product development process (Simpson 2003). For instance, Volkswagen has applied platform technology across their Audi, Volkswagen, Seat and

Skoda brands. Black & Decker has developed a common platform with extensive component reuse both across different brands and across different product types. Product platforms have contributed to reduced cost, shorter development cycles and the ability to maintain a broad product range while standardizing and reducing the number of different components and configuration elements (Wuuren and Halman 2001). The impact of product platform technologies has been more limited within the maritime industries, and in particular on a vessel level as a consequence of the high degree of customization, not only on the vessel configuration, but also on the make of core systems components. Thus, platform technologies have had a higher degree of adaptation among ship equipment suppliers.

One of the forerunners in Norway in this technology area was Ulstein Design. They developed a product platform for offshore supply and service vessels, see Fig. 10.8, and used this platform to configure individual vessels based on customer requirements. Their vision has been that the design reflected in the very early specification phase shall be as consistent as possible with the downstream detail engineering, and in the end production, with as little (re)work as possible.

Modularization is related to product platforms in terms of being the building blocks from which the product platform is built. By adding, removing, replacing or scaling modules, the product platform can be targeted towards specific markets or customer requirements. Core research challenges include efficient strategies and methods for determining the subdivision into modules and the number of variants of each, the recombination of these modules into product families of products, and how these are leveraged to target specific market segments and niches. The primary trade-off in the platform design process is between commonality and distinctiveness (Simpson 2003), or between cost-cutting and increasing market shares (Ericsson and Erixon 1999).

10.3.2 Design Process Efficiency by Configuration-Based Design Based on Modularity

An important driver for modularity in the design phase is to reduce the lead time and resource expenditure in responding to tender invitations. Today, even for routine designs, it is quite common that this process starts from a previous tender, possibly for another customer with slightly different requirements. This is then “cleaned” for project-specific content, and the particular requirements for the current customer are incorporated. Typically, the tender documents need to be checked with the different disciplines, such as structures, machinery and electrical. Obviously, both quality and response time are under pressure.

With a modular design platform with a well-structured configuration system on top, this process may be considerably improved both in terms of efficiency, quality and reduced risk, as well as indirectly through increasing the likelihood of winning

Fig. 10.8 Selected products in the Ulstein Design portfolio (*Source* Ulstein Design)

the contract. For a ship design office, this is important for improved productivity, as illustrated in Fig. 10.9.

Generally, a design configuration system, can be defined as: "A (software) system that enables a structured definition of a valid design solution from a given set of

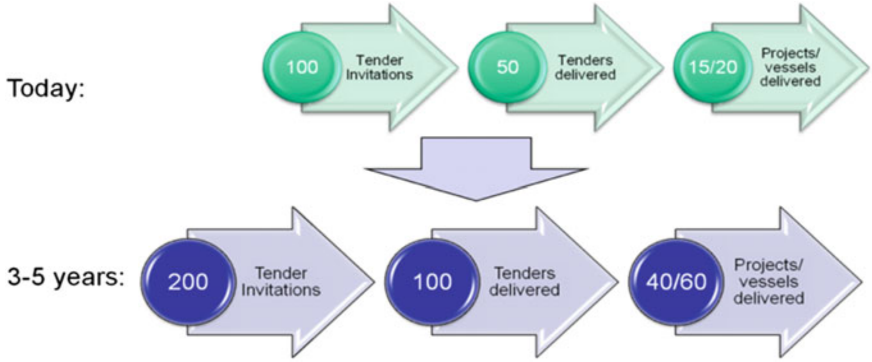

Fig. 10.9 A modular design platform may improve the efficiency and quality of tender project development, and possibly leading to both increased handling capacity and higher hit rate (Erikstad 2009)

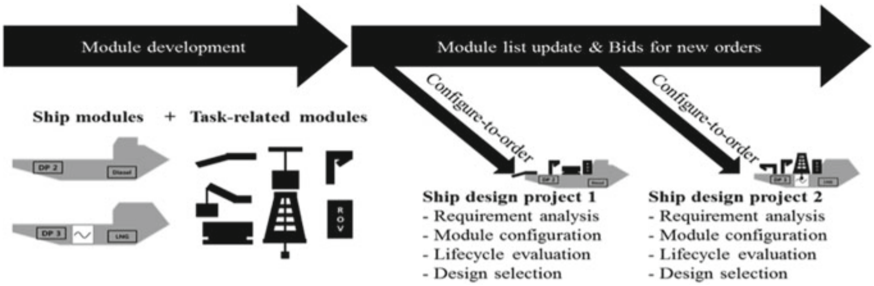

Fig. 10.10 Dividing the design process into a platform development stage and a "configure-to-order" stage (Choi et al. 2018)

customer requirements, by applying predefined rules and templates to select, scale and synthesize a collection of modules" (Brathaug et al. 2008). This decouples the design work into two distinct stages, a platform development stage in which the modules are developed and integrated into a product platform, and a "configure-to-order" stage in which individual tenders and designs are customized towards the individual needs of each customer. This is illustrated in Fig. 10.10.

Configuration may be described as a particular class of routine design, in which the major design elements—modules—are known, and that these can be combined into a solution that meets the customer requirements without involving the development of new solution elements. Configuration is in many aspects the opposite of the more common "copy-and-edit" approach taken in projects with short lead times and only a limited set of changes from existing projects (Fig. 10.11).

The adaptation of configuration-based design in ship design has been relatively limited in segments other than low-complexity, standardized vessels. This is likely because of the complexity related to highly customized requirements and the extensive interrelationships between different systems. Further, non-technical factors may

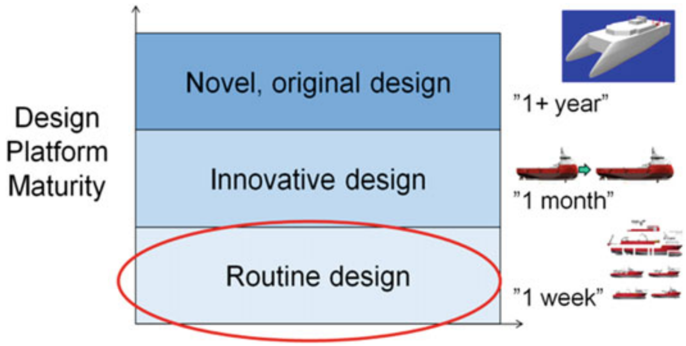

Fig. 10.11 Configuration of a module-based platform as a specific class of short lead time, routine design process

be important, such as the shipbuilding culture for "customized prototypes", and less tradition for standardized platforms. This leads to a focus on the individual projects rather than process improvements. Compared to many other industries facing a similar complexity level (say, automotive and aviation), the typical length of a series in particularly European shipbuilding is short. This implies fewer projects to share the costs of developing a configurable product platform.

A product configuration system will comprise three main elements:

1. A collection of configuration entities. This mainly consists of a collection of modules, combined with parameter sets both on a vessel and on a module level. The parameters will further be divided into those representing customer and functional requirements, and those representing a description of the design solution. The secondary representation contains a 3D model, a textual specification and performance documentation, all which can be derived from the primary representation.
2. A configuration process representation. It is preferable to base the process implementation on a workflow management system. This enables a "plug-in" type of external application integration, as well as a declarative, configurable process logic definition.
3. A configuration knowledge representation that captures the rules and constraints required for defining legal, meaningful product variants from the module platform (Fig. 10.12).

10.3.3 Modularity Supporting Design Exploration and Innovation

Like Lego bricks, modules can be used to explore the design space and create innovative design solutions by rearranging modules into different spatial configurations. Some examples of this are system-based design (Erikstad and Levander 2012),

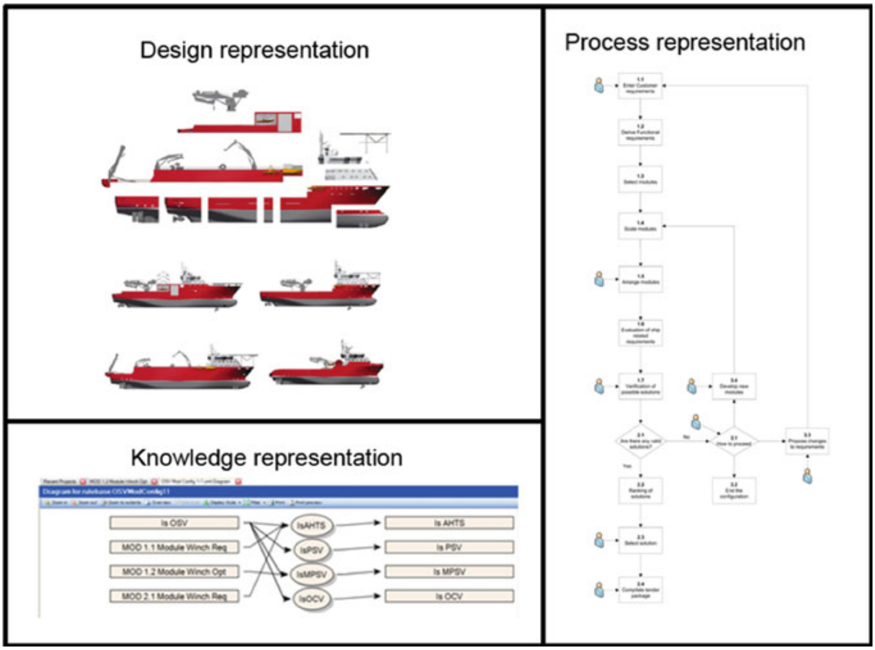

Fig. 10.12 The three main elements of a product configuration system (Brathaug et al. 2008)

building-block design (Andrews 2003) and the packing approach (van Oers 2011). In particular, this is applicable to what has been termed "configuration-driven ships, that is, ships were the "performance of the vessel is driven by the arrangement of spaces" (Droste et al. 2018) connections between modules—configuration-driven ships—driven by the layout/arrangement of the vessel.

In system-based design (SBD), the modules are derived from the functional breakdown of the vessel. For most of the functions, one or a set of corresponding modules may be defined. Each module is scaled according to the area and space requirements derived from existing vessel general arrangements as part of the SBD model. The sized modules can then be arranged either freely, or by using templates defining the topology of the modular arrangement. The template states where a module should be positioned, while the breadth and height are automatically scaled based on the main characteristics of the vessel. Then, the length is scaled to satisfy the volume demand. As an example, the winch module be placed in front of the deck module and made as wide and high as possible within the constraints and then scaled by length.

Modules combined with templates will support a quick and partly automated sketching of the design solution (Vestbøstad 2011). The key point here is the decoupling between the modules selection/scaling, and the arrangement synthesis, thus reducing the needs for the "balancing out" process captured in the design spiral model (Fig. 10.13).

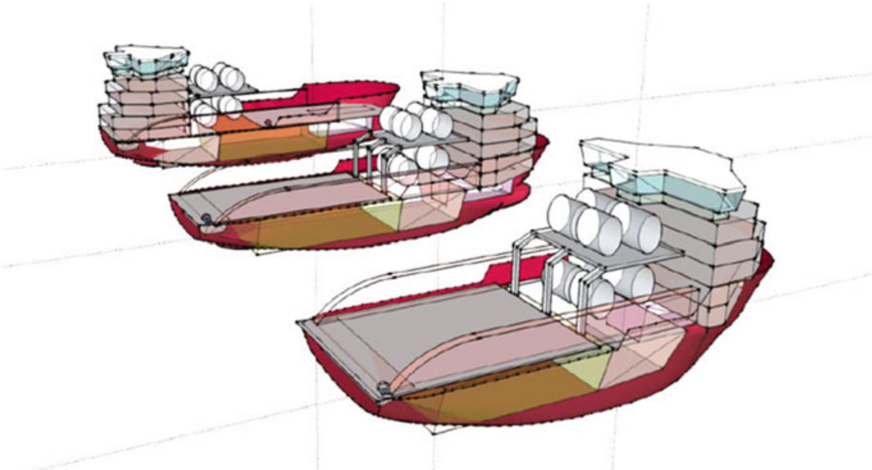

Fig. 10.13 3D models showing alternative vessel configurations based on different templates, all using the same set of modules derived from functional area and volume requirements (Vestbøstad 2011)

Fig. 10.14 Configuration of a vessel from building blocks from a library, for rapid evaluation and requirements elucidation in early design stages (Andrews 2011)

This is similar to the "building block approach", see Fig. 10.14, advocated by Andrews points to the importance of establishing a module-based platform that can be configurated in different ways to support the exploration of alternative solutions, as well as providing a basis for understanding and communication with key stakeholders the impact of the initial requirements (Andrews 2011).

The same underlying principles are further developed towards arrangement optimization by van Oers et al. (2007) and optimization (Daniels and Parsons 2007). Here, a set of modules to be contained in the ship is defined, and an optimization routine

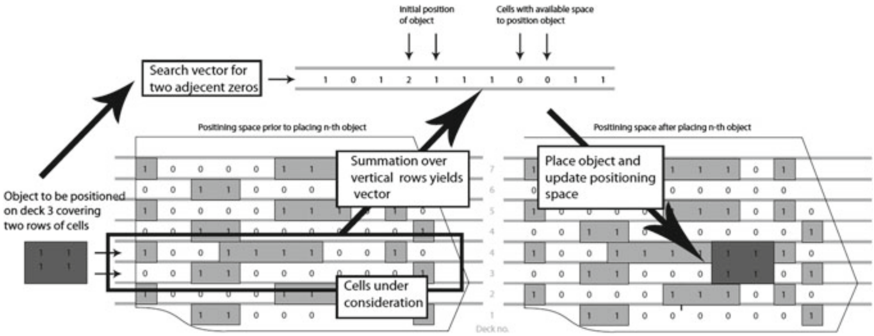

Fig. 10.15 Module-based approach used in the arrangement optimization in the early design of a warship, in van Oers et al. (2007)

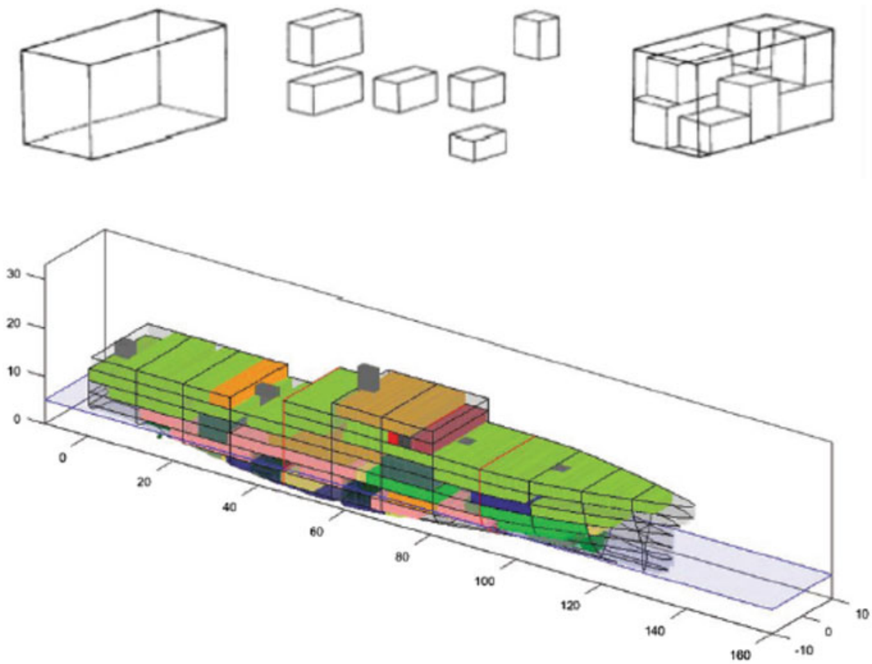

Fig. 10.16 Arrangement-driven design based on a modular architecture (Droste et al. 2018)

finds the solutions that best balance a set of criteria, see Fig. 10.15. This requires the definition of a set of distinct modules, and their corresponding interfaces both with the ship platform and towards other modules (Fig. 10.16).

The examples above were based on deriving the modules from the functions. Alternatively, the modules can be derived directly from the block structure of the vessel. One example is the Sigma class corvette that is designed and built by Damen

Fig. 10.17 SIGMA modular naval vessel from Damen Schelde (https://www.damen.com)

Schelde Naval Shipbuilding. “Sigma” is an abbreviation for “Ship Integrated Geometrical Modularity Approach”. In this design, the hull segments are modularized and can be assembled in different numbers and sequences, thus using a sectional modular approach. Off-the-shelves equipment is used to the extent possible. The modular approach allows the client to configure a vessel out of these standard blocks, and different versions with 12, 13 and 14 sections have been sold to three different navies. This is an example of sectional modularity. The advantage is a relative simple configuration pattern, but at the expense of flexibility in terms of function-space allocation (Fig. 10.17).

10.3.4 Modularity in Ship Design—Summarized

Modularity is an important driver also at the design stage of ship’s lifecycle. Modules encapsulate complexity, thus enabling both more efficient processes, as in product platforms and configuration-based design, as well as enabling a wider search for new and innovative solutions throughout the design space.

10.4 Modularization in Ship Production

In the production phase, modularity is important for

- Supply chain design and production outsourcing
- Modular production and early outfitting
- Procurement packaging.

In the ship production phase, a modular approach offers a number of opportunities for improvements. First, it is an enabling technology for more flexible, and increasingly, global production chains. A clear modular structure, with well-defined interfaces between the modular “chunks”, opens up for the outsourcing of a larger share of the total production. Alternatively, by enabling the reuse of standardized components across multiple design variants, it may provide a basis for a higher degree of automated production of longer component series. This may result in an insourcing of production, enabled by automated production that possibly is competitive in high-cost countries like Norway.

10.4.1 Effects on the Ship Production Value Chain

A core question is to what extent there is a connection between the shipyard’s modularization strategy and the supply chain structure. And given that this connection exists, which one is the “cause” and which one is the “effect”? Historically, the connection between modularization and outsourcing has been weak. The former has been approached as a design and manufacturing principle in engineering communities, while outsourcing has been discussed within the realms of economics, management and strategy (Fixson et al. 2005).

The product’s architecture is a key determinant for the opportunities for manufacturers outside the company boundaries to produce individual components to be part of the final product. A classic example referred to in many papers is the modular structure introduced with IBM’s 360 system. This opened up for individual manufacturers to provide components to this platform, eventually driving prices down and making components such as hard drives and memory chips commodities.

The impact that modularization has on the production value chain may also lead to changed power balances between the different actors in the value chain. One example is the shift in control over the specification. In a more “traditional” process, the shipyard to some extent plays the role of a subcontractor designing and developing a solution constrained by the requirements in the outline specification. With a modular, product platform-based design, this is shifted towards a situation where the owner is, at least in principle, selecting from a set of possible designs derived from a platform. Thus, the yard has to some extent regained the control of the specification.

10.4.2 Early Outfitting

Thus, the definition of a product architecture based on a functional model of the product is an important first step in a modularization strategy. There has been some work related to this in Norway some ten years ago, related to the MARINTEK lead project “Procurement in the Sales Phase”. In this project, several diagrams were developed for the main systems of the vessel. One example of this can be seen in Fig. 10.18.

Though these systems diagrams were primarily developed to serve as a basis for the specification of procurement packages, they may be used as the architectural

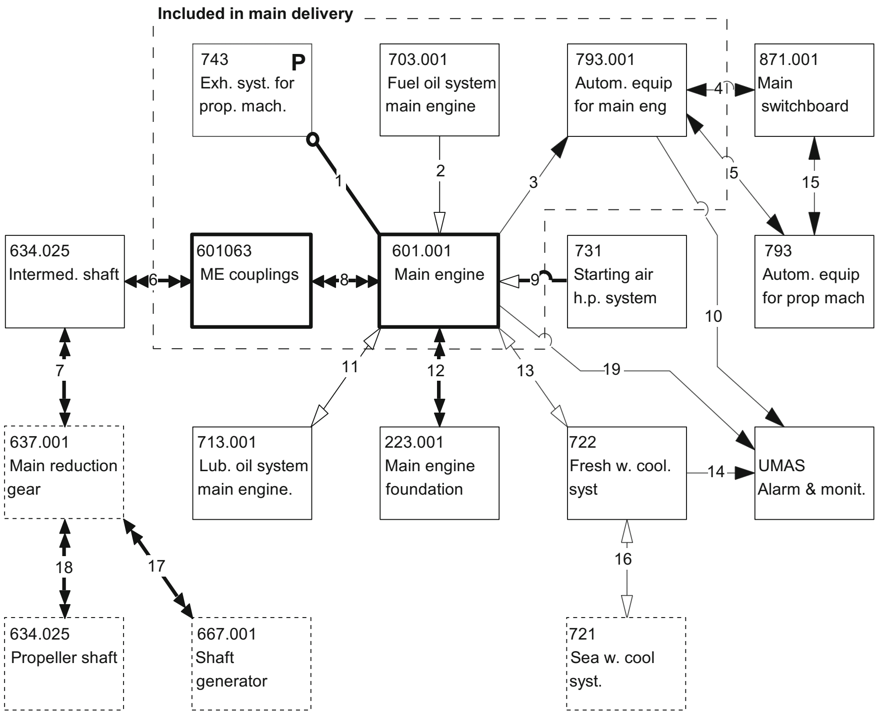

Fig. 10.18 System diagram for the main propulsion system (Marintek 1998)

backbone for defining modular product platforms for ships. This process would involve the grouping of a set of functional entities as a modular "chunk", and the definition of the interface towards other modules based on the various relations between functional units depicted as different types of arrows in the diagram.

The overall aim was to develop a rational methodology supporting the procurement process in shipyards. This was a collaboration project between Ulstein Yard and MARINTEK. A core topic was the procurement of project critical equipment, where a coherent framework for performance-based specifications was developed (Fig. 10.19).

These specifications were based on a functional modelling of core ship systems. These are used as a backbone for the procurement plan, and for identifying the scope, content and interfaces of the individual specification packages. Thus, this project may provide valuable input to the process of defining the required modular architecture to serve a global sourcing strategy.

In the maritime industries, the product platform concept has been employed first and foremost with equipment manufacturers. One example is Wärtsilä which has developed sales configuration principles and software. Their vision was that a significant part of the engineering and production planning, as well as price quotes, should be a direct result of the enactment of different configuration rules (Sortland 2001).

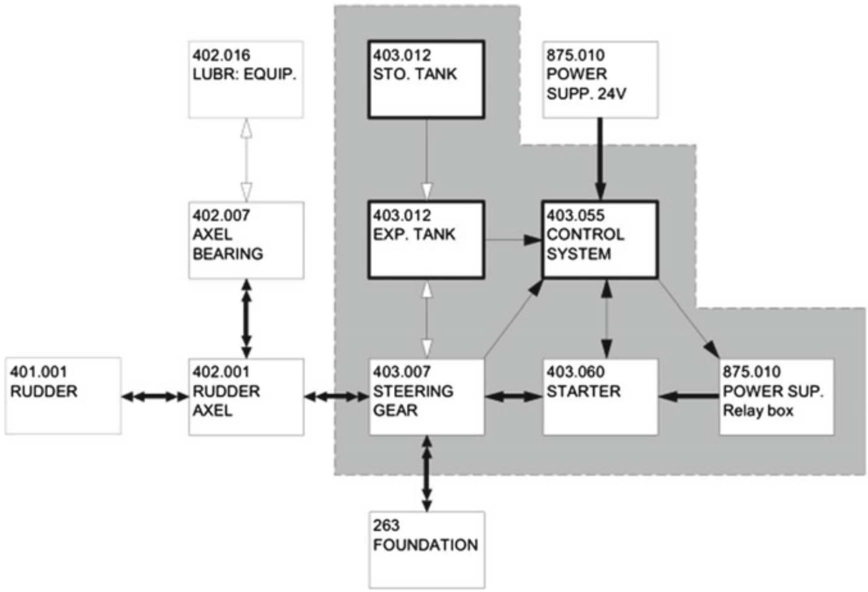

Fig. 10.19 Identifying procurement modules by functional grouping

Another example from the maritime industry is Rolls-Royce Deck Machinery. They have performed extensive work in using modularization and product platform principles. This has caused a complete redesign of some product lines, significantly reducing the number of configuration elements. This is illustrated in Fig. 10.20. The result is both in a significant increase in the range of possible product configurations offered to customers, a substantial shortening of development time for new products and both reduced costs and throughput time in the sales projects (Andreassen 2005) (Fig. 10.21).

10.5 Modularity in Operation

The incentives for modularization from an operational point of view may be

- Later modifications, for instance because of new regulations, technical development, or changed operating profile/mission
- Easy component/system replacement because of failures or breakdown
- A maintenance policy based on component/module rotation and "offline"/"off-site" maintenance. This module rotation maintenance can be found in the aviation industry
- A "service-oriented" operating regime involving remote monitoring and operation, typically by the system supplier.

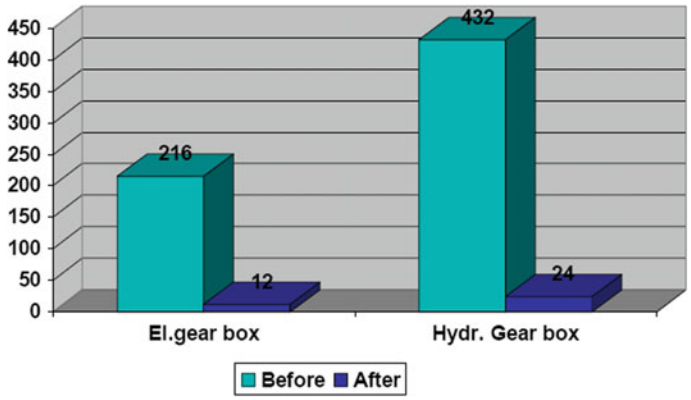

Fig. 10.20 Number of configuration elements before and after PDM project at Rolls-Royce Deck Machinery (Andreassen 2005)

Fig. 10.21 Modularity has also played a significant role in cruise ship cabin manufacturing. Traditionally, cabins were outfitted as an integral part of the shipbuilding project (Jogeva 2014)

10.5.1 Modularity for Flexibility in Operation

In the operations phase, modularity is a central strategy for offering ships with operational flexibility that can adapt to changes in the vessel's operating environment, whether this is related to regulations, technology, missions, markets, fuel, etc., see Fig. 10.22. A key research area is the use of real options in design, that is, decisions

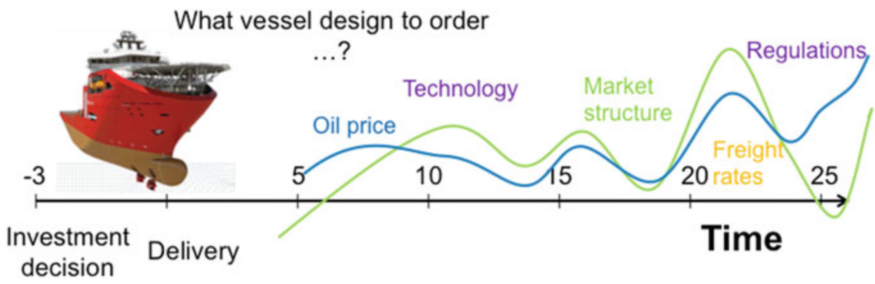

Fig. 10.22 Modularity is an enabler for providing flexibility to handle future uncertainty (Erikstad and Rehn 2015)

related to investments in future operational flexibility already at the newbuilding stage. Examples of such investments range from providing sufficient structural and powering support for upgrading cranes, to investing in hybrid powering systems and additional power reserves beyond what is required for the vessel's first contract.

Modularity plays a key role in this. The profitability of exercising flexibility in operation will be dependent on both the time it takes, and the cost incurred. A proper modular architecture will generally provide a more competitive cost-benefit ratio for exercising options than an integral architecture with the same functionality.

Time aspects are also of importance, which leads to the choice between *versatility* versus *retrofittability* (Rehn 2018). A given set of lifecycle capabilities of the vessel can either be made possible by a multi-functional vessel capable of handling all required missions, or by a modular design for which the mission capabilities are retrofitted in operation when the need arises. Both the cost profile (CAPEX, OPEX) and the *agility*, i.e. the time delay to enter new missions, will be significantly different for these two alternatives. There is no obvious best strategy—for different market conditions and different sets of mission requirements we have seen both solutions being preferable in retrospect. Generally, strong markets tend to favour versatile vessels, while weak markets and a high degree of uncertainty tend to favour retrofittability (Fig. 10.23).

Also, for naval vessels, the importance of flexibility in the operational phase has been addressed. In recent years, there has been a considerable focus on what is termed "Modular Adaptable Ships" (MAS), in particular within the US Navy (Doerry 2016). Naval vessels have to meet an extensive range of missions to cover all national security requirements. They typically have high procurement cost, combined with long development and production cycles. Thus, most naval programmes experience significant changes in mission requirements as well as technology development, with a corresponding high impact on both the total cost and mission capability. The Littoral Combat Ship (LCS) is perhaps the archetypical example of the use of modules for providing multi-mission flexibility in operation. The goal with the LCS program in the US Navy was to develop a near-shore combat ship that could be developed at a low cost, and with a flexibility that made it possible to rapidly shift from one type of warfare to another. It consists of a base module—sea frame—that

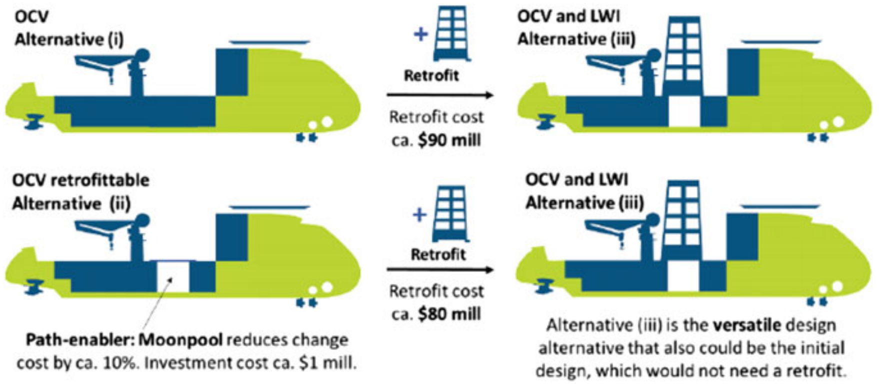

Fig. 10.23 Preparing for module installations will influence the total retrofit cost for an OCV (Rehn and Erikstad 2018)

is the warship platform. In addition, a range of different modules may be plugged in, providing capabilities such as anti-surface warfare, mine countermeasures, anti-submarine warfare, intelligence, surveillance and reconnaissance, special operation forces support and logistic support. These mission modules integrate to the extent possible, into the sea frame's command and control architecture (Fig. 10.24).

10.5.2 Modularity for Easy Retrofit and Modernization

In the US Navy, the combination of modularity and flexibility is considered as one of the primary strategies for reducing the time and cost of modernizing in-service vessels and adapt to uncertain future operating scenarios (Schank et al. 2016). The MAS initiative has many aspects, including very specific recommendations for ways to reduce mid-life modernization costs. This includes

- Improve access to modernized equipment, such as designing for easy access to any major equipment that has a reasonable expectation of being replaced during the vessel's lifecycle. This must be balanced towards survivability
- Minimize the number of foundations changed during a modernization, which implies designing new equipment towards the existing foundation standards. From a modular perspective, this relates to interface management
- Minimize the amount of new cable and fibre during a modernization, by power margins, extra electrical capacity and new equipment designed for utilizing existing infrastructure
- Increase power, cooling, and data exchange. This pertains in particular to bus type modular systems, where new systems with same interfaces may be re-installed, but with higher requirements in term of power
- Increased pre-installation testing, improved planning, and coordination alternative.

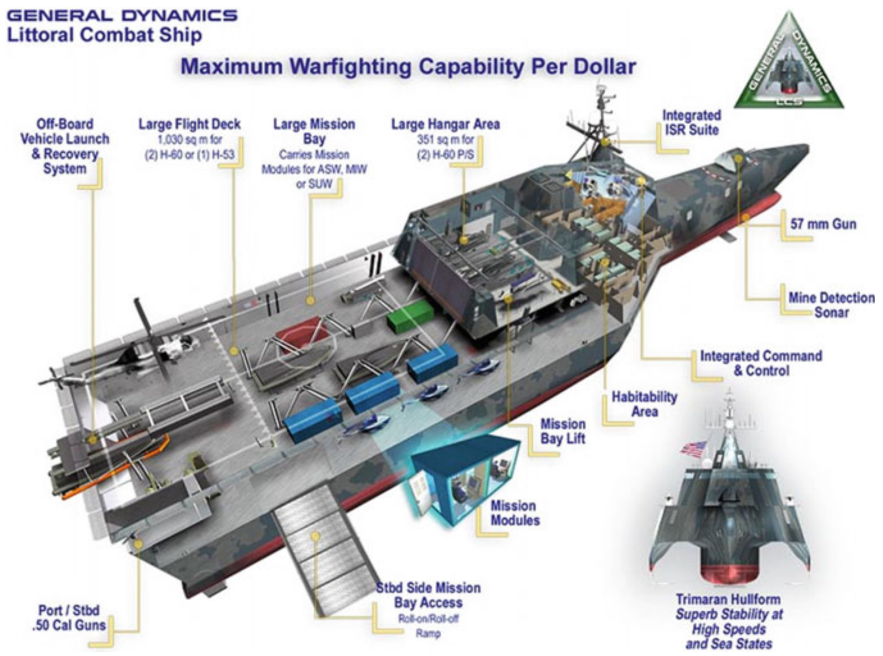

Fig. 10.24 Littoral Combat Ship providing operational flexibility through replaceable mission modules in a bus modular architecture (Doerry 2016)

10.5.3 Design Methods for Modular Adaptation in Operation

Having discussed the benefits and challenges of providing operational flexibility by modularity, the next question becomes how design stage decisions for developing the associated operational platform can be supported. In Choi et al. (2018), an optimization model for a modular adaptable ship (MAS) platform is presented. The model selects modules to be associated with slots of the vessel platform in a set of likely operating scenarios during the ship lifecycle, with the overall goal of minimizing the deviation between the desired capabilities derived from the associated missions and the achieved capabilities of the vessel operating platform.

Figure 10.25 illustrates the relationship between ship modules, slots and task-related modules using a class diagram described by the unified modelling language (UML).

In the corresponding optimization, these entities are captured in a goal programming model (Eqs. 10.1–10.10). The objective function (10.1) minimizes the normalized, weighted deviations from desired capabilities. The actual mission capability is a function of vessel platform variables ($\boldsymbol{x}$), slot variables ($\boldsymbol{y}$) and module variables ($\boldsymbol{z}$) and is compared with the desired capabilities B_{np} in (10.2). Equations (10.3)–(10.9) are feasibility constraints capturing slot assignment rules, vessel technical and

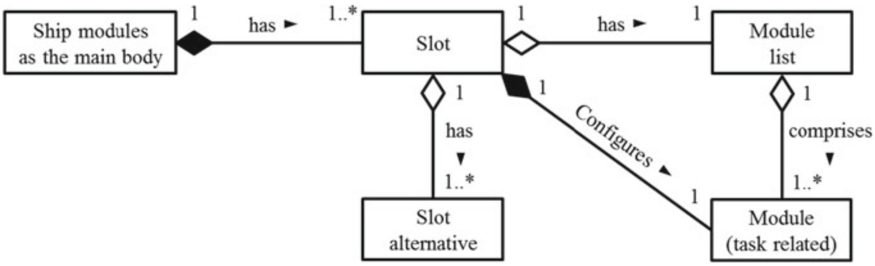

Fig. 10.25 Description of ship modules, slots and task-related modules using a class diagram in the unified modelling language (Choi et al. 2018)

economic performance (stability, life cycle cost, …) and allowable module combinations. Equations (10.10)–(10.12) are model variable bounds. The details of the model can be found in Choi et al. (2018).

$$\text{Min} \quad \sum_n \sum_p \frac{W_{np}^-}{R_p} \cdot d_{np}^- + \sum_n \sum_p \frac{W_{np}^+}{R_p} \cdot d_{np}^+ \tag{10.1}$$

$$f_{np}^U(\mathbf{x}, \mathbf{y}, \mathbf{z}) + d_{np}^- - d_{np}^+ = b_{np} \quad n \in N, \ p \in P \tag{10.2}$$

$$d_{np}^-, \ d_{np}^+ \geq 0 \quad n \in N, \ p \in P \tag{10.3}$$

$$y_{sa} \cdot z_{nsm} \leq H_{sam} \quad n \in N, \ s \in S, \ m \in M_s, \ a \in A_s \tag{10.4}$$

$$(1 - F_{sa}) \cdot y_{sa} \cdot z_{n_1 sm} = (1 - F_{sa}) \cdot y_{sa} \cdot z_{n_2 sm}$$
$$n_1, \ n_2 \in N, \ s \in S, \ m \in M_s, \ a \in A_s \tag{10.5}$$

$$\sum_{a \in A_s} y_{sa} = 1 \quad s \in S \tag{10.6}$$

$$\sum_{m \in M_s} z_{nsm} = 1 \quad n \in N, \ s \in S \tag{10.7}$$

$$g_{nj}(\mathbf{x}, \mathbf{y}, \mathbf{z}) = 0 \quad n \in N, j \in \left\{1, \ldots, N^{EC}\right\} \tag{10.8}$$

$$k_{nk}(\mathbf{x}, \mathbf{y}, \mathbf{z}) \leq 0 \quad n \in N, \ k \in \left\{1, \ldots, N^{IC}\right\} \tag{10.9}$$

$$\begin{matrix} x_i \in \{0, 1\} & \text{if is a binary variable,} \\ L_i^X \leq x_i \leq U_i^X & \text{otherwise,} \end{matrix} \quad i \in \{1, \ldots, |\mathbf{x}|\} \tag{10.10}$$

$$y_{sa} \in \{0, 1\}. \quad s \in S, \ a \in A_s \tag{10.11}$$

$$z_{nsm} \in \{0, 1\}. \quad n \in N, \ s \in S, \ m \in M_s \tag{10.12}$$

The model has been applied for designing a standard operation platform for a modular adaptable offshore support vessel (OSV) and comparing this with a multipurpose vessel having the same capabilities across missions. As we can see in Fig. 10.26, the mission capabilities are basically the same, though the flexible platform has the ability to downscale non-required capabilities in the platform supply operations. In a

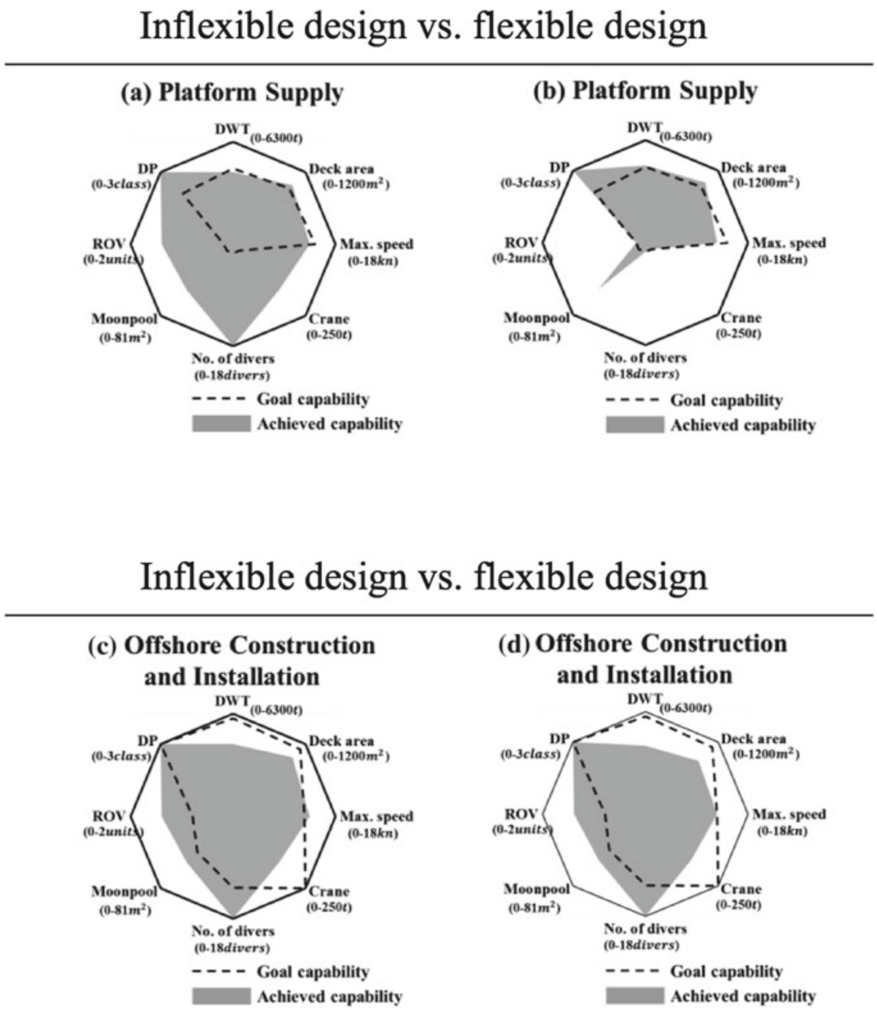

Fig. 10.26 Capability diagrams for both flexible and inflexible designs for two mission types (Choi et al. 2018)

lifecycle cost perspective, as seen in Table 10.1, we see that modular adaptation can reduce the CAPEX by requiring a smaller vessel platform that in this case is partly offset by reconfiguration cost. Thus, it is not possible to draw a general conclusion on the preferences between modular or not—it will depend on both the uncertainty and variability of the vessel's operating context, as well as the cost structure associated with a modular platform.

Table 10.1 Cost comparison of flexible (modular) and inflexible platforms

Lifecycle cost of optimal platforms				
Design	Expected lifecycle cost	Platform acquisition cost	Expected module acquisition cost	Expected ship reconfiguration cost
Inflexible design	$61.31 M	$32.31 M	$29 M	$0
Flexible design	$58.91 M	$28.24 M	$29 M	$1.68 M

10.6 Conclusions

In this chapter, we have seen that different stakeholders have different motivations for modularization. Key drivers and motivating factors are a higher product variety and customization using product platforms, improved production efficiency through standardization on parts, reduced lead time both by isolating functional enhancements as well as supporting parallel development and production, reduced risk and cost and efficiency improvements through outsourcing and globalization of supply chains.

Modular ship designs aimed at providing operational flexibility, such as the Littoral Combat Ship, may contribute to a cost-efficient modernization of obsolete equipment, upgrades, and adaptation to changed external conditions (new markets, trades, regulatory regimes, etc.). This may both contribute to increasing the operational efficiency of the vessel, as well as extending the vessel's operational life.

Modularity may contribute to a more efficient recycling of the vessel along the interfaces defined by the modular architecture and possibly also to the reuse of those components for which the economic lifetime is longer than for the ship itself.

We have also seen that modularity in most cases comes at a cost. These include less optimized physical architecture, and correspondingly increased weight and size. An integral architecture with the same technical performance will typically be more energy efficient. Thus, designing modular solutions is a complex process in which the costs and benefits must be carefully balanced.

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Chapter 11
Application of Reliability, Availability and Maintenance Principles and Tools for Ship Design

Vincent Le Diagon, Ningxiang Li, Loïc Klein and Philippe Corrignan

Contents

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Abstract Reliability, Availability and Maintainability (RAM) is one of the most performing tools to assess the performance of a system, which is computed in terms of operational availability and its Life-Cycle Cost. Results from a RAM study allow identifying possible causes of operational losses and examining possible system improvements, making this analysis a tool for decision-making allowing costs versus benefits analysis. Reliability, Availability and Maintainability is not commonly addressed in ship design. However, the level of complexity and automation of ships is more and more increasing due to environmental regulations and economical concerns, with a clear trend towards future autonomous shipping. This calls for an evolution of the design of complex ships equipped with many systems, operated in complex multiple operational profiles and involved in critical operations, where malfunctions would result in large impacts on human, asset or the environment. In this context, key focus areas for ship design are ensuring and verifying safety and reliability, and accounting for the systems maintenance and Life-Cycle Cost. In this context, this chapter focuses on the applicability of RAM analysis to ship design. After an elicitation of the RAM objectives, an overview of existing analysis methods is presented. Then important items such as target ships, specificities of ship design, main ship systems to be analysed, RAM analysis process, most suitable methods, main required functionalities of RAM tool and availability of reliability data are discussed. The actual integration of RAM analysis in the global ship design process is to be developed and demonstrated within the HOLISHIP project.

Keywords Ship design · System engineering · Reliability · Availability
Maintainability · RAM · Life-Cycle Cost

11.1 Description of RAM Objectives and Methodology

11.1.1 RAM Objectives

Asset systems are designed to perform a function in order to achieve a minimum production or service level. However, asset failures reduce the capability of the system to meet these targets and, at the same time, increase the operational costs.

This is why asset failures should be considered at the design phase in order to assess the system design in view of optimizing its performance and Life-Cycle Costs.

RAM is one of the most performing tools to assess systems design. Indeed, RAM modelling estimates the performance of a system, which is computed in terms of operational availability or production's capabilities. The results from a RAM modelling will identify possible causes of production losses and can examine possible system alternatives. The RAM study is thus a tool for decision-making allowing costs versus benefits analysis.

11.1.2 RAM Methodology

RAM modelling simulates the configuration, operation, failure, repair and maintenance of all assets included in a system. The inputs for a RAM modelling of a system include the physical components, equipment configuration, Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR), maintenance philosophy and logistics and operational profile. The outputs determine the resulting operational performance of the system over its life cycle.

11.2 RAM Applications

Accounting for RAM is not new in engineering design, even at early, conceptual, design stage (Stapelberg 2009). The following section presents different RAM applications in industries where this methodology is usually applied.

11.2.1 Aircraft Industry

One of the first industries to apply the RAM analysis was the aircraft industry. Safety is one of the major issues to be addressed in aircraft design, and this is achieved by ensuring an extremely reliable design. Thus, RAM is conducted with the main objective to assess the reliability of the different critical systems for airplanes' operations and safety. RAM process allows defining the components' reliability requisites and assets' redundancy level necessary to meet minimal aircraft performance and safety.

11.2.2 Railway Industry

In the railway industry, RAM analysis is often used to estimate the Life-Cycle Costs (LCC) of train concept designs. Indeed, RAM gives good indication of the maintenance requirements, especially for unplanned repairs, and consequently their associated costs over the train's life cycle.

Railway companies realized that the costs of operation of trains are significantly higher than the costs of acquisition, and that the profitability is much more driven by the operational expenditures (OPEX) than by capital expenditures (CAPEX). Given this situation, railway companies have been guiding their investment on new trains with lower cost of possession (CAPEX + OPEX) and not only trains with low cost of acquisition (CAPEX only). This forced the train builders to take into consideration the impact of maintenance costs on their design. This is one of the main reasons for the raise of RAM analysis in the railway industry since the 70s.

11.2.3 Oil and Gas/Offshore Industry

With the increase in the price of oil since the 70s crisis and the discovery of new deep sea oil and gas reservoirs, offshore exploration has been more and more attractive despite the high cost of investment and operation. In fact, the attractiveness of the offshore facilities lies in their ability to produce large volumes of oil or gas with the least possible shutdown.

In order to achieve this goal, RAM analysis is performed by modelling the full supply chain from wells via production platforms or FPSO or FLNG to storage tanks at onshore terminals. Production bottlenecks are identified on the whole supply chain (storage tanks, main processes, subsea assets, distribution systems, utilities systems, maintenance utilities, etc.), and modifications on the design and maintenance and sparing philosophies are applied interactively until the minimum production availability target is achieved in RAM simulations.

11.2.4 Defence Industry

Integrated Logistic Support (ILS) is widely used by the defence industry as it is a management approach to plan and develop optimized support for the army in order to assure the right availability of the arsenal during military missions. The RAM analysis in the ILS process ensures the deployment of the right necessary sources that maximize the arsenal availability and minimize the operational costs of the mission.

During the arsenal conception, RAM helps to assess that each element performs its operational function effectively with the adequate reliability and easy maintainability in a safe and cost-effective way (DoD 2005).

11.2.5 Energy Industry

The goal for any power generation system is to meet or exceed the customer's expectations for operation and efficiency. It means reliable operation, minimal planned outages and delivering the expected product yields. As time goes by, the plant assets' performance has a trend to decrease with age while power production demand increases with population growth. So power plant RAM studies are performed with the feedback cumulated during the past years of operation in order to evaluate the real capability of the power plant to ensure the required production for the upcoming power demand. The conclusion of such studies reveals when and where to invest in plant modernization and new supply chain strategies in order to increase plant performance but also to reducing power generation costs.

11.2.6 Process Industry

Most process industries (such as refineries, petrochemical plants and power plants) carry out periodic planned shutdowns for general maintenance and restoration campaigns. For the plants where several configurations of shutdown are possible—plants with multiple production trains, or plants where units can be stopped independently while others continue producing thanks to intermediate storage capacities—RAM studies can be used to assess the impact of each configuration on annual overall availability. This practice allows optimizing the plants shutdowns, i.e. programming sequences of plant shutdowns that reduce production losses due to planned downtime and maintenance resources costs too.

11.3 Motivation for RAM Analysis in Ship Design

11.3.1 Current Situation and Trends

As explained previously, accounting for RAM is not new in engineering design, even at early, conceptual, design stage. However, although this is considered in various industrial sectors (see Sect. 11.2), it is not commonly addressed in ship design. Actually, although some consideration to this topic have been found in the early 80s (Davis and Graham 1982), very few references to reliability analyses of ship systems are found in the literature, focusing on marine propulsion system (Jurjević et al. 2012; Corrignan et al. 2018) or dynamic positioning system (Ebrahimi 2010).

The reliability of marine systems is mainly accounted for today from a safety assessment point of view. As a matter of fact, classification rules, industrial standards (e.g. International Marine Contractors Association—IMCA) or international regulation impose FMEA or FMECA analyses to be performed, and verified, for many different applications and situations, such as ship control and automation systems, risk-based qualification of new technology, offshore access systems, gas fuel/dual fuel systems, computer-based systems (e.g. dynamic positioning), steering gear and exhaust gas treatment systems.

Although being a necessary first step in the analysis of system reliability, FMECA remains a qualitative and static analysis, that does not allow to determine the availability of ship system, where reliability of equipment, resilience of the system architecture (with possible system reconfiguration in case of component failure) and repair and maintenance strategies need to be addressed all together.

However, the level of complexity and automation of ships is more and more increasing due to environmental regulations and economical concerns. This calls for an evolution of the design of complex ships equipped with many systems, operated in complex multiple operational profiles and involved in critical operations, where malfunctions would result in large impacts on human, asset or the environment. Key identified focus areas are:

- developing a closer collaboration between design teams, system suppliers and classification societies;
- ensuring and verifying safety and reliability;
- accounting for the systems maintenance and Life-Cycle Cost.

Developments towards autonomous shipping are underway. The achievement and demonstration, of a sufficient level of reliability of autonomous ships, with a first focus on ship machinery, are clearly identified prerequisites to allow their safe and economically efficient operation (Brocken 2016; Bureau Veritas 2017; Blanke et al. 2017).

As a consequence, shipyards, naval architects and equipment manufacturers focus more and more on total cost of ownership (i.e. CAPEX plus OPEX) rather than on CAPEX only, as traditionally done, which gives freedom to propose their customers various CAPEX and OPEX strategies.

11.3.2 Expected Benefit of RAM at Early Ship Design Stage

Accounting for total cost of ownership should be addressed very early at concept design stage. As a matter of fact, decisions on design solutions that have large impacts on CAPEX are made very early. This is the case for the propulsion and powering architecture and equipment which represent a large share of the ship capital cost. Choices on equipment technology and/or grade, as well as on redundancy, have a strong impact on the ship equipment cost but also on the general arrangement.

As described in Sect. 11.6, performing a RAM analysis requires details on the systems to be analysed, on the intended ship operations and can be resources and time-consuming. Various strategies to work around these issues can be implemented in order to perform RAM analyses at early design stages, as investigated in the EU HOLISHIP project. Adapting RAM models from previous projects, creating RAM models for various generic systems architectures, building catalogues of equipment reliability data, using data from public databases (see Sect. 11.6.3), etc., are possible ways to perform RAM analyses in a quick, efficient and reliable way.

11.3.3 Main Target Ship Types for RAM Analyses

RAM analysis is primarily beneficial for complex ships, where complexity does not result only from complex technology but can arise from an integration of many engineering systems and their interactions. The following ship types can be listed in this category:

- Specialized vessels such as offshore supply vessels, with dynamic positioning operations, anchor handling operations, etc.
- Offshore floating structures with dynamic positioning
- Passenger ships
- Navy ships.

In addition, as indicated previously, the design of autonomous ships will require a high level of reliability of their systems, in particular concerning power and propulsion. Autonomous ships will first target ship types with a simple design and relatively simple equipment, i.e. general cargo ships, container ships, bulk carriers and oil and chemical tankers (Brocken 2016).

Hence, most ship types will benefit from performing RAM analysis at design stage in the next future.

11.4 Specificities of Ship Design from RAM Analysis Point of View

RAM studies are routinely performed in various industries as presented in Sect. 11.2. However, each case application has its own specificities, and sometimes the RAM analysis need to be adapted accordingly.

In the case of ship design, RAM analysis can easily get more complex in comparison with other applications due to the following specificities:

1. A large variety of ship types exists, and each one is designed to perform different operations such as sailing, manoeuvering, loading/off-loading in harbour or more specifically special operations such as anchor handling, towing/tugging, oil recovering, firefighting, exploring and others. The more operations the vessel can perform, the more the RAM model get in complexity, and it can get even more complex when sequence and time of operations can vary in time.
2. The systems that make up a ship have sometimes multiple functions, and their components are activated and deactivated according to the operation performed by the ship. For example, on a diesel electric ship, the power supply system is responsible for generating electrical power to the ship systems but also power for propulsion. In this example, depending on the propulsion and powering architectures which constitutes the power system, the loss of a power generator can have different impact ranging from total loss of systems and power, to abortion

of a dynamic positioning operation but keeping the ship propulsion operational. Those kinds of considerations will be important, although complex, to model.

3. The interdependency and interactions between some equipment or systems can be extremely strong, although not always direct or straightforward, and the loss of an equipment can lead to the unavailability of other components. A simple example is the functional relationship between the Main Diesel Engine and the Main Electrical Switchboard which are apparently independent. However, the Main Switchboard supplies the auxiliary machines which are critical to Main Engines' functioning. Thus, the loss of power distribution from the Main Switchboard may lead the loss of the Main Engines. Another example is the Sea Water System, the failure of which can lead to the simultaneous loss of multiple systems.
4. Logistics of ships repairing are very particular due to the fact that vessels are (or should be) always travelling from one location to another. Some vessels sail around a specific area, but others sail all around the world. Moreover, large vessels can store spare parts on board with maintenance crew to repair failures onboard, while smaller vessels have few or no resources onboard dedicated to ship maintenance, so repair can only be performed in ports or yards. All these considerations have to be carefully taken into account in the RAM modelling because they can significantly impact the RAM results.
5. External factors like weather and sea conditions, or more broadly speaking seasonality.
6. Finally, a RAM study generally aims at evaluating the availability of a system. Availability is normally defined by either of the following formulas:
   A = [Total time the system is in good functioning state]/[Total time the system is in good functioning state + Total time the system is in failed state + Total time the system is under repair];
   or
   A = [Total production that the system generates in a given time]/[Maximum production that the system can generate in this given time considering that no failure occurs].
   Then, the concept of availability is quite difficult to apply to ships since they are designed to perform operations, missions or services and not to produce a good, like it is the case in factories where you can relate unavailability with a loss of production (and consequently loss of revenue). In the case of ship operations, it is difficult to relate a percentage of unavailability to outperformance. All depends on which ship operation is more impacted by the unavailability. Moreover, vessel's performance can also be impacted in case propulsion cannot produce the required speed to achieve their mission. In this case, the vessel is still available (because still functioning) but not in its full capacity. A way to work around this issue is to follow a different rationale in order to obtain the performance indicators from a RAM study. For instance, instead of using the availability concept, the RAM could provide results like the percentage of successful mission without delay (over a total of possible missions). This kind of indicator is much more plausible for the study in view of taking further decisions during a project.

Due to the complexity induced by all these specificities, performing a RAM study on ships is quite challenging. It requires very solid assumptions but also a RAM tool with flexible modelling features.

11.5 Main Ship Systems for RAM Analysis

Apart from structural and hull systems, the RAM analysis can be performed on almost any system of a ship: machinery system, cargo system, navigation system, power generation system, propulsion system, dynamic positioning system, etc.

However, efforts in RAM studies should be focused on the most critical systems of the ship, and the analyses must be in adequacy with the stakeholders' expectations and requirements.

The first systems to be identified are the safety-related systems, i.e. those that are essential in case of emergency, like emergency power generation or firefighting system. System's whose loss of function leads to major safety issues, loss of vessel integrity or control, etc. Propulsion and manoeuvering systems are to be considered as safety-related systems.

For safety-related systems, the RAM analysis will focus on the reliability of the systems in order to assess the probability of them to fail during the vessel's life cycle. If this probability is not acceptable according to safety criteria, the design must be improved. It is part of the RAM analysis to identify the components with the highest influence on system unreliability. Design changes, such as implementing redundancy or components' reliability improvements, are then suggested. Finally, the safety of the resulting alternative designs is reassessed with a new RAM analysis. This process is repeated until the system reliability meets the safety requirements.

The common systems to all ships that are critical to safety, environment and ship mission are propulsion/manoeuvering and powering systems. These systems are the ones where RAM analysis can offer real added value in the ship design.

Recently, the international community has been more and more concerned about the environmental protection, especially concerning air pollution. Because of that, the ship designers are addressing more importance to the environmental impact of the ships during the design phase. The power generation system is one of the main systems to focus on environmental issues due to fuel consumption and resulting pollution emission. In order to reduce the environmental impact of power generation systems, designers generally develop multiple solutions including different types of generators configured in different possible structures.

The RAM analysis is able to assess the utilization rate of diesel engines and generators during the vessel's life cycle. This output can be used as complementary information for energy efficiency analysis in order to estimate which solution is the one that produces the less aerial emission.

Vessels are designed to perform specific mission or to provide required service. Every time the mission or service is not provided, serious penalties are undergone either by loss of revenue or by fines payment. In those cases, the systems to be identified and assessed are the ones that have direct impact on the vessel's performance. The systems depend on the type of vessels but also on the purpose/mission of the vessel. For most of the vessels, propulsion is critical for ship mission. For cruise ship, for example, air conditioning can be very critical for company's reputation and consequently for its business.

For those systems, the RAM analysis will focus on the availability of the system and its effect on vessel's mission and/or service. The bottleneck components, i.e. the most important contributors to unavailability/vessel underperformance, are identified, and design improvements and/or operating and maintenance strategies enhancements are foreseen. A RAM analysis is performed with the modifications, and the new vessel performance is calculated. A "cost-benefit" and Life-Cycle Cost (LCC) analyses are then carried out to evaluate what changes are worth applying.

11.6 RAM Study

RAM studies can be performed in several ways depending on the scope and the goals of the study. The successive steps for conducting a generic RAM study, that may vary from study to study, are described hereafter.

11.6.1 RAM Study Process

The first step of a RAM study is the definition of the scope to be analysed. It means that the barriers of the system to be assessed have to be delimited. At this stage, the systems can be divided into subsystems, assemblies, subassemblies, etc., until components level (generally at equipment) or even into subcomponents (e.g. parts of an equipment).

The specifications, operational modes and functions of the components are collected in order to help defining the system configuration and functional links between equipment, i.e. which equipment are required to be running and those that are in standby mode (redundancy).

11.6.2 Criticality Analysis

An essential step before starting modelling is the Criticality Analysis. This analysis consists in defining the impact of equipment failures on the system performance. It is usually done by means of a Failure Modes, Effects and Criticality Analysis (FMECA) where it is possible to assess the functional effects of equipment single-point failures on other equipment and on the system itself. This exercise seeks comprehensiveness, which is a pillar of RAM analyses.

11.6.3 Reliability Data Collection

The main data to be collected for the RAM analysis are Mean Time To Failure (MTTF) and Mean Time To Repair (MTTR) for each equipment considered in the scope of work. Those data are usually collected from industrial reliability data books (like OREDA 2009; IEEE 1984 or MIL HDBK 217F) and then reviewed by different stakeholders—mainly operators, but also equipment manufacturers, process specialists, etc.—based on their experience from similar projects.

11.6.4 RAM Assumptions

Assumptions should be established in order to define what considerations are taken in the RAM model. Assumptions usually consist in operational and maintenance parameters and conditions used to simulate a realistic case. However, some aspects cannot be modelled; thus, some assumptions have to be defined for simplifying the model (e.g. failure due to human errors are not considered in the model) or for adapting the model due to a lack of information (e.g. in design phase, the spare parts strategy is not already defined, so it is considered in the model that spare parts are all available when needed).

In order to obtain the most consistent possible model, all aspects of the system should be covered by the assumptions and taken into account in the RAM model. The assumptions include aspects such as equipment behaviours and failure types, operational characteristics, maintenance organization, spare part resources, logistics, preventive maintenance, external factors and system life cycle.

11.6.5 RAM Modelling, Simulation and Calculation

Once the scope of work and all assumptions are established, the system can be modelled in a RAM tool.

Depending on the selected tool, the system is represented by a model such as Fault Tree, Reliability Block Diagrams (RBD), Petri nets or functional “bricks and links” that recreates component behaviorial modes (e.g. functioning, failed, repairing…) and the system functional architecture (e.g. redundancy between equipment). In a simpler way, each equipment is represented by an element called “event”, “block” or “brick” which is linked to other elements. The way elements are linked depends on their functionalities and the impact of their failures on the system performance.

Nowadays, innovative RAM tools are able to model other kinds of items which are not pieces of equipment but that can have an influence on the system performance, such as maintenance utilities, spare parts or even external factors such as weather.

For each equipment, reliability and maintainability data are entered in the model, together with other data defined in the RAM assumptions such as logistics times and production profile.

Deterministic RAM tools will convert the RAM model into complex reliability, availability formulas. The formulas can calculate several performance indicators such as the average availability of each equipment and the system itself over the system life cycle.

A Monte Carlo-based tool will simulate cycles of operations over the system life-cycle duration. The RAM tool will simulate equipment failures and repairing based on the probabilistic reliability data entered for each equipment.

As the tool performs the simulations, the impact of the sequence of failures and repairs on the system performance over its life cycle is progressively computed and measured.

11.6.6 Results Generation

After modelling and simulation, several indicators can be extracted in order to assess the system performance but also to determine the weaknesses of the system that would need to be improved.

The main result that is generated is the system overall availability, and it is usually compared to the project target availability which is previously defined by the stakeholders.

The second most significant result is the ranking of the elements sorted by their contribution to the system unavailability. This ranking can also be done at subsystem and assembly level or by equipment types. Such a ranking shows the bottlenecks of the system and good indication of ways of design improvements or operation and maintenance enhancements.

Many other performance indicators can be extracted from the RAM simulation/calculation for further analysis. For example, the number of repairs performed for each equipment can be calculated and used in order to calculate OPEX costs related to corrective maintenance in a Life-Cycle Cost analysis.

Another output is the time that each equipment is running yearly, so it can be possible to calculate their energy consumption and eventually their CO_2 equivalent emission for environmental analysis.

Usually, all identified design, operation, maintenance or logistics, improvement solutions are subject to a new RAM simulation called "sensitivity case". The comparison between the "sensitivity cases" allows the stakeholders to measure the gain in performance for each improvement and decide on the best strategy.

11.7 RAM Modelling

Several RAM modelling methods exist and are available in commercial tools. The choice of the method depends on several criteria such as complexity of the system to be modelled, type of application, type of required results, type of inputs and extent of the assumptions to be considered. The following sections present the most common modelling methods currently used in RAM studies with their pros and cons.

11.7.1 Boolean Formalisms

Description

In the RAM process, the systems to be analysed are modelled by means of a diagrammatic representation of its components and their interactions contributing to the system functionality.

Classical methods based on Boolean formalisms are Fault Trees, Event Trees and Reliability Block Diagrams (Stapelberg 2009; Prosvirnova 2014).

Traditionally, the most used modelling method is the Reliability Block Diagram (RBD) which represents the components in a series of blocks connected in parallel or series configuration (see Fig. 11.1). Each block represents a component of the system with a failure rate and a Mean Time To Repair. Parallel paths are redundant, meaning that all of the parallel paths must fail for the parallel network to fail. By contrast, any failure along a series path causes the entire series path to fail.

Pros

This modelling is easy and fast to implement. This is well adapted for process flow systems as it is the case for oil and gas production.

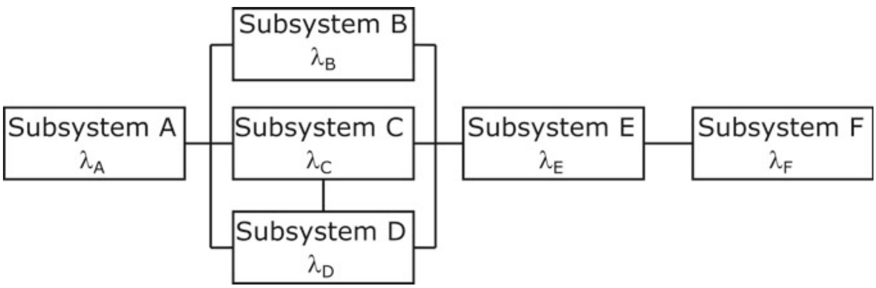

Fig. 11.1 Example of Reliability Block Diagram (RBD) representation of a system

Cons

The presentation may be confusing as the sequence of reliability blocks may not follow the sequence of the equipment in a process (RBD is not a Process Flow Diagram—PFD).

Boolean formalisms put very strong constraints on events (failures) to be considered. All events are assumed to be statistically independent. Among other consequences, it is not possible to take into account the order in which events occur and events can occur any time, no matter the current state of the system. This prevent from modelling the dynamic behaviour of a system.

Systems that have different operational modes usually are operated under different equipment configurations. In those cases, a different RBD representation has to be made for each possible operational mode.

For systems with different product flows, a specific RBD model needs to be built for each product process flow.

11.7.2 States/Transitions Formalisms

Description

Classical States/Transition formalisms are Markov chains and stochastic Petri nets (Stapelberg 2009; Prosvirnova 2014).

States/transitions' formalisms make it possible to represent dependencies between components, such as cold redundancies, resources sharing and sequences of actions. Hence, they can handle dynamic models. This greater capability has, however, a price in terms of practical calculability.

Markov chains used for safety analyses are probabilistic finite state machines. They have a graphical representation (see Fig. 11.2) where:

- The system states are represented by circles;
- The transitions between states are represented by arrows labelled with the probabilities. These probabilities typically correspond to the failure rate λ or the repair rate μ of the components of the system.

Some states are considered as operational for the system under study (some components may be failed in these states), and others are considered as failure states.

A system should verify the Markov assumption to be modelled by a Markov chain. This assumption says that the "system evolution depends only on the current state of the system", which means that the process has no memory. This strong assumption is verified if the delays associated with components failures and repairs are exponentially distributed.

A Petri net is a mathematical modelling language for the description of systems with dynamic discrete events. It is also known as a place/transition (PT) net. A Petri net is basically a directed bipartite graph, in which the nodes represent transitions (i.e.

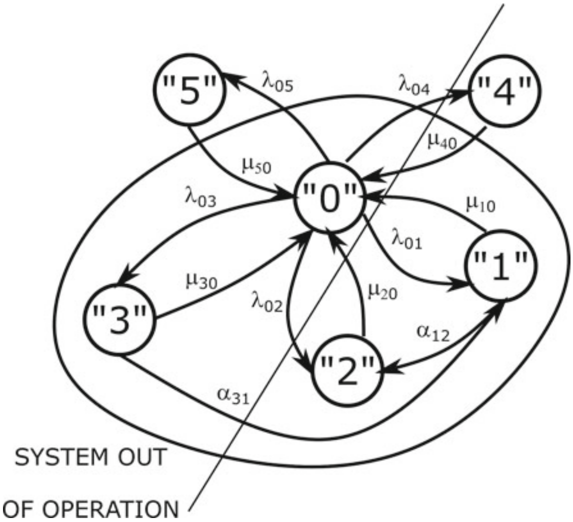

Fig. 11.2 Markov model of ship propulsion system (Jurjević et al. 2012)

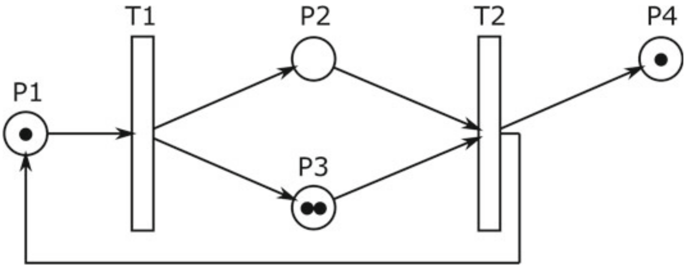

Fig. 11.3 Example of Petri net representation of a system

events that may occur, represented by bars) and places (i.e. conditions, represented by circles) (see Fig. 11.3).

In a RAM model using Petri net, the places represent the equipment states. States are basically "In operation" and "Failed". Other states can be added, like "Partial failure" and "Total failure", in order to differentiate failures that lead to degraded modes or critical failures. "Standby" state can be added for redundant equipment and so on. The nodes represent basically failures and repairs (transition from "In operation" state to "Failed" state, and vice versa). Extra nodes can be added according to the transition between states, like it is the case for redundant equipment which need a specific transition from the "Standby" state to "In operation" state.

Petri nets can also be used to model components other than equipment, for example maintenance utilities and spare parts.

Pros

Markov chains and Petri nets are useful to represent dynamic models.

A Petri net is a very flexible method which allows modelling complex systems. It also provides the possibility to integrate in the RAM model logistics supports such as maintenance and spare parts resources. Petri nets allow the description of systems as hierarchies of reusable components.

Cons

Markov chains become rapidly difficult to handle due to the exponential growth of the number of states. Its graphical representation is convenient for small systems and becomes hard to visualize for large models. The formalism does not allow the description of systems as hierarchies of reusable components.

For both types of methods, the modelling can be time-consuming (compared to RBD) for systems with many components. It is difficult to represent flow propagation like in Reliability Block Diagrams. It is also difficult to understand and visualize the representation of the system for people that are not familiar with Markov chains or Petri net representation.

11.7.3 Model-Based Models

Description

With the advances in computation, several modelling methods have been developed since the 90s in order to meet the need of modelling systems that are more and more complex. These methods incorporate the principles of "traditional" RAM methods such as RBD and Petri net, but with more functional approach. The result is the development of so-called Model-Based methods that keep the benefits of the "traditional methods" but with a more understandable and simple representation of the modelled system.

These methods use high-level modelling languages such as AltaRica (Prosvirnova 2014). The modelling consists of representing equipment as "bricks" which are linked one to another with functional links. This allows simplifying of the representation, as all the states of the equipment are not visually presented in the model, even though they are incorporated in the brick itself (see Fig. 11.4).

Pros

Compared to classical approaches, Model-Based methods present the following advantages:

- RAM model representations are close to functional and physical architectures of the systems under study. In addition, they can be graphically animated and the incident or accident scenarios can be visualized and discussed. This makes them easily understandable and sharable among the design team.

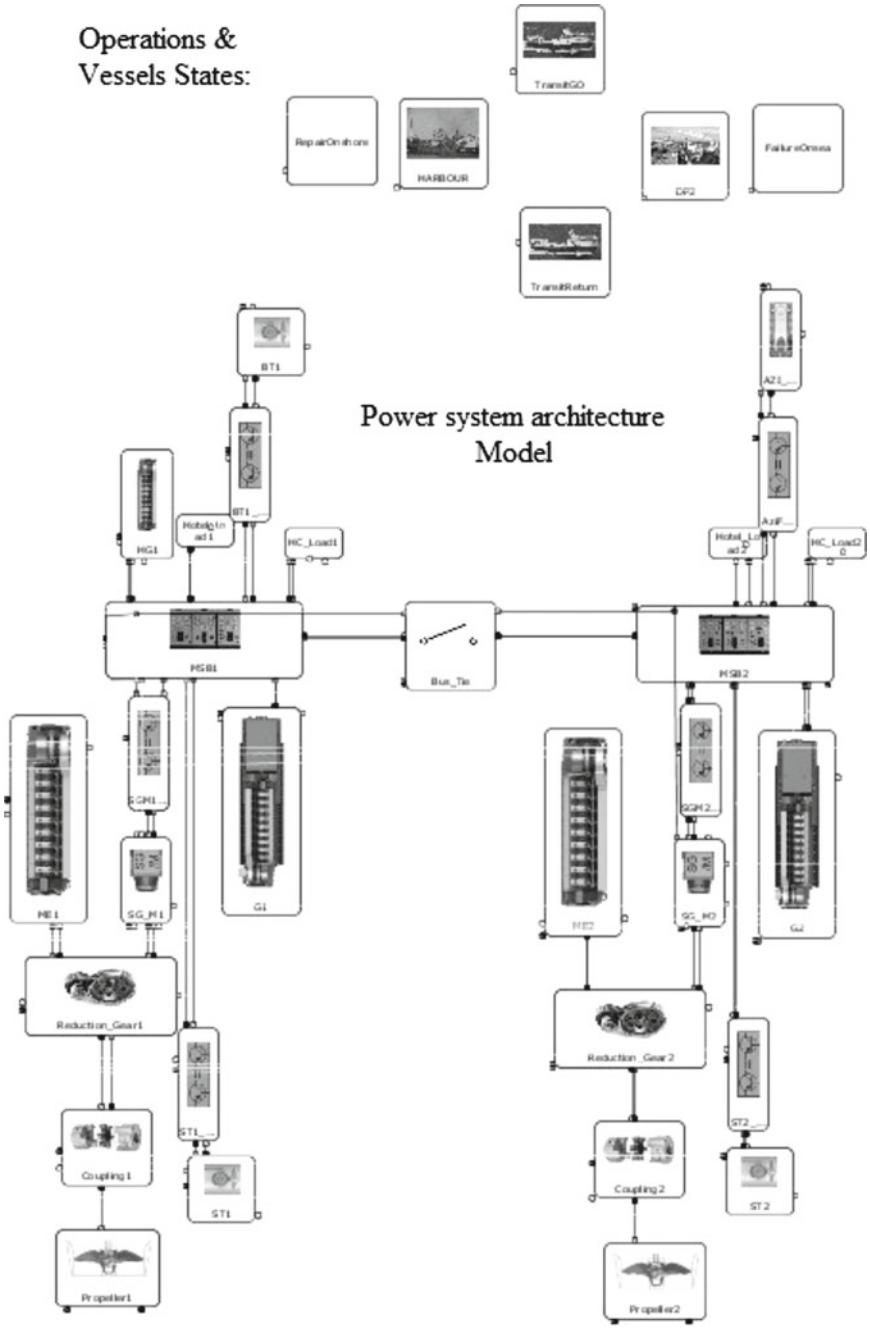

Fig. 11.4 Power system architecture modelling in SIMFIA (Corrignan et al. 2018)

- Additionally, it is much easier to propagate changes in system specifications, as well as to trace changes.
- RAM model structures are close to models designed by other system engineering disciplines (e.g. energy performance modelling) which makes the integration of RAM analyses with other system design processes easier.
- In general, high-level modelling languages have a greater expressive power than Boolean formalisms such as Fault Trees or Reliability Blocks Diagrams. It is therefore possible to capture phenomena, such as spare redundancies and shared components.
- High-level modelling enables the reuse of models at the component level (via the design of libraries) and at the system level (via the adaptation of a model designed for a project to another project).

Cons

This modelling method is still time-consuming and calculation resources consuming specially for very complex systems, since Monte Carlo simulations must be performed to capture the dynamic behaviour of the system.

11.7.4 Most Suitable Modelling for Ship Design

The RBD models can be used if the functionality of the system to be modelled is very simple with low interferences with other ship systems which is rarely the case.

Otherwise, the most suitable modelling methods for ship design are the Petri net method and the Model-Based method due to ships specificities (see Sect. 11.4). As a matter of fact, these methods can model systems with a high level of complexity in terms of design, interaction with other systems and logistic issues.

The choice between Petri net and Model-Based methods depends more on the user skills and experience with this method. The system representation which is offered by Model-Based methods is quite interesting to help the RAM analyst communication with the naval architect and/or the system engineers.

11.8 Main Required Functionalities of RAM Tools

The following sections present the main functions required from the RAM modelling and simulation tool during the different steps of a RAM study.

11.8.1 Step-by-Step Analysis for Verification

Several functionalities are important to allow the RAM analyst checking the correct behaviour of a model prior to simulation.

Event log report of all failure, mobilization and repair

This allows going through a whole simulated life cycle and checking exactly what happened during the simulation and that no abnormalities occurred. Whenever a piece of equipment fails, the impact of this failure on the production or the mission is calculated, the moment at which the repair begins is recorded, as well as the time at which the equipment is put back in service. Therefore, if a low availability is observed on a particular life cycle, it is possible to analyse it in order to understand the cause of downtime.

The most sensitive part of a model is the different conditional logic to be put in place in order to simulate a particular behaviour, such as the replacement of an equipment only when several equipment of the same type fail simultaneously. Another example would be to repair equipment only when the ship is back to port.

Step-by-step simulation

This functionality enables the user to simulate the calculations one event at a time. Therefore, the user can manually trigger any failure on equipment and check what occurs next.

This allows visualizing the impact of a failure on the whole system and to ensure that redundant equipment in standby would take over adequately. It also allows checking the correct propagation of failure (e.g. failure of pump electric motor leading to stop of the pump) and impact on the system. Moreover, it makes it possible to verify that the change of operation mode is correctly performed.

11.8.2 Type of Calculation

Exact analytical calculation

The reliability of a piece of equipment is given by Eq. (11.1):

$$\boldsymbol{R}(\boldsymbol{t}) = \boldsymbol{e}^{-\boldsymbol{\lambda t}} \tag{11.1}$$

with λ being the equipment failure rate (i.e. the ratio of the total number of failures to the total observation time, for a stated period in the life of an item).

Therefore, by establishing the failure criteria of the system and representing it in the form of Reliability Block Diagrams or Fault/Event Tree, it is possible to calculate the system reliability using reliability equations. The model components are either in series, in parallel, or a combination of both.

The reliability of series configuration is given by Eq. (11.2):

$$\boldsymbol{R}_{series} = \prod_{i=1}^{n} \boldsymbol{Ri} \tag{11.2}$$

And the reliability of parallel configuration is given by Eq. (11.3):

$$\boldsymbol{R}_{parallel} = 1 - \prod_{i=1}^{n} (1 - \boldsymbol{Ri}) \tag{11.3}$$

Using Eqs. (11.1), (11.2) and (11.3), it is possible to calculate the system reliability. However, this method is difficult to apply for complex models. Therefore, simulations are used.

Monte Carlo simulation

Monte Carlo simulations attempt to replicate or approximate real-life occurrences by mathematically modelling projected events using random numbers. In practice, this means that although probabilistic distributions are being used to model the failure and repair characteristics of the components within a production system, each unique timing and sequence of events will yield different performance results.

By running a number of trial run simulations (usually called life cycles) each based on a different random number seed and aggregating the results over all of these life cycles, the Monte Carlo simulations can represent the overall performance of a model and the variability of that performance.

Each life cycle has its own random number seed, which determines the timing of the events of that life cycle. The life-cycle availabilities should be provided, together with a list of each life cycle, its availability and the simulation seed for that life cycle. Any given life cycle could then be reproduced exactly by entering the random number seed, in order to analyse the series of event in this particular life cycle.

11.8.3 Results

Typical outcomes of a RAM simulation are the system reliability and availability, in order to understand the potential performance of the installation. The installation can also be subdivided in smaller systems, including utilities, and the contribution to unavailability of each component, each group of equipment, and each system of interest can be obtained. This allows identifying bottlenecks of the installation, and focusing on these items is a key to improve the system performance.

For ship design RAM analysis, the performance indicators such as percentage of successful mission without delay (over a total of possible missions) can also be provided.

Outputs like the number of equipment repairs and number of maintenance utility mobilizations during installation life cycle are also interesting to extract from RAM study for further Life-Cycle Cost (LCC) analysis.

11.8.4 Sensitivities

Following the first round of results, sensitivity cases are performed, in order to compare several design or operational options or investigate potential solutions to improve the system availability. Therefore, it is possible to:

- Include additional redundancy on an equipment or group of equipment;
- Take into account spare lead times of sensitive equipment;
- Assess the availability of the repair teams and eventually increase the number of personnel;
- Change a set of assumptions;
- Use field data and compare with generic databases.

11.8.5 Life-Cycle Cost (LCC) Calculations

Based on the observed number of failure of each system components, it is possible to determine the cost of the failures, which includes the maintenance costs and the cost of the installation unavailability.

The maintenance costs include all the costs linked to:

- Equipment repairs
- Spare part costs and storage
- Maintenance team salary
- Vessels and tools mobilization
- Etc.

The costs linked to the installation unavailability include:

- Non-production costs
- Additional costs to keep up with the production
- Off-specification products costs
- Penalties
- Etc.

The model allows affecting a cost to each failure event, which enables to assess the total cost of running the installation.

11.9 Reliability Data for RAM Analysis

The data required to perform a RAM analysis are at least:

- The Process Flow Diagram (PFD), Piping and Instrumentation Diagram (P&ID), General Arrangement of the installation

- The basis of design
- The equipment list
- A cause an effect matrix to understand the effect of the different equipment failure
- The Mean Time To Fail (MTTF) of each equipment
- The Mean Time To Repair (MTTR) of each equipment
- All the preparation times foreseen to carry out an equipment repair (e.g. equipment isolation, permit to work delivery, tools sourcing, scaffoldings…)
- The maintenance philosophy envisaged by the company/owner/operator (e.g. is the failed equipment immediately repaired? or is the repair delayed until the next planned stop?).

Specifically for the ship designs, extra data are to be provided such as:

- Main One Line Diagrams
- Description of operational modes of the vessel
- Spare part strategy (which spares are stored onboard, in warehouse onshore or not stored at all)
- Preventive maintenance strategy (performed onboard, at port and periodic surveys)
- Logistic times in case of equipment failure:
  - mobilization time of maintenance crew
  - mobilization time of maintenance utilities (or rescue)
  - Spare lead time (according to spare part strategy)
  - Preventive maintenance time (according to preventive maintenance strategy).

The single most important issue in the RAM process is the data used to describe the unplanned failure and subsequent repair of equipment (i.e. MTTF and MTTR). It is fundamental that the data are appropriate and that the project team has confidence in it. Without such confidence, the benefits that could be realized from the study will be limited. As the study proceeds, data from the following sources should be incorporated into the RAM model:

- Operator historical and maintenance records (if any);
- Generic industry sources, e.g. (OREDA 2009), (IEEE 1984), (MIL HDBK 217F 1991);
- Vendor data; and
- RAM workshop (discussions with operational personnel).

In case data are not available in generic industry sources, discussions with operational personnel are a good alternative to define the equipment reliability data. Once the model is completed and the simulation performed, it is always possible to fine tune and revise the MTTF and MTTR of the most contributive equipment and compare the results with a range of data. This would give an interval of confidence related to the equipment reliability. Another way to revise the data in case they are not available in generic data sources is to subdivide the equipment in subcomponent and perform a detailed Failure Mode Effects and Criticality Analysis on it.

11.10 Conclusions

This chapter focused on the applicability of Reliability, Availability and Maintainability (RAM) analysis to ship design.

As already demonstrated in other industries where it is commonly applied, RAM analysis is expected to become a powerful tool for ship design optimization, in terms of Life-Cycle Cost performance. From an operational point of view, it is also very helpful for the definition of equipment maintenance strategies (preventive maintenance, spare parts management).

RAM analysis is primarily beneficial for complex ships, where complexity does not result only from complex technology but can arise from an integration of many engineering systems and their interactions. This naturally concerns ship types such as specialized vessels (e.g. offshore supply vessels, with dynamic positioning operations, anchor handling operations), passenger ships and navy ships. However, considering the current trend for developing highly automated or even autonomous cargo ships, almost all ship types will be eventually concerned in the short future.

Thanks to new modelling methods and tools, the complexity and specificities of ships systems and operations can be captured. Such modelling may, however, become rapidly complex and time-consuming. Consequently, in order to perform RAM analyses at early design stages, strategies to work around these issues need to be implemented. Adapting RAM models from previous projects, creating RAM models for various generic systems architectures, etc., are possible ways to perform RAM analyses in a quick, efficient and reliable way. This will be further investigated in the EU HOLISHIP project for the concept design of an offshore supply vessel.

RAM modelling, both at concept and design stages, relies on data related to equipment failures and time to repair. Whereas generic industry data sources exist, there is no database specific to marine equipment today. The building of such a database would be instrumental for a larger deployment of RAM analysis in ship design.

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Chapter 12
Life Cycle Performance Assessment (LCPA) Tools

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Contents

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Abstract In this chapter, the assessment of both the economic and environmental performance of a vessel over its life cycle is addressed, having as a reference approach the Life Cycle Performance Assessment (LCPA) Tool under development in HOLISHIP project. First, on the basis of a literature review, the concepts of life cycle cost and life cycle assessment are briefly recalled. The ideal target is that these two issues shall be integrated and adapted into the ship design process within a circular economy perspective. Then, a separate reference is made to the end of ship's life phase, explaining the possible strategies to be adopted and highlighting the limitation in estimating energetic and economic performances of this phase in an early design stage. The issue is nevertheless of increasing interest to this regard, as well. A brief review of Codes and Rules related to End-of-Life assessment procedures is also presented. After this, the selection of Key Performance Indicators (KPIs) adopted for the LCPA tool is discussed. These KPIs have been divided in two separate categories: environmental and economic. A methodology to compare KPIs for different ship configurations is then proposed, with an attempt to perform an integrated assessment of environmental and economic aspects. Finally, the relation between KPIs and vessel characteristics is presented. Depending on the level of detail available, the calculation of KPIs and its accuracy are varying accordingly. Finally, issues of uncertainty of certain parameters (e.g. fuel price, freight rates) and their effect on the KPIs are briefly addressed, and ways to their consideration are outlined. Results of application of the HOLISHIP LCPA will be presented in the planned Volume II of the HOLISHIP project.

Keywords Life cycle · Ship design · LCC · LCA · Circular economy · LCPA CER · KPI · Uncertainty

12.1 Introduction

The EU Project HOLISHIP (HOLIstic optimization of SHIP design and operation for life cycle) aims to the design and optimization of ships and other maritime assets by the development of integrated software (s/w) tools encompassing their entire life cycle. In particular, a specific work package of the project addresses the development of a tool capable of an "all-in-one" Life Cycle Cost (LCC) and Life Cycle Analysis (LCA) assessment of ships and maritime assets in general that will be applied to 9 Application Cases of different types of ships included in the project.

This comprehensive approach represents a considerable step forward, since at the moment only parts of a vessel's life cycle are integrated on common data and software platforms. Therefore, the decision-making process is mostly based on the synthesis of best solutions of singular sub-problems, considering a superposition principle in order to achieve the best possible design. Another issue is that shipyards and owners usually are inclined to optimize their product aiming to their own separate objectives. On one side, shipyards would like to produce the vessel satisfying the customer request at the lower cost, guaranteeing all technical requirements stated in the contract to fulfil completely the design contractual specification. On the other hand, shipowners prefer to tune their fleet to reduce operational costs and increase revenues. Nevertheless, it is recognized that better performances and lower costs and environmental impact can be obtained if different operational profiles and ship configurations are analyzed since early design stages in a life cycle holistic perspective. Therefore, a life cycle analysis on ship environmental impact and costs could represent a benefit for both shipyards and shipowners.

The tool, once finally released and integrated on the HOLISHIP platform, will give the possibility of optimizing both economic aspects and environmental impact of a ship design considered throughout the initial and contract design phases, from the perspectives of the designer/shipbuilder as well as of the shipowner. This will be performed with the calculation of selected Key Performance Indicators (KPIs), which will be postprocessed to obtain a unique LCPA Index describing the performance of a ship configuration compared to other investigated designs.

12.2 Methodologies for the Assessment

The HOLISHIP Project deals with the assessment of economic, environmental/energy performances of different vessel types in various possible scenarios. Such performances can be related with different operational profiles, maintenance strategies or other features of the vessel. In this context, both a Life Cycle Costing (LCC) and a Life Cycle Assessment (LCA) procedure will be integrated and adapted for the shipping field, in order to let the designer compare different vessel configurations.

LCC and LCA are well known and widely applied concepts in many fields: they are defined in ISO standards, respectively, in ISO 15686-5 (2008) and ISO 14040 (2006). In the following, a short presentation of LCC and LCA will be given, in consideration of the specific purposes of HOLISHIP.

12.2.1 Life Cycle Costing (LCC)

The concept of LCC was born in 1965 in USA, when the United States Logistics Management Institute used the term Life Cycle Costing in a military-related document. After this document, three guidebooks were produced by the US Department of Defence in the early 1970s, which express the main concepts of Life Cycle Costing, as stated by Okano (2001). Since then, many practices and theories on Life Cycle Costing have taken place and many publications have been issued.

In an attempt to improve the design of products, reducing design changes and time to market; *concurrent engineering* or *life cycle engineering* has emerged as an effective approach to address issues in today's competitive global market (Bernard et al. 2013). The principal unique aspect of life cycle engineering is that the complete life cycle of the product is kept into consideration and addressed in each phase of

Fig. 12.1 Typical life cycle stages

	Company cost	Users Cost	Society Cost
Design	• Market Recognition • Development		
Production	• Materials • Energy • Facilities • Wages, Salaries, etc.		• Waste • Pollution • Health Damage
Usage	• Transportation • Storage • Waste • Breakage • Warranty Service	• Transportation • Storage • Energy • Materials • Maintenance	• Packaging • Waste • Pollution Health Damage
Disposal/ Recycling		• Disposal /Recycling Dues	• Waste • Disposal • Pollution • Health Damage

Fig. 12.2 Life cycle stages and costs (Asiedu and Gu 1998)

the product development. Life cycle engineering goes beyond the life of the product itself and simultaneously considers the issues of the manufacturing process and the product service systems. The ideal situation is to implement such aspect in a *circular economy* perspective.

There are three coordinated phases that need to be considered in life cycle product design, as represented in Fig. 12.1. The life cycle of the product begins with the identification of the needs and extends through design, production, customer use, support, and disposal or recycling.

A general overview of the costs subdivision among company (e.g. the shipbuilder), users (e.g. shipowners) and society is given in Fig. 12.2, for the life cycle stages of Design and Production, Utilization Phase (e.g. Ship Operation) and Disposal/Recycling.

Among the various elements in the list in Fig. 12.2 (Asiedu and Gu 1998), it is possible to identify which costs merely regard a LCC analysis (i.e. first two columns from the left, "Company Cost" and "Users Cost"), and the ones related to health and environmental issues, which instead are typical of a LCA (i.e. last column on the right, "Society Cost").

12.2.2 Life Cycle Assessment (LCA)

LCA is the assessment of the environmental impact of a product or a service throughout its lifespan (Langdon 2006). The first well-known study was conducted by Coca-Cola in 1969 for the recycling of aluminium cans. However, in the 1970s, these approaches were based on a single stage of a product's life, such as production, or a single issue, such as wastewater; therefore, they were not particularly effective in achieving effective environmental benefits.

In 1979, the Society of Environmental Toxicology and Chemistry (SETAC) was founded as a non-profit professional society to promote multidisciplinary approaches while studying environmental issues. In the late 1980s, life cycle assessment emerged as a tool to better understand risks, opportunities and trade-offs of product systems as well as the nature of environmental impacts. At the first SETAC-sponsored international workshop in 1990, the term "life cycle assessment" (LCA) was coined. The advantage of LCA over point-source regulation is that it avoids shifting a product's environmental burden to other life cycle stages or to other parts of the product system, since it considers all the life cycle of a product.

LCA can assist in the following aspects (Langdon, 2006):

- Identification of improvement opportunities for the studied product or service throughout its whole life.
- Decision-making in industry, governmental and non-governmental organizations.
- Selection of relevant environmental performance indicators and adequate measurement techniques.
- Marketing opportunities for products, e.g. an environmental claim, eco-labelling scheme, or environmental product declaration (EPD).

12.2.3 LCC and LCA in the Shipping Sector

In recent years, different methodologies for both LCC and LCA have emerged, generating in some circumstances confusion and conflicting interests. Many hybrid techniques were born to try to consider some aspects of LCC in a LCA assessment and vice versa. Indeed, methodological differences and different weights for environmental, economic and societal priorities lead to conflicting results from the policy issues and business points of view.

Furthermore, while broadening the different methodologies to conduct sustainability assessments, fragmented developments by a variety of research disciplines led to blurred distinctions and as consequence, synergies between tools become harder to identify (Hoogmartens et al. 2014). This is also why it is important to synthesize and merge the aspects of these two assessments into a single tool, which represents the purpose of this work in the frame of HOLISHIP Project.

As explained, LCC and LCA are two methodologies that analyse different aspects of the life cycle of a product. Still, it is difficult to apply integrally both procedures in ship design. Moreover, it would be better to perform a unique analysis which considers economic, environmental/energy aspects at the same time.

Ideally, with respect to LCC and LCA in shipping industry, ship design for shipping should consider the whole product life cycle, stretching from ship concept design to scrapping/recycling in a consistent way. However, at the moment, only parts of a vessel's life cycle are integrated on common data and software platforms. Therefore, the decision-making process is mostly based on the synthesis of best solutions of singular sub-problems, considering a superposition principle in order to achieve the best possible design.

Another issue is the fact that *shipyards* and *shipowners* usually optimize their product in an independent way, with their own separate perspective, as already pointed out. Therefore, a life cycle analysis on environmental impact and costs could represent a benefit for both shipyards and shipowners.

HOLISHIP fills the gap between the design and life cycle analysis, starting from results already obtained from other European projects such as Joint Operation for Ultra Low Emission Shipping (JOULES), where LCA simulations of different ship configurations were performed to evaluate the potential emission reductions from shipping industry. In this sense, the tool to be developed will be an evolution of the JOULES's one (Wurst 2016).

12.2.4 Cost Estimation Methods and Adoption of KPIs

A crucial problem in LCC analysis is cost estimation. Cost estimation methodologies can be summarized in three basic groups: analogous estimation, parametric estimation and bottom-up estimation. Most of the existing models can either be directly associated with one of these three methods, or be a conjunction of two or with all three basic models shown in Fig. 12.3.

The *analogous* costing methodology is characterized by adjusting the cost of a similar product relative to differences between it and the target product. This estimation technique relies on the assumption that similar products have similar costs. Based on stored past designs, the costs of the actual design are estimated with regard

Fig. 12.3 Three main cost estimation methods

to the similarities and differences between the two cases. This case-based approach is useful at the early design stage. With past cost data available, it is possible to produce good approximation in minimum time.

Multiple historic cases can be used to establish a baseline function or model, where one of the main products attributes fits linearly with the product costs. This baseline can then be used to estimate manufacturing cost of a product based on its value for this main attribute. The method can be further enhanced with the use of extra parameters or cost drivers (complexity factors) which give account to part differences from the established baseline (Asiedu 1998; Hueber et al. 2016).

The prime principle of *parametric cost estimation* is the building of the "Cost Estimation Relationships" (CERs). The CERs are mathematic relations between the costs of a product or a system and some of its parameters known as "Cost Drivers". With CERs it is possible to predict part-costs based on the part size. The models can use one or more parameters or variables, such as weight, size and number of drawings for the mathematic correlation between these parameters and product costs. The cost drivers are bound to be highly influential on the cost changes or at least follow the trend of the costs. One cost estimation model can or will consist of different CERs. The drawback of this method is that it depends on a historic database; thus, the uncertainty of usage outside this database range can lead to wrong results. Furthermore, it is not robust enough to depict technology changes or altered system requirements (Asiedu 1998; Hueber et al. 2016).

In *bottom-up estimations*, all work steps with their costs for material, work, infrastructure, etc., are added up to produce the products final costs. For this kind of estimation, or calculation, deep understanding of the process, process interactions, and the part design details have to be available. The advantage of this method is the level of detail and the direct relation between systems and component (it is able) to provide. This would be especially useful for cost-sensitive product design as it could give direct cost impact feedback to designers in their design process. On the other hand, the biggest drawback of the engineering "build-up" or bottom-up approach is the large effort to perform the estimation and the large volume of required product details. Nevertheless, it offers an easily understandable process and is the only method to be applicable to new technologies and/or products (Asiedu 1998; Hueber et al. 2016).

Among the three methods, *parametric cost estimation* (Shetelig 2013) is the most appropriate for a preliminary assessment in early design. All three cost estimation approaches are in theory suitable for different stages of the design phases, but it is the amount and detail level of data available that determines which approach is appropriate. HOLISHIP goal is to investigate the cost effects of main changes in high-level performance requirements, both for LCC and LCA, usually discussed already in early phases of a new shipbuilding project, where none or only a small portion of the costs are assigned. For this purpose, a top-down parametric approach represents the best choice to use as a basis, eventually in combination with an analogous approach, when data are available.

To synthetize results of environmental and economic life cycle analyses, a global *Life Cycle Performance Assessment* (LCPA) is being developed and implemented in a tool. This procedure merges aspects of LCA and LCC, evaluating economic and environmental-energy Key Performance Indicators (KPIs), or the relevant quantities that are calculated by the software to perform the cost and emission assessment, merging them into a global index, the above-mentioned LCPA Index. Following this new approach, it is also possible to define KPIs directly related to the maritime environment (such as the Energy Efficiency Design Index or EEDI). This procedure has been developed to compare and rank different configurations rather than assessing absolute values of single KPIs, which would be more difficult due to lack of data and uncertainties in cost prediction models. Details of the methodology are given in Sects. 12.5 and 12.6.

12.3 End-of-Life Phase

In this section, an overview of ship's End-of-Life phase is presented, analysing the current state of the art and its integration in HOLISHIP project, in particular referring to the LCPA tool.

12.3.1 Alternatives for End-of-Life Phase

In order to analyse alternatives for End-of-Life phase, it is very valuable to introduce concepts of circular economy to complete the overview of the total cost of an asset in a life cycle perspective. The circular economy is a view intended as an alternative to the traditional linear economy based on production, use and disposal-off. Resources are instead kept in use for the longest time possible, extracting the maximum value from them whilst in use, then recovering and regenerating products and materials at the end of each service life. Therefore, the concept of circular economy is strictly related to remanufacturing and recycling of the ship and its components. The transition to a more circular economy is an essential contribution to the EU efforts to develop a sustainable, low carbon, resource-efficient and competitive economy. In this view, HOLISHIP may play an active part in the achievement of this awareness.

Remanufacturing represents a key strategy within the circular economy. There are different ways of proceeding when a product (ship) reaches its final stage, as it is depicted in Fig. 12.4 (Jansson 2016).

There are several conceptual methods suitable to be applied (Jansson 2016) at the End-of-Life phase: reusing, which is the simple reuse of a product with no modifications; recycling, which deals with the extraction of a product's raw materials for use in new products; remanufacturing, that is a series of manufacturing steps acting on an End-of-Life part or product to return it to like-new or with a better performance with warranty to match; disposal, that is when the object is not considered as useful and therefore it becomes a waste to be disposed-off.

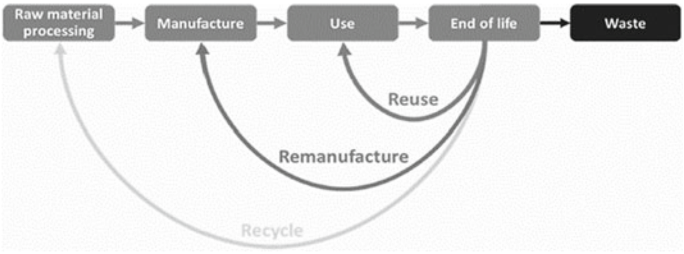

Fig. 12.4 Recycle, remanufacture and reuse and final waste of a product (Jansson 2016)

Disposal (e.g. ship dismantling) represents the least favourable option in circular economy, since it generates the higher amount of waste among all alternatives. On the other hand, remanufacturing, reusing and recycling in particular, especially already taken into consideration in preliminary phase of ship design, are the best strategies in terms of sustainability. In recent years, Administrations are proposing new regulations to comply with when a ship reaches its end of life. For this purpose, ships recycling are addressed in the Hong Kong Convention developed by the International Maritime Organization (IMO). This covers the design, construction, operation and preparation of ships so as to facilitate safe and environmentally sound recycling, without compromising safety and operational efficiency (IMO 2009). It can also be observed that remanufacturing opportunities are more evident in ship repair activities focused on component level and specific sub-systems (Jansson 2016).

Quantifying and predicting End-of-Life costs, revenues and environmental impact of a ship, during the design phase, is difficult and rather far to be state of the art. One of the biggest issues to overcome, linked with remanufacturing and circular economy applied to the shipping industry, is the evaluation and development of a vessel at the design stage taking into account these aspects. This is because ships are among the most complex systems built by humans, especially in the case of passenger ships and navy ships.

In order to increase the profitability of this sector and reduce emissions, it is necessary to evaluate economic and environmental performances of a ship not only to satisfy contract specifications, but also for operation and remanufacturing phases in a life cycle perspective, applying the concepts of circular economy. In this scenario, at least the well-known Life Cycle Costing (LCC) and Life Cycle Assessment (LCA) analyses have to be implemented in the proper way in the design of new units. In fact, they are both best practices well developed and applied in many sectors but not enough implemented in the shipping industries.

12.3.2 KPI Inputs for End-of-Life Assessment

It has been above mentioned that the assessment for the End-of-Life can be analysed as an economical and energy issue. This is the reason why both economic and environmental indicators are used for the End-of-Life assessment.

Regarding the economical KPIs, the cost of disposal, the resale value, the cost of recycling and the cost of reuse and remanufacture are considered as well. In the following, a list of the appropriate economical KPIs is presented, with reference to the indicators selected in Sect. 12.4:

- Net Present Value (NPV): The NPV uses as input the **Cost of Disposal or Resale Value or Recycling (L)** which concerns the End-of-Life phases of the ship. Hence, it is a favourable KPI for the End-of-Life assessment.
- Average Annual Cost/Benefits (AAC/AAB): This indicator takes also into account the **Cost of Disposal or Resale Value or Recycling**.
- Maintenance and Repair Costs (M&R costs): Necessary inputs for this calculation are the **horsepower** (machinery replacement parts, for example), **ship size** and the **number of crew members** aboard (paint and cleaning compound).

As far as environmental indicators are concerned, cumulated energy demand (CED) and global warming potential (GWP) cannot be absent from the End-of-Life assessment. Specifically,

- Cumulated Energy Demand (CED): Necessary inputs for this calculation is the **mass of the material** that will be used for ship's construction and the **energy demand for materials** as steel, aluminium, copper, etc., used by the shipyard. The cumulated energy demand for the building of a ship in the yard uses as input data the **energy used per year** and the total ship production per year (in GT).
- Global Warming Potential (GWP): This indicator can be calculated [tCO_2eq.] using the **energy on the shipyard** (electrical, heat, fuel and others) as well as **relevant materials** used for construction of the vessel (Wurst 2016).

12.3.3 Data Required for End-of-Life Assessment

The HOLISHIP project deals with the fascinating decision-making process named ship design. It is well known that traditionally this is a linear iterative process, efficiently represented by the so-called design spiral of Evans, where the level of known details about the ship is improving at any spiral.

In the HOLISHIP project, the design synthesis model is implemented (see Fig. 12.5). It is a systemic approach that, thanks to the modern computational tools, allows in principle the designers to perform the whole virtual testing of the ship at a design stage.

The availability of computational methodologies and tools is changing the perspective of details knowledge increment during the design process. It seems that the

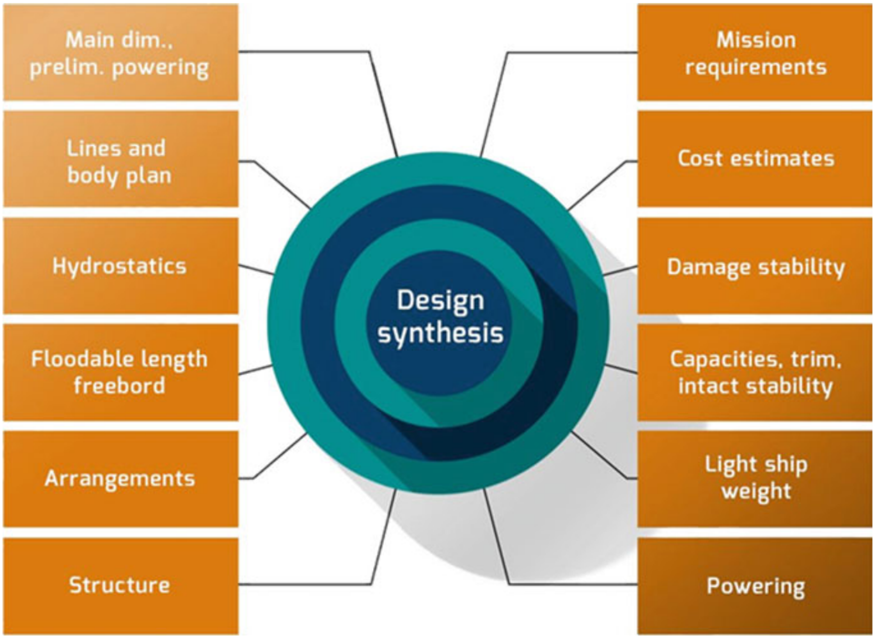

Fig. 12.5 Design synthesis model adopted in HOLISHIP (Harries et al. 2017)

ship is thoroughly defined since the very beginning, but it is still inevitable that the design process at an early stage has a lower level of knowledge about ship characteristics in comparison with the following steps. The Life Cycle Performance Assessment is of course affected by this increasing level of known details about the ship under development. It is required to understand how it is possible to estimate such performances with an acceptable accuracy, relying on the details that are available at the specific moment.

In the HOLISHIP Project, due to the present preliminary design nature of the current LCPA tool, the development has been focused on Design and Production and Operational phases. The predominant importance of these two phases of ship Life Cycle is in any case underlined by Kameyama et al. (2007), with specific reference to the environmental impact in terms of emissions.

As far as the End-of-Life phase, some differences can be spotted in case of disposal, reuse, remanufacturing or recycling. Considering cost and environmental impact of a disposal strategy, this seems not to require a high level of detail to be known. The impact of a disposal strategy could be assumed based on analogies with similar vessels, and it can be associated with some technical parameters of the ship, such as the type of engines installed and their power, ship dimensions. Obviously, better considerations could be developed with a high level of detail of the vessel design. However, this strategy has not been contemplated; the production of waste related with it and the incompatibility with European long-term strategy suggest focusing on other aspects of a vessel life cycle.

A reuse strategy implies a series of maintenance procedures to be carried out in order to extend the lifetime of a ship. It is strongly influenced on the mission requirements of the vessel in its future life. In fact, sometimes the ship is reused by the same owner to fulfil the same requirements; therefore, once a good level of detail of systems on board is known, cost and environmental impact for this procedure could be evaluated. However, usually, at a design stage, it is not known whether the vessel will continue to fulfil its design purposes or if it will be retro-fitted changing mission requirements and systems on board, since this mainly depends on future market and economic scenarios. For these reasons, it makes lower sense to focus on this aspect, plenty of possibilities, in a preliminary design stage.

Finally, remanufacturing and recycling costs/earnings and environmental impacts are the most interesting even though influenced as well by future market scenarios. Still, it is almost impossible to estimate these impacts without a very accurate and deep level of detail available of the ship design. In fact, remanufacturing and recycling are based on material and technical characteristics of each component on board, which are to be better identified in detail in successive stage of design. Therefore, for similar design configurations, it is difficult to estimate economic and environmental impacts variation. Another complication which arises is that more strategies can be adopted when a vessel reaches its final stage, complicating the assessment of this phase at a design stage.

12.3.4 Energy-Economic Evaluation of End-of-Life Procedures

Ships come to the end of their operational life after about twenty-five to thirty years, depending on the vessel type and market conditions; vessels at the end of their life are usually sold and dismantled to recover steel, which constitutes the largest part of a ship's structure, and other valuable outfitting components that can be reused or recycled. If it is carried out in an environmentally sound and safe manner, shipbreaking represents a sustainable method of disposing of End-of-Life vessels; it brings economic and environmental benefits by providing employment opportunities and enabling ninety-five per cent of a ship to be reused or recycled (IMO 2009).

Revenue/Costs of a ship sold for recycling

The economics of the ship recycling industry and the forces behind demand and supply on the ship recycling market are interrelated with three other markets that shipowners operate on: the new building market, the second-hand market and the freight market. To some extent, the ship recycling market serves as a buffer balancing demand and supply in the freight market with increase scrapping when the global demand for sea transport moderates.

Price of recycled steel (Cost of materials)

Once a shipowner has decided to scrap a vessel, the price offered by the ship recycler is heavily influenced by the price of second-hand materials, in particular the price for reusable steel. When the demand for steel and other reusable items grows, steel prices increase and the ship scrappers' earning potential also increases. As a consequence, the ship scrapper's willingness to pay for a vessel for decommissioning grows (and vice versa for a weakening in the demand for steel and other reusable items) (ECDGE 2007).

12.3.5 International Regulation

At international level, the regulation which is in force is the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal of 1989 (United Nations 1989), which applies to ships which go for demolition from one country to another and can be classified as hazardous waste.

In practice, however, the Basel Convention and its transposing law in the EU, Regulation (EC) No. 1013/2006 (European Parliament 2006) on shipments of waste, have been applied only rarely with regard to waste ships.

The European Parliament formally adopted the new EU Ship Recycling Regulation (EU SRR) on 22 October 2013 and entered into force on 20 December 2013 (European Parliament 2013). The EU regulation is similar to the Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships, 2009, (Hong Kong Convention) which has not yet entered into force internationally.

This Regulation is aimed at facilitating early ratification of the Hong Kong Convention 2009—both within the EU and in other countries outside the EU—by applying controls to ships and ship recycling facilities on the basis of the Convention. It aims to ensure that vessels are recycled in EU-approved facilities worldwide (ABS 2014).

The new EU Ship Recycling Regulation means that EU-flagged vessels of 500 GT and over will be required to carry an Inventory of Hazardous Materials (IHM). When calling at EU ports, vessels from non-EU countries will also be required to carry an IHM identifying all the hazardous materials on board. EU-flagged vessels must also be scrapped at a ship recycling facility approved by EU.

As regards the restrictions on the use of hazardous materials, Article 4 SRR prohibits the new installation not only of materials which contain asbestos, polychlorinated biphenyl (PCB) or controlled substances as defined in Regulation (EC) No. 1005/2009 (European Parliament 2009) but also those containing perfluorooctane sulfonic acid (PFOS) and its derivatives, in line with recent EU chemicals legislation (Regulation [EC] No. 757/2010), (European Parliament 2010).

The Hong Kong Convention contains altogether 21 articles setting out the general legal provisions and working mechanisms and an Annex with the actual technical requirements for the design, construction and operation of ships for the operation of ship recycling facilities, and for reporting and enforcement mechanisms (IMO 2009).

12.4 A Selection of KPIs for an Holistic Approach

In last years, regulations scenario for the shipping sector is changing its basic approach. In parallel with prescriptive approach, nowadays it can be more and more likely that a performance-based approach can be accepted. This has a direct influence in the ship design process; Key Performance Indicators could be the right way to measure ship performance to assess the quality of ship designs.

One of the benefits of using KPIs in ship design is that the comparison of different projects can be easily performed comparing the value assumed by each KPI. Since a KPI is a measure of the performance of the ship in one specific aspect or sector, the designer can easily understand which ship design performs better, as a good balance in all different aspects. Considering all the main families of performance that can be measured, KPIs can be defined for technical, economic, environmental and safety issues and they can be adapted according to the considered ship type.

Therefore, KPIs can be also used to assess the life cycle performance of a ship, focusing in particular on economic and environmental aspects. As a product of a literature review performed, two classes of KPIs have been developed, focusing on the selection of parameters which are significant to measure performance in a life cycle perspective, in particular with reference to HOLISHIP project and Application Cases. This list can be modified and updated according to the needs and general boundaries of a particular ship design. Main sectors of transport industry have also been analysed, focusing the target on similarities with the shipping industry.

Economic KPIs

– **Building Cost (BLD)**: It is the cost sustained by the shipyard to build the vessel. Cost estimation techniques should be adopted in order to evaluate this figure. However, different techniques can be adopted based on the level of detail known and developed for a ship design. Generally, in a preliminary design phase, Cost Estimation Relationships (CERs) are developed to link main technical ship parameters with the main aspects of Building Cost (more details on this available in Sect. 12.5 of the present chapter).
– **Capital Expenditure (CAPEX)**: Capital expenditures are, in this context, the funds that a shipowner uses to purchase a vessel from a shipyard. This cost is influenced by two main factors; on the one hand, depending on the type of ship and the technological level installed, CAPEX can increase or decrease. Therefore, the cost in this scenario is directly related to the shipyard Building Cost. On the other hand, it is known that cost is also highly influenced by the market situation at a specific moment. For this reason, the ratio between BLD and CAPEX can change significantly. Then, the price for the shipowner depends on the present

market trend when the contract is stipulated, and it is in a certain way not so strictly correlated to the production cost (BLD cost) as it would be expected.

– **Operating Expenditure (OPEX)**: Operating expenditures are a result of the ongoing costs that a shipowner pays to run its business. A main subdivision of OPEXs has been provided by Stopford (2009):

  - Operating cost
  - Voyage cost
  - Cargo handling
  - Capital
  - Interest
  - Maintenance and repair.

– **Maintenance and repair costs (M&R costs)**: They are a part of OPEXs, but they can be also used independently to assess costs related to maintenance of systems (especially machinery) and structures. This value is directly influenced on the type of systems and maintenance approach adopted.

– **Average Annual Cost (AAC)**: This parameter is useful when designing ships that are not expected to generate a direct economic income, such as naval vessels, coast guard vessels, yachts for leisure and others. It can also be applied when alternatives considered would have equal income and can be expressed as (Lamb 2003) (Eq. 12.1):

$$\mathrm{AAC}[€] = A_0 * \mathrm{CR}(i, T) + Y + L \tag{12.1}$$

where

- i: Discount rate
- T: Life time under investigation
- A_0: Initial investment costs [€]
- CR: Capital recovery factor, it is used to distribute an initial investment over the lifetime of a product, considering the discount rate and the lifetime under investigation
- Y: Annual operating expenses (average) [€]
- L: Cost of disposal or resale value or recycling [€], negative if it is a revenue

If necessary, this parameter can be related to vessel's productivity by mean of the **Required Freight Rate (RFR)** (Eq. 12.2):

$$\mathrm{RFR}\left[\frac{€}{\mathrm{productivity}}\right] = \frac{\mathrm{AAC}}{P} \tag{12.2}$$

where "P" is the annual "productivity" of the vessel, which can be measured accordingly, depending on the considered of ship type. In any case, it should take into account both the ship cargo capacity and the intensity (e.g. in terms of speed) in which it performs its main tasks.

– **Net Present Value (NPV)**: The NPV is probably the most popular economic measure. It is an index on the profitability which is evaluated by subtracting the present values (PV) of cash outflows (including initial cost) from the present values of cash inflows over a time. It can be calculated using the following formulation (Eq. 12.3):

$$\text{NPV}[€] = -A_0 + \sum_{t=1}^{T} (R_t) * (1+i)^{-t} - L * (1+i)^{-T} \tag{12.3}$$

where

– R_t: Yearly cash flow at period t [€]
– Other parameters are defined in (12.1).

However, despite its popularity, NPV sometimes needs to be used with caution. One weakness arises by being dimensionally dependant. For this reason, a single large configuration could seem more interesting for a NPV perspective compared to lower scale designs, even though smaller, more numerous proposals might produce a greater cumulative NPVs, assuming that the supply of investment is limited. In order to correct this drawback, it is possible to simply divide each proposal by the initial investment, leading to the **NPV Index (NPVI)** (Lamb 2003) (Eq. 12.4):

$$\text{NPVI}[-] = \frac{\text{NPV}}{A_0} \tag{12.4}$$

– **Average Annual Benefits (AAB)**: This measure is used to correct another limitation of the NPV, which can deliver unfair comparisons between long- and short-term investments. To overcome this problem, the NPV can be converted to a uniform annual income stream of equivalent value. This can be done multiplying the present amount by the capital recovery factor (CR) appropriate to the unit's expected life and the interest rate used in finding NPV. This uniform amount is defined as the AAB (Eq. 12.5):

$$\text{AAB}[€] = \text{NPV} * \text{CR}(i, T) \tag{12.5}$$

Moreover, defining an **AAB Index** similarly to a NPV Index (Lamb 2003), it is possible to avoid the NPV's two weaknesses at the same time, just by dividing the AAB by the investment to obtain the average annual benefit per unit of money invested (Eq. 12.6):

$$\text{AABI}[-] = \frac{\text{AAB}}{A_0} \tag{12.6}$$

– **Earnings Before Interests, Taxes, Depreciation and Amortization (EBITDA)**: This accounting measure is used to represent shipowners' net earnings, prior to interest expenses, taxes, depreciation and amortization are subtracted, as an indicator for the company's current operating profitability.

- **Return on Investment Capital (ROIC)**: It is a ratio used to measure the profitability and value-creating potential of economic activities after taking into account the amount of initial capital invested (CAPEX) (Eq. 12.7):

$$\text{ROIC}[-] = \frac{\text{Net Operating Profit} - \text{Taxes}}{\text{Initial Investment}(A_0)} \tag{12.7}$$

Environmental KPIs

- **Energy Efficiency Design Index (EEDI)**: The EEDI index is a parameter introduced by the IMO-MEPC in 2011, and it indicates the energy efficiency of a ship in terms of CO_2 generated (grams or tonne per mile cargo carried). It is calculated for a specific reference ship operational condition. The aim is that, by imposing limits on this index, IMO will be able to drive ship technologies to more energy-efficient ones. Over time, the required EEDI level will be possibly even reduced gradually leading to more energy-efficient ships (IMO 2012) (Eq. 12.8):

$$\text{EEDI}\left[\frac{g\text{CO}_2}{\text{ton} * \text{mile}}\right] = \frac{\text{CO}_2\,\text{emissions}}{\text{transport work}} \tag{12.8}$$

- $\mathbf{NO_x}$ and $\mathbf{SO_x}$ emissions (during operation): These parameters measure the grams of NO_x/SO_x generated per unit of transport work. These emissions are regulated by MARPOL Annex VI; the regulatory framework is imposing in recent years more and more strict criteria depending on the sea area in which the ship is sailing. NO_x emissions mainly depend on the type of engines installed on board, while SO_x emissions are mainly related to the type of fuel used to produce energy.
- **Cumulated Energy Demand (CED)**: This parameter is employed to assess the energy used to produce the ship (materials and yard production) and the energy used during operation of the ship from burning fuel in primary energy converters, as well as energy used to produce these fuels and provide them at ships bunker station (well to tank). It therefore considers the energy consumption of the whole ship context.
- **Particulate Matter (PM)** (during operation): Particulate matter is in the focus of many NGOs but also of the IMO, because black carbon (as part of the composition of PM) has a health impact close to cities but also may have an impact on the radiative forcing. Thus, a reduction of PM is crucial to decrease the environmental impact from ships. This parameter is particularly relevant when the ship is operating in ports or near coastal areas.

All environmental KPIs (EEDI, NO_x, SO_x, CED, PM) are always divided by the transport flow, as defined in Eq. 12.8 for EEDI, in order to compare ship configurations with different sizes. In this way, KPIs do not depend on the size and productivity of the ship. Otherwise, it could not be reasonable to compare environmental perfor-

Table 12.1 KPIs for life cycle analysis

Economic KPIs	Environmental KPIs
BLD	EEDI
CAPEX	NO_x
OPEX	SO_x
M&R costs	CED
AAC	PM
RFR NPV (NPV Index) AAB (AAB Index) EBITDA ROIC	

mances of ships with different capacities, since for example a smaller ship would obviously perform better considering absolute values of emissions or energy demand.

Since KPIs should be evaluated during the design of a new vessel, relations between KPIs and main technical characteristics of the ship shall be developed. The purpose is to analyse different configurations of systems and ship operational profiles in a preliminary design phase and measure the variation of KPIs. To do this, a ship breakdown structure (SBS) has been adopted for the development with a variable level of accuracy depending on the stage of the design process. The work developed represents a typical example of parametric/top-down approach, as described by Shetelig (2013).

To summarize, here is a list of the selected KPIs for a life cycle analysis of economic and environmental aspects of a ship design (Table 12.1).

12.5 A Methodology for an Holistic Approach

Traditionally, economic and environmental aspects in a life cycle analysis of a ship are analysed separately, without usually considering the whole life cycle of the vessel but just focussing on defined sub-domains.

The proposed methodology does not aim to radically overturn this mindset; this traditional attitude has been followed as well but an attempt has also been made in order to formulate a merged Index able to integrate costs and environmental impact in a single value.

However, when trying to merge assessments of different backgrounds, some critical issues always emerge, due to the different nature of the specific analyses. In this scenario, three main issues raised while discussing the hypothesis of different calculation procedures, which are summarized as follows.

Firstly, the issue is to compare numerically with a standard procedure KPIs with different unit of measure and order of magnitude. For this purpose, non-dimensional coefficients have been introduced; in this way, KPIs can be properly compared and ranked.

The second issue is related to the numerical range assumed by KPIs' coefficients. KPIs' coefficients should have the same range, and moreover, they should assume a comparable internal variation for each KPI considered. Moreover, it is also critical that both absolute and relative values are considered in the analysis. The importance of different KPIs in the decision process will be expressed by appropriate weight factors.

Lastly, some environmental KPIs could have an acceptance threshold given by rules. In this situation, the calculation process should be able to consider these limitations.

Depending on the parameter taken into account and the characteristics of its optimum values, coefficients have been defined for three different classes (earning, cost and environmental) of KPIs as follows. The procedure developed allows a global comparison of different design configurations, while it cannot be applied if a single ship design is considered. In this case, it is less likely that the designer is interested in evaluating KPIs coefficients, since it is not the case of a comparison with other vessel configuration for a more rationally based selection.

- Earning parameters (such as NPV)

For these KPIs, the optimum value is reached when the parameter assumes the higher value; therefore, KPIs for different ship designs are ranked and compared based on their maximum; a non-dimensional coefficient for the *i*th scenario can be evaluated as:

$$0 \leq c_i^{\mathrm{NPV}} = 1 - \frac{\mathrm{NPV}_{\max} - \mathrm{NPV}_i}{\mathrm{NPV}_{\max} - \mathrm{NPV}_{\min}} \leq 1 \tag{12.9}$$

In this way, coefficients are always defined between zero and one, even if some or all solutions are negative (which represents a loss of capital). Moreover, there is always a solution with coefficient equal to zero (worst) and another one with coefficient equal to one (best).

- Cost parameters (such as CAPEX, OPEX):

For these KPIs, the optimum value is reached when the parameter assumes the lower value; therefore, KPIs for different ship designs are ranked and compared based on their minimum; a non-dimensional coefficient for the *i*th scenario can be evaluated as:

$$0 \leq c_i^{\mathrm{OPEX}} = 1 - \frac{\mathrm{OPEX}_i - \mathrm{OPEX}_{\min}}{\mathrm{OPEX}_{\max} - \mathrm{OPEX}_{\min}} \leq 1 \tag{12.10}$$

Again, the coefficient is always defined between zero and one. There is always a solution with coefficient equal to zero (worst) and another one with coefficient equal to one (best).

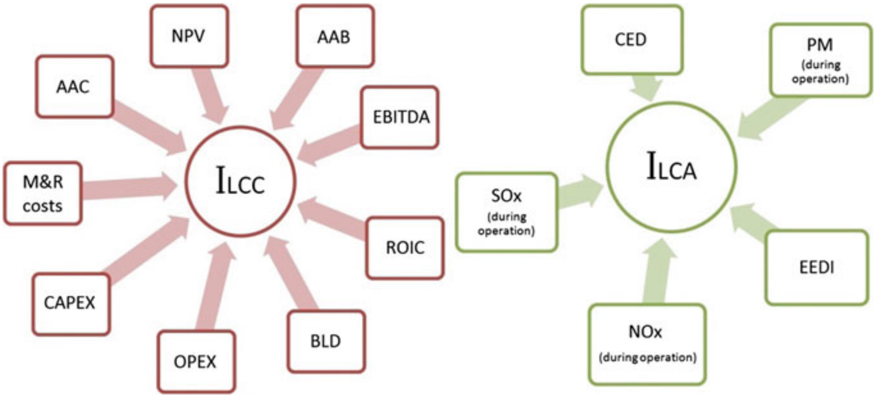

Fig. 12.6 LCC Index and LCA Index

- Environmental parameters (such as CED)

They can be processed similarly as costs, since the best solution is the minimum one:

$$0 \leq c_i^{\mathrm{CED}} = 1 - \frac{\mathrm{CED}_i - \mathrm{CED}_{\min}}{\mathrm{CED}_{\max} - \mathrm{CED}_{\min}} \leq 1 \tag{12.11}$$

It is important to remind that environmental parameters (such as EEDI) could have a limitation given by rules. In this situation, solutions with $\mathrm{KPI_i} > \mathrm{KPI_{lim}}$ should not be considered in the calculation process.

Defining coefficients in relation to best and worst values of design configurations analysed, the calculation process fails when all solutions studied produce the same value for a certain KPI (i.e. $\mathrm{NPV_{max}} = \mathrm{NPV_{min}}$). This happens because reference KPIs values are taken internally and there is no external reference solution to compare results with. If denominator is equal to zero, that is a certain KPI for different solutions is the same, that KPI should not be considered in the decision-making process, since it does not influence the final result.

For this reason and to give ship designers the freedom to investigate aspects which they are more interested in, a selection of KPIs is defined before evaluating a final index for the overall assessment of ship design configurations.

With the aim of checking and keeping track economic and environmental performances, two separated coefficients (LCC Index and LCA Index) can be calculated before merging them in a single LCPA Index. Doing this, when merging these two aspects, relative weights of Indexes can vary according to the designer point of view (Fig. 12.6). This can be formulated as follows:

$$I_{\mathrm{LCC}} = \sum_{i=1}^{N_{\mathrm{LCC}}} f_{i,\mathrm{LCC}} * c_{i.\mathrm{LCC}} \leq 1; \quad \text{where: } \sum_{i=1}^{N_{\mathrm{LCC}}} f_{i,\mathrm{LCC}} = 1 \tag{12.12}$$

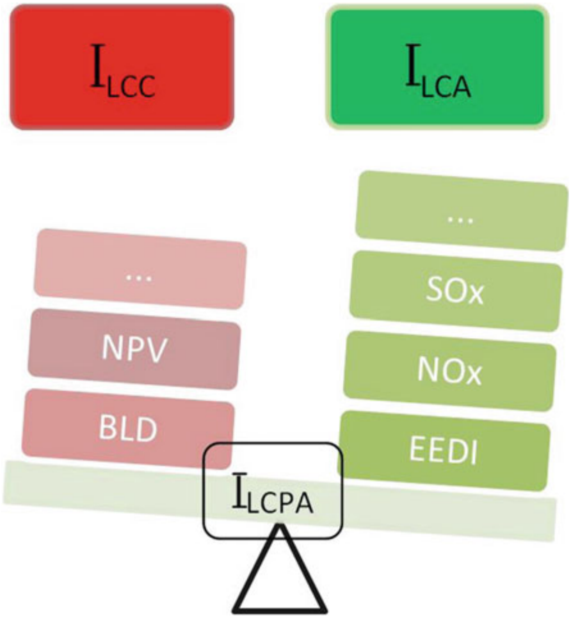

Fig. 12.7 I_{LCPA} as a global index weighing LCC and LCA aspects

$$I_{\mathrm{LCA}} = \sum_{i=1}^{N_{\mathrm{LCA}}} f_{i,\mathrm{LCA}} * c_{i.\mathrm{LCA}} \leq 1; \quad \text{where: } \sum_{i=1}^{N_{\mathrm{LCA}}} f_{i,\mathrm{LCA}} = 1 \tag{12.13}$$

Finally, a global LCPA Index is calculated as follows:

$$I_{\mathrm{LCPA}} = f_{\mathrm{LCC}} * I_{\mathrm{LCC}} + f_{\mathrm{LCA}} * I_{\mathrm{LCA}}; \quad \text{where: } f_{\mathrm{LCC}} + f_{\mathrm{LCA}} = 1 \tag{12.14}$$

One of the advantages of this methodology is that the procedure is not affected by the selected KPIs used to perform calculations: other economic and environmental parameters could be adopted to study different design alternatives without changing the main structure of the combined analysis. Furthermore, the assessment of safety performances could be introduced as a separated family of KPIs, evaluating an index similarly as for LCC and LCA. In this scenario, the social equity problem could be handled in a safety perspective. This could allow a deeper holistic comparison of ship designs, towards a Life Cycle Sustainability Assessment.

Another relevant aspect of this methodology is that the user can assign a variable relevance to KPIs in the decision-making process, as well as increase or decrease the importance of LCC or LCA analyses in the final assessment according to the requests of shipowners and shipyards, or of any other interested stakeholder (Fig. 12.7).

On the other hand, freedom to assign weights at all stages of the process has a strong influence on final results obtained. Changing the influence of a KPI could result in a strong variation in the final assessment, therefore the best design identification changes consequently. This is acceptable because the ship should accomplish the needs of shipowners and shipyards. However, before implementing this methodology in a formal assessment, some restrictions to weights should be defined, in particular when related to environmental aspects.

12.6 LCPA and KPIs Calculation

In this section, the HOLISHIP LCPA tool workflow will be presented. The tool developed can be applied for a preliminary stage of ship design, when a low level of information is known. Due to the low degree of detail available in this phase, reliable calculation of End-of-Life phase cannot be performed, as discussed in Sect. 12.3. The structure is also developed to allow a comparison of different vessel configuration, comparing LCC, LCA and LCPA Indexes from KPIs calculation.

The main structure of the tool can be defined in 5 steps, as shown in Fig. 12.8:

- **KPIs selection**

In this part of the tool, the user will be able to select which KPIs are interested in for the analysis. Moreover, the weight of each KPI for the LCPA Index calculation will be assigned. Depending on the KPIs selected, certain data are required to run the analysis. The system shall be able to recognize which data shall be inserted or neglected. As explained in Sect. 12.5, the choice of KPIs and their relative weight has a strong influence on the results obtained.

- **Reference ship data**

As discussed in Sect. 12.2.4, there are three main strategies to calculate costs for a new ship design, while, on the other hand, environmental parameters are evaluated through a direct calculation from operational profiles and engine characteristics, and therefore, they are based on physical considerations. For cost estimation, the tool adopts a hybrid analogous–parametric estimation model. Practically, due to the high amount of data which are required to run a reliable parametric cost estimation process, formulations to predict economic KPIs are referred on technical and cost data of a reference ship, which represents the starting point of the analysis of different vessel configurations. Therefore, coefficients for parametric configurations, which have been developed through physical and statistical considerations available, are defined through an analogy with the reference ship. This is also an advantage, since parametric formulation is calibrated on a vessel which is similar to design alternatives studied.

Fig. 12.8 LCPA tool structure

Table 12.2 SBS of building cost

First level	Second level	Third level
Building cost	1.1a Structures (materials) 1.1b Structure labour cost	1.1.1 Hull
		1.1.2 Superstructures
	1.2a Machinery (systems) 1.2b Machinery labour cost	1.2.1 Main engine/s
		1.2.2 Electricity generators
		1.2.3 Power transmission
		1.2.4 Propeller/s
		1.2.5 Steering system
		1.2.6 Boilers/heat recovery systems
		1.2.7 Manoeuvering system
	1.3a Auxiliaries and outfitting (systems) 1.3b Auxiliaries and outfitting labour cost	1.3.1 Electricity distribution
		1.3.2 Engine aux. systems
		1.3.3 Firefighting—safety systems
		1.3.4 Anchoring
		1.3.5 Bilge systems
		1.3.6 Ballast system
		1.3.7 Painting and coatings
	1.4 Systems for payload	Depend on the type of ship
(Considered separately)	1.5 Shipyard indirect costs	1.5.1 Design effort
		1.5.2 Shipyard operational costs

From an analysis of KPIs selected for the project, it has been assessed that Building Cost and OPEX are the two pillars to evaluate the economic performance of a vessel. Therefore, the collection of data has been based on the Ship Breakdown Structure (SBS) developed for these two cost categories (Tables 12.2 and 12.3). The SBS will be also used to define the items modelled in the LCPA structure. The level of detail of the analysis is also variable depending on the degree of information available for the reference ship and other design alternatives.

- **New design configuration**

Herein, similarly to the reference ship data, technical data of the new ship are inserted, based on the SBS. Cost data are not required in this section (except for few SBS items, if they are known). Costs are calculated through an extrapolation of the reference ship values or developed from statistical data and physical/economic considerations.

Table 12.3 SBS of OPEX

First level	Second level	Third level
OPEX	3.1 Operating costs	3.1.1 Crew number
		3.1.2 Crew wages
		3.1.3 Stores
		3.1.4 Lubricants
		3.1.5 Administration and management
	3.2 Voyage costs	3.2.1 Fuel consumption
		3.2.2 Fuel price
		3.2.3 Port charges
		3.2.4 Canal dues
		3.2.5 Tugs
	3.3 Cost related to payload	3.3.1 Cargo type
		3.3.2 Cargo handling gear
	3.4 Capital	3.4.1 Size of loan
		3.4.2 Length of loan
		3.4.3 Interests
	3.5 (4.) Maintenance and repair	3.5.1 Operational maintenance
		3.5.2 Scheduled dry dock
	3.6 Insurance	3.6.1 Hull and machinery and war risks
		3.6.2 P&I

- **LCPA structure**

This part is the core of the tool. It is where data of the new ship are used to predict costs and emissions through the life cycle of the ship. The model of the ship has been built following the three phases of her life cycle (Fig. 12.9):

- Phase 1: Design and construction
- Phase 2: Ship operation
- Phase 3: End-of-life.

As already highlighted in Sect. 12.3, Phase 3 has been left aside for a moment, since it requires a high level of detail from the design which is not compatible with a preliminary stage of a design process.

Calculation of economic and environmental KPIs based on input data relies on the following steps:

- Creation of cost estimating relationships (CERs) for each SBS voice
- Time integration of economic cost categories up to the lifetime identified
- Calculation of emissions based on operational profiles and fuel consumptions.

This procedure is performed for both the reference ship and new design configurations.

- **KPIs and LCPA calculation**

Based on the selection of KPIs in the first module of the tool and calculation of costs and emissions in the LCPA structure, KPIs can be calculated for all ship configurations analysed. After the collection of all KPIs, coefficients can be defined and the LCPA Index can be assessed for each ship configuration, obtaining the best design, as explained in Sect. 12.5. It is important to highlight that this procedure is subjective, because KPIs selection and weight of coefficients totally depend on the user. Moreover, only cost and emissions are evaluated, while other aspects of the ship (such as safety) are not implemented in the current version of the tool.

12.7 Consideration of Uncertainties

Every time a forecast on a performance is attempted, the issue of uncertainties modelling shows up. When dealing with Life Cycle Performance Assessment during the ship design, there is of course a projection into the future that implies the assumption of parameters which are not certain at the time of the analysis. In this scenario, even a deterministic process could lead to a wrong result, with no chance to identify the risk associated with the uncertain nature of the problem. An example has been shown by Plessas and Papanikolaou (2018): with reference to the NPV calculation of a tanker, it has been pointed out that the most crucial uncertainty parameters during the investment investigation are the freight rate on the income side and the fuel price on the

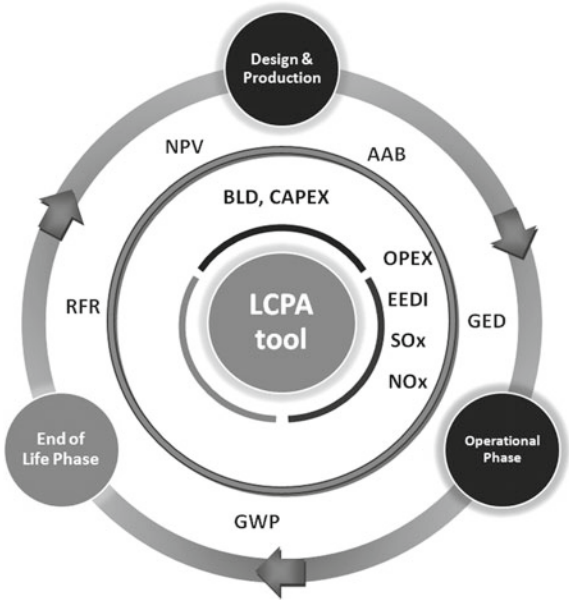

Fig. 12.9 Stages of a vessel life cycle and LCPA tool

expenses side, introducing a uniform stochastic distribution for a range of each of the above parameters. In the study, a Monte Carlo method is used with 1500 random combinations of freight rates and fuel prices in order to investigate the probability of having a negative NPV (Fig. 12.10).

To further frame the issue of uncertainties within the ship design process, it is worthwhile to mention that they can be classified in two separated families:

- Uncertainties specifically related to the ship design process: they depend both on the accuracy of models used in the ship design (e.g. CFD vs statistical regression methods for calm water resistance calculation) or on factors which directly affects the input of the design process (e.g. operational scenarios, loading conditions, real engine performances)
- Uncertainties related to external parameters able to affect the ship life cycle performance but not involved in the ship technical features definition during the design process. These can be fuel cost, discount rate, days of ship operation, etc.

In the frame of the HOLISHIP project, only external parameters uncertainties are modelled in the LCPA tool. Uncertainties related to the accuracy of models for the specific ship performance calculation (resistance, strength, …) are properly addressed during the relevant results analysis.

Besides Monte Carlo simulations, another approach, used within the JOULES project, is the analysis of a limited number of representative scenarios around an average value, selecting extreme data within a defined range. This method can help to easily define possible best and worst scenarios related to KPIs calculation of a particular ship design; however, it cannot provide the probability of occurrence of uncertain parameters combination. Nevertheless, this can be captured with a Monte Carlo approach.

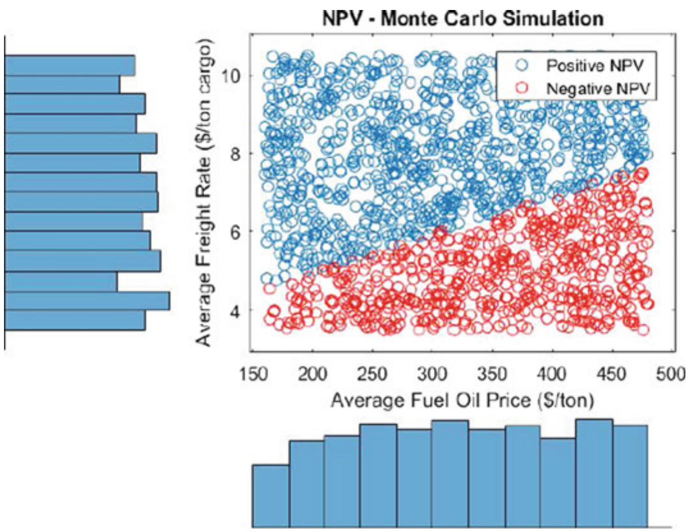

Fig. 12.10 Influence of uncertainties on life cycle calculations

12.8 Conclusions and Comments on Application Cases

The Life Cycle Performance Assessment (LCPA) tool developed in HOLISHIP, following an “holistic” vision of the ship design process, will give the possibility to better frame the best design solutions from the point of view of both economic aspects and environmental impact, eliciting the perspective of the designer/ship builder as well as of the shipowner.

One of the advantages of this methodology is that other economic and environmental parameters could be further added if necessary and adopted to study different design alternatives without changing the main structure of the combined analysis.

In addition to further KPIs identification and integration, an important issue is the availability and selection of adequate data for the implementation of such KPIs. The auspice is that, thanks to future improvements in data availability and management foreseen in the twenty-first century, this issue will be overcome. Testing this methodology with different designs will be also important to try to define weights in Indexes relations (which can be arbitrary chosen at the moment).

In fact, the developed LCPA tool will be applied to assess life cycle performance of different vessel types that will be studied as application cases in the next phase of the project and be published in Volume II of the HOLISHIP book. In this perspective, it is to be reminded that the LCPA tool enables the comparison of alternative ship design configurations rather than the assessment of absolute values of KPIs of a single vessel.

Future works about Application Cases will validate and possibly help to expand the applicability of the LCPA tool.

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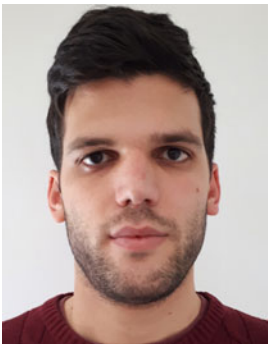

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Chapter 13
Modelling and Optimization of Machinery and Power System

Sverre Torben, Martijn de Jongh, Kristian Eikeland Holmefjord and Bjørnar Vik

Contents

Abstract This chapter describes modelling and optimization of machinery systems in a holistic design process. After descriptions of the main components and typical architectures of power systems are introduced, a holistic approach to power system modelling is discussed. Then a three-step process for optimization and verification of a machinery and power system is introduced, which is illustrated on the basis of an offshore support vessel (OSV).

Keywords Power system · Machinery · Propulsion · Holistic design
Operational profile · Power generation · Power distribution
Power consummation

13.1 Introduction

Design of machinery and power systems for a ship is a complex, multidisciplinary task requiring skills in areas like mechanical transmissions, electrical systems, hydraulic systems and control systems. Optimization of the power system in a holistic ship design process further adds complexity by considering the additional interactions in subjects like hull resistance, hull propulsion interaction, pitch/rpm optimization,

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seakeeping performance, station keeping performance and constraints of arrangement of machinery components due to size and shape of available spaces.

The power system architecture, configuration and operation have a significant impact on the performance of the ship in terms of KPIs like CAPEX, OPEX and emissions. The design space for the machinery and power system could be very large considering the vast number of components making up the system. A number of possible solutions delivering the required functionality exist, and the optimum solution for a given ship will be different for different operational profiles for the ship.

Focusing on environmental footprint, energy efficiency and related legislations have an important impact on the power system composition. Technologies enabling high efficiency and low emissions are favoured. Electrical technology is widely used in power systems to enable a high overall operational efficiency. This ranges from use of permanent magnet motors for thrusters, frequency converters enabling optimum operation of engines and pitch-loss reduction, batteries assuring backup power, load smoothening and even emission-free operation for fully electric systems. Renewable energy sources like solar, wind and wave energies, and waste energy recovery systems are other examples of energy sources improving the environmental footprint. Alternative fuels like LNG and H2 are also providing potential reduced emission in some applications, and fuel cells are being introduced in applications like ferries and cruise vessels.

The introduction of a number of new technologies (e.g. electrical technologies, alternative fuels) enables a broad spectre of complex power system solutions. Identifying the optimum solution from this large design space in a holistic ship perspective and life-cycle perspective can be a complex task and suboptimization of the power system alone will normally not lead to the best overall solution. The machinery system represents in many cases a large part of both capital and operational expenditures for a ship, and different options may provide a very different performance result in terms of environmental impact.

13.2 Definition/Composition of Machinery and Power System

The machinery and power system is a combination of components with one or several of the three functions: power generation, power distribution and power consumption. In addition, most of these components have separate auxiliary systems, which have to be included when performing the optimization process of the complete system. Table 13.1 is a compilation of the most commonly used components that together will make up the overall machinery and power system. The components are a composition of multi-physics interactions involving both hydrodynamics, mechanics, electrics, hydraulics and exhaust flow. Modelling and optimizing of a machinery and power

Table 13.1 Machinery and power system components

Power generation	Power distribution	Power consummation
Engines • Reciprocating engines • Gas turbine engines • Nuclear engines • Waste heat recovery	**Mechanical transmission** • Gears • Shafts	**Propulsion** • Azimuth thrusters • Tunnel thrusters • PM thrusters • Pods • Shaft line & rudders
Energy storage • Battery • Fuel cells • Ultra-capacitors • Flywheels	**Electric power** • Switch boards • Transformers • Frequency converters • Cables • Breakers • "Energy storage" • Power-Take-In (PTI)	**Heavy consumers** • Cranes • Winches • Pumps • Handling frames • Specialized equipment • "Energy storage"
Generators • Generator sets • Shaft generators/Power-Take-Out (PTO)	**Hydraulic power** • HPU • Piping • Valves	**Hotel loads** • General hotel loads • Equipment specific • Auxiliaries systems
Renewable energy • Solar panels • Wind power • Wave power		

system will have to include all these aspects to ensure that every relevant impact to an efficient design solution is considered.

The composition of components also strongly influences both maintenance requirements, emissions and the possibility of autonomy. An autonomous vessel design will have a very high reliability requirement, as a chief engineer will not be on-board to resolve small issues during operation. More conventional reliability requirements also define specific boundaries to what is allowed when operating in specific high demand areas, for instance, close to an offshore oil and gas platform.

A power system can be defined with a certain number of base topologies. The most conventional one is the mechanical one, where one engine is directly connected to one propulsion unit, while the electrical power system is completely separated using generator sets or other energy generating components. This is a simple set-up with a limited amount of optimization possibilities for the power system. It can, however, be the most efficient power system for a vessel, as it has certain advantages over more complex and "electrified" topologies. This will, for instance, be an optimal topology for certain operational profiles, typically a long-distance freight vessel with a very consistent propulsion power requirement and low electrical power requirement.

The basic power system topologies are:

- **Mechanical**—Propulsion drivetrain purely mechanically driven

- **Electrical**—Propulsion drivetrain purely electrically driven
- **Hybrid Shaft**—Combined mechanical and electrical propulsion drivetrain

Each of the basic power system topologies can be further divided into a number of different solutions with energy storage, DC grid, pitch propellers, variable rpm on engines, different fuel types, full-electrical and charging systems, etc. An example of diesel electric architectures and a hybrid shaft architecture are shown below.

A traditional diesel electric propulsion system is shown in Fig. 13.1. This uses Active Front End (AFE) technology for stable clean voltage quality and fast response to load changes. This architecture is widely used in offshore support vessels like Platform Support Vessels (PSVs). The number of generators installed is defined by the maximum power requirements and the operating profile. When transiting at slow speed or in standby mode, some engines can be turned off for optimal fuel performance.

The diesel electric architecture shown in Fig. 13.2 has a single integrated drive switchboard for the whole vessel utilizing a common DC bus. All the frequency converters, breakers and main switchboard are housed in a single cabinet for a space saving footprint. It is also much simpler to install as many connection terminations can be done at the factory, and the cooling system installation on-board will be less distributed, as all cooling for converters will be centralized in one cabinet. Ship service power for hotel and other loads (230, 440, 690 V switchboards, etc.) will be powered from the same cabinet. Additional battery power can be efficiently integrated on the DC bus with minimal conversion losses for slow speed transits or for load smoothing. All engines can operate at variable speeds to maximize their efficiency, and output is automatically adjusted to the demanded power.

The hybrid shaft generator (HSG) architecture shown in Fig. 13.3 is a very flexible set-up that can be reconfigured for different operational tasks of the ship. It enables fixed voltage and frequency at the switchboard during variable engine speed (PTO), paralleling of shaft generator and auxiliary gensets (PTO), full diesel/gas electric operation (PTI) and electric boosting of main propeller (PTI). This enables a unique operational flexibility, where an optimal design will evaluate all different possibilities

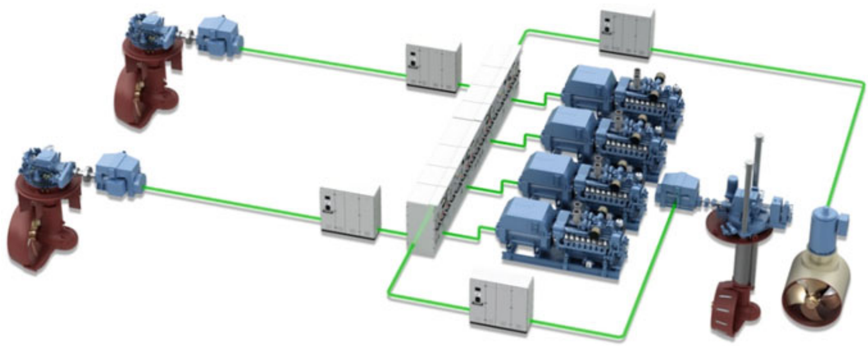

Fig. 13.1 Traditional diesel electric propulsion system

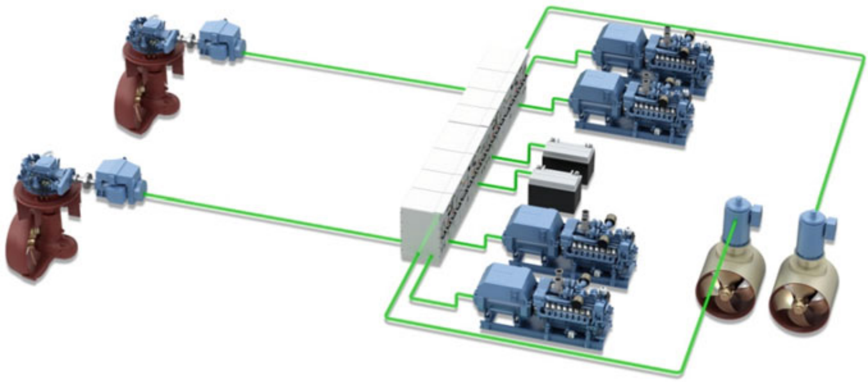

Fig. 13.2 Diesel electric propulsion system with integrated drive switchboard

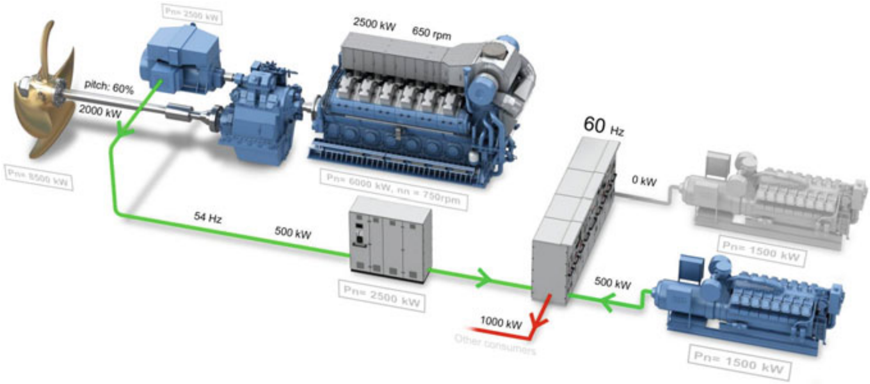

Fig. 13.3 Hybrid shaft generator system

of operation to determine the most efficient operation. The hybrid shaft solution can be combined with set-ups of common AC bus and DC bus as well as energy storage providing load peak shaving on the main shaft line through the PTI/PTO.

13.3 Holistic Approach to Power System Modelling

The design process of defining the optimum power system architecture and composition is a complex task. Appropriate models of the components and the multi-physics interaction of the components must be created in order to explore the design space in the holistic design process. The needed properties of the models depend on the design stage. During early design stage, where the purpose is to select overall architecture and dimension components, low-fidelity models in a static or quasi-static simulation environment are required. For verification of the performance of the design in different operational scenarios with realistic dynamic loads, higher fidelity models are needed for a real-time simulation set-up. In order to create realistic loads and system behaviour, the most important control systems should be included, preferably using the actual control system in a software-in-the-loop (SIL) or hardware-in-the-loop (HIL) set-up. If the actual control systems are not available, these should be emulated since control systems are important for the total dynamics. In, for instance, a crane operation in DP, the DP system must be included. The DP system controls the thrusters, which usually are the largest power consumers.

The Power Management System (PMS) is also important to be included if safety functions are to be evaluated. It could also be important to add operators to the set-up, since operator response is an important part of safety.

A machinery component has many properties, and a model of the component should represent the properties relevant for the design task in question. For example, properties related to energy efficiency, mechanical and electrical losses are typically important in the quasi-static optimization process, while in the dynamic simulations characteristics like inertia of rotating machinery and available sensors for the control system become crucial.

A number of different tools for creation of models of machinery components and systems exist. Some examples of commercially available tools are MATLAB/Simulink, SimulationX, Algoryx and 20-sim. These tools contain toolboxes and libraries that can be used to create component models. Based on these tools and/or basic equations, company-specific tools for machinery and power system simulation have been developed. The power system optimization tools used in the HOLISHIP project are GES from TNO, SEECAT from BV, COSSMOS from DNVGL and MPSET from Rolls-Royce Marine.

For the design optimization process based on low-fidelity models and quasi-static simulations, a large number of iterations through nested loops are performed to explore the design space. While the execution of each model can be very fast, the large number of iterations determines the performance of this kind of simulations. The number of iterations can be reduced by introducing constraints to limit the design space, e.g. based on rules and regulations.

For dynamic simulation of operational scenarios using higher fidelity models, execution of each model becomes more demanding. Furthermore, with control systems and operators in the loop, the simulation must run in real time. Thus, the available time for execution of the models is restricted, and the level of fidelity of the models must therefore be balanced with available computing power.

In many cases, available high-fidelity simulation models have been developed using different simulation tools. In these cases, standards like Functional Mock-up Interface (FMI) might be used to set up simulations, where models from different tools can be combined by exporting the simulation models as Functional Mock-up Units (FMUs), and using a master algorithm implementing the FMI protocol to execute the overall simulation and take care of communication between the FMUs. FMUs can be exported from any of the commercially available tools mentioned above.

Required input to the optimization process is a description of the operational profile of the vessel being designed. For some ships, this may be fairly simple, with long periods of sailing at constant speed followed by manoeuvring in port and periods stationary at the berth. For others, such as offshore anchor handlers, the profile will be far more complex, with time spent in transit, towing, deployment and tensioning rig moorings, standing by in dynamic positioning, manoeuvring and idle with only the hotel electrical load to be supplied. Thus, the operational profile will define a series of tasks and subtasks for the ship in question; what will the ship be used for, and for what proportion of the time it will be performing each tasks. Subtasks are defined to cover parameters like speed or bollard pull, operational areas and weather conditions for a task. The load profile of the main consumers must also be determined for each subtask. Dependent on vessel type, the operational profile can be either a repeatable time-dependent profile or yearly profile where the sum of each performed task is lumped together over a whole year. When energy storage and shore-connection power are incorporated as a power input, it is crucial to evaluate the operational profile in a time-dependent manner, allowing the full benefit of an energy storage into the optimization algorithms. Figure 13.4 shows a top-level operational profile example, while Fig. 13.5 shows the next level of details as a typical structure of the operational profile used as input to the optimization process.

The optimization method can then find what type of machinery installation could best handle the range of tasks, which are further analysed to decide the number, size and operation of main engines, gensets, and batteries and so on. The output from the

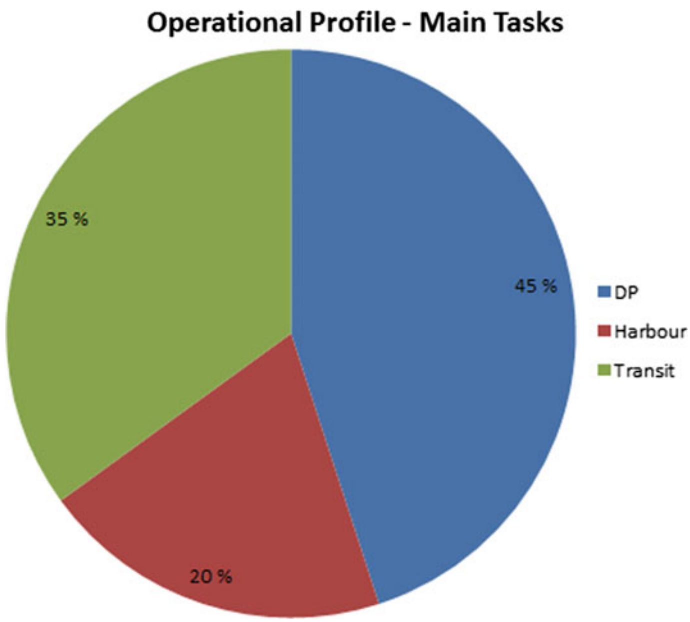

Fig. 13.4 Top-level operational profile example

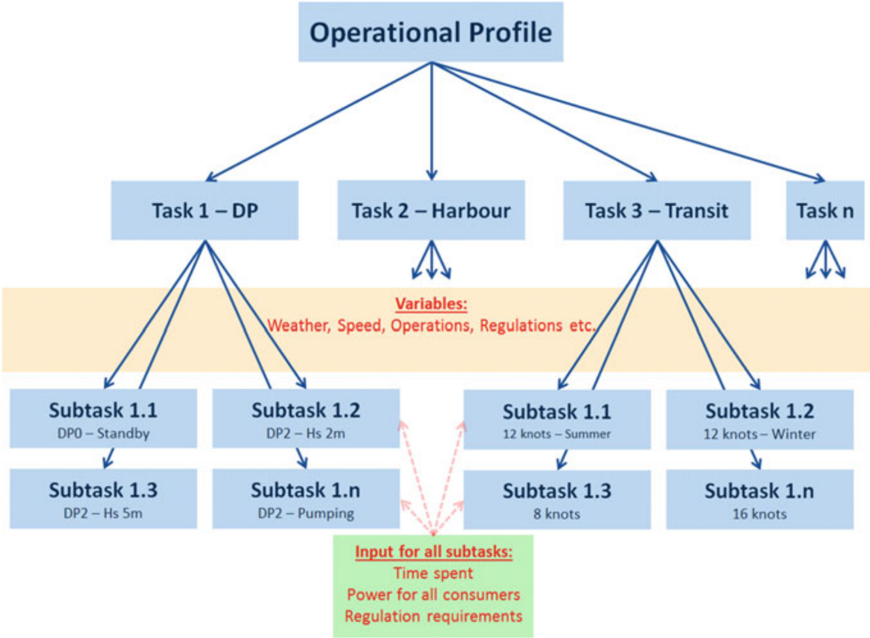

Fig. 13.5 Structure of operational profile with tasks and subtasks

process will be information on the best configuration of these elements to give the optimal power solution for each of the operating modes.

For each of the tasks and subtasks, the complete estimated power consumption is used as input. Table 13.2 illustrates an example of the amount of information required to enable a complete optimized machinery and power system design. The input could also be in required thrust instead of kilowatt on any thruster unit, as long as the modelling takes potential loss and pitch into account. The input of each type of task will also activate different sets of rules and regulations, which the optimization process must take into account. The example with the DP subtask being a redundant system for any single point of failure, meaning that the system must be able to supply the given power and thrust for any single failure without starting new equipment.

13.4 Optimization and Verification of Power System Concept Design

This section proposes a method for conceptual design of the power system for a ship in a holistic design process. The three main steps are:

Step 1—High-level conceptual design: The purpose of this step from a power system perspective is to define and size the ***main consumers*** for the vessel based on

Table 13.2 Example of input required for a subtask

DP—subtask 1.2—Hs 2 m and crane operations	
Time spent in subtask	400 h
Hotel loading	300 kW
Crane loading	800 kW
Main propeller SB	300 kW
Main propeller PS	300 kW
Tunnel thruster Aft 1	200 kW
Tunnel thruster Aft 2	200 kW
Tunnel thruster Fwd 1	400 kW
Tunnel thruster Fwd 2	400 kW
Retractable thruster Fwd	600 kW

the mission requirements. The type of vessel and its mission can be everything from a double-ended ferry transporting people and cars over a fjord to an offshore service vessel performing complex subsea operations in harsh weather condition. To define the main consumers, basic design and sizing of the hull must be performed in this step. Typical main consumers are:

- Propulsion units/thrusters
- Heavy consumers like deck machinery and pumps
- Hotel loads

Step 2—Power system conceptual design and optimization: The purpose of this step is to define the optimum ***architecture***, the ***main components*** and the ***control strategy*** to supply the main consumers defined in Step 1. A key input to this step is a detailed description of the operational profile of the vessel. Optimization is based on a set of KPIs defined for the vessel in a life-cycle perspective. These should cover areas like safety and reliability, life-cycle cost and emissions.

Step 3—Power system concept verification: The purpose of this step is to verify the performance of the proposed power system conceptual design from Step 2 in typical operational scenarios. These can be both normal operational scenarios and fault situations. The focus in this step is typically on dynamic loading of the power system in the most demanding operational scenarios.

Based on the results from the testing and verification performed in Step 3, there might be a need to go back to Step 2 or even Step 1 to adjust the design. This closes the holistic design loop for the conceptual design phase (see Fig. 13.6).

These three steps are outlined in more detail based on design of an offshore support vessel (OSV) as an example.

Based on basic operational requirements, the high-level design process starts with dimensioning of the vessel. This on its own requires a multi-parameter optimization using several iterations. Traditionally, this is done by manually evaluating option, often supported by very basic calculations. The aim of the designer at this stage is to

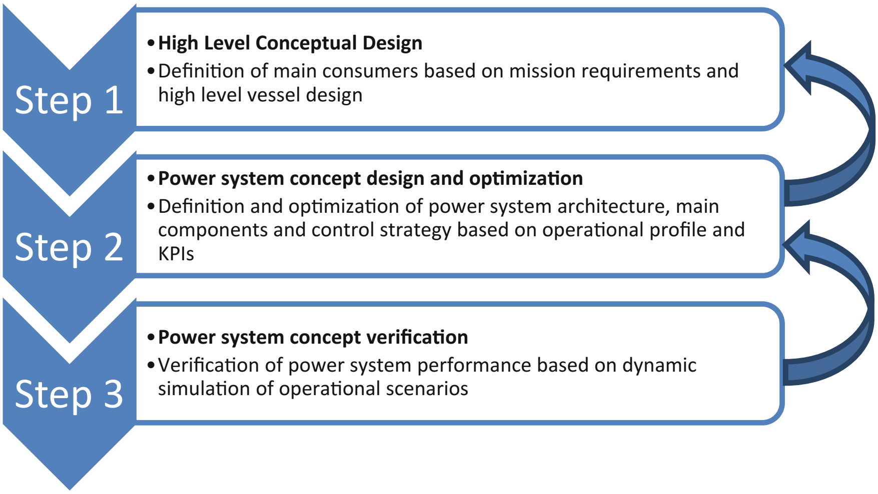

Fig. 13.6 Three-step holistic design process for power systems

find optimizations where a change in vessel parameters leads to a positive effect on linked parameters, the positive design spiral.

However, these manual calculations limit the size of the design space that can be explored, and more complex vessel requirements show the limits of these simple calculation methods.

As input, a definition of the mission and design requirements are needed. These include the following:

- Tasks definition (both main tasks and subtasks)
- Operational scenarios defined as a high-level operational profile
- Expected environmental conditions in which the vessel is to fulfil it tasks
- Operational restrictions
- General design requirements (space requirements, accommodation, etc.)
- Applicable rules and regulations, industry guidelines, etc.
- Mission equipment (e.g. cranes, winches, accommodation services, etc.)

Since the calculations are on a high level, reference vessel information is of importance to benchmark the design variations. The goal is not to evaluate absolute performance values, but to perform a relative comparison. This allows a fast evaluation without the need for detailed system information.

The following design information of the reference vessel is needed:

- Initial sizing of the hull
- Initial definition of machinery and propulsion arrangements
- Initial sizing of consumers

Table 13.3 Step 1—high-level conceptual design

Step 1	High-level concept design
Objective	Define the main consumers of the power system
Input	Owners' specifications, mission requirements, constraints
Method	High-level design and sizing of hull, propulsion system, machinery and equipment based on input requirements and constraints. Use of automatic Design Space Exploration (DSE) and optimization techniques
Output	Definition of power system loads from propulsion/thruster units, heavy consumers and hotel functions

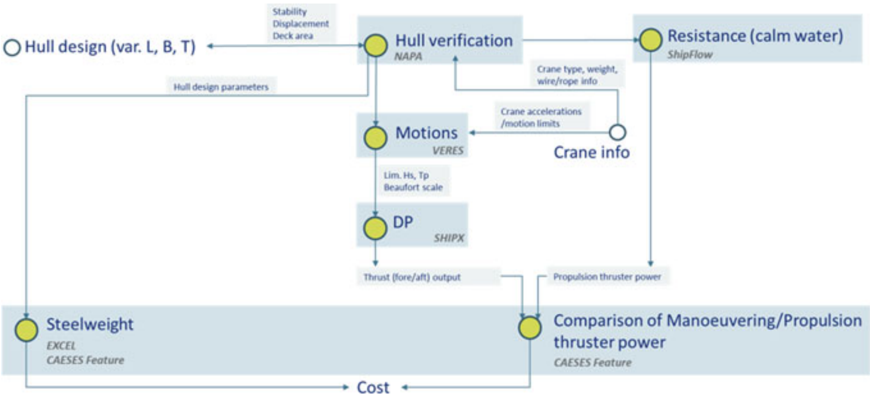

Fig. 13.7 Example of a Step 1 workflow

The definition of the high-level design parameters is not only based on technical performance. Economic and environmental factors like CAPEX, OPEX and environmental factors like emissions are also taken into consideration.

With these basic parameters in place, the thrust requirement for each thruster and propulsion unit can be defined, and from that the power requirement for the various tasks can be determined. This is required input for a more detailed power system evaluation and optimization in the next step (Step 2, see Table 13.4).

An example of a Step 1 (see Table 13.3) workflow is shown in Fig. 13.7.

However, based on the Design Spiral principle, with increasing knowledge of the design details, the Step 1 assessments must be revisited at a later stage to check whether the initial results are still valid or to further optimize the design.

Finding the optimal power system is investigated after the first high-level conceptual design step where one or several top-level solutions are determined. There are a large number of possible combinations of machinery and power system components that will be able to perform the required operations of the top-level conceptual design. The investment cost and operational cost will, however, be very different, and the operational profile of the ship is the key in designing the most optimized power

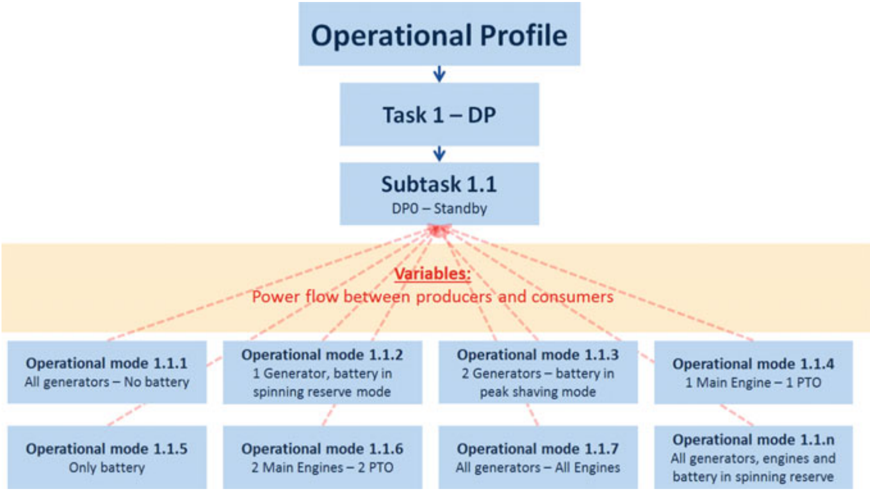

Fig. 13.8 Operational modes for a subtask

system for each concept. The emissions, as well as system reliability, will also have large variations between the different power systems.

The operational profile consisting of the *operational tasks* of the vessel, and how long it is performing each task at which time frame are described in Fig. 13.4. Tasks are further divided up into *operational subtasks by* taking into consideration environmental and operational effects as shown in Fig. 13.5. This is purely based on the power consumers as defined in Step 1 (Table 13.3) and is independent of the power producers and power distribution solution. To define this, the description of the *operational modes* is needed.

The different operational modes of a ship and its power system describe how all the power generation and power distribution components can be operated to ensure that the power consumers are given the correct amount of power for all the subtasks. The power systems can have many different operational modes available for performing a specific subtask. Each mode involves a number of power sources like engines, gensets and batteries, and a control strategy controlling the power flow from the sources to the consumers through the distribution system. Figure 13.8 illustrates how one specific subtask can be operated in a large number of ways.

However, one of those modes is the ideal mode for that operational subtask, given the specific power system components. The combined optimization of sizing the power sources and controlling them is crucial in that design process. The sizing of the power sources must be performed to ensure that there is enough power for any given subtask in the operational profile with adequate safety margins and fulfilling applicable regulation requirement, e.g. for dynamic positioning. The control logics of how the components are operated in all subtasks is required when optimizing a complete power system, as this will determine all the operational KPIs.

In the optimal machinery and power system design, all components mentioned in Table 13.1 and all possible architectures should in principle be considered. However, this can lead to excessive execution time for the simulations. To limit the design space and simplify the design and optimization process, an experienced ship or system designer will define initial criteria that will rule out a many of the more obvious unsuitable solutions, reducing the amount of simulation time needed for evaluating the rest of the possibilities.

The operational modes are defined based on the logic behind the control of the power flow from power sources to consumers. On-board a vessel this is assured by the Power Management System (PMS), adapted for the specific power system of the vessel. For the optimization process, a simplified, more flexible logic that can be automatically adapted to the different operational modes is needed. This can be referred to as the Power Flow Control (PFC). The PFC allows multiple systems to be optimized with limited or no input from the user, or with specific input related to emission zones, regulations, noise requirements, etc.

The PFC combined with the sizing of the power sources and the overall topology will define the performance of the ship. The performance can be characterized by a set of KPIs, which enables multi-parameter optimization of the ship and its power system. The mentioned process is illustrated in Fig. 13.9.

The overall KPIs are summarized to the following categories:

- **CAPEX**—Investment cost of power and propulsion system
- **OPEX**—Operational cost of power and propulsion system
- **Emissions**—Environmental impact of power and propulsion system
- **RAM**—Reliability, Availability, and Maintainability of the power and propulsion system

The different KPIs are driven by different sub-KPIs, such as running hours, loading of engines, fuel consumption, maintenance requirements. Furthermore, the overall power system optimization process must allow for different KPIs to be weighted based on customers preferences. In general, the fuel consumption and emissions are the minimization goals for any specified power system, while RAMS-related KPIs set limitations to the operation and CAPEX sets limitations or goals for the overall power system design.

A goal for the ship designer or system designer is to allow for exploration of the design space with a large degree of freedom. A function that must be implemented to ensure this freedom is the ability to perform sensitivity analysis on the optimized power system. It is crucial that the designer and future owner of the vessel are aware of the constraints within which the vessel should operate. There will always be a level of uncertainty of the inputs in the power system optimization process, and a small change in the input should not result in a large reduction in efficiency of the "optimized" system.

A simple example of this could be a small change, for instance, 1% increased power consumption in an operational task due to hydrodynamic estimation errors. If this results in the increase of one engine at optimal loading, to two engines at a low power loading, then the vessel could end up with a non-optimized solution

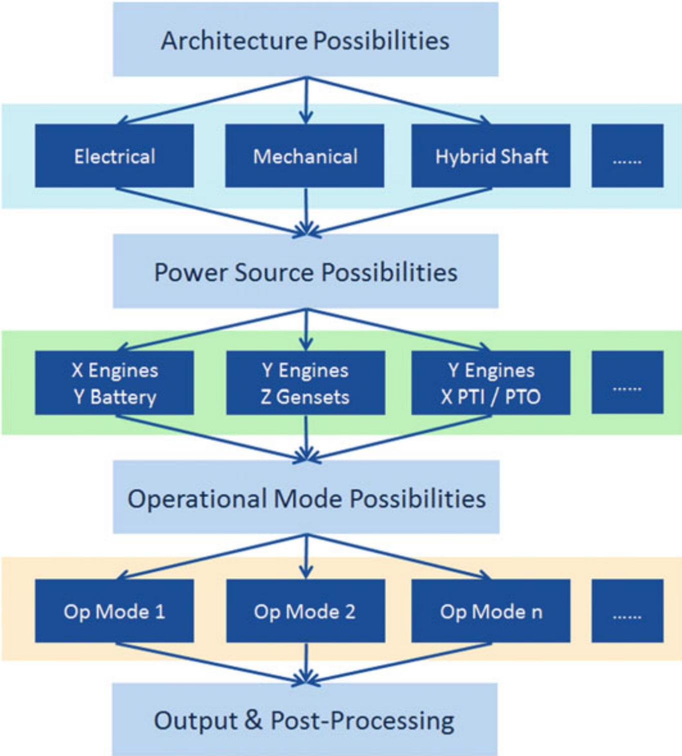

Fig. 13.9 Overview of the power system optimization process

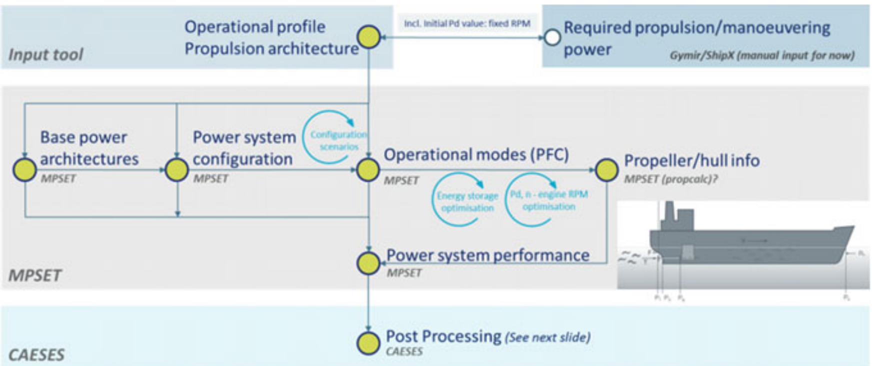

Fig. 13.10 Example of a Step 2 workflow

with a large increase in OPEX. These types of investigations must be facilitated and visualized in the power and propulsion system optimization process.

An example of a Step 2 workflow (see Table 13.4) is shown in Fig. 13.10.

Table 13.4 Step 2—power system concept design and optimization

Step 2	Power system concept design and optimization
Objective	Definition and optimization of power system architecture, main components and control strategy
Input	Operational profile including loads from Step 1 User requirements, design and legislative constraints, etc. KPIs and optimization objectives
Method	Quasi-static simulation of a large number of alternative designs based on the input requirements and constraints Assessment of performance with regard to KPIs like CAPEX, OPEX, fuel consumption, emissions and reliability, using adequate tools Performance through multi-objective optimization Sensitivity analyses on performance
Output	Optimized power system definition for given operational profile KPIs in steady-state operation Sensitivity data

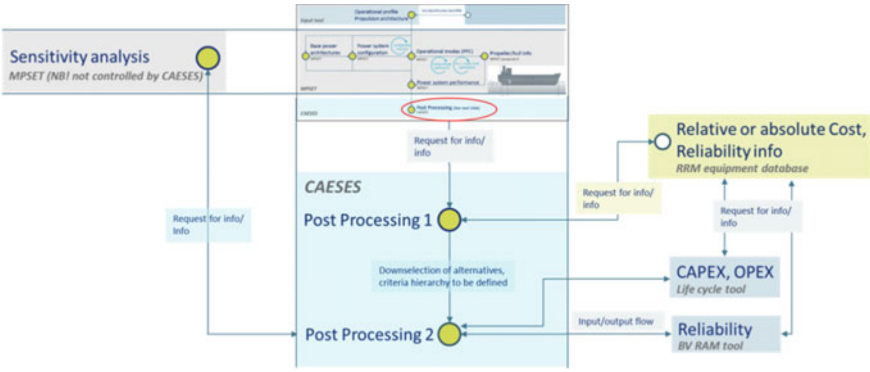

Fig. 13.11 Example of a Step 2 post-processing workflow

An example of the post-processing of the data from the power system performance tool connecting with other tools for RAM analysis and LCC assessment for a multi-parameter optimization and sensitivity analysis is shown in Fig. 13.11.

To verify and further optimize the power system concept defined in Steps 1 and 2 (see Tables 13.3 and 13.4), dynamic simulations of operational scenarios, including control and monitoring systems, should be performed. This allows for interactions between different components in the electrical, mechanical and digital domains to be analysed.

The dynamic simulator should be able to produce a realistic load profile in critical operational scenarios, with transient environmental effects such as wave loads and wind gusts affecting the hull and the power system. This will not only help verify the power system design, but also the performance of the whole vessel design in terms of, e.g., DP capability or other operational limitations.

Table 13.5 Step 3—power system concept verification

Step 3	Power system concept verification
Objective	Verification of power system performance Testing of PMS strategies Final sizing of energy storage units
Input	Power system definition from Steps 1 and 2 Variables: type and capacity of energy storage elements Definition of operational scenarios including fault situations
Method	Dynamic simulation
Output	Dynamic loading of engines and gensets State Of Charge (SOC) of energy storage units Performance of various PMS strategies with energy storage KPI in dynamic conditions

A more realistic load profile makes it possible to optimize the power system further, leading to systems that are not oversized for a given load profile and vessel design. This optimization could involve testing of alternative control strategies and sizing of key power system components (e.g. energy storage units for hybrid power systems).

The robustness of the vessel and its power system should also verified by injecting faults into any system and analysing the response of the vessel, power system and relevant control systems. Each task of the vessel operational profile may differ on the robustness requirement. For example, in DP2 and DP3 operations, the vessel should be able to maintain position after any single fault in the power system if a consequence analysis alarm is not issued. This can in many cases be verified in a dynamic simulation.

The outcome of the dynamic simulation is a dynamic load profile for critical operational scenarios and performance of the vessel and the power system with this load profile. KPIs like fuel consumption and emission in dynamic conditions can also be calculated. Technical specifications can be updated based on the outcome of the dynamic simulations. Reiteration of Steps 1 and 2 may also be needed based on the findings from the dynamic simulations, thus closing the HOLISHIP design loop.

An example of a Step 3 (see Table 13.5) simulator set-up is shown in Fig. 13.12.

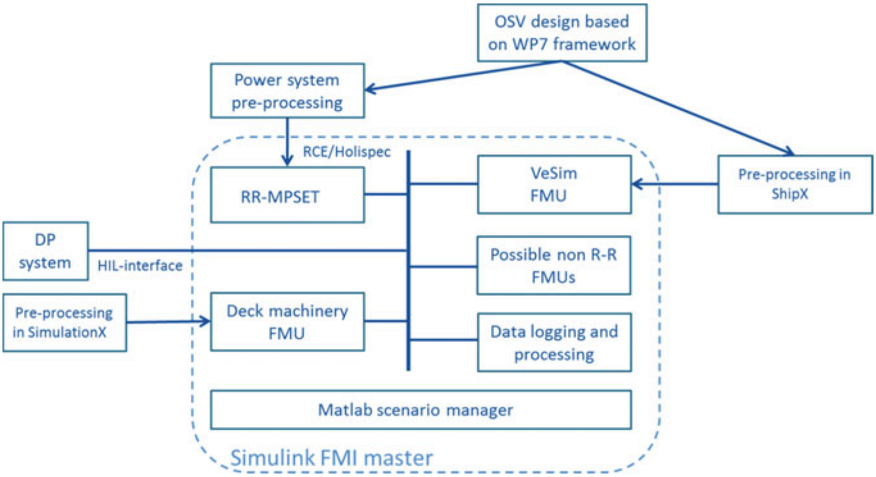

Fig. 13.12 Example of Step 3 simulator set-up

13.5 Application Example

Application cases will be described in HOLISHIP Book volume 2.

The AC OSV shall be implemented for both platforms in the HOLISHIP project, i.e. the holistic design and optimization platform and the Virtual Verification Framework. This application case includes a complex machinery system. The AC OSV is planned to be demonstrated through three different demo cases to implement important parts of a holistic design process and to perform virtual verification of the design. These three cases span the design process from early concept to detailed system evaluation and are conform to the generic three-step process proposed above.

13.6 Conclusions

Design optimization and verification of machinery and power systems is an important part of a holistic design process, with major impact on the overall performance of the vessel based on KPIs like CAPEX, OPEX, emission and availability. Multidisciplinary interactions like hydrodynamic performance, general arrangement and control systems behaviour must be considered. Furthermore, machinery and power system consists in many cases of a large number of components and architectures, which results in a large design space of possible solutions. This chapter has described how the machinery and power system can be optimized in a holistic design and verification process through a three-step process.

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Chapter 14
Advanced Ship Machinery Modeling and Simulation

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Contents

Abstract Ship machinery is nowadays evolving in more complex and multidisciplinary systems and needs to cope with regulatory requirements, efficiency targets, market pressures, and safety constraints. Performance improvement has become a

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difficult task, as new decision-making tools are required to manage the increasing complexity of technologies and systems. Model-Based Systems Engineering (MBSE) is a holistic approach capable to analyze the integrated performance of complex systems by shifting the focus from the isolated components to the integral system and its behavior. MBSE utilizes advanced computer-aided modeling and simulation methods and tools, to develop "digital twins" of technology components and to test their combined performance in integrated systems. Such methods are widely used in industries like aeronautics, electronics, chemical/processing, and space exploration and have been recently introduced in shipping. This chapter describes approaches of how to practically implement MBSE in ship systems and demonstrates its benefits at selected marine applications.

Keywords Model-based systems engineering
Complex ship systems modeling and simulation

14.1 Marine Energy Systems: Need for an Integrated Approach

Modern ship machinery systems tend to be highly complex, incorporating multidisciplinary technologies, operating under variable mission profiles, and being subject to lots of constraints for space footprint, weight, flexibility, and safety (Dimopoulos et al. 2014). Due to the stringent requirement of having complete autonomy of onboard resources, ship machinery systems are usually characterized by a higher degree of integration compared to their land-based alternatives. In addition, their design and operation are subject to constraints from international or local regulations, such as pollution prevention, safety of life at sea, functional safety, and redundancy (MARPOL 2010; SOLAS 2009). Moreover, market pressures to reduce shipping operational costs put the emphasis on the energy efficiency improvement of the vessel from the early design phase, thus making the optimization of ship systems a complex techno-economic problem. Finally, new technologies and fuels emerge in the market as options to achieve better performance, resulting in an even more complicated decision-making landscape.

Systems Engineering (SE) offers a novel holistic approach to assess the integrated performance of complex technical systems (NASA 2007; Pantelides and Urban 2004). The philosophy is to shift from the decoupled analysis of system components to the assessment of the system totality, thus looking at the "big picture" when making technical decisions. SE integrates multiple disciplines, such as engineering, mathematics, control, automation, logistics, and project management, to better comprehend and manage system complexity. By combining knowledge for the individual parts of a system and their interconnections, SE methodologies analyze how each component may influence the entire performance and vice versa. Such analyses can be performed with the use of computer-aided modeling and simulation techniques, often termed as Model-Based Systems Engineering (MBSE). MBSE approaches are commonly used in many industries, such as in aeronautics, defense, electronics, chemical/processing, oil and gas, and space exploration (NASA 2007; Pantelides and Urban 2004; Stephanopoulos and Reklaitis 2011). While computer-aided tools are broadly used in naval architecture and marine engineering (McNatt et al. 2013; Papanikolaou 2010; Rodriguez and Fernandez-Jambrina 2012), MBSE has been introduced in commercial shipping in the last decade (Dimopoulos et al. 2014), demonstrating sound advantages in managing the increased complexity of marine systems, vessels, and structures.

This chapter presents how MBSE approaches can be practically implemented in shipping, from defining a range of application areas to the description of mathematical formulas of ship machinery component models. Starting from a series of practical engineering problems in ship design and operation, the scoping of MBSE solutions is described together with an outline of the main objectives, constraints, and decision parameters. Then, a typical workflow is presented on how to use MBSE to solve technical problems in shipping, from setting the case specifications and assumptions to developing mathematical models for conducting model-based analyses. The chapter continues with the description of a generic mathematical framework to model the governing mechanisms in ship machinery elements and their system connections. Then, the structure of ship machinery system model libraries is discussed through the example of the advanced DNV GL COSSMOS (Complex Ship Systems Modeling and Simulation) modeling framework (Dimopoulos and Kakalis 2010; Dimopoulos et al. 2014; Kakalis and Dimopoulos 2012). Finally, the chapter ends with the presentation of illustrative applications of MBSE in shipping.

14.2 Process Modeling and Simulation

14.2.1 Types of Problems and Application Areas

MBSE can support decision-making over a wide range of applications in shipping, from the early design phase of a vessel to its whole life cycle (Dimopoulos and Kakalis 2010; Dimopoulos et al. 2014; Kakalis and Dimopoulos 2012). As follows, an attempt is made to group the various MBSE scopes for solving practical ship design and operation problems:

– *Design optimization*: This category of problems utilizes MBSE to determine the optimal design and operation of onboard machinery with respect to techno-economic metrics, such as energy efficiency, safety, and cost-effectiveness. Compared to other approaches, MBSE allows the consideration of the actual mission envelope of the machinery system, thus leading to results of essential interest for the shipbuilder, owner, and operator. This approach provides the so-called design-by-trade ability.

- *Operational performance analysis, benchmarking, and optimization*: In this category of problems, the objective is to evaluate performance, rank and compare alternative technical solutions and their combinations, with direct quantification of techno-economic and safety performance metrics. As such, the benefits from the use of new technologies can be assessed subject to the realistic operating conditions of a vessel. Furthermore, the same tools used for the performance assessment can be employed for the optimization of strategies, with a typical example being the analysis of advanced energy management, etc.
- *Sensitivity analysis*: In several engineering problems, the assessment of solutions' sensitivity is required to form the decision envelope. Typical examples are the investment assessment and the sensitivity analysis over variant mission profiles.
- *Diagnostics*: MBSE tools can provide knowledge over systems behavior under real-service conditions, giving thereby the ability to trace malfunctions, or disruption events from normal operation.
- *New technology assessment*: ballast water treatment systems, desulfurization scrubbers, selective catalytic reaction systems, etc.

The above types of problems can be encountered in various application areas in fleet in service, newbuildings, and retrofit applications (Dimopoulos et al. 2011, 2015; Georgopoulou et al. 2015, 2016; Kakalis et al. 2013; Stefanatos et al. 2012, 2014, 2015a, b). For fleet in service, MBSE can be applied for the evaluation of power and fuel consumptions under real-service conditions, targeting at optimizing the operating performance. The same MBSE tools used for optimization can be also implemented to monitor performance, analyze non-optimal onboard decisions and activities, and identify improvement strategies. Furthermore, crew awareness on best practices can be supported by MBSE through the analysis of current and optimized strategies. To summarize, all these solutions fall under a general application area of benchmarking and competitive asset management support. Specific examples for fleet in service applications include oil tanker cargo operations (e.g., discharge and cargo heating) monitoring and benchmarking (Stefanatos et al. 2015a), energy management improvement coupled with advanced thermodynamics (Stefanatos et al. 2012), assessment of power management strategies in diesel–electric vessels and improvement suggestions (Stefanatos et al. 2015b), etc. Finally, for fleet in service, MBSE can support the development of novel methods for reliability assessment and diagnostics, such as for the model-based tracing of failures, the simulation of failure events, the assessment of prevention measures and their results, as well as the quantification of risks and associated impacts (Manno et al. 2015).

For newbuildings, a common application area of MBSE is the solution of "design-by-trade" problems, where the optimal system design is identified considering the actual operating profile of the vessel and comparing entire machinery configuration alternatives (Dimopoulos et al. 2011; 2015; Kakalis et al. 2013; Stefanatos et al. 2014). Furthermore, in this stage of ship life cycle, modeling and simulation tools can support the optimization of ship subsystems, such as engines, auxiliaries (gen sets, variable-frequency-driven pumps, cooling networks, etc.), cargo handling systems (e.g., LNG reliquefication plants and gas compression technologies), waste heat recovery, economizers, shaft generators, steam/power turbine systems, volatile organic compound recovery systems optimal sizing, sulfur reduction scrubbers and estimation of additional fuel consumption, hybrid battery propulsion techno-economic assessment. Finally, MBSE tools can be used to support decision-making on environmental compliance and to analyze the potential benefits from the use of advanced technologies in novel ship designs (Georgopoulou et al. 2015, 2016).

For retrofit applications, MBSE can be used to techno-economically compare solutions and optimize their benefits. Typical application area for all ship types is the integrated assessment of existing ship systems with newly installed environmental compliance technologies (Georgopoulou et al. 2015). For gas carrier reliquefication plants, typical problems include the techno-economic comparison of vendor options and optimal sizing (Dimopoulos et al. 2015). In bulk carriers, MBSE can be indicatively used on the assessment of battery systems for crane operations.

14.2.2 Generic Problem Description/Workflow

A typical workflow to manage a technical problem through MBSE includes the following series of actions (Fig. 14.1):

1. *Case specifications*: Identify the systems of interest and the key components comprising them. Describe the case objectives and the performance aspects to be observed, as well as define a set of metrics that quantify this performance. Identify the system specifications, features, and properties, including the range

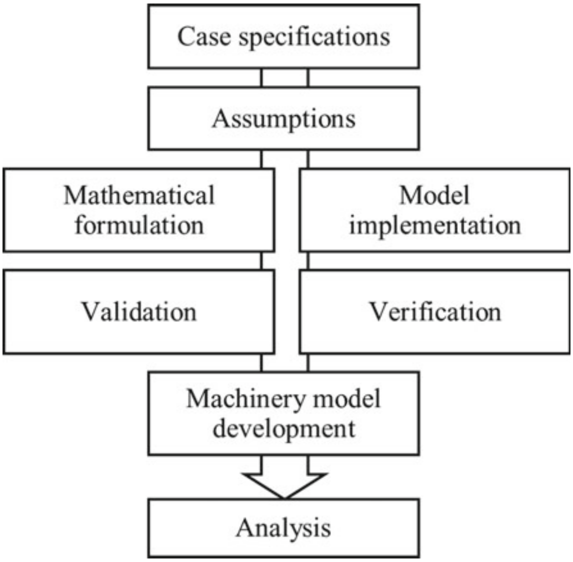


Fig. 14.1 Generic workflow to manage a technical problem through MBSE

of application, the nominal and operational settings, and any technical and operability constraints.

2. *Assumptions*: Define the case assumptions considering the scope of the case and the metrics to be assessed, as the granularity of the models depends on case objectives. This step affects the upcoming activity of mathematical formulation, which, for example, may be steady-state (design/off-design) or dynamic (transient operation), simple regression or use of spatially distribution domains, etc.
3. *Mathematical formulation*: Develop the mathematical formulation that captures the governing mechanisms (mechanical, chemical, electric, thermodynamic, heat transfer, fluid flow, etc.) that describe the behavior of the components and systems. Hence, the modeling assumptions are defined in advance and affect the final mathematical formulation, which, for example, may be steady-state (design/off-design) or dynamic (transient operation), simple regression or use of spatially distribution domains. Furthermore, the proper selection of the mathematical equations is important, as it may offer the opportunity to simultaneously assess different system states with the same single model. This feature is often referred to as the ability of a model to be generic and reconfigurable.
4. *Model implementation*: Program the mathematical models in an appropriate computer-based process modeling environment. There are several equation-oriented modeling environments in the market, allowing the solution of highly complex systems of differential and nonlinear algebraic equations and offering the necessary object-oriented and open software architecture capabilities.
5. *Validation*: Validate the individual component models, both separately and in subsystems if required, through comparison against experimental and/or measured data. This process ensures the fidelity of the models and helps in understanding the individual behavior of each component with respect to design and operational decision-making parameters.
6. *Verification*: Each model is verified through several targeted simulation studies (usually at its extreme conditions) and parameter sensitivity analyses. This activity aims at checking the model behavior at a wide range of application, as well as understanding its numerical stability.
7. *Ship machinery system model development*: Develop a generic and reconfigurable model of the ship machinery systems of interest, through the so-called hierarchical flowsheet synthesis using the individual component models as "building block." Some platforms provide the option to link the flowsheet with other computer-aided tools, allowing the exchange of information between different software, the use of external models developed on other platforms, etc. This ability supports the implementation of holistic approaches in the virtual testing of technical systems, as it allows the integration of multidisciplinary tools to create the digital twin of a technical system within its environment and with its dependencies.
8. *Model-based systems analysis*: Assess the performance of the technical system using the digital twin. In this final task, the model is used to perform simulations and quantify the performance metrics that were identified in Step 1. The assess-

ment may include steady-state or transient calculations, sensitivity analyses, etc., depending on the scope of the study.

The above procedural steps are applicable at various levels, from the analysis of a single system element to complex integrated systems.

14.3 Mathematical Formulation of the Process Modeling Framework

In MBSE, a system component is mathematically modeled by combining sets of equations of the following types:

- *Captured phenomena*: The modeling of a technical component starts with the definition of the mechanisms to be captured. Essential laws, like the conservation of mass, energy, momentum, and electric current, are usually present in most mathematical model representations. Furthermore, the model expands to include formulas of the specific process phenomena to be accounted for relevant to the specific component function: heat transfer, mass transport, chemical reactions, etc. Additional formulas are defined for the description of thermophysical properties, such as heat capacity, density, as functions of other properties like temperature and pressure. The model mechanisms can be mathematically formulated in various ways, corresponding to different scope, assumptions, and levels of fidelity. Depending on the granularity and the scope of the modeling approach, the engineer can choose the best fitting model to reflect its intended use.
- *Sizing and cost features*: The mathematical formulation usually includes a set of parameters and variables that represent component geometrical properties, dimensions, and cost aspects. Depending on the scope of the problem, either high-level or detailed representation can be used.
- *Connectivity rules*: The model includes a set of connectivity rules that allow its communication with other models, importing or exporting information.

In the next paragraphs, a generic set of Partial Differential Algebraic Equations (PDAEs) that express key conservation laws, governing phenomena, and connectivity rules is presented.

14.3.1 Conservation Equations and Physical Phenomena

Conservation laws, expressed by PDAEs, describe how different mechanisms can change the quantities of a physical mean inside a defined control volume. Examples of quantities are the mass, the energy content, the momentum, or the electric current. The conservation laws can be mathematically formulated in different ways depending on the control volume state (e.g., solid, liquid), the energy form (e.g., mechanical, electric), as well as the incurred assumptions.

As an example, the conservation of mass species inside a control volume may change in time subject to mass transport (MT) driven by velocity u and chemical reactions (CR), as described by the below equation (Dimopoulos et al. 2014):

$$\frac{\mathrm{d}c_i}{\mathrm{d}t} + \nabla(u \cdot \Delta c_i) = \xi_{MT,i} + \xi_{CR,i} \forall i = 1, \ldots, N_{\text{species}} \tag{14.1}$$

The equation system is completed with the initial conditions for the species concentrations in the control volume, and the boundary conditions, such as the species incoming/outgoing flows and velocities. The mass transport source ξ_{MT} may depend on diffusive terms $D_i \cdot \nabla^2(c_i)$ which are usually defined by using experimentally derived diffusion coefficients.

In fluid flow, energy balance can be expressed by the following equation (Dimopoulos et al. 2014):

$$\frac{\mathrm{d}u_V}{\mathrm{d}t} + \nabla(u \cdot u_V) = \psi_{\mathrm{HT}} + \psi_{\mathrm{ER}} + \psi_{\mathrm{CR}} + \psi_{\mathrm{CV}} + \psi_{\mathrm{RW}} \tag{14.2}$$

where the gradient term accounts for energy transport, and the source terms, ψ, may account for heat transport (HT) due to convection and/or radiation, (electro-) chemical reactions (ER, CR), volume changes (CV), and work phenomena (e.g., rotating shaft) (RW) within and/or across the boundaries of the control volume, respectively. The initial condition describes the energy content of the control volume in the beginning of the observation period, and the boundary conditions describe the incoming/outgoing energy flows. Volume change ψ_{CV} and rotating shaft work ψ_{RW} sources usually appear in reciprocating components such as diesel engines, piston compressors.

For solid bodies (e.g., heat exchanger walls), the energy balance can be given by Fourier's expression (Dimopoulos et al. 2014):

$$\rho \cdot C_p \frac{\mathrm{d}T}{\mathrm{d}t} = -k \cdot \nabla^2 T \tag{14.3}$$

where T is the solid body temperature. This equation can be complemented with boundary conditions of various types depending on the problem formulation. As an example, Robin-type conditions are employed when heat transfer due to conduction and/or reactions taking place in the boundary, and Neumann-type conditions are applicable if the interface is adiabatic.

In electrical networks, the conservation of energy can be derived from Kirchhoff's law (Dimopoulos et al. 2014):

$$\mathbf{U} = \mathbf{R} \cdot \mathbf{I} + \frac{\mathrm{d}}{\mathrm{d}t}(\mathbf{L} \cdot \mathbf{I}) \tag{14.4}$$

where **U** is the electric voltage, **I** is the current, **R** is the system of resistances, and **L** is the physical inductance, respectively.

Finally, the momentum conservation equation accounts for the changes caused in the momentum of a mean due to the application of boundary surface and body forces ζ_F, pressure variations, and changes due to transport phenomena. For fluid flow, momentum balance can be expressed by (Dimopoulos et al. 2014):

$$\frac{\mathrm{d}(\rho u)}{\mathrm{d}t} + \nabla\left(\rho u^2\right) = -\nabla p + \zeta_F \tag{14.5}$$

In many engineering problems, the above equation degenerates to a simplified pressure drop correlation, due to the low impact of pressure dynamics. In mechanical problems, a common form of ζ_F sources is the gravity forces (pumps, piping networks, etc.) due to the elevation of a fluid at a height z (Dimopoulos et al. 2014):

$$\zeta_F == \rho \cdot g \cdot \nabla z \tag{14.6}$$

For rotating shafts, the angular momentum balance can be expressed by (Dimopoulos et al. 2014):

$$2\pi \cdot I_S \cdot \frac{\mathrm{d}\omega}{\mathrm{d}t} = \sum_{\text{in}} M_i + \sum_{\text{out}} M_j \tag{14.7}$$

When chemical (or electrochemical) reactions take place, a kinetic system model is considered, which in general can be expressed as follows (Dimopoulos et al. 2014):

$$\sum_{i}^{N_{\text{species}}} \nu_{ij} A_i \; \forall j = 1, \ldots, N_{\text{reactions}} \tag{14.8}$$

The system properties (e.g., reaction rates r, enthalpies of reactions ΔH, and stoichiometric coefficients ν_{ij} of the reacting species) are usually determined by experiments and affect the respective source terms in the mass and energy balance formulations as follows (Dimopoulos et al. 2014):

$$\xi_{\text{CR},i} = \frac{1}{V} \sum_{j}^{N_{\text{reactions}}} r_{\text{CR},j} \nu_{ij} \; \forall i = 1, \ldots, N_{\text{species}} \tag{14.9}$$

$$\Psi_{\text{CR}} = \frac{1}{V} \sum_{j}^{N_{\text{reactions}}} r_{\text{CR},j} \Delta H_{\text{CR},j} \tag{14.10}$$

For electrochemical reactions, the source terms are:

$$\Psi_{\text{ER}} = \frac{j}{2F} \sum_{j}^{N_{\text{reactions}}} \Delta H_{\text{ER},j} = \frac{1}{V} \sum_{j}^{N_{\text{reactions}}} r_{\text{ER},j} \Delta H_{\text{ER},j} \tag{14.11}$$

14.3.2 Connectivity Equations

A component model usually includes an interface of connectivity equations, allowing the ability to communicate with other component models in a system. This interface is a set of equality constraints between internal model variables (e.g., mass flowrates, concentrations) and system properties or the interface of other component models. Four types of connectivity equations can be identified: (a) fluid flow, (b) mechanical power flow, (c) control signal, and (d) electrical connections and can be generally formulated as follows (Dimopoulos et al. 2014):

$$C_j \langle \mathbf{X} \rangle_{\text{outlet}} - C_{j+i} \langle \mathbf{X} \rangle_{\text{inlet}} = 0 \tag{14.12}$$

where the component port vector variable **X** may comprise of mass/molar flow properties, power flow, or electrical connection features:

$$\mathbf{X} = \begin{cases} [p, h, \dot{m}, \boldsymbol{x}], \text{fluid flow} \\ [\omega, M], \text{mechanical} \\ [U, I, f, PF], \text{electrical} \end{cases} \tag{14.13}$$

For control port connections, any type of feature can be exchanged between components.

14.3.3 Thermophysical Properties

In the case of working fluids, the need arises for the use of equations of state (EOS) to calculate thermophysical properties, like density, enthalpy, and heat capacity. In general, EOS comprises a system of functions of thermodynamic properties (temperature, pressure, composition) of the form (Dimopoulos et al. 2014):

$$\mathbf{X} = f(p, T, \mathbf{x}) \tag{14.14}$$

To ensure unified treatment of fluid properties within a system model, the same EOS model should be employed in all system components. Examples of EOS are the IAPWS-97 model for water and steam and the Redlich–Kwong–Soave model for standard fluid mixtures (Infochem 2009; Wagner et al. 2000).

14.4 Individual Component Models and Processes Library

14.4.1 Model Libraries

The development of dedicated MBSE model libraries for shipping application provides with the ability to represent any type of onboard machinery system in the computer. Such libraries exist in literature, and one with a wide range of proven applications is the DNV GL COSSMOS modeling framework.

The DNV GL COSSMOS library contains a wide list of component models of ship machinery systems, as shown in Table 14.1 (Dimopoulos et al. 2014). Each component model comprises a set of mathematical equations, as described in Sect. 14.4, and has been developed following the principles of paragraph 14.3. Models of different complexity are included in this library, from spatially distributed dynamic systems to even zero-dimensional steady-state forms, allowing the development of system models of different accuracy level fit-to-purpose for their intended use. Table 14.1 categorizes the component models depending on their purpose in ship machinery systems. The next paragraphs further describe the key features of each model category.

14.4.2 Primary Energy Converters

Primary energy converters are responsible for the conversion of the fuel's chemical energy to other useful energy forms, like work, heat, or electricity. Key example is the combustion engine and specifically the diesel engines, which are the most common choice for onboard power production. Fuel cells convert the fuel chemical energy to electric energy. Technology options include the molten carbonate fuel cell (MCFC) and the high-temperature proton exchange membrane fuel cell (HT-PEM) (Dimopoulos et al. 2013; Ovrum and Dimopoulos 2012).

In DNV GL COSSMOS, there is a variety of primary energy converter models of different granularity. As an example, three individual diesel engine models of different complexity are included in the library:

- A lookup model is based on linear interpolation of existing engine performance data as given in the respective project guides or sea trials (Dimopoulos 2009; MAN 2011; Meier 1981; Wartsila 2011).
- A mean value model (Dimopoulos et al. 2014; Meier 1981) is steady-state and semi-empirical, approaching the in-cylinder phenomena as an equivalent flow restriction with heat addition. This model can be combined with other turbomachinery and heat exchange models, to arrive at a complete representation of the diesel engine, turbocharger, charge air cooler, and exhaust gas path system.

Table 14.1 DNV GL COSSMOS component model library (Dimopoulos et al. 2014)

Categories	Component models
Primary energy converters	Diesel engine (different models exist for variant granularity: lookup/mean value/detailed), dual-fuel engine, gas turbine (lumped thermodynamic/lookup), fuel cell MCFC model (detailed/lookup), HT-PEM model, boiler burner, battery
Secondary energy converters	Steam turbine (back-pressure/condensing), Compressor, turbine, power turbine, blower, displacement compressor (scroll/screw), simple pump, centrifugal pump, variable-speed-driven pump, absorption chiller, generator, motor (synchronous/asynchronous), thermo-electric generators
Flow transportation	Valve (gas and liquid), Joule-Thomson valve, flow mixer/splitter, pipe, plenum (gas and liquid), tank
Heat exchange and phase separation	Steam drum/evaporator, steam drum, deaerator, cross-flow evaporator, condenser, cross-flow heat exchanger, tubular heat exchanger, plate heat exchanger, auxiliary boiler (not including the burner), smoke tube boiler
Electrical system components	Frequency converter, transformer, inverter, rectifier, distribution bus, electric load
Control and automation	Proportional-integral-derivative (PID) controller, sensor, actuator, measurement device, power management unit
Power flow	Rotating shaft, torque load, torque combiner, reduction gear, propeller
Mass separation and (bio) chemical reactors	Tubular steam methane reformer, exhaust gas treatment units (sox scrubbers), selective catalytic reactors (scr) for nox reduction, ballast water treatment unit (lump)

– A dynamic phenomenological model of the in-cylinder processes, including sub-models of the inlet/exhaust valve, inlet ports, and reciprocating engine cylinders (Merker et al. 2006).

14.4.3 Secondary Energy Converters

Secondary energy converters operate with secondary energy forms which have been transformed from primary energy sources in other system components. Typical examples include electrical machines, which convert electricity to work and vice versa, and steam turbines that convert steam internal energy into mechanical work.

Compression and expansion components transfer energy between a rotating shaft and a fluid stream. Such ship machinery system components include compressors, turbines, blowers, fans, pumps, etc. Their performance can be approached in variant ways, such as the use of characteristic maps (pressure ratio, mass flow, isentropic efficiency, and rotational speed) and lump expressions of the polytropic compression and expansion process (Hiereth et al. 2007). The heat transfer phenomena that take place in these processes can be approached by dynamic heat conduction and convection equations, using semi-empirical expressions for the heat transport coefficients (Perry et al. 1999).

The steam turbine performance models have been developed using the standard method that is described in the publication (SNAME 1973). This approach was extended and adapted to modern steam turbine generators in Dimopoulos 2009 and Dimopoulos et al. 2014, accounting for steam extraction at both condensing and back-pressure units. The model is steady-state and covers both design and off-design performance assessment. The steam turbine isentropic efficiency is evaluated using a "base efficiency," which is an empirical function of the nominal steam turbine power output, multiplied by correction factors for pressure/temperature inlet, exhaust back-pressure, and load factor. The complete list of functions is given in (Dimopoulos 2009; SNAME 1973).

14.4.4 Flow Transport Equipment

Flow transport equipment includes components such as pipes, pumps, valves, tanks. Four types of models can be identified:

– *Models of flow regulation/restriction devices, such as valves*. This kind of models usually estimates the flow passing through a valve using a characteristic law for the valve's stem position. Implementation of characteristic valve maps is also possible.
– *Models of flow pressure increase, like pumps*. Such models usually employ characteristic maps of the pump performance (power, head, capacity, efficiency) combined with thermodynamic fluid property calculations (Perry et al. 1999).
– *Models of flow pathway components, such as pipes and ducts*. This category of models usually employs semi-empirical pressure drop correlations of the fluid flow rate and the friction effects (Perry et al. 1999).
– *Models of plenums, such as tanks*. These component models usually take into account the pressure variation effects in the plenum due to the in/outflows, phase, or composition change. As such, mass and pressure accumulation as well as wall heat transfer phenomena can be accounted for using dynamic conservation equations.

14.4.5 Heat Exchange and Phase Separation

Several systems onboard are governed by heat exchange phenomena, such as engine cooling systems, fuel treatment, heat recovery, steam network, and cargo heating/cooling. For heat exchanger components (economizer, evaporator, superheater), different modeling features can be adopted depending on the desired level of granularity:

- Lumped or spatially distributed domain analysis along the main dimensions (i.e., length or surface).
- Steady-state or dynamic energy balances.
- Thermal storage effects in the metal walls.
- Effects of geometrical features.
- Heat transport correlations describing the amount of heat transferred per contact area; here, different semi-empirical correlations are applicable depending on the fluid phase and properties (Astrom and Bell 2000; Bejan and Kraus 2003; Dimopoulos et al. 2014; Shan and Sekulic 2007).
- Finally, various pressure drop expressions can be used, accounting for lumped or detailed geometrical features.

14.4.6 Electrical System Components

This category of components, including frequency converters, buses, transformers, inverters, and electric loads, is usually represented by steady-state equations as the timescale of the dynamic phenomena taking place is at the order of microseconds. On the other hand, the secondary converters like electric motors and generators can be dynamic models with a timescale at the order of milliseconds (Seenumani et al. 2010).

14.4.7 Control and Automation

Control and automation components are required for the simulation of dynamic phenomena, where specific controlling strategies are implemented, regulating the behavior of system components. Most common model is a generic Proportional-integral-derivative (PID) controller, which can represent any simple control loop feedback mechanism. The actuator model can represent signal delays, on/off actions, and lower/upper bounds. The measurement device model can transfer information between models, applying over and above sensor bias and errors.

14.4.8 Power Flow

Power flow models describe elements of the ship propulsion powertrains and rotating machinery, such as shafts, gearboxes. The models can be either steady-state or dynamic, implementing a power flow efficiency metric and the angular momentum conservation equations and assuming a moment of inertia for the system components.

14.4.9 Mass Separation and (Bio) Chemical Reactors

Mass separation phenomena take place in aftertreatment systems, such as exhaust gas treatment units. The main principle is the use of either physical mechanisms (e.g., desorption) or chemical reactions to selectively remove substances from ship waste streams, such as SOx and NOx from the exhaust gas stream. A simple representation of such systems may comprise semi-empirical correlations of the separation efficiency as function of thermodynamic properties and chemical agent rates. For higher analytic capability, detailed distribution domain formulation and reaction kinetic schemas can be used instead.

14.5 Integration with Other Software Platforms

14.5.1 Objective

Many engineering problems expand beyond the analysis of complex machinery systems, to their interaction and dependence on other elements of the ship/product ecosystem. As an example, defining the best design solution for a specific vessel requires the integrated assessment of optimal hull design, strength and stability analysis, machinery selection and optimization, etc. Therefore, there is a need for integrating different software to holistically and multidisciplinarily analyze such products. This can be materialized by implementing functions for data exchange and communication between the individual software used at suitable integration platforms/environments. Advanced MBSE tools not only integrate different component models to analyze complex machinery systems, but also allow for their integration with other software platforms and external models.

In the shipping industry, the EC funded project HOLISHIP (2018) aims at the integration of various ship design software tools for the holistic ship design optimization. Ship design is performed at stages, each implementing a set of software to calculate different aspects, such as hull lines, stability, vessel motions, dynamic positioning, resistance and propulsion, lightship and steel weight, machinery system performance, operating and capital costs. These tools are often used at different stages of the design process and with different level of detail. However, if the ability to integrate different software under a single automated design loop is provided, then it is possible to define the best fitting solution at an early stage of the process, saving time, efforts, and costs. The COSSMOS framework is used as an integral part of this project providing the machinery assessment capabilities integrated into the holistic ship design process.

14.5.2 Building a Model with Exchange and Co-simulation Capabilities

In order to allow for the integration and use of COSSMOS with the multidisciplinary design platforms and software used in HOLISHIP, co-simulation and model exchange interfaces are required.

Co-simulation is an essential step toward the accomplishment of a holistic approach in ship design, as it offers the capability of building the ship's cyber-physical system by combining different tools of variant time steps and calculation capabilities. In model exchange and co-simulation, models are treated as "black boxes," containing their formulation, semantics, and suitable solvers. Each black box is used as a foreign object to perform calculations inside flowsheets of different software or integration platforms.

Making different multidisciplinary models to "talk-to-each-other" is a process that can be materialized in various ways depending on the software architecture and functionalities, the available connectivity protocols, the problem scope and information exchange requirements, etc. Some modeling and simulation platforms include information exchange functions offering the ability to build models that call external tools to perform calculations required for the completion of the first ones' activities. Examples are the foreign process interface (FPI; see PSE 2009) and the FMI/FMU protocols. Each protocol contains specific libraries and functions that allow information exchange (get, send, etc.) and streaming.

Model-to-model connectivity can be operated either in a local computer, or remotely through the Web. As an example, data streaming at a local computer can be materialized via Windows sockets and implementing a master/client functional relation between different software. Microsoft Azure Internet of things (IoT) functions allow data streaming through the Web. Depending on the frequency of information exchange, this structure can be materialized to practically result in concurrent simulations.

Currently, in COSSMOS and in conjunction with HOLISHIP, co-simulation interfaces are supported. These include FMI/FMU protocol functions used as wrappers of external software calls and batch application interface that allow integration of COSSMOS under multidisciplinary integration platforms (Fig. 14.2).

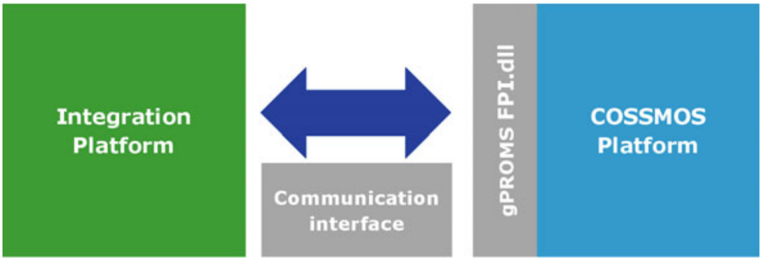


Fig. 14.2 Generic workflow to integrate COSSMOS under a multidisciplinary design platform

14.6 Illustrative Applications

14.6.1 Hybrid-Electric Propulsion Systems

Hybrid-electric ship powertrain concepts, i.e., propulsion systems combined with energy storage devices, are considered as solutions for potential fuel consumption reduction in various ship types. A generic hybrid-electric propulsion configuration (Fig. 14.3) connects prime movers (engines) with electric generators and energy recovery devices, aiming at covering the onboard propulsion and electric demand from the motors, thrusters, auxiliary equipment, and hotel loads (Stefanatos et al. 2015b). Apart from energy efficiency, this kind of technology is attractive for highly transient power-intensive ship operations, such as dynamic positioning (DP) of offshore supply vessels. In such cases, the energy storage devices can act as instant power reserve and fast redundancy, when peak loads need to be covered on time. The increased complexity of these systems generates the need of advanced simulation techniques to optimally dispatch the loads among prime movers, generators, and the batteries and ultimately arrive at the best power system management strategy that meets demands when needed at the lowest cost. Such challenges need to be solved in the early design phase along with other decision-making aspects, such as technology maturity level, weight limitations, safety and operability constraints, and capital costs. In total, this complex landscape is an ideal case to demonstrate the use and benefits of model-based system engineering in shipping.

DNV GL has successfully used model-based approaches for the integrated analysis and optimization of the first commercial ship with battery hybrid-electric propulsion, the Viking Lady offshore supply vessel (Stefanatos et al. 2015b). DNV GL COSSMOS was used to quantify the hybrid-electric operational performance utilizing actual information collected from the vessel's data acquisition system. The system performance was analyzed and optimized to arrive at significant fuel savings of 15% on annual basis, as shown both from the model predictions and confirmed from the onboard sea trial tests (Stefanatos et al. 2015b).

Viking Lady's hybrid powertrain (Table 14.2) consists of four synchronous three-phase alternating current (AC) diesel generators, supplying electric power to five

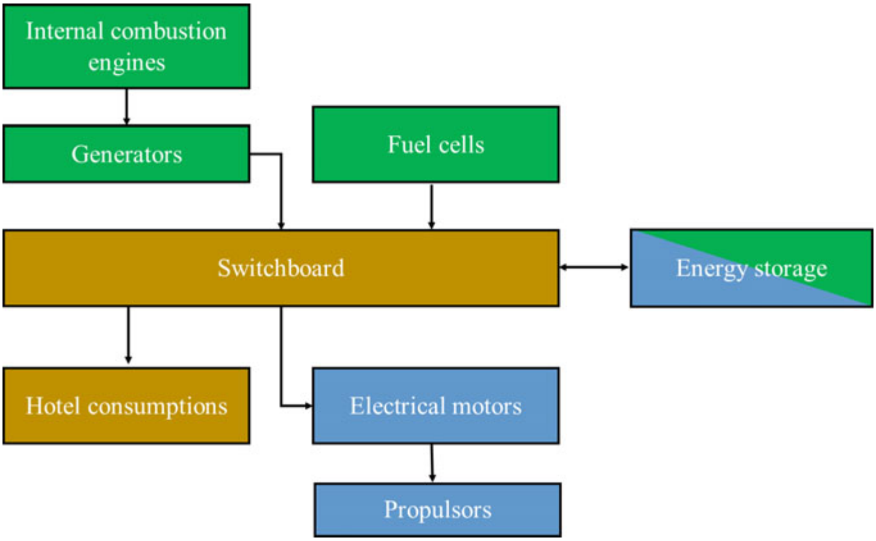


Fig. 14.3 Generic hybrid-electric propulsion system configuration

Table 14.2 Viking Lady's electric propulsion system specifications (Stefanatos et al. 2015b)

		Nominal power (kW)	Speed (rpm)
Production side	Diesel engine	4 × 2000	720
	Generator	4 × 1920	720
Consumption side	Propulsion motor	2 × 2300	1200
	Thruster motor	2 × 1200	1200
	Retractable thruster motor	1 × 800	1000
		Power capacity (kWh)	
Energy storage	Li-on battery	450	
		Voltage (V)	Frequency (Hz)
Transmission	Switchboard	690	60.3

asynchronous AC motors and any hotel load onboard. In turn, the AC motors are coupled to frequency converters for speed regulation and drive the ship propulsors: two podded propellers, two tunnel thrusters, and a retractable maneuvering pod propeller. The system was modeled in DNV GL COSSMOS (Fig. 14.4) with the capability to perform both steady-state and transient performance analyses. Each component model was calibrated on manufacturers' data and validated against vessel's commissioning and acceptance tests, exhibiting good agreement both for steady-state and dynamic conditions. All automation and control equipment were included, and the power management strategies were based on actual vessel operational conditions.

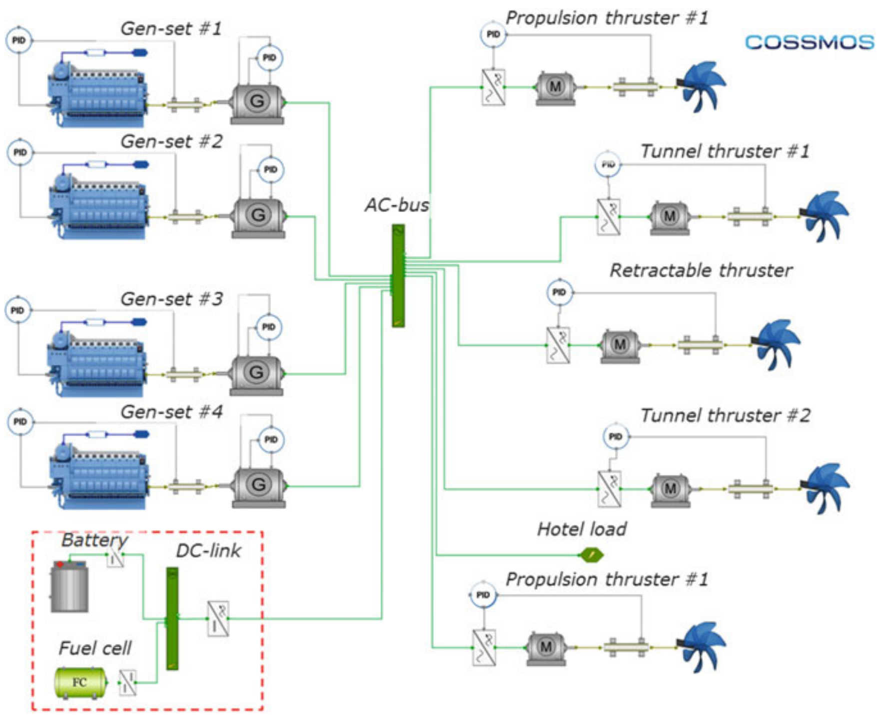


Fig. 14.4 Complete hybrid-electric propulsion system COSSMOS flowsheet model (Stefanatos et al. 2015b)

A set of onboard measurements for a period of two years (prior to the installation of the battery) was processed to derive the operational profile of the vessel. Then, DNV GL COSSMOS was used to reproduce the operating profile and identify strategies for fuel reduction, including the power-intensive DP mode (Stefanatos et al. 2015b).

All operating modes were optimized on an annual basis. DP mode optimization mainly resulted in the battery covering the transient loads (peak shaving) and the gen sets supplying the base demand at almost constant load. As such, significant efficiency benefits of approximately 20% were observed (Stefanatos et al. 2015b). Furthermore, the use of hybrid operational strategies for all annual operations resulted in savings of approximately 17.7% (Fig. 14.5) (Stefanatos et al. 2015b). The optimization did not stay only on fuel savings but also considered maintenance aspects for the way that the prime movers and battery were used. The gen set's constant load operation and the fine-tuning of battery charge–discharge condition can result in reduced maintenance operation.

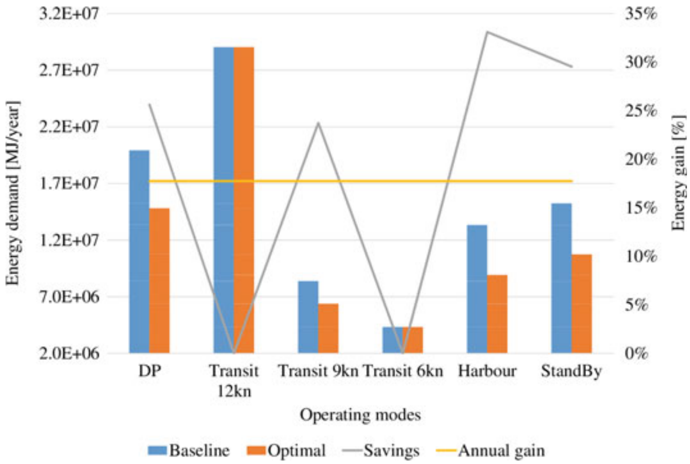


Fig. 14.5 Estimated annual savings from hybrid-electric propulsion (Stefanatos et al. 2015b)

14.6.2 Desulfurization Scrubbers

MSBE approaches can be beneficial in supporting shipping companies to decide on which is the best solution for regulatory compliance fitting to their needs. As strict environmental regulations are being imposed in local and global regimes, the use of integrated to solve dilemmas on best compliance in both newbuilding and retrofitting applications becomes important. This paragraph presents a practical example of the model-based analysis of a marine diesel engine with scrubber for exhaust gas sulfur emissions removal (Georgopoulou et al. 2015). The objective is to analyze how the engine performance can be affected by variant scrubber designs and engine loading conditions.

In a typical wet desulfurization system, the exhaust gas stream is diverted from the engine's duct to a scrubbing column. Inside the column, water (sea for open-loop and fresh for hybrid or closed-loop systems) is sprayed from the top, absorbing the gas sulfur compounds and cleaning the gas stream. Apart from the parasitic loads of the scrubbing system, the interaction between the column and the engine system can impact the efficiency of the marine energy system. The scrubbing process drops the pressure of the exhaust gas affecting the engine back-pressure and the efficiency of the marine energy system. If a forced-draft fan is used to recover the pressure drop, extra electric consumption is caused.

An integrated model of a marine power plant with a seawater scrubber in DNV GL COSSMOS is shown in Fig. 14.6. The plant comprises a 37,000 kW slow-speed two-stroke marine diesel engine, three turbochargers, one economizer at the exhaust gas path for steam production, and a seawater desulfurization scrubber (Georgopoulou et al. 2015). The diesel engine is modeled using a mean value model, the turbomachinery components are modeled based on functions of polytropic transition with

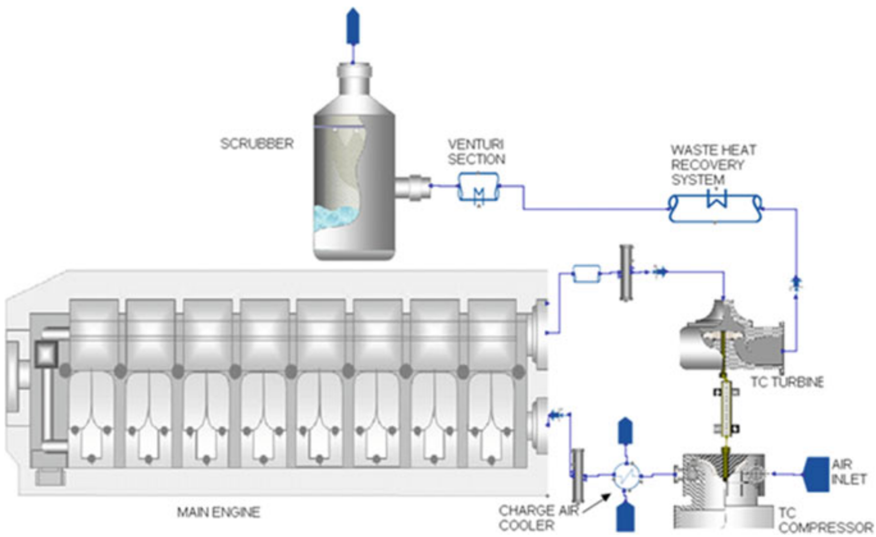


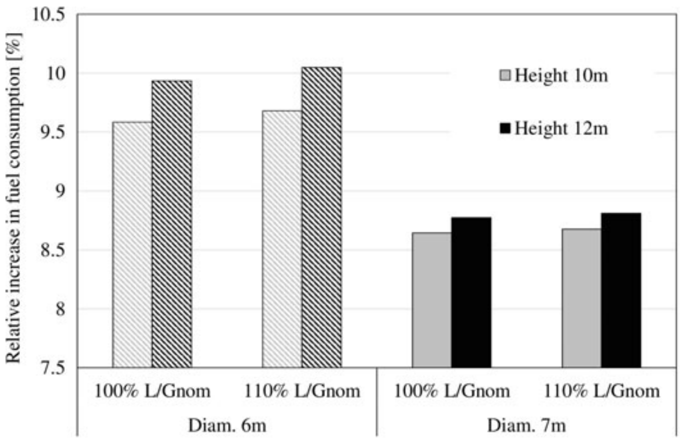
Fig. 14.6 Marine energy system with exhaust gas desulfurization in DNV GL COSSMOS (Georgopoulou et al. 2015)

heat exchange, and the desulfurization scrubber is modeled as a two-dimensional gas-to-liquid mass transport column with chemical reactions.

To demonstrate the impact of scrubber design on the engine operation, it is assumed that the scrubber design characteristics vary within ranges of typical market designs for the range of the engine power rating. In particular, various designs are evaluated with the height being from 10 to 14 m, the diameter from 6 to 7 m, and the liquid flowrate within 10% of a nominal point. The designs are then compared against two performance indicators:

– The relative increase in fuel consumption due to exhaust gas pressure drop in the scrubber.
– The sulfur-to-carbon emissions ratio (SO_2 ppm/$CO_{2\,\%}$v/v), which is used to correlate the desulfurization efficiency performance against low-sulfur bunkers (IMO 2009).

Figure 14.7 presents the model results for the scrubber impact on the engine fuel consumption and the emissions at 90% engine loading. Each column represents a combination of scrubber features: height, diameter, and L/G ratio. The horizontal line shows the regulatory limit for emissions ratio which corresponds to 0.1% sulfur content. As expected, the desulfurization effect increases with increasing seawater flow rate and column dimensions. On the other hand, the increase in wash water or the column height has negative effect on fuel consumption due to the higher pressure drop in the flue gas. A positive increase in the diameter results in a wider gas/liquid passage, reducing the pressure drop and its negative impact.



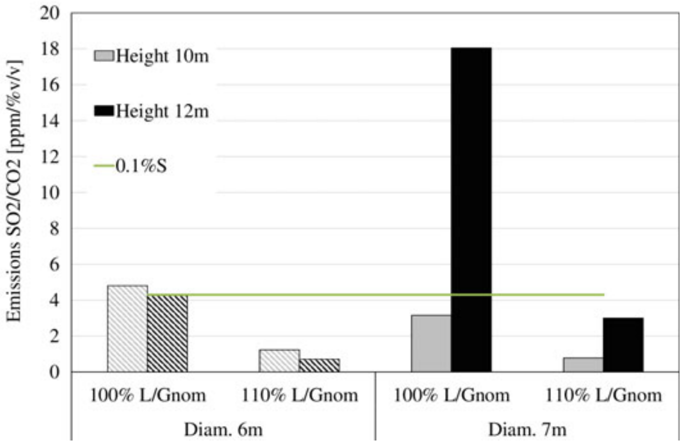


Fig. 14.7 Performance analysis of the scrubber design for different scrubber designs (height, diameter, and liquid-to-gas flow ratio) (Georgopoulou et al. 2015)

The negative effect of pressure drop on fuel consumption can be mitigated by using forced-draft fans, which in turn consume electric loads. For this specific case study, the mean increase in electric loads is about 5% (Fig. 14.8), mitigating the initial negative effect in total fuel consumption by half (Georgopoulou et al. 2015).

Through this case study, the use of MBSE to analyze regulatory compliance solutions was demonstrated. As observed from the simulations, the scrubbing system drops the exhaust gas back-pressure, thereby causing the turbocharger to operate at lower compression ratio and air flow. As such, the engine operates at higher fuel consumption for the same power demand. This negative effect is even lowered by half if a forced-draft fan is used to recover the exhaust gas pressure drop. The model quantified the total impact at the order of about 5% increase in electric loads at

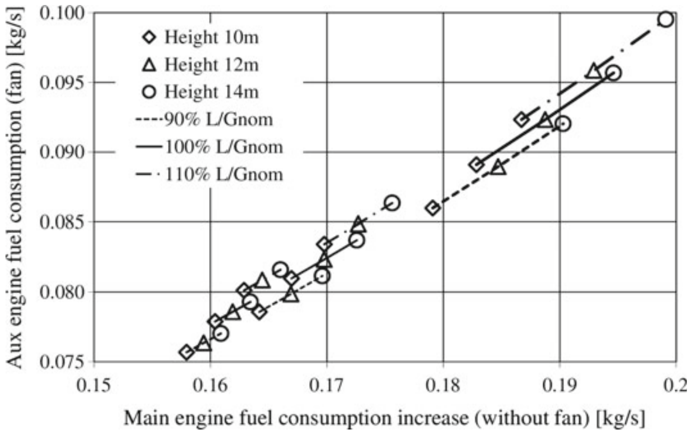


Fig. 14.8 Parametric analysis of the marine energy system with FGD scrubber and forced-draft fan at different scrubber designs (Georgopoulou et al. 2015)

90% main engine loading. Of course, the purpose of this case is illustrative, and the results depend on the specific scrubber features, so they cannot be generalized for all scrubber types and systems.

14.6.3 LNG Carrier Newbuilding Configuration Alternatives

Model-Based Systems Engineering can effectively support the early ship design phase when the optimal selection among various alternatives is required for highly complex machinery systems and operations. A good example is LNG carrier's propulsion and cargo handling systems, where many technical options are applicable to their performance being dependent on the operating conditions and fuel prices. This paragraph presents the use of DNV GL COSSMOS for the concept development of an LNG carrier's integrated machinery including propulsion and energy recovery technologies (Dimopoulos et al. 2015). Different technology alternatives and machinery configurations were evaluated subject to her actual representative operational profile, thus leading to the selection of the best fitting solution with the optimal sizing of components.

Figure 14.9 presents an outline of the integrated propulsion and cargo handling systems for an LNG carrier (Dimopoulos et al. 2015). Propulsion power can be supplied by either electrically or mechanically driven systems. In case of mechanical propulsion, electricity for hotel loads, auxiliaries, and boil-off gas (BOG) handling can be covered by (dual- or liquid-fueled) gen sets and optionally by shaft generators (power take-out) from the main engines. In the case of electric propulsion, electricity demand is covered by the main engines. Heat loads can be covered by conventional fuel-fired auxiliary boilers, and optionally by exhaust gas economizers coupled on

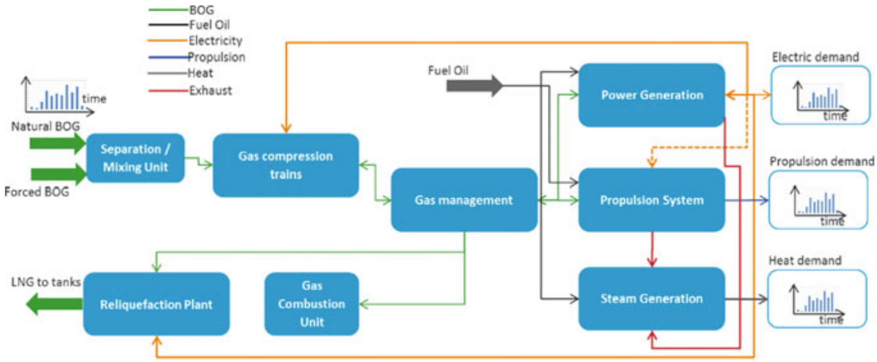


Fig. 14.9 LNG carrier generic marine energy system (Dimopoulos et al. 2015)

the main (and/or auxiliary) engines. Heat demand may result from steam-driven equipment and various heating needs onboard. The prime movers burn primarily LNG fuel from cargo evaporation in the tanks (BOG). If there is no sufficient BOG from natural evaporation, then forced boil-off is generated to supply the engines with the required fuel. Prior to engine supply, the BOG is treated in compression trains to reach the required pressure levels for the engines (high pressure for the main engines and low for the auxiliaries). When surplus BOG is generated, either this is burnt in a gas combustion unit or fed back to the tanks through a reliquefication plant.

Apart from the system complexity, another feature that complicates the assessment of these systems is the variation of BOG composition depending on the operational profile and its subsequent effect on the engine performance. Appropriate modeling and simulation as well as physical property calculation can capture these effects, providing thus pragmatic understanding of the system performance under realistic conditions.

The case vessel is an LNG carrier of 175,000 m^3 cargo capacity with a typical trade route from East Coast US to Japan of 9700 nautical miles (nm) distance and about 98% cargo methane content (Dimopoulos et al. 2015). Figure 14.10 presents a modal analysis of the LNG carrier's power, heat, and electricity demand at different operating conditions and vessel speeds (Dimopoulos et al. 2015). A generic model of her integrated machinery system was developed in DNV GL COSSMOS (Figs. 14.11 and 14.12), allowing the ability to compare electric and mechanical propulsion, to assess the performance of shaft generators and exhaust gas economizers, and optimally to size gas-fuel compression trains and a BOG reliquefication plant (Dimopoulos et al. 2015).

The model was used to size the BOG compression train and arrive at the best choice for minimum capital and operating cost. The less costly combination of number of compressors and their nominal flowrate was determined, subject to the ability of handling the maximum possible gas flow as worst-case scenario. The best option corresponded to two compressors of nominal rate equal to the 75% of the maximum predicted BOG flow (Dimopoulos et al. 2015). Then, the techno-economic feasibility

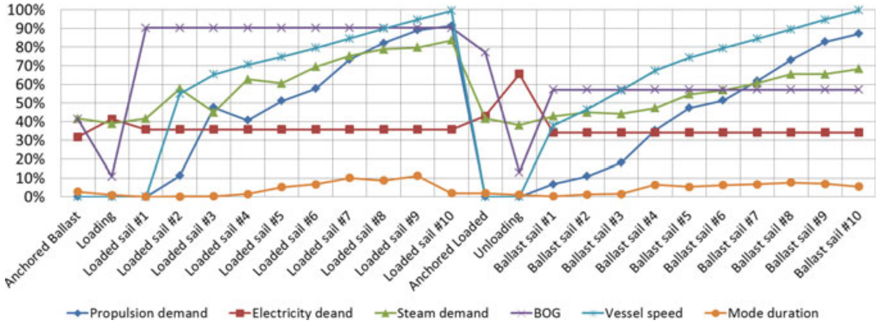


Fig. 14.10 Modal analysis of the power, heat, and electricity demand at different operating conditions for an LNG carrier (Dimopoulos et al. 2015)

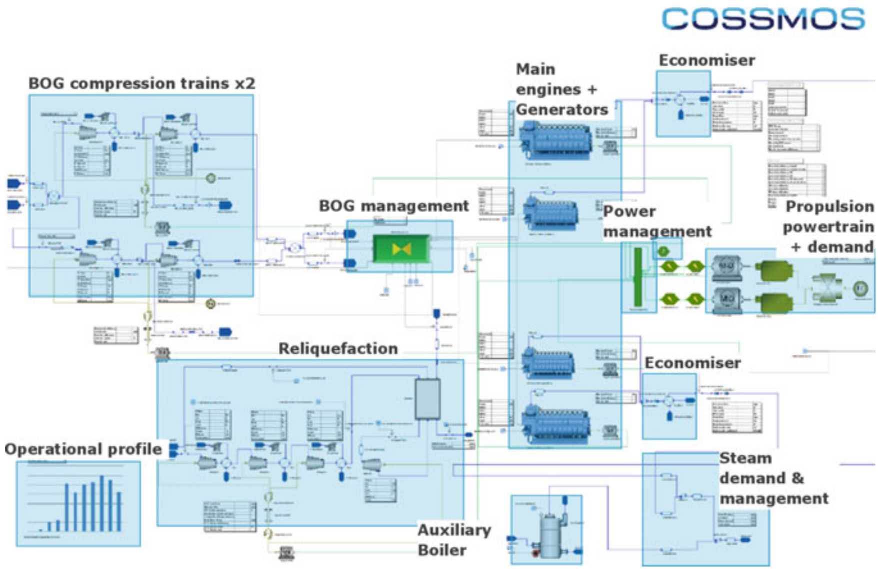


Fig. 14.11 Generic electric propulsion LNG carrier machinery configuration in the DNV GL COSSMOS framework (Dimopoulos et al. 2015)

of reliquefication plants of different sizes was assessed. It was found that the payback period in case of mechanical propulsion (Four years for a system of about 2500 kg/h) was more than 30% lower compared to the electric configuration (Dimopoulos et al. 2015). Finally, configuration and technology alternatives were analyzed, leading to the result of about 5% overall efficiency improvement with mechanical propulsion and 0.5 million USD annual savings in operational costs. With the addition of engine economizers and shaft generators, the overall gain raised to about 8%, resulting in a total ship machinery energy efficiency of more than 54% (Dimopoulos et al. 2015).

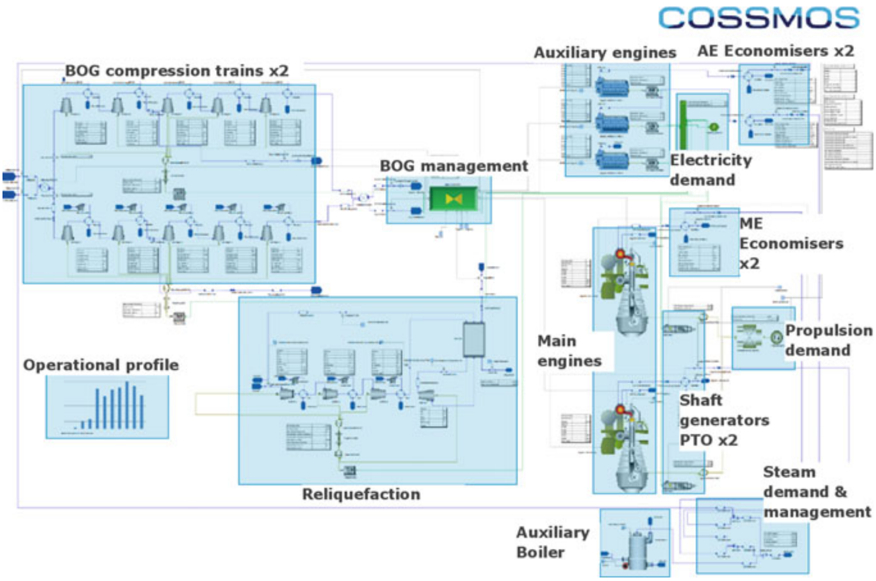


Fig. 14.12 Generic mechanical propulsion LNG carrier machinery configuration in the DNV GL COSSMOS framework (Dimopoulos et al. 2015)

14.6.4 COSSMOS Use Under an Integration Platform for the HOLISHIP Project

This paragraph presents an application case of the HOLISHIP project for the holistic concept design and optimization of an offshore supply vessel (OSV) (de Jong et al. 2018). The objective was to optimize the vessel's dimensions for best CAPEX and OPEX performance and subject to mission profile and cargo handling (crane type and lifting capacity) requirements. The cost elements included the investment cost of equipment for propulsion and machinery, construction cost represented by the steel weight, and operational costs represented by the fuel consumption.

To achieve this goal, different software tools were integrated under the CAESES platform (CAESES 2018), allowing the analysis of a wide range of solutions for the vessel dimensions, hull design features, and power system architectures. Figure 14.13 shows the problem implementation in CAESES. At each design loop, a dedicated hull parametric model was used to explore the design space and produce a hull form to be tested for its holistic performance. The NAPA software tool was then used to verify hull performance and address any constraints' violation. Hydro-dynamic and hydro-static calculations were performed to assess the hull performance and to estimate the main onboard consumers in all operating modes (e.g., transit, DP). The required thrust is determined by the station keeping tool and the resistance tools. Thrust is then converted to required installed power generation. The consumers' evaluation was used to size the propulsion systems. In turn, our COSSMOS tool

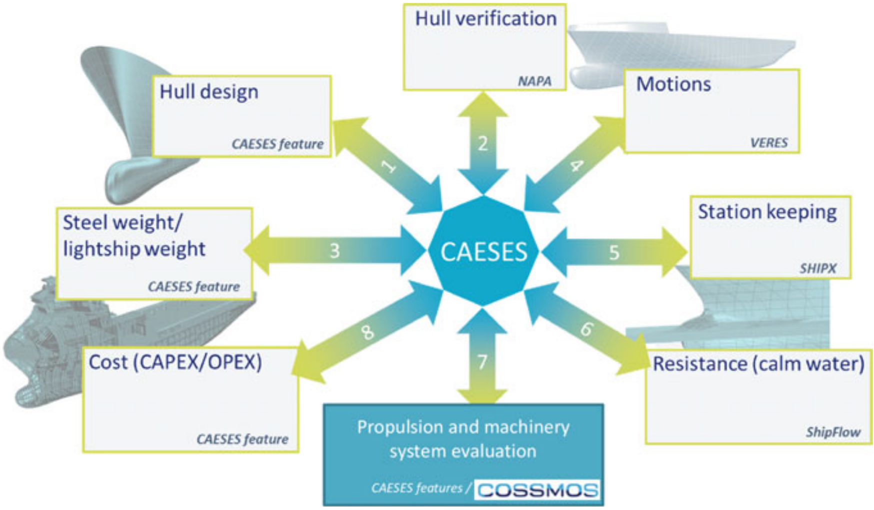


Fig. 14.13 Ship design software tools integration under the CAESES platform, including COSSMOS for machinery assessment

was used to evaluate the performance of different propulsion system architectures and minimize the fuel consumption subject to the sizing constraints. The CAESES integration platform utilized batch application communication, file exchange, and CAESES built-in functions to support the design loops.

The case specifications are shown in Table 14.3, including a high-level operating modes analysis of her annual operation. Figure 14.14 presents the OSV propulsion system model in COSSMOS. Diesel–electric configuration was assumed, consisting of four identical generating sets, two aft thrusters, two forward thrusters, and one azimuth thruster. Mechanical power is provided to the thrusters via electric motors, powered in turn by the main switchboard via frequency converters. In transit and harbor modes, the diesel generators cover all electric loads in the main switchboard, including hoteling and thruster demands. In DP mode, the switchboard is split into two parts, each connecting a pair of generators to about half of the consumers (one aft, one forward thruster, and about half the hoteling loads). The azimuth thruster demand can be dispatched to either one or two switchboards, with this parameter being a power management optimization variable.

In each design loop (corresponding to a specific hull form), COSSMOS was used to evaluate the best engine size and power management strategy for minimum fuel consumption, subject to the annual modal analysis of Table 14.3. A set of four different engine models was assessed, with their power output ranging from 1920 to 3710 kW. Figures 14.15 and 14.16 present the results for a selected solution. Apart from the evaluation of all individual solutions generated by the hull parametric model, COSSMOS also provided a detailed analysis of the results, including the performance of each different engine model, as well as the energy flow through the system.

Table 14.3 HOLISHIP OSV case 1 specifications for different operation modes

		Sailing mode	DP mode	Harbor
Time spent	(%)	40%	40%	20%
Aft thruster #1	(kW)	1511	1500	0
Aft thruster #2	(kW)	1511	1500	0
Fore thruster #1	(kW)	0	950	0
Fore thruster #2	(kW)	0	950	0
Azimuth thruster		0	880	0
Hotel	(kW)	400	400	400
Switchboard mode	(–)	Closed	Split	Closed
Nominal power aft thrusters	(kW)	3000		
Nominal power fore thrusters	(kW)	1900		
Nominal power Azimuth thruster	(kW)	880		

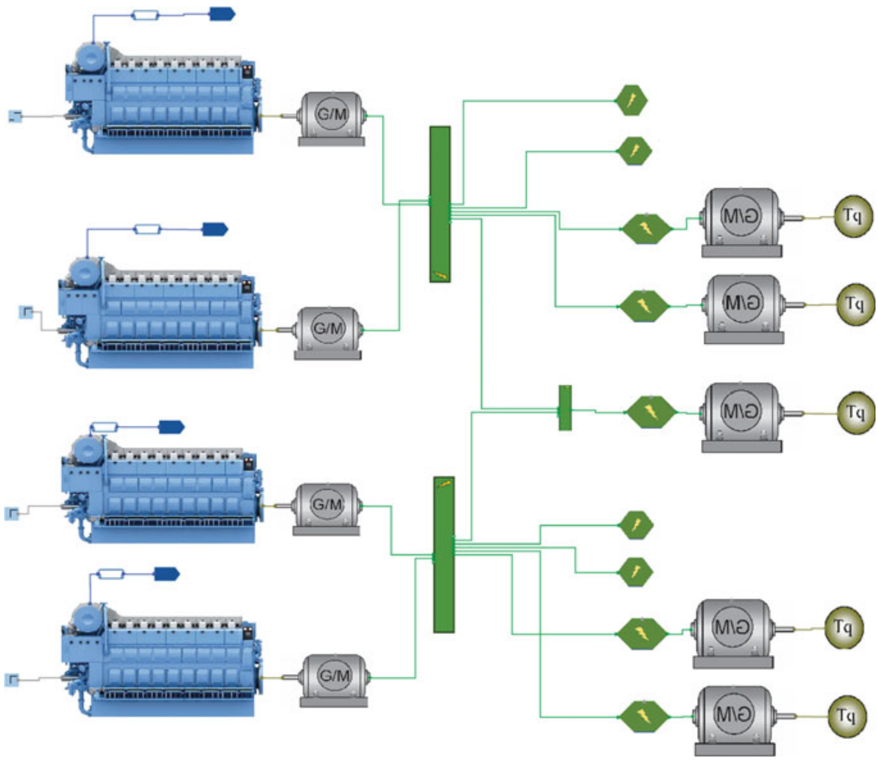


Fig. 14.14 COSSMOS machinery model for the HOLISHIP application case on diesel–electric OSV

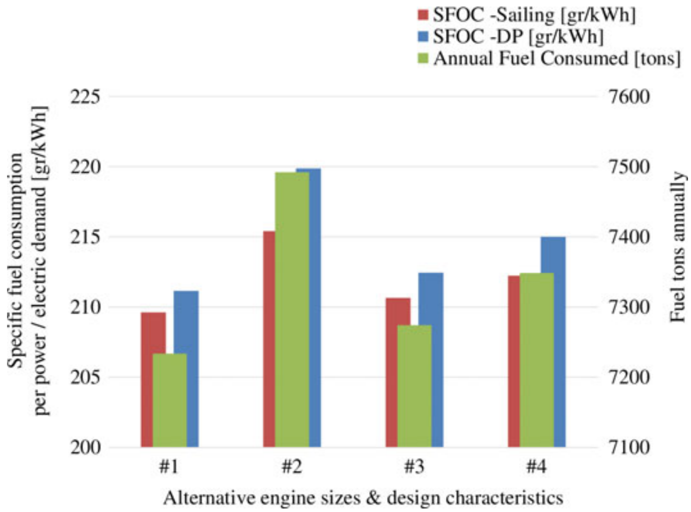


Fig. 14.15 Specific and annual fuel consumption of the best design solution for each different engine model

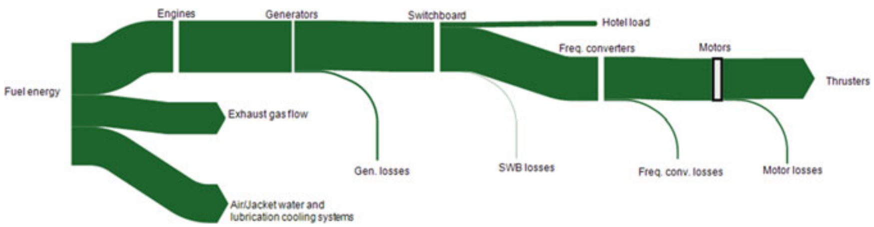


Fig. 14.16 Energy flow across the propulsion system

14.7 Conclusions

In this chapter, the implementation of Model-Based Systems Engineering approaches for solving complex problems in ship's design and operation was shown. Starting with the mathematical formulation of the phenomena that govern machinery equipment, a generic workflow was presented on how to develop libraries of ship component models allowing the creation of the so-called digital twins of vessels in the computer. With the use of the ship digital twin, the modeling, simulation, and optimization of her complex machinery systems can be accomplished in steady-state and transient conditions. The more generic a digital twin library is, the wider the range of studies (design, operation, control, and dynamics) becomes, allowing also the analysis of various aspects of the user's interest, such as efficiency, operability, safety, cost. Moreover, the digital twin serves as test bed to carry out virtual "experiments" at low cost.

Three cases were shown for hybrid-electric propulsion, environmental compliance, and advanced concept design; all of them accomplished with the use of the DNV GL COSSMOS modeling framework for integrated marine machinery systems. DNV GL COSSMOS is an enabling framework to analyze complex phenomena at system and component levels and assess and optimize the design and operation of integrated systems satisfying technical and operational constraints. Such mathematical modeling techniques, numerical solution algorithms, and modular computer-based tools are expected to become essential in analyzing and optimizing ship machinery systems under realistic operational profiles. The digital transformation of the maritime industry is taking place in this era, and innovation in this field is a competitive advantage for business continuity and future adaptation.

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Chapter 15
HOLISPEC/RCE: Virtual Vessel Simulations

Maarten Flikkema, Martin van Hees, Timo Verwoest and Arno Bons

Contents

Abstract Where other transport industries benefit from large series production, shipbuilding only builds a low number of ships per design. Therefore, the costs for prototyping are too high requiring other prototyping and demonstration solutions. Numerical simulations can provide a solution for this. In order to use numerical simulations in prototyping, proper numerical tools for relevant components are needed, as well as a framework capable of coupling these tools. HOLISHIP proposes a solution by coupling the tools through the Internet, where the tools remain on the server of the owning company, protecting the Intellectual Property Rights (IPR), but providing controlled access to the framework. HOLISHIP developments started from the CPACS/RCE framework developed by partner DLR for the aviation industry. RCE is the communication framework used to connect tools and CPACS is the common data interface so that each connected tool uses the same data to calculate with.

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15.1 Introduction

Numerical models are becoming more and more a standard in ship design. Increased accuracy of the models and ever soaring computer power make the use of both high- and low-fidelity tools possible. With this increasing computer power and model accuracy, it becomes possible to use numerical simulations also for demonstration and verification purposes. Therefore, the HOLISHIP project develops the Virtual Vessel Framework (VVF) called HOLISPEC/RCE.

The nature of ship design is different from aircraft design. Lead times are short, and the possibility for innovations is limited. It is a worldwide, highly competitive market with a large number of relatively small companies. A design must be finished in a matter of months and often engineering continues into the building process. Specialised subcontractors are frequently involved in the design and engineering process, and concurrent design technologies, where multiple contractors work on a shared product model, are adopted for detailed engineering. For early design, interoperability between tools from different disciplines and different locations is not quite possible. It is one of the ambitions of HOLISHIP to achieve.

HOLISHIP does not focus on concurrent engineering for which several software solutions are available on the market; its focus is on the earlier stages of design, for which the level of software integration and interoperability is quite limited and where designers use their locally available tools and knowledge. In addition, they make use of the services of specialised service providers, e.g. hull lines optimisation, workability analysis, CFD calculations. Data exchange is on the level of lists, tables and drawings, in digital format or even on paper. The designer manages this information flow and distributes tasks to specialists in his/her environment. The designer integrates the results of these analyses and calculations in the design up to the level of accuracy and certainty required for the project phase.

Ships are often built in small series of only a couple of ships of the same design, comparing to the car and aviation industry where hundreds and even thousands of the same design are produced. New design concepts are tested using actual real-life prototypes in these industries, as the cost of the prototype can be spread over many cars and planes. For ships, spreading the cost for a prototype over a small series drastically increases their price. At the same time, ship owners and operators are reluctant to apply innovative solutions without a proper demonstration that it will actually work. Summarising: there is a need for prototyping in the shipping industry, but the costs are too high.

Numerical simulations can provide a solution for this. By coupling simulation tools for different components of the vessel, the complete vessel can be simulated. With this, a virtual sea trial can be conducted testing all components and their interaction. This can be done either for the complete ship or for sets of components as long as all components affecting each other are adequately modelled. Coupling of tools of different fidelity can increase the speed of the simulation if the demonstration is only focussed on a specific part of the ship.

In order to use numerical simulations in prototyping, proper numerical tools for relevant components are needed, as well as a framework capable of coupling these tools. Numerical tools are available with many companies, all having their own expertise. Coupling of these tools through a framework requires these tools to be available for the framework. Companies are, however, reluctant to provide the tools for a framework, as it contains a lot of their IPR. HOLISHIP proposes a solution by coupling the tools through the internet, where the tools remain on the server of the owning company, protecting the IPR, but providing limited and controlled access to the framework. For this, the Virtual Vessel Framework (VVF) will make use of the DLR tool RCE that is an integration framework able to connect to calculation tools on different servers to workflows.

When simulating over the internet, the tools can remain a black box for the workflow designer. It is, however, the intention that not only the tools are connected, but also the expertise. In principle, RCE can call the tools on the various servers and run them without any interference. Each tool will provide output; however, expertise is needed to judge the output. The VVF is therefore not only a framework connecting tools, but also a framework connecting expertise.

To be successful as a software integration platform, the VVF should do just that support designers with the use of state-of-the-art tools in the earliest possible stages of design in order to avoid unpleasant surprises in later stages of the project. The handling, management and distribution of design data and analysis results are an important cost factor in ship design. Data handling and calculation management are an important service which the VVF should provide.

Virtual sea trials, as discussed above, are one of many possible applications for a virtual vessel framework (VVF). An example of other applications is testing of new manoeuvring configurations early on in the design of the vessel. By coupling the hydrodynamic models and the machinery models to a bridge simulator, the feel of the manoeuvring configuration can be tested apart from only the numerical evaluations.

In this chapter, Sect. 15.2 describes the need for coupled simulations and what is needed from a technical point of view to achieve that. In Sect. 15.3, the use of simulations in concept design is elaborated, while in Sect. 15.4, the use of simulations in design verification is discussed. Section 15.5 provides insight into the available models and frameworks to perform coupled simulations. Finally, Sect. 15.6 provides example applications.

15.2 Why Do We Need Coupled Simulations?

Ship design follows an iterative process of requirement definition, concept development, design verification and operational optimisation and adoptation. During each stage of the design process, simulation tools with different fidelity are used. The fidelity can be increased when more detailed information is available as the design progresses. High-fidelity tools require more detailed input and calculation time (and calculation power) to perform a simulation that focuses on more specialised parts of the system, while low-fidelity tools require limited input, which are fast and generic. Variation in fidelity is therefore based on the balance between, available information and time, versus, acceptable risk during design decisions (required accuracy to make a valid design choice). When you have all the time in the world, you will use the highest fidelity tools primarily depending on available information to perform a simulation. In practice, available time and acceptable risks will prioritise fidelity for each part of a simulation.

Being able to vary the fidelity of simulation tools during a simulation helps designers to prioritise accuracy of design aspects. It enables having many quick design variations with relatively low-fidelity simulation tools at the conceptual design stage, while having accurate high-fidelity simulations during design verification. Or, start a simulation at low fidelity, and increase fidelity using other simulation tools based on previous outcome. Or, simulate high-risk aspects at high fidelity while saving time on low-risk aspects using low-fidelity simulation tools.

For example, bridge simulators can be used during the requirement definition phase to investigate how to meet operational goals. Some models during the real-time simulation will be simplifications of high-fidelity tools (for instance an engine model), while other models may be very accurate (ship hydrodynamics). Fidelity will depend on the simulation goals. And input for this real-time simulation can be based on a first conceptual design using simulation tools in a variety of fidelity also used in the conceptual design following this requirement definition phase. Moreover, at some stage during such a simulation, the simplified models could be replaced with more high-fidelity tools or even the real components. For instance, performing a real-time simulation using the dynamic positioning consoles of a supplier, radar systems, or even real engines. And the bridge simulator can be used at a later stage to verify concepts in operational conditions.

Availability of information, tools and expertise plays an important role as well. You can only use the information and tools you have access to and know how to use. Ownership of information, tools and expertise is not required as long as access to information and tools is possible, with support by expert. This requires network communication to share and use data, tools and expertise; managing data consistency, dependencies and execution order of tools; and nd enabling experts to be part of the simulation steps adding required expertise when necessary.

Last but not least, 3D modelling and spatial arrangement become increasingly important with increasing fidelity and maturing design. A framework to incorporate all these aspects is not trivial. It puts specific requirements on the framework and the common information model, communication protocol, between all stakeholders.

The above ambitions require capabilities to perform (e.g. hydrodynamic) analyses and simulations with the highest possible fidelity during the earliest phases of ship design. This translates into the following technical needs:

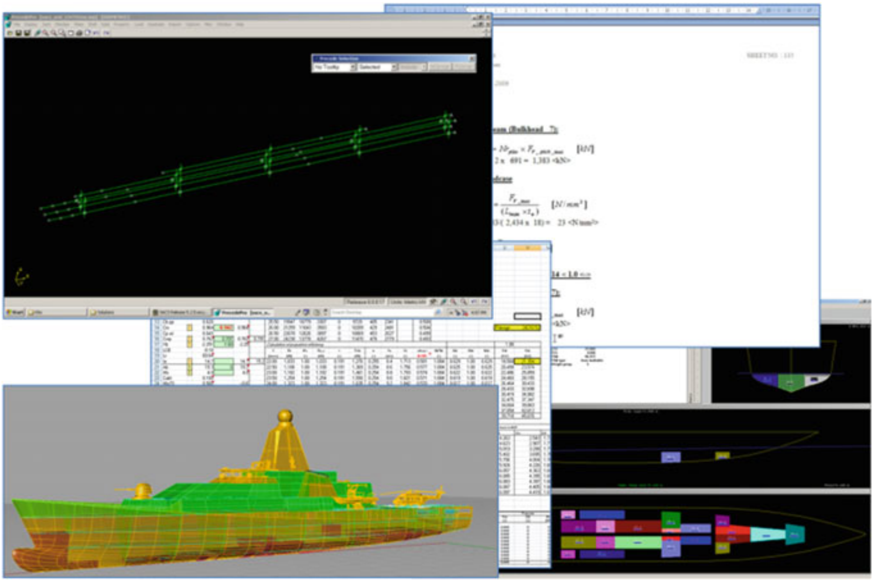

Fig. 15.1 Tools used in the early design stage

- To use and reuse existing tools and data from different sources
- To arrange analysis, simulation and design into streamlined processes
- To create processes that provide guidance and ease-of-use for complete chains of pre-processing, simulation and post-processing
- To perform data and calculation management in order to maintain data consistency reducing human errors.

These requirements are neither special nor new; there are many commercially available (ship design) tool suites and frameworks, which provide such capabilities. What is missing is connectivity between tools from different providers. This applies to tools used in the earliest stages of design, to hydrodynamic simulation tools and to engineering system simulation tools. In Fig. 15.1, a random selection of tools is shown which are used in early design. Interoperability between these tools is limited and virtually non-existent between tools of different organisations. In practice, information exchange between these tools is performed manually by means of scripting.

All challenges aside, being able to couple simulation tools and analysis of varying fidelity in a flexible way, will increase both efficient and effective decision making, achieving safer, cleaner and smarter ships.

However, integrating all necessary tools needed into one single system is unattractive from a maintenance and reusability point of view. Distributing tasks over different applications has two main advantages. First, using different applications enables concurrent design and engineering between geographically distributed team members. Secondly, the maintenance of different design disciplines can be divided over several domain experts. Hence, distributing different tasks over different applications avoids extensive and inflexible design and engineering suites, which are hard to maintain.

An important aspect of design and analysis tool development and interoperability is software standardisation. Standardisation in software development is a key to create tools that can be developed, maintained and used over longer periods of time. Examples of standardisation are coding standards, the layout of user interfaces, data representation of input and output, etc. Deeper forms of standardisation are related to the building blocks of software, software architectures and the use of frameworks such as A microsoft.net framework. Software developers are keen on searching and using similarities between tools and applications. Specialised environments appear on the market to exploit this quest. Examples are commercial building block methodologies like MATLAB\Simulink, but there are also many software providers who created proprietary architectures that fulfil the specific needs of their applications and clients. Examples are CAESES from Friendship Systems, GES by TNO and XMF and QUAESTOR by MARIN, being participants of HOLISHIP. These parties invested time, money and specialist knowledge in these frameworks for which the VVF will not be a drop-in replacement. Due to the high level of standardisation already present in these frameworks, single interfaces between each of these frameworks and the VVF are considered feasible.

15.3 Simulations in Concept Design

15.3.1 Introduction

One of the challenges in using simulation and analysis tools in the earliest stages of design is their need of geometric information as input. Depending on the fidelity of tools, input can range from simply a set of parameters up to detailed descriptions of the shape of hull and appendages. Before creating any geometric representation of a design concept, a study should be made of the design requirements on the basis of which the main dimensions are determined. The tools used in this process, if any, are mostly very specific for the trade or purpose of the vessel and are sometimes referred to as Concept Variation (Exploration) Model. A CEM/CVM contains low-fidelity versions of analysis tools and allows to search the design space for optimal design starting points.

15.3.2 Data Representation and Exchange

The simulation of ship systems requires information on components, their positions within the spatial arrangement and how they are interconnected. The efficient creation of hull shape and internal arrangement is a key activity before any useful simulation and analysis can be performed. For the purpose of creating hull shape and subdivisioning, many commercial solutions are offered, either based on general purpose CAD systems such as CATIA, AutoCAD or Rhinoceros^{TM}, or proprietary such as NAPA or PIAS. In practice, these tools are able to export geometric information in different formats, which can be used as input, e.g. FEM or CFD calculations. The creation of such input can be automated in a workflow, but frequently additional operations and checks on that data have to be implemented in order to make it suitable input for the simulations.

Apart from geometric input, simulation and analysis tools require operational information which in general is provided in parametric (tabular) form. Summarising, one of the key issues in using (advanced) simulation and analysis tools *is the earliest possible creation of a geometric representation of a design concept*. From this representation, preferably in some CAD system, it is possible to provide useful input to simulation and analysis tools. Most of the modern CAD systems contain an API or a scripting language (e.g. Python), by means of which data can be prepared and/or manipulated. Most interfacing between CAD and any other tools is dedicated and bilateral.

One of the primary reasons for 'bilateralism' in the interfacing between tools is the fact that there is no common understanding with regard to the way in which data objects are named and represented. One of the aims of the HOLISHIP project is to create a shared information model. In this way, it should become simpler to create interfaces between CAD and simulation tools. In Sect. 15.5.1, this is discussed in more depth. A relatively simple 'HOLISPEC' information model is proposed, which is tested in the following demonstration case.

15.4 Simulation in Design Verification

Increasingly real-time simulations guide our decisions in design and operation of ships. Simulation-based design verification in ship design aims to check if the created ship design meets the defined operational capabilities. Ship design starts with the question: 'what do we want to achieve?' So, what tasks does the ship have to perform under which operational conditions. Next, the impact on technical solutions has to be determined. The ship designer will deduce the design requirements from the operational requirements. Based on the design requirements, the designer will develop several (concept) designs to achieve the operational requirements. In order to achieve effective, feasible and affordable ships, numerous design variations and their performance and costs need to be assessed.

An integrated holistic ship design approach is needed to allow such design studies. In (early) ship design, tasks are performed by using a variety of computer applications and (real time) simulations that are not always available on the same computer or even within the same organisation. Often multiple specialists are involved in the design process using their proprietary tools. The components for successful simulation in design verification are modelling methods and computational tools, virtual reality environment, an infrastructure for collaborative engineering and integration technologies and tools.

Real-time simulations also allow the man in the loop evaluating the operational performance of ship designs. By using bridge simulators, a virtual environment becomes available by which complex ship and offshore operations can be simulated at different design stages, including human factors. Besides design verification of seakeeping and manoeuvring performance, also the environmental limits of hazardous operations can be assessed. Furthermore, real-time calculated hydrodynamic loads, velocities and accelerations can be input, e.g. strength analysis and the performance assessment of propulsion and energy systems. Section 15.3 gives an example of ship systems in ship design that are created and verified by GES simulation.

15.5 Available Tools and Frameworks

15.5.1 RCE and CPACS

Within HOLISHIP, it is proposed to use the remote component environment (RCE) platform as developed by DLR in Germany, mainly used in the aerospace industry (Seider et al. 2012, 2013). RCE is an environment to create distributed workflow solutions. RCE instances installed on different servers give access to selected tools installed on those servers. In Fig. 15.2, an example configuration is shown with two RCE clients, each in their company domain and an RCE host in the cloud on which a number of tools are installed as remote components. The companies A and B can use tools on the RCE host in the cloud as part of their proprietary tools via their own RCE client.

Workflows can be created in which a number of RCE nodes are involved. Data exchange between tools installed on RCE nodes exchange data meeting the CPACS XML schema (Common Parametric Aircraft Configuration Schema) for application

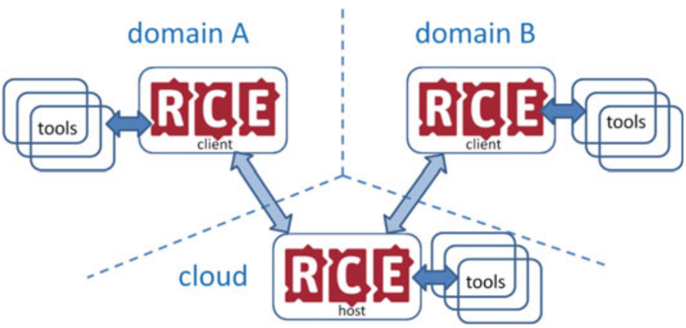

Fig. 15.2 Two companies sharing capabilities through RCE

in the aviation industry, cf. http://cpacs.de. One of HOLISHIP's ambitions is to develop an XML Schema (XSD) for the maritime domain (loosely) based on the design philosophy of CPACS. The starting point is that tools using a shared definition of the data types can be more easily connected.

The CPACS XSD contains a description of all the object types that are used to represent the components, their topological relationships and to some extent their relations. CPACS also forms a semantic network in which the relationships are not explicitly described although they can be understood. On the highest level, CPACS describes the vehicles, their use (missions), their physical environment (airports, flights), their economic environment (airlines), their (design) studies and the tools used in the design process.

Therefore, the CPACS XSD not only describes the types involved in aircraft design and analysis, it also provides the framework to organise the instances of all types in such way that it can be used to represent a fleet of vehicles in their operational environment. CPACS is a well-defined and mature XML schema of a complex domain, the purpose of which is to represent an aircraft product model with sufficient accuracy to represent input and output of simulation tools used in aircraft design and analysis.

Given the fact that CPACS is considered as a guideline to create a similar domain model for maritime applications, it was studied in detail, first by creating a taxonomy from CPACS. CPACS describes the domain by means of 957 complex types. The conversion of CPACS into a taxonomy yields a hierarchy of about 4750 instances of these complex types in which over 17.000 parameters (elements and required attributes) are present. Obviously, CPACS is a rich description of aircraft and analyses which comprises the needs of all tools and studies that are performed within the design process. In Table 15.1, the global structure of CPACS is presented.

15.5.2 Holispec

CPACS, as presented in the above-simplified structure, seems not to be that different from the general approach followed for large objects in the maritime industry. There are many ways to create a conceptual model of a complex artefact like an airplane or a ship. Such models attempt to create consensus about what the artefact is, how it is arranged and assembled, which are its properties and capabilities, etc. A higher-level goal is to allow concurrency, to exchange and share features of a concept/design between the relevant domains and parties active in the design (and manufacturing) process. Table 15.2 presents a proposal for a similar structure for maritime applications.

Conceptual models such as CPACS and the above proposal are rooted in the assumption that parties are prepared to adopt a shared vision on how an artefact should be conceptually modelled. There have been many attempts to achieve this in the past, and the need is real. ISO 10303 took 30 years to develop and is used in particular in the CAD community to exchange topological information in a neutral manner. The

Table 15.1 CPACS global structure

- CPACS
  - Header?
  - Vehicles
    - VehicleType
      - Positioning/reference?
      - Structure
        - Positioning/reference
        - Spatial Arrangement
        - Structural Assembly
        - Placement of Component keeping structure together?
        - Data Preparation for Analyses??
      - Large Components & Placement
      - Systems
        - Component functions and connections forming systems
        - Data Preparation for Analyses?
      - Secondary Geometric Objects & Placement
      - Global Particulars (Data Preparation for Analyses??)
      - Analyses
        - Data Preparation for specific Analyses
    - Geometry Database (geometric description of any physical object in any vehicle)
    - Components Database (description of any non-structural component in any vehicle (in CPACS only engines)
    - Structural Elements Database (description of any structural component in any vehicle)
    - Materials Repository (incl. fluids)
  - Vehicle Applications
  - Vehicle Management
  - Studies??
- CPACS

exchange of CAD data is a huge headache in the field, so ISO 10303 is created as a neutral representation with minimal information loss. This standard is informally known as 'STEP', which stands for 'Standard for the Exchange of Product model data'. The STEP-file (ISO 10303-21) is an implementation of the STEP standard that represents 3D object in computer-aided design (CAD) and related information. STEP tooling is proprietary, and the focus is primarily on the exchange of production-related information and not on data exchange in earlier stages of design. Although extremely important, STEP is less relevant to the conceptual design stage, where geometrical information is required by analysis tools that are used as decision support in the dimensioning of the concept and for the selection of major components. In recent years, also earlier stages of design are drawing the interest of the STEP community.

Holistic ship design requires a methodology by which we can represent and exchange data between analysis processes. Different analysis processes require different views on the (same) set of data which describes a design (concept), such as compartment oriented, surface oriented, system oriented and function oriented, cost oriented, production and assembly oriented. Analysis methods in the relevant domains will be in need of design data, which is organised in (maybe) one of the views mentioned. One problem with a modelling approach as adopted in CPACS is that the relations between the elements in the model are not explicit, it is interpretable

Table 15.2 'Maritime CPACS' global structure proposal

- HOLISPEC
  - Header?
  - Vessels
    - VesselType
      - Positioning/reference?
      - Structure
        - Positioning/reference (planes, points)
        - Surface-based spatial arrangement (decks, bulkheads, walls)
        - Compartment-based spatial arrangement (tanks, holds, cabins etc.)
        - Structural assembly
          - Surfaces (shell, divisions)
          - Component interfaces (foundations, ducts, piping?)
        - Data Preparation for Analyses??
      - Primary component positioning (propulsion, engines, cranes)
      - Systems
        - Components
        - Connections
          - Fluids and gasses
          - Energy
          - Data
        - Assembly
        - Data Preparation for Analyses?
      - Secondary Geometric Objects & Placement
      - Global Particulars (Data Preparation for Analyses??)
      - Analyses
        - Data Preparation for specific Analyses
    - Geometry database (hull lines, structural elements, components etc. in any vessel)
    - Structural components database (as defined in any vessel)
    - Non-structural components database (as defined in any vessel)
    - Component Repository ('static' data)
    - Materials and Fluids Repository ('static' data)
  - Missions
  - Vessel Management
  - Studies (design, concept variation)
- HOLISPEC

as 'part of', 'requires', 'consist of', etc. It is difficult to separate or incorporate the above views in a structure which explicitly defines a floor beam, rib, stringer, etc., as separate classes. It rightfully suggests that an aircraft should be assembled in a specific sequence and manner. This is workflow, the process of dimensioning choosing and piecing together a complex system from subsystems or components.

If we exchange information of the design concept, it should be relatively simple for the party performing design simulations to retrieve their 'input' or view from the design data. They will subsequently enrich the design data with behaviour which basically only exists in their realm. Communication with the other members of the community involved in the design is limited to specific results in which other domains are in need of. An example is the seakeeping behaviour from which to derive inertia forces and moments in a crane foundation for which data has to be passed from hydrodynamics to structure. Another example is propeller forces and moments to calculate shaft loads and vibrations or as input moment and revolutions to a diesel engine model.

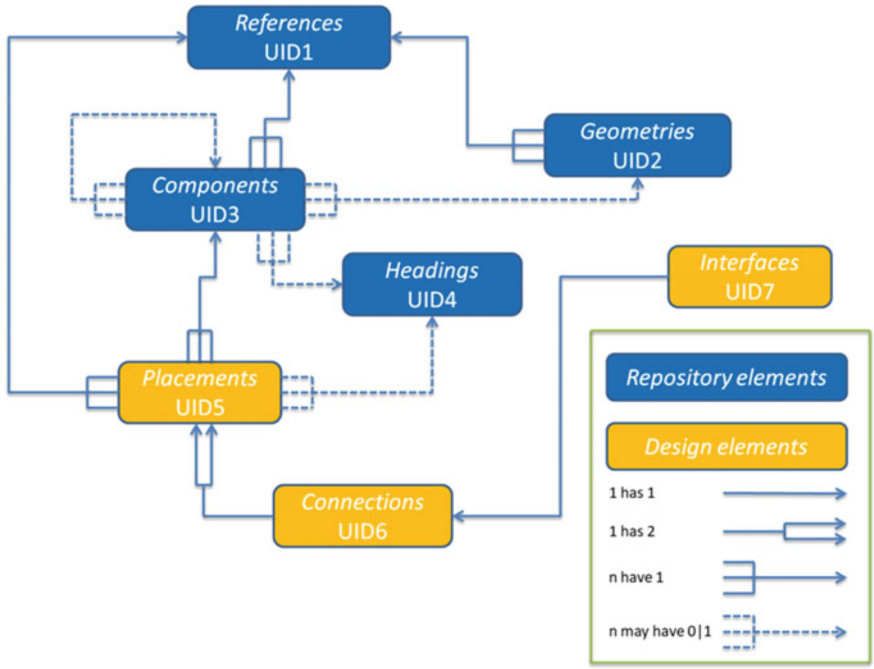

Fig. 15.3 HOLISPEC information model

Analysis and simulation tools need varying subsets of the information describing a design (views). Hydrodynamic tools' main focus of interest is the shape of the hull and appendages and operating conditions. Energy system design and analysis requires information about system components, connections and functions. Life cycle cost analysis needs information about components, maintenance, materials, cost factors, etc., so information partly originates from the design concept representation and partly from operational environment (the world). Hydrostatics and construction need spatial information, switching between a surface-based and compartment-based views.

In Fig. 15.3, an information model is presented with the least possible number of types which has been developed by the author by combining CPACS with results from earlier work by MARIN on Quaestor and XMF.[1,2]

The blue rectangles represent '*repository elements*' that can be declared once and used (referred to) many times. The orange rectangles represent '*design elements*', components that actually exist in the design. The HOLISPEC data model as proposed above consists of seven tables, each containing elements (instances) of one of the

[1]QUAESTOR, MARIN, http://www.marin.nl/web/Organisation/Business-Units/Maritime-Simulation-Software-Group-1/Software-Workflow-solutions/Quaestor.htm.

[2]XMF, MARIN, http://www.marin.nl/web/Organisation/Business-Units/Maritime-Simulation-Software-Group-1/Software-Workflow-solutions/XMF.htm.

seven types. From these tables, different views should be created on the basis of relatively simple query algorithms. The relations between the elements in the model are unidirectional: an **Interface** element 'knows' its **Connection** element; a **Connection** element does not know whether it is also an interface, this can only be found by querying Interfaces on its UID value. In the same manner, a **Placement** element does not know its **Connection**(s); these can only be found by querying *Connections* on its UID value. In order to find all system components, simply gather all **Connection** references from *Interfaces*, gather all **Placement** elements from these **Connection** references and remove double **Placement** elements by UID.

15.6 Applications and Case Studies

As it is already mentioned, virtual simulations can be applied throughout the design process of ships. The main focus of HOLISHIP is on applications in the concept testing and final demonstration phases. These two types of applications are discussed in more detail below.

15.6.1 Concept Testing

Concept testing encompasses testing of (sub) systems in the complete (simulated) working environment. These systems can be or contain new innovative solutions which need to be demonstrated to convince ship owners and operators to install the system on their vessel.

As testing of (sub) systems primarily focus on the working of those systems, these need to be modelled in the highest possible accuracy. Other components which do not directly influence the systems of interest still need to be simulated in order to allow for the complete ship operations modelled in a lower accuracy. This is called multifidelity simulations, coupling models of varying accuracy. The benefit of this is that models which are not directly in the centre of the simulations can be chosen to run faster, speeding up the total simulations.

For example, if the focus of simulations is on the dynamics of a main engine in frequently varying loads (as experience in a seaway), the main engine needs to be simulated in high fidelity. The varying loads can, however, be simulated using a low-fidelity simple sinusoid rather than a high-fidelity simulation of the added ship resistance in waves. If irregular waves are desired, any combinations of sinusoids can be used. This practice greatly speeds up the simulations, while the principle of the effect on the main engine remains the same.

In HOLISHIP, a concept testing demonstrator will be created. For a selected ship, two-rudder configurations will be designed. The hydrodynamic manoeuvring behaviour of both configurations will be calculated using HOLISPEC/RCE framework. By coupling these simulations to a bridge simulator, the human element is

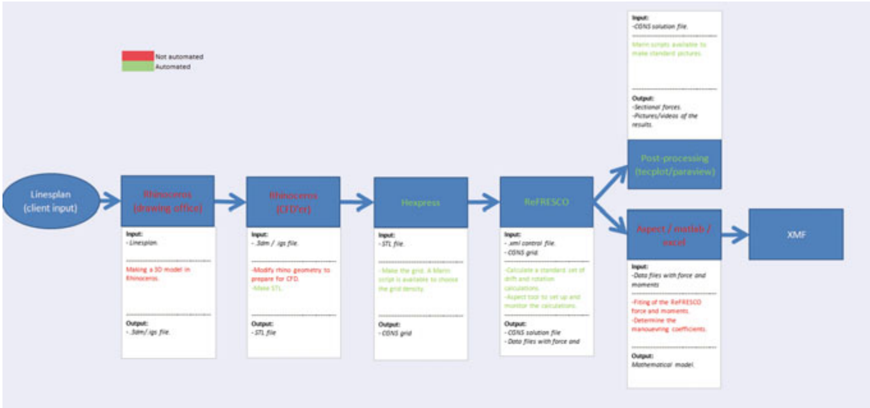

Fig. 15.4 Simulation flow for HOLISHIP demo

introduced in the design process. An experienced captain can sail in and out of various ports with both configurations and say which rudder configuration feels better for this ship in the selected ports. This human experience is put next to the traditional manoeuvring figures such as turning circles and zigzag behaviour to evaluate the rudder concept most suitable for the ship at hand.

For concept testing of the rudders, not all ship components have to be simulated and those simulated do not have to be simulated at the same level of fidelity and complexity. In the HOLISHIP demonstration case, the following components will be simulated:

- Hydrodynamic manoeuvring behaviour: high fidelity
- Hydrodynamic resistance and propulsion characteristics: medium or low fidelity
- Steering gear response: high fidelity
- Main propulsion engine: medium fidelity
- Bridge simulator: high fidelity.

As the calculation time for some components is slower than real time, use of response surfaces will be made. Figure 15.4 shows the planned simulation scheme for the HOLISHIP demonstration case.

A multidimensional response surface of the manoeuvring coefficients will be calculated for various speeds and rudder angles which are loaded in the bridge simulator. The speed–power relation will be calculated using a relatively simple method resulting in a speed–power curve which is loaded into the bridge simulator. Both the steering gear and the main propulsion engine will be connected to the real-time bridge simulator and the real-time behaviour of the captain.

15.6.2 Virtual Sea Trials

Validation of the design currently is done by sea trials after the ship has been built. Next to possible production errors, also design flaws may arise during the sea trials. Design flaws should preferably be identified earlier before production starts so that the design can still be improved. Virtual sea trials are the solution to this.

In virtual sea trials, compatibility of systems can be checked and simulated in real time. Design flaws can be checked using these simulations. Production errors cannot be prevented still leaving necessity for performing sea trials, although within a much reduced scope. Virtual sea trials will focus on validation of the performance such as the speed–power relation and manoeuvring performance. Wherever possible, hardware in the loop testing can be implemented with, for instance, the main engine on the test bed.

In order to perform virtual sea trials, high-fidelity simulation models need to be coupled. Accurate models are needed for this part of the simulation, which in turn more often than not result in a longer simulation time. Large calculation capacity is needed, also considering that results of some simulations may lead to re-calculating earlier simulations with the updated status of the vessel.

Application of hardware in the loop is not much different than having the human in the loop as given in the example on concept testing above. The challenge is that a real-time application is inserted in the simulation, which requires input and provides output aiming to be used in the simulations. By simulation framework developed in HOLISHIP (HOLISPEC/RCE), it is not possible to couple dynamic simulations. Hardware, or human factors, in the loop can only be performed by using response surfaces of the systems in direct connection to the real-time application. These response surfaces can be determined based on high-fidelity simulations, and dynamic effects between the systems can, however, not be simulated in this way. For this to be happen, coupled simulations are required.

15.6.3 Coupled Simulations

Coupled simulations go beyond the capabilities of HOLISPEC/RCE but are needed for future simulations. In coupled simulations, various tools can run at the same time and during the calculation can exchange information and status updates. Coupled simulations make it possible to also model the dynamic interactions between components. These kinds of simulations will also require a large computational power to have all the coupled simulations run at the same time.

The increased accuracy of coupled simulations with respect to the application of HOLISPEC/RCE make coupled simulations more applicable for virtual sea trials and hardware in the loop simulations. MARIN, amongst others, is working on coupled simulations for the hydrodynamic domain. The XMF framework is already capable of coupling various MARIN hydrodynamic tools.

15.6.4 Simulations in Concept Design: A Case Study

In order to demonstrate the feasibility of exchanging design data using the information model as introduced in Sect. 15.5, a conceptual design tool is envisaged in which:

(1) the shape of the hull, appendages and propulsor(s) are described as well as the internal subdivisioning
(2) the primary components are placed as well as of payload items sufficient to perform preliminary weight estimation
(3) the geometric information is available to perform hydrodynamic analyses (resistance and propulsion, seakeeping and manoeuvring)
(4) and integrates with ship system design and simulation in TNO/GES.

Geintegreerde Energie Systemen or General Energy Systems (GES) is an engineering system simulation tool suite developed by TNO in the Netherlands (van Vugt et al. 2016). GES is and has been used in a variety of applications and R&D projects, amongst other EU projects like RETROFIT, JOULES, ULYSSES and INOMANSHIP.[3,4,5,6]

Within HOLISHIP, it is intended to use data from either the DAMEN Combi Freighter (Fig. 15.5a) or the Liquefied Gas Carrier (Fig. 15.5b).

The internal arrangement is created in Rhino in the COSMOS workflow (**CO**mpositional **S**hip **MO**delling **S**cheme). COSMOS is based on a workflow which is developed since 2015 by MARIN in cooperation with the Royal Netherlands navy as an accurate ship and submarine space partitioning and weight management methodology to be used in conceptual design. In van Hees and van den Broek-de Bruijn 2018, further details are provided. COSMOS provides a 3D design environment by a merger of knowledge-based systems and workflow technology (Quaestor3) with the CAD system Rhinoceros™. The workflow has been, at least in part, designed according to the data modelling principles introduced in Sect. 15.5.2.

GES on the other hand is used to create and verify ship systems through simulation in operational conditions. As a consequence, all major system components and their connections will be defined in GES prior to performing any system simulation. As a case study, it was considered feasible to integrate the process of ship systems design with the naval architectural design, as all connections and components will be defined in GES. GES is based on (generic) system diagrams and deals with the selection, connection and modelling of components by which working compositions are created. GES comprises an extensive library of system components and subsystems

[3]RETROFIT: Retrofitting ships with new technologies for improved overall environmental foorptint, http://www.retrofit-project.eu.

[4]JOULES: Joint Operation for Ultra Low Emission Shipping, http://www.joules-project.eu/Joules/index.xhtml.

[5]ULYSSES: Ultra Slow Ships, https://cordis.europa.eu/result/rcn/156322_en.html.

[6]INOMANSHIP: Innovative Energy Management System for Cargo Ships, https://cordis.europa.eu/result/rcn/185049_en.html.

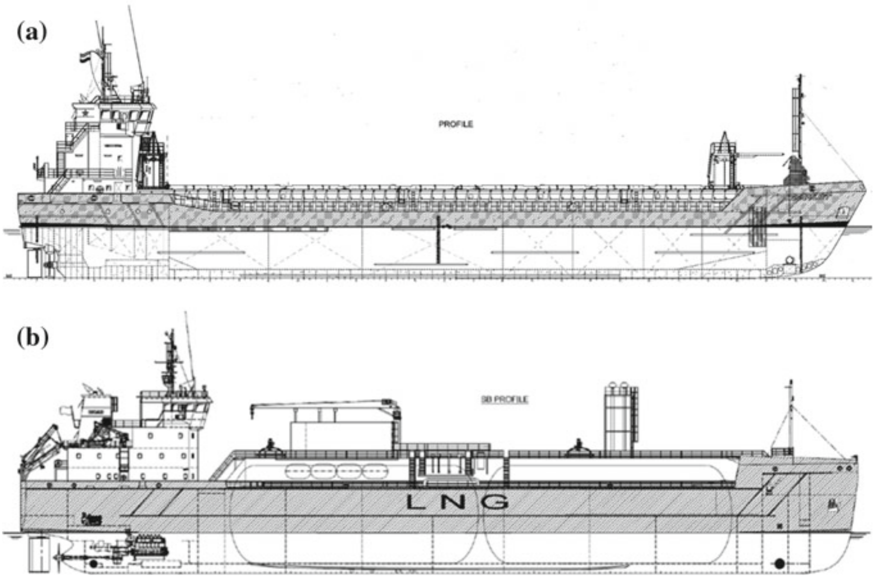

Fig. 15.5 **a** DAMEN Combi freighter 3850, courtesy DAMEN Shipyards, **b** DAMEN Liquefied gas carrier 7500 LNG, courtesy DAMEN Shipyards

from which systems can efficiently be configured. Simulations can subsequently be performed on the basis of which components and connections can be sized.

In Fig. 15.6, an example GES model is shown which is used in this case study. COSMOS on the other hand deals with the spatial layout, the placement of components, weight management, hydrostatics and hydrodynamic behaviour etc.

In order to exchange information between these two processes, the first is to create an information model for GES based on the one presented in Fig. 15.5. A few iterations are required to create a workable information model in the form of an XML schema describing most of the relevant types and properties in about 90 lines. The model is recursive since any component may exist of a composite of other components and is based on the proposed HOLISPEC information model that is introduced in Sect. 15.5.2.

A GES simulation model can then be exported as XML according to the scheme as referred to above and imported in COSMOS, either through RCE or immediately. From this dataset, COSMOS creates all system components in the vessel's topological model on the initial locations available in the GES model, either based on geometry data received from GES or based on scaled geometric primitives (cabinets, pumps, e-motors diesels, etc.). This allows the naval architect to import system components on the basis of a (running) simulation model and to (re)arrange them in such way that constraints with regard to space allocation, construction and maintenance are met. As all components are identified with a unique (128 bits) number, any new position can be posted to GES to update its simulation model, e.g. taking into account the new

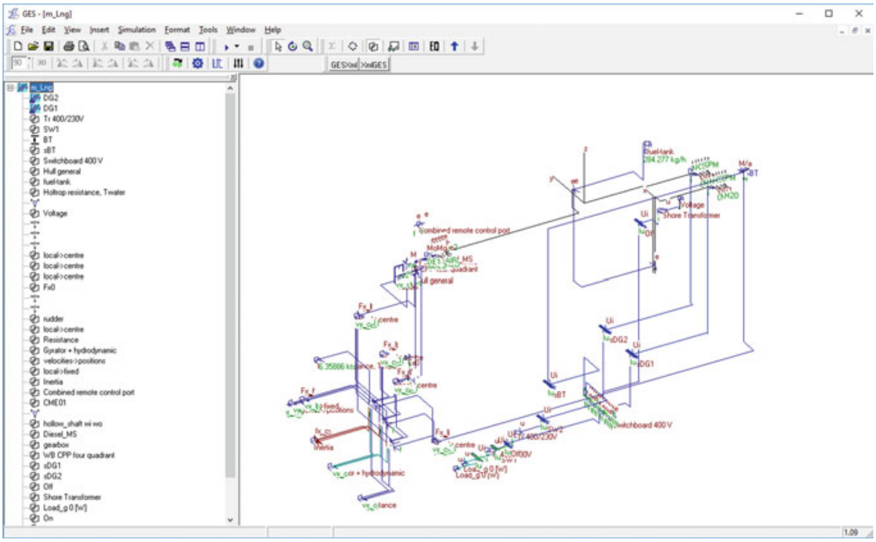

Fig. 15.6 Example screen dump GES model

position and its implications on the connections (heat loss, pipe/cable resistance, etc.). The presence of the components and connections in the 3D model provides input to the calculation of mass and hydrostatics and to the cost estimation.

In this way, a shortcut is created between systems engineering and naval architecture which improves efficiency and accuracy of the conceptual design process. It is a clear example of interoperability between two important disciplines in conceptual ship design and the role of information modelling in its creation.

This example of interoperability requires for each of the disciplines an expert in the loop which makes it rather peer-to-peer integration than workflow. RCE is primarily designed to perform sequences of data-driven calculation jobs of which input and output data are flowing through the RCE nodes. For parts of the process, this may be the case; some of the hydrodynamic prediction tools may be used in that way. However, judgment of the results may require an expert (designer) in the loop. Although RCE workflows are generally not designed as such, it is possible to set it up it for this purpose.

From the result of uploading a GES model as shown in Fig. 15.7, it is obvious that the components in the simulation model are not positioned in realistic locations. Also, the components are still represented by simple DXF models which do not represent the actual component geometry. Given these current limitations, in Rhino through COSMOS, it is possible to move the components around, while their connections are continuously updated. Figure 15.8 shows the result of a rearrangement of the components in the above system.

Once a federation is established between GES and COSMOS, the system components and their connections exist within COSMOS. Any changes made to the

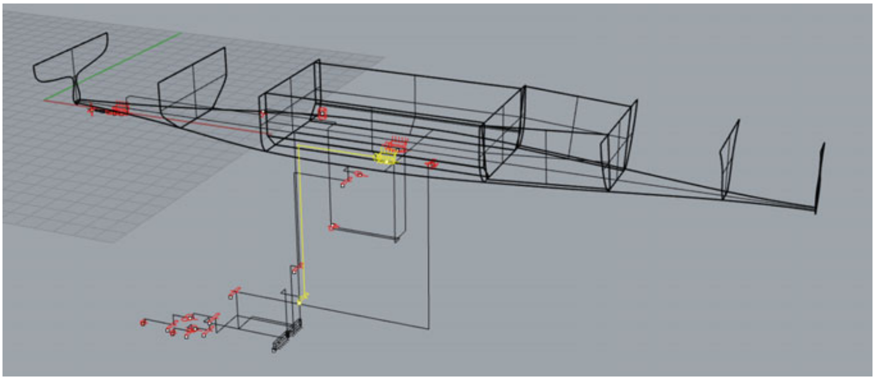

Fig. 15.7 GES model uploaded in COSMOS, screen dump

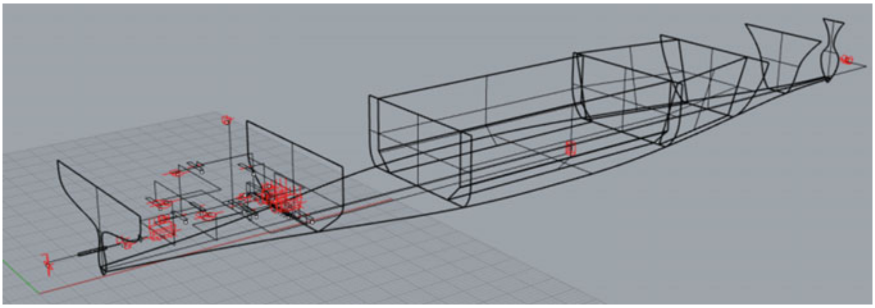

Fig. 15.8 Rearranged GES model uploaded in COSMOS, screen dump

COSMOS arrangement will be forwarded to GES through RCE after which the GES simulations can be repeated. COSMOS should provide GES with updates of performance curves once they are updated. In a similar way, COSMOS can provide GES with operational profiles to generate systematic data of diesel and propulsor response which can be reused in a bridge simulator to mimic an engine model. As each simulation model (subsystem and system component) will have a unique 128 bit ID, a federation (through RCE) can be recreated based on stored data on both sides.

The approach to compositional modelling in the early stages of ship design as provided by COSMOS teaming up with a systems engineering simulation tool like GES is attractive, in particular for weight critical designs. Weight management and hydrostatics can be updated after any change in the systems arrangement. Although routing of the connections is currently only orthogonal in COSMOS, estimates of connection lengths will be fairly accurate. Connections can be dimensioned on the basis of results from GES, and their contribution to weight and COG can be added to the workflow.

15.7 Conclusions and Way Ahead

With the development of HOLISPEC/RCE in the HOLISHIP project, significant steps have been made into distributed simulations. This is an essential part of improved collaboration in ship design. Rather than needing all required simulation tools on the same network like state-of-the-art design frameworks do, HOLISPEC/RCE allows to connect safely over the Internet. This opens up the possibility to share the access to simulation tools without having the share the tool or the IPR in the tool.

Using the HOLISPEC/RCE framework, ship designs can be integrally simulated with specialist tools from specialist partners. With this new innovative design, solutions can be tested and demonstrated in quick way. Some of these tools connected to the framework have internally other tools running in co-simulation. The RCE framework itself does not allow for co-simulation.

With some tools capable of co-simulation and some tools capable of distributed, the next step is to allow for distributed co-simulation over the Internet. This adds complexity as the tools should be integrated more thoroughly than only input and output. Also, the speed of the connection through the Internet needs to be sufficient to allow for this interaction. Although these are large steps, this is the way ahead beyond the HOLISHIP project.

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Terminology of Some Used Important Notions

Attained subdivision index A	The attained subdivision index, A, is a measure for the probability of survival of a ship in case of a statistically probable damage (SOLAS Convention). It should be less than the so-called required subdivision index, R, which is the minimum value for the attained subdivision index A and represents a generally accepted (imposed in regulations) survival level for the ship under consideration, corresponding to her size and the number of people onboard exposed to the collision hazard. Thus, through the direct comparison of A and R of a ship, her level of relative safety with respect to her survivability in case of collision is established
Constraints	Constraints in ship design optimisation refer to 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), e.g. minimum metacentric height above ship's mass centre (GM) or maximum oil outflow index (OOI). The safety constraints may be extended by a second set of criteria characterised 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 optimisation problem and may be assessed on the basis of probabilistic assessment models
Design optimisation	The selection of the best solution out of many feasible ones on the basis of a criterion (single-objective optimisation), or rather a set of criteria multi-objective optimisation)
Design parameters	This refers to a list of parameters (vector of design variables) characterising the design under optimisation; for ship design

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A. Papanikolaou (ed.), *A Holistic Approach to Ship Design*,
https://doi.org/10.1007/978-3-030-02810-7

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	this includes ship's main dimensions, unless specified by the shipowner's requirements (length, beam, side depth, draught) and may be extended to include the ship's hull form, the 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 optimised
Inherent ship functions	*Inherent ship functions* (or functionalities) are those related to the carriage/transport of certain payload (for cargo carrying ships), namely ship's hull including superstructures, and to the transfer from port A to port B with certain speed, which requires the disposal of certain engine power/propulsion unit and required amount of fuel in ship's tanks
Payload ship functions	For cargo ships, the *payload functions* are related to the provision of cargo spaces, cargo handling and cargo treatment equipment. Likewise for passenger ships, the payload functions are trivially referring to the provision of passenger accommodation and public spaces
Heuristic methods	Methods based on the knowledge gained through a process of trial and error, often over the course of decades
Holism	from Greek «όλος», meaning entire, total; *holism and reductionism* need, for proper account of complex systems, to be regarded as complementary approaches to system analysis
Holism principle	(according to *Aristotle*, Metaphysics): The whole is more than the sum of the parts, namely the synthesis of parts and their functions are altered through interaction and this is reflected in the whole
Optimisation input data	In ship design optimisation, this includes first 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). The input data set may include besides numerals of quantities also more general types of knowledge data, like drawings (of the ship's general arrangements) and qualitative information that needs to be properly translated for inclusion in a computer-aided optimisation procedure
Optimal ship	The optimal ship with respect to her whole life cycle is the outcome of a holistic optimisation of the entire ship system for its life cycle
Optimisation	The identification of the best out of a series of generated feasible options
Optimisation criteria or objective functions	This refers to a list of mathematically defined performance/efficiency indicators that may be eventually

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	reduced to an economic criterion, namely the profit of the initial investment. Independently, there may be optimisation criteria (merit or objective functions or goals) that are formulated without direct reference to economic indicators; see, e.g., optimisation studies for a specific X ship function, like ship performance in calm water and in seaways, ship safety, ship's strength including fatigue. The ship design optimisation criteria are, in general, complex nonlinear functions of the design parameters (vector of design variables) and are, in general, defined by algorithmic routines in a computer-aided design procedure
Optimisation of ship design in a holistic way	The multi-objective optimisation of ship design considering *simultaneously* all (holistically) design aspects of the ship system and for the entire ship's life cycle. It is achieved by addressing and optimising several (in a bottom-up approach) and gradually all aspects of ship's life (or all elements of the entire ship's life-cycle system), at least the stages of design, construction and operation; within a holistic ship design optimisation, we should herein also understand exhaustive multi-objective and multi-constrained ship design optimisation procedures even for individual stages of ship's life (e.g. conceptual design) with least reduction of the entire real problem
Optimisation output	This includes the entire set of design parameters (vector of design variables) for which the specified optimisation criteria/merit functions obtain mathematically extreme values (minima or maxima); for multi-criteria optimisation 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
Pareto set of solutions	A set of feasible solutions of a multi-objective optimisation problem for which improvement for one objective cannot be achieved without worsening of at least one other objective. Thus, instead of a unique solution, a multi-objective optimisation problem has (theoretically) infinite solutions, namely the Pareto set of solutions. There are decision-support methods enabling the rational assessment of the Pareto solutions according to the decision-maker's preferences, e.g. by use of the so-called utility function's technique
Reductionism principle	The 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, like shop design

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Required subdivision index R	The required subdivision index, R, is the minimum required value for the attained subdivision index A and represents a generally accepted (imposed in damage stability safety regulations, SOLAS) survival level for the ship under consideration, corresponding to her size and the number of people onboard exposed to the collision hazard
Risk (financial)	The likelihood of loss or of less-than-expected returns
Risk (general)	The likelihood of loss of an acceptable state or of a worse-than-expected state condition
Safety	A societally acceptable state of risk
Survivability (of a ship)	In engineering, survivability is the quantified ability of a system, subsystem, equipment, process or procedure to continue to function during and after a natural or man-made disturbance; a ship's survivability may be defined as the ability of the ship to continue to function after an environmental disturbance (e.g. effect by seaway) or a damage to her hull or equipment caused by collision, grounding or weapon impact (naval ships)

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