Apostolos Papanikolaou *Editor*

A Holistic Approach to Ship Design

Volume 2: Application Case Studies

Springer

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ISBN 978-3-030-71090-3 ISBN 978-3-030-71091-0 (eBook)
https://doi.org/10.1007/978-3-030-71091-0

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

The present book is the 2nd volume of the HOLISHIP project book that complements the 1st published volume: Papanikolaou, A. (ed), A Holistic Approach to Ship Design, Vol. 1: Optimisation of Ship Design and Operation for Life Cycle, SPRINGER Publishers, ISBN 978-3-030-02809-1, January 2019. The book derives from the knowledge gained in the second phase of the project HOLISHIP (http://www.holiship.eu).

HOLISHIP is a Large-Scale Project under the Horizon 2020 Transport Research programme of the European Commission (Contract Number 689074) in which 40 European maritime industry and research partners[1] joined forces to develop the next generation of a ship design software system for the needs of the European maritime industry. The book focuses on applications of developed methods and tools to a series of case studies and outlines, in addition, the outcome of two additional EU funded Horizon 2020 research projects related to ship design, namely, the projects SHIPLYS and LINCOLN.

The book is introduced by a brief review of the HOLISHIP project activities in Chap. 1 by the project manager, *Dr. Jochen Marzi* (HSVA). An elaboration of the tools integrated into the HOLISHIP platform CAESES® for the application case studies is presented by *Dr. Stefan Harries* and *Claus Abt* (Friendship Systems) in Chap. 2. The optimisation of the design and operation of an Offshore Support Vessel (OSV) is presented by *Sverre Torben* (Kongsberg Maritime), *Martijn de Jongh* (Kongsberg Maritime) and their team in Chap. 3. Light weight design issues of cruise vessels are presented in Chap. 4 by *Arthur-Hans Thellmann* (Meyer Werft), *Tim Schouwer* (Meyer Werft), *Wibke Mayland* (CMT) and *Santiago Ferrer Mur* (CMT). In Chap. 5, the design for maintainability of the engine system of a research vessel is elaborated by *Chiara Notaro* (CETENA), *Prof. Paola Gualeni* (University of Genoa), *Matteo*

[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 Universuty of Athens-Ship Design Laboratory, Kongsberg Matitime AS, Sirehna, SMILE FEM, Starbulk, TNO, TRITEC, Uljanik Shipard, Univ. Genoa, Univ. Liege, Univ. Strathclyde, van der Velde, IRT-Systemx.

Maggioncalda (Fincantieri) and *Carlo Cau* (CETENA). The concept and contract design of a multi-purpose ocean vessel is elaborated in Chap. 6 by *Romain Le Néna* (Naval Group), *Julien Calvignac* (Sirehna) and *Alan Guégan* (Sirehna). The virtual vessel mockup for the simulation of the maneuvering of a cargo ship is elaborated in Chap. 7 by *Patrick Hooijmans* (MARIN) and his colleagues. In Chap. 8, the hydrodynamic optimisation of a containership and a bulkcarrier, as well as the presentation of a weather routeing system is presented by *Prof. George Zaraphonitis* (NTUA), *Aggeliki Kytariolou* (NTUA), *George Dafermos* (NTUA), *Scott Gatchell* (HSVA) and *Anders Östman* (SINTEF). Chapter 9, co-authored by *Dr. Chara Georgopoulou* (DNV-GL), *Lefteris Koukoulopoulos* (DNV-GL) and *Dr. George Dimopoulos* (DNV-GL), deals with applications of COSSMOS® software system to the optimisation of marine energy systems and retrofitting solutions. Chapter 10, co-authored by *Justice Anku-Vinyoh* (Elomatic Oy) and his team, is dealing with the concept design of a gravity base foundation for an offshore platform operating in icy shallow waters. In Chap. 11, the optimisation of a conventional and an advanced engine/propulsion technology RoPAX design are elaborated by *Dr. Cantekin Tuzcu* (TRITEC), *Cameron Dinsdale* (TRITEC*), Jack Hawkins* (TRITEC), *Prof. George Zaraphonitis* (NTUA) and *Fotis Papadopoulos* (NTUA). In Chap. 12, the design of a double ended ferry is elaborated by a team led by *Markus Jokinen* (Elomatic Oy) and his team. Chapter 13 by *Ujjwal Bharadwaj* (TWI Ltd) outlines the essential outcome of EU funded design project SHIPLYS (Ship Life Cycle Software Solutions): Concept for Ship Newbuilding and Retrofitting Bids. Finally, Chap. 14 by *Brendan P. Sullivan* (Politecnico di Milano), *Monica Rossi* (Politecnico di Milano) and *Prof. Sergio Terzi* (Politecnico di Milano) deals with an outline of the EU funded design project LINCOLN (Lean Innovative Connected Vessel). The book is complemented by a glossary/list of acronyms and a comprehensive list of references.

Editor of the book's material is *Professor Apostolos Papanikolaou* (HSVA/NTUA), assisted by *Mrs. Aimilia Alissafaki* (NTUA).

The target readership of this book is engineers and professionals in the maritime industry, researchers and post-graduate students of naval architecture, marine engineering and maritime transport university programs. The book closes a gap in the international literature, as no other books are known in the subject field covering comprehensively the complex subject of holistic ship design and multiobjective ship design optimisation for life cycle, both from the point of view of methods and tools (Vol. I), as well as by comprehensive application studies led by the European maritime industry (Vol. II).

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.

The present book does not aim to be a textbook for post-graduate studies in naval architecture and related disciplines, 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.

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 contributed to the book's material. As editor of this book, I am indebted to all authors of the various book chapters reflecting their long-time research and rich expertise in the field. Also, the contributions of the whole HOLISHIP partnership to the presented work are acknowledged. Last but not least, the funding by the Horizon 2020 Programme of the European Commission (DG Research), Contract Number 68907, is acknowledged.

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December 2020

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About the Editor

Prof. Dr.-Ing. Habil. Apostolos Papanikolaou studied Naval Architecture & Marine Engineering at the Technical University of Berlin (Germany). He is Professor Emeritus of the National Technical University of Athens (NTUA, Greece) and Visiting Professor of the University of Strathclyde (United Kingdom). He was Director of the Ship Design Laboratory of NTUA for more than 30 years and was also Senior Scientific Advisor of the Hamburg Ship Model Basin (HSVA, Germany) for the period of the HOLISHIP project. He headed more than 75 funded research projects and is author/co-author of over 640 scientific publications dealing with the design and optimization 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, amongst 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 (RINA), Fellow of the Society of Naval Architects and Marine Engineers (SNAME), Schiffbautechnische Gesellschaft (STG), Distinguished Foreign member of the Japanese Society of Naval Architects and Ocean Engineers (JASNAOE) and International Vice President of SNAME.

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Abbreviations

ν-Shallo	Non-linear potential flow code for wave resistance analysis of ships in calm water by HSVA
2D	Two-dimensional
3D	Three-dimensional
AC	Air Conditioning
AC	Alternating (electric) Current
AC	Application Case
AES	Atlantec Enterprise Solutions GmbH, Germany
AHC	Active Heave Compensated
AHTS	Anchor Handling Tug Supply
AI	Artificial Intelligence
ANN	Artificial Neural Networks
AP	Acidification Potential
API	Application Programming Interface
AS2CON	Alveus L.L.C, Croatia
ASCII	American Standard Code for Information Interchange
ATD	Astilleros de Sandander SA, Spain
B2B	Business-to-business relationship
B2C	Business-to-customer relationship
BHD	Backhoe dredger
BIM	Building Information Modelling
BMS	Battery Management System
BMT	BMT Group Ltd, UK
BRep	Boundary representation
BuDa	Bubble Diagram (architecture diagram tool of SIREHNA)
BV	Bureau Veritas, France
C++	Object-oriented computer-programming language
CABIN	TNO Software Tool
CAD	Computer Aided Design
CADMATIC	Marine design software by CADMATIC, The Netherlands
CAE	Computer Aided Engineering

CAESES®	Computer Aided Engineering (CAE) System Empowering Simulation by FRIENDSHIP SYSTEMS AG, Germany
CairnBuilder	Continuous integration tool (part of SAR management tool of SIREHNA)
CAPEX	CAPital EXpenditures/EXpenses
CASD	Computer Aided Ship Design
CAx	Acronym for various Computer Aided solutions for design, simulation, engineering etc.
CCT	Cost Calculation Tool
CED	Cumulative Energy Demand
CEM	Concept Exploration Model
CFD	Computational Fluid Dynamics
CI	Continuous Integration
CMT	Center of Maritime Technologies GmbH
CNR	National Research Council of Italy
CODAD	Combined Diesel and Diesel
CODLAD	Combined Electrical and Diesel
CoP	Coefficient of Prognosis
COSSMOS®	COmplex Ship Systems MOdelling and Simulation by DNV GL, Greece
CP	Controllable Pitch
CPACS	Common Parametric Aircraft Configuration Schema of DLR
CPP	Controllable Pitch Propeller
CPU	Central Processing Unit
CRN	Comfort Rating Number
CSG	Constructive Solid Geometry
cST	CentiStokes: unit of kinematic viscosity = 1 mm^2/sec
CVM	Concept Variation Model
DAD	Diesel and Diesel
DC	Direct (electric) Current
DE-ferry	Double-ended ferry
DF	Dual Fuel (engine)
DG	Diesel Generator
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Research Center)
DMT	Design Management Tool
DMU	Digital Mock Up
DoE	Design of Experiment
DP	Dynamic Positioning
DP2	Dynamic Positioning at harsh weather
DTD	Document Type Definition
DWT	Deadweight [ton]
DXF	Drawing Interchange Format (file)
EC	European Commission
ECAs	Emission Control Areas

EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EERV	Emergency Response and Recovery Vessel
EP	Eutrophication Potential
ESS	Energy Storage System
EU	European Union
FEM	Finite Element Method
FERG	Ferguson Marine Engineering Ltd, UK
FFD	Free-form Deformation
FMI	Functional Mockup Interface
FMU	Functional Mockup Units
FOC	Fuel Oil Consumption
FPM	Fully-parametric Modelling/Fully-Parametric Model
$FreSCo^+$	RANSE solver by HSVA and Technical University Hamburg-Harburg
FRP	Fibre-Reinforced Polymers
FRU	Fuel from sludge Recovery Unit
GA	General Arrangement
GA	Genetic Algorithm
GBF	Gravity base foundation
GES	General Energy System software tool of TNO
GITLAB	Open source Software development management tool
GMt_0	Initial transversal Metacentric Height
GNSS	Global Navigation Satellite Systems
GRIF	GRaphical Interface for reliability Forecasting (RAM tool by Satodev)
GUI	Graphical User Interface
GWP	Global Warming Potential
GZ	Righting Arm (stability)
H2	Hydrogen
HC	Heavy Consumer
HFO	Heavy Fuel Oil
HILLTOP	High level topology
HOLISHIP	HOLIstic optimisation of SHIP design and operation for life cycle (EU H2020 project)
HPC	High Performance Computing
Hs	Significant wave height
HSB	Hochschule Bremen (University of Applied Sciences), Germany
HSVA	Hamburg Ship Model Basin, Germany
html	Hypertext Markup Language
iges (igs)	Graphics Exchange Specification file for exchange of geometry data
IMO	International Maritime Organisation
IMU	Inertial Measurement Units
INM	Institute of Marine Engineering

IoT	Internet of Things
IPR	Intellectual Property Rights
ISO	International Standards Organisation
IST	Instituto Superior Tecnico, Portugal
KbeML	Knowledge Based Engineering Modelling Language
KM	Distance from Keel to Metacentre
KPI	Key Performance Indicator
L_{BP}	Length between perpendiculars [m]
LCA	Life Cycle Assessment
LCB	Longitudinal position of Centre of Buoyancy
LCC	Life Cycle Cost
LCCA	Life Cycle Cost (LCC) analysis
LCF	Longitudinal Centre of Flotation
LCPA	Life Cycle Performance Assessment
LDM	Lean Design Methodology
LFO	Light Fuel Oil
LHS	Latin Hypercube Sampling
LINCOLN	Lean Innovative Connected Vessels (EU H2020 project)
LNG	Liquid Natural Gas
L_{OA}	Length over all [m]
Lpp	Length between perpendiculars [m]
LR	Lloyd's Register EMEA IPS, UK
LSMDO	Low Sulphur Marine Diesel Oil
LTF	Lean Transformation Framework
M&R	Maintenance and Repair
MARIN	Maritime Research Institute Netherlands
MARPOL	International Convention for the Prevention of Pollution from Ships
MBB	Main Bus Bar
MBSE	Model-Based Systems Engineering
MCDA	Multi Criteria Decision Support Analysis
MCR	Maximum Continuous Rating
ME	Main Engine
MEPC	IMO Marine Environment Protection Committee
MI	Maintainability Index
MOGA	Multi-objective Genetic Algorithm
MPOV	Multi-Purpose Ocean Vessel
MPSET	Marine Power System Evaluation (tool of KONGSBERG)
MRT	Mean Repair Time
MTBF	Mean Time Between Failures
MTBM	Mean Time Between Maintenance
MTTR	Mean Time To Repair
NAPA®	Naval Architecture Package for ship design by NAPA Oy, Finland
NEWDRIFT+	3d potential flow, panel code for seakeeping, drift and added resistance analysis of ships and floating structures by SDL- NTUA, Greece

NiAlBr	Nickel-Aluminium Bronze (Propeller material)
NM	Nautical Mile
NMVOC	Non-Methane Volatile organic Compound
NOx	Nitrogen Oxide
NPV	Net Present Value
NSGA	Non dominated Sorting Genetic Algorithm
NSGA II	Non-sorting Genetic Algorithm (also NSGA 2)
NTUA	National Technical University of Athens, Greece
NURBS	Non-uniform Rational B-Spline curve/surface
OPEX	Operational Expenditures—Operating Cost
OSV	Offshore Support Vessel
PAX	Passenger Number
PBS	Product Breakdown Structure
PE	Polyethylene
PET	Polyethylene Terephthalate
PIDO	Process Integration and Design Optimization
PIR	Polyisocyanurate
Platform	Assembly of disparate systems and tools that are integrated in order to work with each other
PLM	Product Life cycle Management
PM	Particulate Matter, total suspended particles
PMS	Power Management System
PMT	Project Management Platform
png	Portable Network Graphics (file)
POD	Pitch propeller mounted on a steerable gondola
PoE	Power-over-Ethernet
PPM	Partially-parametric Modelling/Partially-parametric Model
PPT	Production Planning Tool
PTO	Power Take Off
QFD	Quality Function Deployment
R&D	Research and Development
R&I	Soil Replacement & Caisson Infilling
RAM	Reliability, Availability and Maintainability
RANS	Reynold Averaged Navier-Stokes
RANSE	Reynolds-averaged Navier-Stokes equations
RAO	Response Amplitude Operator
RAPID	Non-linear potential flow code for wave resistance analysis of ships in calm water by MARIN
RBF	Radial Basis Function
RCE	Remote Component Environment by DLR
RFR	Required Freight Rate
RIT	Requirement Identification Tool
RNPV	Required Net Present Value
ROI	Return On Investment
RoPAX	Passenger ferry with roll-on/roll-off cargo (mainly trucks and cars)

RS	Response Surface, (for setting-up surrogate model)
RSET	Rapid Ship Evaluation Tool
RSM	Response Surface Model or Response Surface Methodology
R'W	Apparent Sound Reduction Index
RW	Sound Reduction Index
S&R	Search and Rescue
SAC	SHIPLYS stakeholders Advisory Committee
SAR	System Architecture and Requirement tool of SIREHNA
SBC	Single Board Computer
SBCE	Set-Based Concurrent Engineering
SC	Sensitivity Case
SCP	Sustainable Consumption and Production
SDD	Simulation-Driven Design
SDL	Ship Design Laboratory of NTUA
SE	System Engineering
SEASAFE®	Stability calculation tool of Lloyds Register
SEECAT®	Ship Energy Efficiency Calculation and Analysis Tool of BV
SEEMP	Ship Energy Efficiency Management Plan
SFOC	Specific Fuel Oil Consumption
ShipBuilder	General layout sketching tool (part of SAR management tool)
SHIPFLOW®	Ship Flow resistance calculation tool (software by FLOWTECH)
SHIPLYS	Ship Life Cycle Software Solutions (EU H2020 project)
ShipX	A comprehensive workbench by SINTEF Ocean, Norway, containing a variety of marine hydrodynamic analysis tools
SINTEF	SINTEF Ocean
SLD	Single Line Diagram
SME	Small and Medium-sized Enterprise
SOBOL	Sobol Sampling Method for DoE
SOC	State of Charge
SOERMAR	Fundacion Centro Technologies, Spain
SOLAS	Safety of Life at Sea
SS X	Sea State X
SSI	Soil-structure-interaction
STEP	Standard for The Exchange of Product
stl	STereoLithography (file) for exchange of geometry data by means of tri-meshes
SysML	Systems Modelling Language
T&I	Transportation and Installation
TEU	Twenty Feet Equivalent Unit (container)
TSP	Total Suspended Particles
TWI	TWI Ltd, UK
UID	Unique Identifier
UMG	Universal Marine Gateway
USTRATH	University of Strathclyde, UK
UT	Ulstein Trading

VARNA	Varna Maritime Limited, Bulgaria
VEPOST	VEssel POST-processing program (ShipX plug-in of SINTEF)
VERES®	VEssel RESponse program (ShipX plug-in of SINTEF)
VftF	Vessels for the Future
VPN	Virtual Private Network
VVF	Virtual Vessel Framework
WBS	Work Breakdown Structure
WP	Work Package as defined in the HOLISHIP Project
XMF	eXtensible Modelling Framework
XML	eXtensible Markup Language
XSD	XML Schema Definition

Chapter 1
Revisiting the HOLISHIP Project

Jochen Marzi

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

The present book is the second volume of the book "A Holistic Approach to Ship Design" published by Springer Publishers, the first volume of which appeared in 2019 (Papanikolaou 2019). This book forms the official HOLISHIP project documentation of activities. At the time of writing, HOLISHIP—Holistic Optimisation of Ship Design and Operation for Life Cycle (www.holiship.eu)—passed the 4 years milestone and turns on the finish line. A final extension of 4 months became necessary to account for some delays due to the COVID 19 pandemic, internal reconfigurations and adaptations, not uncommon for a project of this size.

Back in September 2016 the project start marked a major milestone in a long line of developments focusing on the development and adaptation of design tools and on application case studies for almost all of the 40 project partners. Embarking from often insufficient tools, lack of functionality or integration, the HOLISHIP project after its first phase has reached an established design system of platforms and individual design/analysis tools to deal with all relevant ship design issues. Figure 1.1 illustrates the interplay of different design disciplines, particularly structural design and numerical flow analysis performed by project partners Tritec Ltd. and HSVA.

During the first phase of the HOLISHIP project the majority of tools, which were found at the start of the project insufficient, in terms of accuracy or functionality, matured and were made ready for service through their integration into the HOLISHIP design platform(s). This integration process—together with a few necessary functional updates of some of the tools—was essentially part of the first phase of the project and is covered in Vol. I of the HOLISHIP book. There a variety of hydrostatic,

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A. Papanikolaou (ed.), *A Holistic Approach to Ship Design*,
https://doi.org/10.1007/978-3-030-71091-0_1

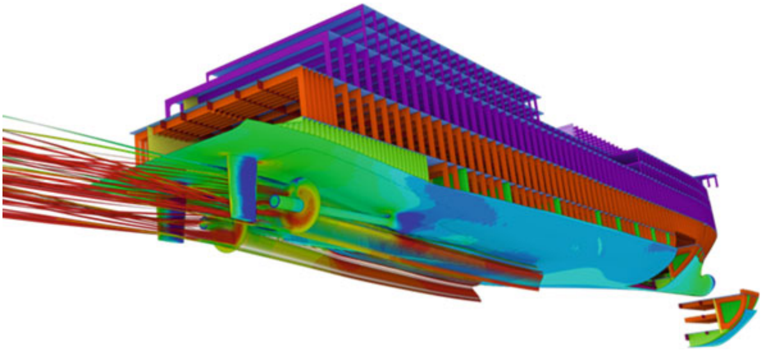

Fig. 1.1 "Holistic analysis of a RoPAX ferry including structural design (courtesy of Tritec Ltd), CAD integration (courtesy of Friendship systems) and HSVA's CFD analysis."

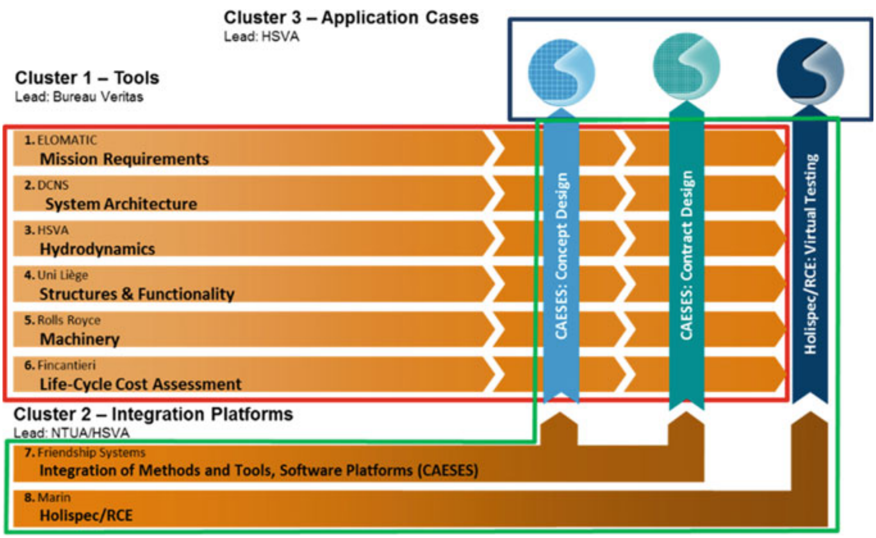

Fig. 1.2 HOLISHIP project structure

hydrodynamic, structural analysis, machinery/engine simulation and costing tools are described in more detail along with their integration strategy in the two design platforms featured in the project, namely the concept and pre-contract design CAESES platform of Friendship Systems and the virtual testing platform HOLISPEC/RCE of DLR.

For the efficient coordination of project activities, phase I developments were bunched into Clusters I and II (see Fig. 1.2) and closely supervised by respective cluster managers. Their outcome created a sound basis for replacing the traditional design spiral by a *design synthesis model* as planned in the project and shown schematically in Fig. 1.3 (example of RoPax ship design).

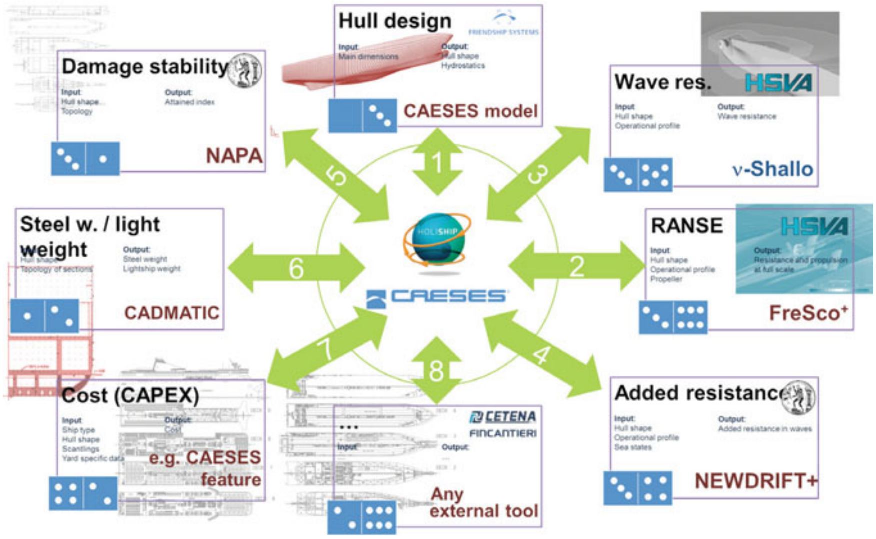

Fig. 1.3 "Synthesis model for the holistic analysis of a RoPAX ferry"

The second phase applied the technologies developed in phase 1 to a range of 9 different Application Cases (AC), each of them being rather different and representing the total breadth of maritime design. Run by technology leaders and acknowledged industry experts, these application cases include the concept and contract design of an OSV with a special focus on energy simulations to capture the needs of complex and energy intensive offshore operations up to pipe laying as well as a rather different case of the design of lightweight superstructure blocks for large Cruise Liners. Further application cases include life-cycle considerations for a Research Vessel which sheds light on the installed equipment and contributes to the concept of predictive maintenance, a new approach towards concept design using a System and Architecture management tool linked to the HOLISHIP platform, a virtual test of advanced manoeuvring devices for small cargo vessels, retrofit of existing large bulk carriers and container vessels for improved operational performance plus three concept design studies. The latter focuses on an offshore platform in ice and two ferries, a double ended coastal ferry and an advanced RoPAX ferry design which demonstrate the early design integration of different disciplines, particularly the interaction of hydrodynamic analysis with structural, stability and cost or LCA analysis according to the overall schema of the HOLISHIP architecture. An overview of this collection of Application Cases is shown in the following Fig. 1.4 which provides an assignment of ACs to the different level of design, concept, contract and virtual testing covered in the HOLISHIP project.

Each of the Application Cases is described in great detail in the following chapters of the present volume II. This marks the successful validation and exemplification of the HOLISHIP design concept and forms the practical end of the project's

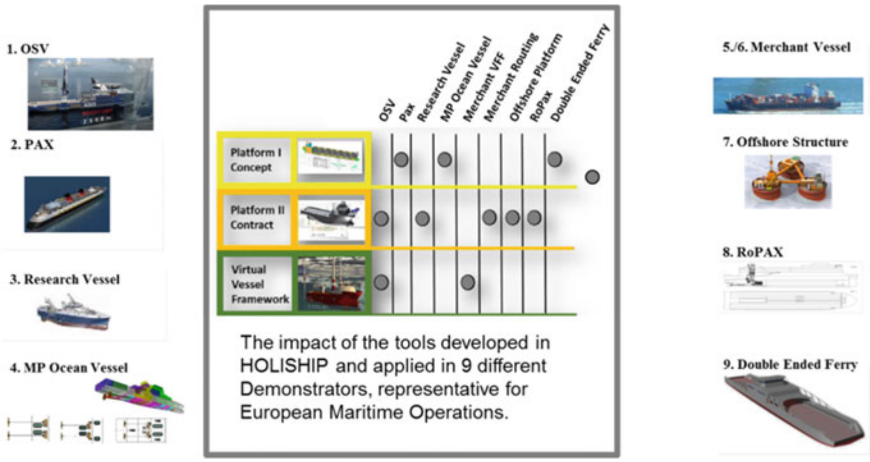

Fig. 1.4 HOLISHIP application cases covered in Phase II

development phase which has been strongly supported by the European Union and received funding from Horizon 2020 research and innovation programme under grant agreement No [689074].

However, this is not the end: HOLISHIP goes forth. At the time of writing partners undertake first steps to establish a joint "Marketplace" to exploit the successful developments in a future commercial operation. This will allow future customers to make full use of advanced design and analysis tools and concepts, either as a complete service or integrating specific components in individual design process. The evolution of this process will be further showcased on the project web site at www.holiship.eu.

Reference

Papanikolaou, A. (ed) (2019). A holistic approach to ship design, Vol. 1: Optimisation of ship design and operation for life cycle. SPRINGER Publishers, ISBN 978-3-030-02809-1, 2019. (Vol. II on Application Case Studies to appear in January 2021).

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Chapter 2
Integration of Tools for Application Case Studies

Stefan Harries and Claus Abt

Abstract This chapter elaborates the bottom-up 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. The focus of the project HOLISHIP and its bottom-up integration platform(s) was the design of maritime assets at the early design phases in heterogeneous environments. As it is often the situation, tools and systems come from different developers, companies and research institutes. So far they have been mostly used as stand-alone applications with the design team being responsible for proper tool execution, data exchange and management. Within HOLISHIP the tools and systems were coupled to CAESES®, i.e., a cross-platform Process Integration and Design Optimization (PIDO) environment that also provides comprehensive Computer Aided Design (CAD) functionality for the parametric modelling of shapes. Any tool or system that can be run in batch-mode can be coupled to CAESES and can be set up in order to exchange data with other tools, supporting the assembly of sophisticated synthesis models. Further developments as were needed for the application cases (AC) of the HOLISHIP project will be presented, complementing the discussion given in Harries and Abt (A holistic approach to ship design, Vol. 1: optimisation of ship design and operation for life cycle. SPRINGER Publishers, 2019).

Keywords Process Integration and Design Optimization (PIDO) · Computer Aided Engineering (CAE) · Simulation-driven Design (SDD) · Synthesis model · Surrogate model · Parametric model · Tool coupling · Collaboration

Abbreviation

AC	Application Case
AI	Artificial Intelligence
ANN	Artificial Neural Networks

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A. Papanikolaou (ed.), *A Holistic Approach to Ship Design*,
https://doi.org/10.1007/978-3-030-71091-0_2

ASCII	American Standard Code for Information Interchange
BRep	Boundary representation
BV	Bureau Veritas, France
B2B	Business-to-business relationship
B2C	Business-to-customer relationship
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAx	Acronym for various Computer Aided solutions for design, simulation, engineering etc.
CADMATIC	Marine design software by CADMATIC, The Netherlands
CAESES®	Computer Aided Engineering System Empowering Simulation by FRIENDSHIP SYSTEMS, Germany
CAPEX	Capital Expenditure
CFD	Computational Fluid Dynamics
COSSMOS	COmplex Ship Systems MOdelling and Simulation by DNV GL, Greece
CoP	Coefficient of Prognosis
CPU	Central Processing Unit
CSG	Constructive Solid Geometry
DE-ferry	Double-ended ferry
DoE	Design-of-Experiment
DP	Dynamic Positioning
DTD	Document Type Definition
DXF	Drawing Interchange Format (file)
EEDI	Energy-efficiency Design Index
FEA	Finite Element Analysis
FFD	Free-form Deformation
FPM	Fully-parametric Modelling / Fully-Parametric Model
FreSco⁺	RANS solver by HSVA
GA	General Arrangement
GA	Genetic Algorithm
GUI	Graphical User Interface
HSB	Hochschule Bremen (University of Applied Sciences), Germany
HSVA	Hamburg Ship Model Basin, Germany
HPC	High-performance computing
html	Hypertext Markup Language
iges (igs)	Graphics Exchange Specification file for exchange of geometry data
m	Number of tools integration in a synthesis model
n	Number of free variables (degrees-of-freedom of the system)
LHS	Latin Hypercube Sampling
MARIN	Maritime Research Institute Netherlands
MPOV	Multi-Purpose Ocean Vessel

NAPA	Naval Architecture Package for ship design by NAPA Oy, Finland
NEWDRIFT	Non-linear potential flow code for seakeeping analysis of ships by NTUA, Greece
NSGA II	Non-sorting Genetic Algorithm (also NSGA 2)
NURBS	Non-uniform Rational B-Spline curve / surface
NTUA	National Technical University of Athens
MOGA	Multi-objective Genetic Algorithm for design space exploration and exploitation
MPOV	Multi-Purpose Ocean Vessel
OPEX	Operational Expenditures – Operating Cost
OSV	Offshore Supply Vessel
PIDO	Process Integration and Design Optimization
Platform	Assembly of disparate systems and tools that are integrated in order to work with each other
PLM	Product Life-cycle Management
png	Portable Network Graphics (file)
RBR	Radial Basis Function(s)
PPM	Partially-parametric Modelling / Partially-parametric Model
RANSE	Reynolds-averaged Navier-Stokes Equations, also RANS equations
RAPID	Non-linear potential flow code for wave resistance analysis of ships in calm water by MARIN
RBF	Radial Basis Function
RCE	Remote Component Environment by DLR (German Aerospace Center), Germany
RoPAX	Passenger ferry with roll-on/roll-off cargo (mainly trucks and cars)
RS	Response Surface, also surrogate model
RSM	Response Surface Model, also Response Surface Methodology
R&D	Research and Development
SDD	Simulation-Driven Design
ShipX	Package for hydrodynamic analysis of ships by SINTEF Ocean, Norway
Sobol Quasi-random	Design-of-Experiment, aiming at evenly populating a design space
STEP	Standard for the Exchange of Product Model Data
stl	STereoLithography (file) for exchange of geometry data by means of tri-meshes
VPN	Virtual Private Network
VTK	Visualization Toolkit
ν-Shallo	Non-linear potential flow code for wave resistance analysis of ships in calm water by HSVA

2.1 Introduction

The bottom-up approach taken within the European R&D project HOLISHIP to flexibly integrate and utilize systems for the design, analysis and optimization of maritime assets, primarily of ships, is discussed and shown by means of selected application cases. Details of these application cases are given in dedicated chapters of this book while the idea of how to integrate tools and systems and, furthermore, how to collaborate between systems, even though they stem from different (and sometimes competing) sources, are discussed here and in (Harries and Abt 2019). The two chapters, i.e., this one and (Harries and Abt 2019), should be understood as complementing material with a slight overlap to still allow for independent reading.

Implementing the HOLISHIP approach by use of the CAESES® design platform (Harries and Abt 2019) some general requirements for the set-up of an efficient ship design process and CAE procedure need to be considered:

- Explicitly state objectives, constraints and free variables and have an agreement on them between the various stakeholders,
- Generate large sets of variants by parametric models from which cause-and-effect relationships can be better understood,
- Identify most influential variables and detect governing constraints,
- Ease the burden of repeated (and error-prone) data transfer,
- Ensure that the right data are exchanged between tools (to be handled by the tool experts for quality control) and that the tools are run consistently for all variants (quality enhancement),
- Prepare decision making by formulating quantifiable objectives and decide on favourable and best designs for multiple objectives in a rational way.

For the platform(s) of HOLISHIP, a key characteristic is *flexibility*, i.e., the flexibility of incorporating additional tools as needed, of extending and/or changing tools as designs (and demands) are progressing and, furthermore, of managing evolving and growing sets of data.[1]

2.2 Approach to Application Case Studies

The main application cases (AC) that utilized CAESES® as HOLISHIP design platform were.

1. Offshore supply vessel (OSV) [responsible partner: Kongsberg]
2. Multi-purpose Ocean Vessel (MPOV) [responsible partner: The Naval Group]

[1]A deliberate choice was made within HOLISHIP to not aim at developing and providing a strict PLM system (product life-cycle management) with access rights (possibly across legal units), design history and version control, diligent change management etc. This would simply have been adding complexity and constitute a new large R&D project in itself. See Sect. 2.5.1, too.

3. Structural design of a superstructure with composite materials [responsible partner: Meyer Werft]
4. Retrofitting of Merchant Ships, including Machinery Outfitting [responsible partners: NTUA and DNV GL]
5. Offshore platform [responsible partner: Elomatic]
6. RoPAX ferry [responsible partner: Tritec]
7. Double-ended ferry [responsible partner: Elomatic]

These application cases are elaborated in respective chapters of the present book.

The synthesis models for four of the above ACs are given in Figs. 2.1, 2.2, 2.3 and 2.4. Table 2.1 presents an overview of tools involved. The diversity of the synthesis models is obvious and corresponds to the situation encountered "on the ground" in which (i) different design environments with diverse tool sets, (ii) different design phases, and (iii) different levels of detail have to be accommodated. Not only can it be seen that many tools had to be connected but that not one synthesis model would fit all purposes. Details of several of these AC are given in Harries et al. (2019) and in Papanikolaou et al. (2019).

In addition, the ACs provided feedback for the adjustment of CAESES (*bottom-up approach*), introducing several challenges that would go even beyond standard design tasks: (i) Quite many different partners and many tools from various developers had to be brought together, and (ii) the process was spread out over several years. The latter implied that, naturally, communication was less stringent than in purely commercial design projects and that the partnership encountered changes typical of long-term projects (e.g. people leaving the project due to career changes, periods of parental leave and sabbaticals, new people being onboarded, adjustments and progress in

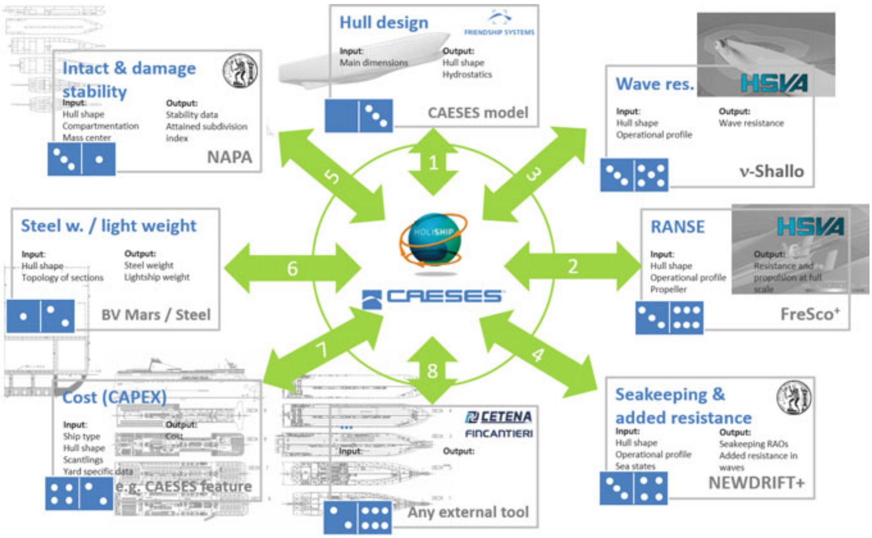


Fig. 2.1 Synthesis model for the design and optimization of a RoPAX ferry (see also Fig. 2.5)

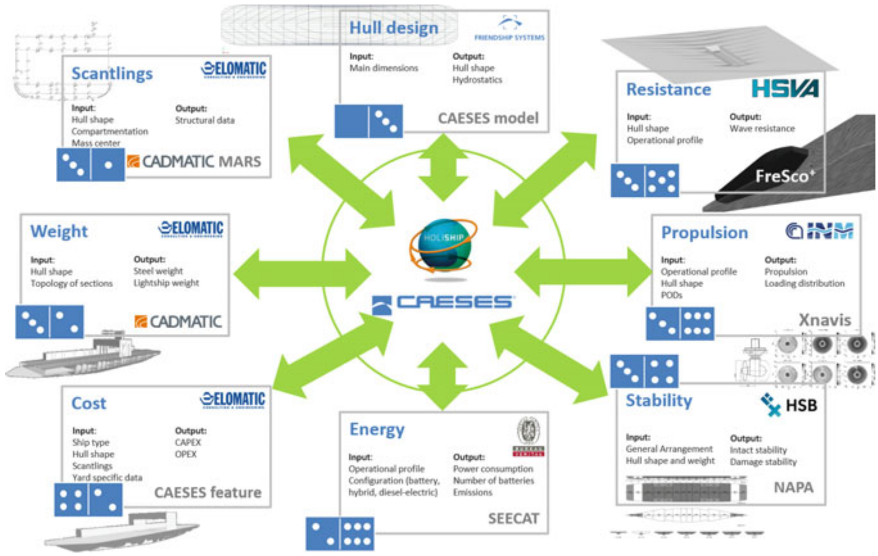


Fig. 2.2 Synthesis model for the design and optimization of a double-ended ferry (Elomatic)

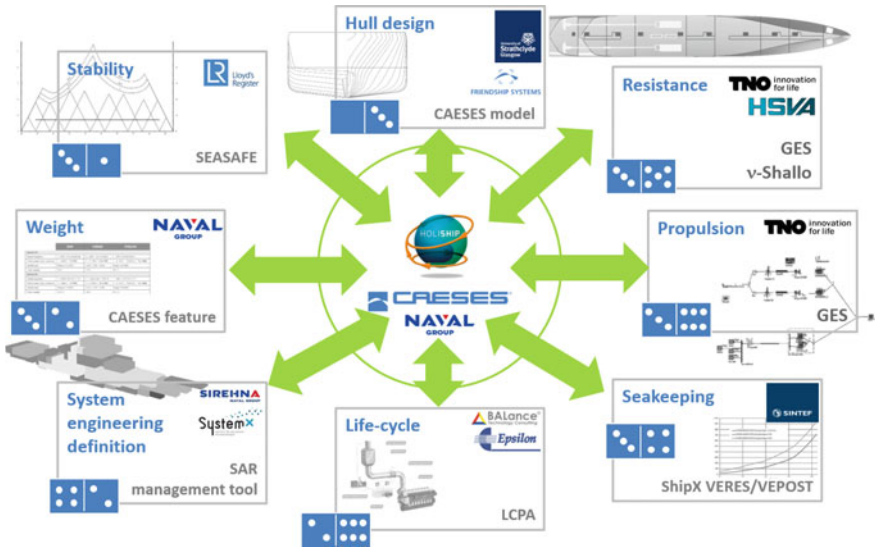


Fig. 2.3 Synthesis model for the design and optimization of a MPOV (The Naval Group)

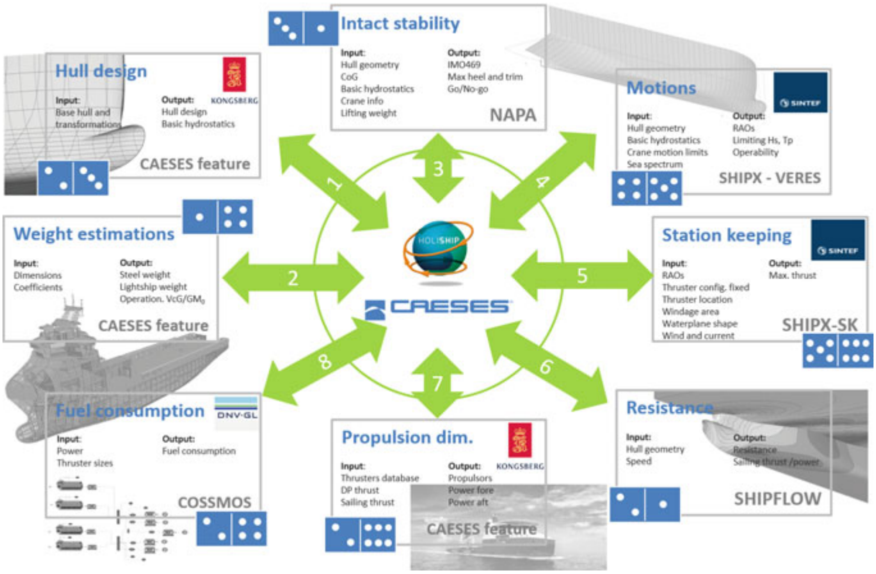


Fig. 2.4 Synthesis model for the design and optimization of an OSV (Kongsberg)

tools). In this sense the HOLISHIP platform(s) were not only tested successfully for technical diversity but also for robustness and the usage within distributed and evolving teams.

Figure 2.5 gives an abstract view of the process that involves several simulations to be executed. Important tools utilized within the HOLISHIP platform(s) and coupled to CAESES® for the ACs are summarized in Table 2.1.

2.3 Recent Improvements of CAESES

In the course of the HOLISHIP project, CAESES® itself was extended and improved. A few selected improvements shall be elaborated here.

2.3.1 Parallelization

For several years there has been a notable shift in processor technology. Today most computers, from workstations to notebooks, offer multi-core chips which strengthen computers to be effective in performing several tasks concurrently. This was different up until a few years ago when processors primarily saw a steady increase in clock speeds. CAESES was originally developed for single-core usage, its origin dating

Table 2.1 Tools utilized within HOLISHIP platform(s) and coupled to CAESES® (excerpt)

Tool coupled	Tool developer	Provider / responsible party within HOLISHIP	WP	AC	Tool's primary purpose and usage within HOLISHIP	Primary input from / via CAESES to tool	Main output from tool to CAESES and for design task
ANSYS Workbench	ANSYS	SMILE	15	Offshore platform	Structural analysis of soil	Caisson geometry, soil parameters	Deformation data for different loads
BV MARS	Bureau Veritas	Bureau Veritas	17	DE-ferry	Rule-based ship structural assessment of plating and longitudinal stiffeners	Hull shape to Cadmatic, midship with scantlings to BV MARS	Midship analysis
BV STEEL	Bureau Veritas	Bureau Veritas	17	DE-ferry	3D beam theory-based ship structural assessment of primary supporting members	Connected via Cadmatic	Connected via Cadmatic
CAESES features	FRIENDSHIP SYSTEMS	Various	7, 12 and 17	RoPAX, MPOV, DE-ferry	Compute auxiliary quantities like weight, costs	E.g. hull geometry, weight estimation and fuel consumption	E.g. CAPEX and OPEX
CAESES features	FRIENDSHIP SYSTEMS	University of Strathclyde	7	RoPAX	Holtrop and Mennen series	Hull parameters	Resistance and power estimate

(continued)

Table 2.1 (continued)

Tool coupled	Tool developer	Provider / responsible party within HOLISHIP	WP	AC	Tool's primary purpose and usage within HOLISHIP	Primary input from / via CAESES to tool	Main output from tool to CAESES and for design task
Cadmatic	Cadmatic	Elomatic	17	DE-ferry	3D modelling of General Arrangement	Hull parameters	Steel weight, position of decks and bulkheads as parameters (optional in Cadmatic Hilltop)
DNV GL COSSMOS	DNV GL	DNV GL	9	Offshore Supply Vessel	Operational analysis of machinery system's performance	Machinery design specifications (thruster nominal points), operational profile	Fuel consumption and emissions
Excel	Microsoft	Meyer Werft	10	Superstructure	Structural and fire analyses	Panels and compartmentation information	Weight and cost of FRP and/or composite panels
Excel	Microsoft	Elomatic / CMT	15	Offshore platform	Caisson geometry check and turnkey cost estimation	Caisson geometry parameters, soil parameters, site conditions	Caisson geometry validity, project cost and duration of installation
FINE/Marine	Numeca	SINTEF Ocean	14	Bulkcarrier	Bulb optimization for retrofitting	Hull geometry	Resistance, propulsion and seakeeping

(continued)

Table 2.1 (continued)

Tool coupled	Tool developer	Provider / responsible party within HOLISHIP	WP	AC	Tool's primary purpose and usage within HOLISHIP	Primary input from / via CAESES to tool	Main output from tool to CAESES and for design task
FreSco+	HSVA	HSVA	7 and 17	RoPAX and DE-ferry	Resistance and propulsion (viscous, incl. free surface)	Hull geometry	Flow field and integrated data for resistance and propulsion
FreSco +	HSVA	HSVA	14	Containership	Bulb optimization for retrofitting	Hull geometry	Resistance, propulsion and seakeeping
GES	TNO	TNO	12	MPOV	Time domain simulation of multi-physics complex systems Statistical resistance estimates (e.g. Holtrop, Harvard, Fung)	Model parameters, selection of propulsion system configuration	Resistance along with gas emissions and fuel consumption
Hexpress	Numeca	HSVA	7, 16 and 17	RoPAX, DE-ferry	Grid generation for flow analysis	Hull geometry	Grid for RANS simulation
LCPA	Balance/Epsilon	Balance/Epsilon	12	MPOV	Life cycle cost and life cycle assessment from design/build and operation to scrapping	Hull geometry, weight estimation and fuel consumption	CAPEX and OPEX

(continued)

Table 2.1 (continued)

Tool coupled	Tool developer	Provider / responsible party within HOLISHIP	WP	AC	Tool's primary purpose and usage within HOLISHIP	Primary input from / via CAESES to tool	Main output from tool to CAESES and for design task
MPSET	Kongsberg (formerly RRM)	Kongsberg	9	OSV	Quasi static time domain simulation of marine power systems		Performance, costs and reliability data
NAPA	NAPA OY	NTUA	7	RoPAX	Design of hull form and internal layout, intact and damage stability	Hull geometry	3D model of internal layout, LS, DWT, transport capacity, stability
NAPA	NAPA OY	HSB	17	DE-ferry	Intact and damage stability	Hull geometry	Stability results
NAPA	NAPA OY	NTUA	16	RoPAX	Design of hull form and internal layout, Intact and damage stability	Hull geometry	3D model of internal layout, LS, DWT, transport capacity, stability
NAPA Steel	NAPA OY	Tritec	16	RoPAX	Weight estimates of steel structure	Hull geometry	Plates, bulkheads, decks, stiffeners
NEWDRIFT+	NTUA	NTUA	7 and 16	RoPAX	Seakeeping, added resistance in waves	Hull geometry	Seakeeping, added resistance
NEWDRIFT+	NTUA	NTUA	14	Containership and bulk carrier	Seakeeping, added resistance in waves	Hull geometry	Seakeeping, added resistance

(continued)

Table 2.1 (continued)

Tool coupled	Tool developer	Provider / responsible party within HOLISHIP	WP	AC	Tool's primary purpose and usage within HOLISHIP	Primary input from / via CAESES to tool	Main output from tool to CAESES and for design task
RCS	DLR	DLR / Marin	7 and 8		Check connectivity of platforms	Any data set from CAESES	Any data set from RCS
SAR	SIREHNA	SIREHNA	12	MPOV	Baseline definition of system architecture, preliminary layout and analysis of stakeholder's needs	CAESES script file storage in SAR management tool for connectors and design engine definition	Import of preliminary tank arrangement for baseline model (from Shipbuilder incl. in SAR tool)
SEECAT	Bureau Veritas	Bureau Veritas	17	DE-ferry	Time domain simulation of multi-physics complex systems	Operational profile and electrical load balance	Fuel consumption rate, battery load balance and emissions
SeaSafe	LR	LR	12	MPOV	Hull and tank layout geometry, and definition of loading condition	Intact stability criteria check	Hull and tank layout geometry, definition of loading condition
SHIPFLOW	Flowtech	Kongsberg	9	OSV	Resistance and propulsion	Hull geometry	Resistance and propulsion
ShipX	SINTEF Ocean	SINTEF Ocean and Kongsberg	9	OSV	Vessel responses	Geometry and parameters	Ship motions and global loads

(continued)

Table 2.1 (continued)

Tool coupled	Tool developer	Provider / responsible party within HOLISHIP	WP	AC	Tool's primary purpose and usage within HOLISHIP	Primary input from / via CAESES to tool	Main output from tool to CAESES and for design task
ShipX / VERES & VEPOST	SINTEF Ocean	SINTEF Ocean	12	MPOV	Vessel motion responses (2D strip theory)	Geometry	RAOs and check of seakeeping criteria
STAR-CCM +	Siemens PLM	Tritec	16	RoPAX	RANS solver	Geometry	Resistance and propulsion
xNavis	CNR-INSEAN	CNR-INSEAN	17	DE-ferry	RANS solver	Geometry	Propulsion data for POD
ν-Shallo	HSVA	HSVA	7 and 16	RoPAX	Potential flow solver for wave resistance in calm water	Geometry	Resistance
ν-Shallo	HSVA	HSVA	12	MPOV	Potential flow solver for wave resistance in calm water	Geometry	Resistance

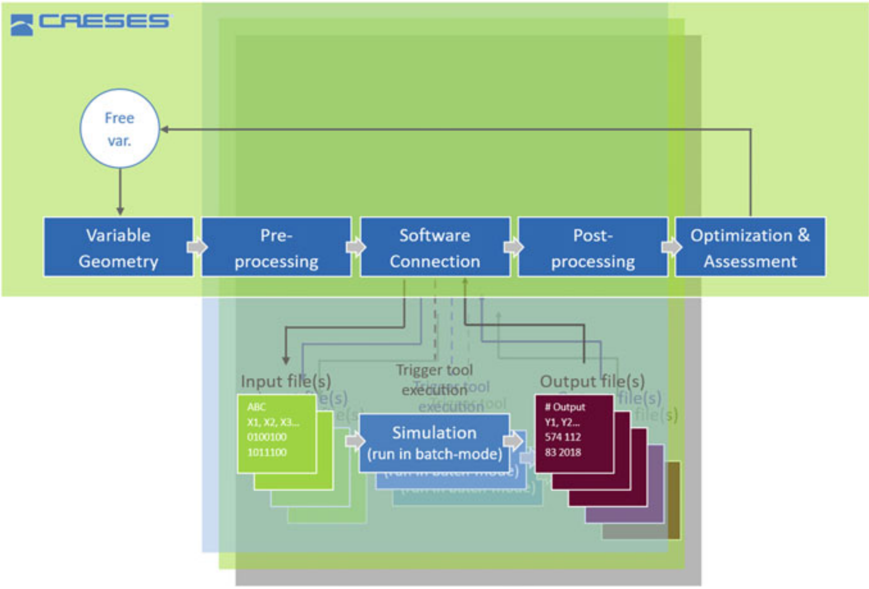


Fig. 2.5 Process of design and optimization as realized within CAESES® for a synthesis model bringing together various simulations

back to 2004 when most CPUs, even for engineering workstations, still offered only sequential task execution.

However, typical hierarchies of (even simple) parametric models feature objects that are independent from each other, and, hence, can be updated in parallel. In order to support this, CAESES had to be adapted and rearranged, leading to the parallelization of the code basis.

The most important advantage for the user can be seen from Fig. 2.6: The parallelized version of CAESES, here CAESES 5, yields a substantial speed-up when building or updating parametric models. Within the context of automated exploitation and exploration in which many CPU hours are spent for high-level computations, say RANS simulations, this speed-up from several dozens of seconds to a few seconds during an update may not be needed. However, when actually building and also when preparing a parametric model for simulation-driven design, the typical work flow requires numerous interactive steps with updates, changes and quality tests. Then, a fast update of geometry is of very high importance.

2.3.2 Complementing Algorithms

CAESES already offers a range of standard algorithms for exploration and exploitation, see (Harries and Abt 2019). In addition, the DAKOTA environment by Sandia

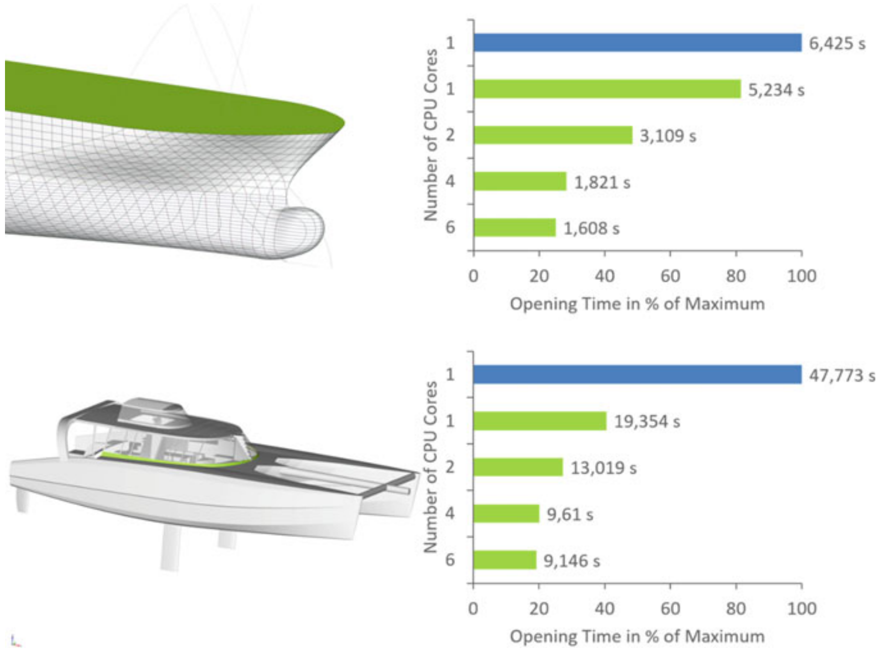


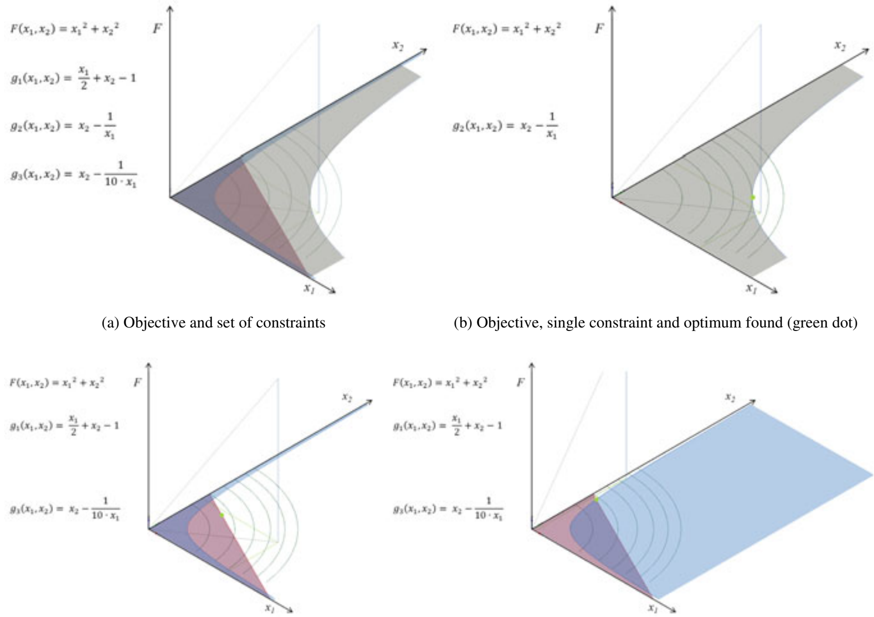
Fig. 2.6 Speed-up via parallelization for two different parametric models, depending on numbers of cores (single-core sequential update given in blue, using CAESES 4.4; parallel updates given in green, using CAESES 5.0)

National Laboratories (dakota.sandia.gov) can be utilized as a plug-in. This connection was further streamlined, making a large number of high-end optimisation algorithms available (see also Sect. 2.3.3). In addition, a new and dedicated search strategy was implemented for early design (as suggested by HSB). The method iteratively linearizes objectives and (inequality as well as equality) constrains as first proposed in (Gudenschwager 1988).

Particularly in early design phases many free variables, bounds, constraints and dependencies are present while the freedom of change and the potential for the right (and threat for an unfortunate) choice of main dimensions is still the highest. In order to support this phase, many relationships need to be formulated, setting up a non-linear and quite extensive set of equations and inequalities. This set is solved by means of a new design engine within CAESES which was called Simplexer. It is an extended implementation of the Simplex algorithm (linear programming).[2]

Figure 2.7 illustrates the Simplexer and the optima found for two-dimensional test cases with one objective (here F as function of x_1 and x_2) and several constraints (here g_j as functions of x_1 and x_2), a two-dimensional test being easier to visualize. The

[2] In order to more easily distinguish this new algorithm from the Nelder-Mead Simplex (non-linear programming), that was already available within CAESES, the slightly different term of Simplexer was introduced.



(a) Objective and set of constraints

(b) Objective, single constraint and optimum found (green dot)

(c) Objective, two constraints (set as inequalities) and optimum found (green dot)

(d) Objective, two constraints (one inverted in comparison to (C)) and optimum found (green dot)

Fig. 2.7 Illustration of the Simplexer for a search in two dimensions, including constraints

constraints actually are inequality constraints for various tests but are formulated as equalities (i.e., for the situation in which the inequality constraints are active). Depending on which constraints are considered and on the starting point for the search, different optima are identified by the Simplexer. The linearization of both constraints and objectives is done internally within CAESES so that the engineer can focus on formulating the design task.

2.3.3 Extended Feature for Surrogate Modeling

2.3.3.1 Response Surface Methodology

When exploring a design space spanned by multiple design variables, often the complex interactions and correlations of the design variables with an objective are rather non-intuitive and hard to grasp. From statistics, *Response Surface Methodology (RSM)* is known as a technique that explores exactly this relationship between a set of design variables and (at least) one evaluation. See also (Harries and Abt 2019).

In simulation-driven design (SDD), often formal optimization algorithms are used to navigate through the design space and efficiently converge towards local or even global optima. But still, a more thorough understanding of how different geometric characteristics affect a solution and how this might be different for another region of the design space offers valuable insight. Such knowledge, which traditionally had to be acquired over many years of research in the field, will allow the designer to make well-educated guesses, as to how and where to modify the shape or even the underlying parametric model, in order to achieve a certain design goal. Furthermore, this capability of surrogate modeling—i.e., to predict, with a certain (known) accuracy, how a complex system will answer to a previously not yet considered set of input arguments—can be used to enhance the performance of a multitude of formal optimization methods originally developed without this technique in mind (Sánchez Castro and von Zadow 2019).

As mentioned above the open source library DAKOTA (Adams et al. 2020)is embedded within CAESES, which offers a variety of methods and tools that can be put to use in this context. The terms *Response Surface (RS), Response Surface Model (RSM)* and *surrogate* are used somewhat interchangeably. All of them follow the same basic idea, which is, to make use of an existing result pool to approximate the response of a system to a change in one or several of the free variables. Such a surrogate, if visualized in 3D space takes the shape of a surface (see Figs. 2.8 and 2.10). On two axes, a certain range of input values for two of the design variables is shown, while the remaining design variables are kept constant at any freely chosen combination of values. On the third axis the prediction of the model for any evaluation within this space can be mapped. Often all three axes will be normalized with a color-coding indicating the absolute measures of the response.

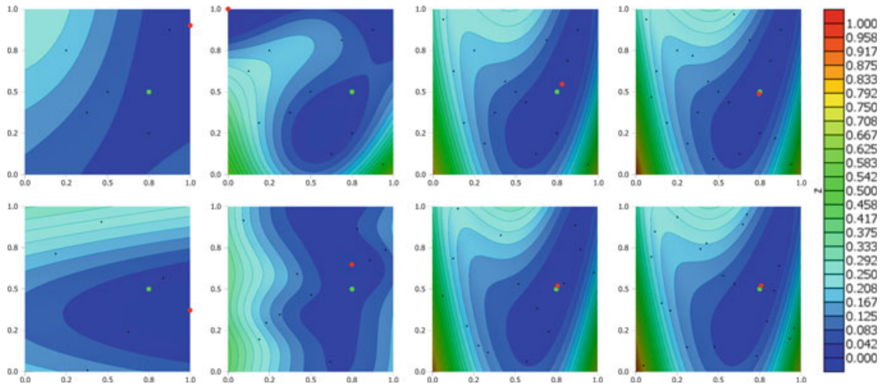


Fig. 2.8 Different surrogates based on a *Sobol* (top row) and *LHS* sampling (bottom row) for 5, 10, 15 and 20 samples; the predicted and the correct optima are indicated via red and green points, respectively

2.3.3.2 Sampling

As a prerequisite for any surrogate, a result pool is needed. This data set is often referred to as training data—especially in the context of *Artificial Neural Networks (ANN).* It should consist of a sufficient number of designs that are conveniently spread throughout the design space. For most simulation-driven design applications, having more designs within the pool will lead to a model of higher accuracy. However, the chosen method of sampling does not only significantly affect the accuracy of a prediction itself but where in the design space the highest accuracy, i.e., the best match to the actual function value, can be found.

From the perspective of an engineer who is already searching for a final, locally optimal design, this region of high accuracy should preferably lie in the vicinity of this design point. However, in an earlier phase of the design process it might still be the objective to just detect potentially interesting regions or simply to acquire a greater understanding of correlations and cause-and-effect relationships. Without being able to look at different surrogates one might not even be able to tell if the problem under consideration is single- or multi-modal, or how well the objective behaves with respect to a certain change in input variables, after all. In such cases, where a prediction of similar accuracy across a design space is targeted, a *Design-of-Experiments (DoE)* method such as *Latin Hypercube Sampling (LHS)* or a *Sobol* sequence is often the most suitable.

2.3.3.3 Illustrating Example

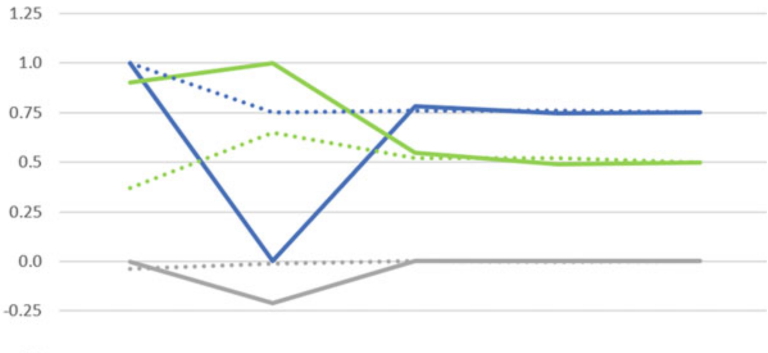
The Rosenbrock function

$$f(x, y) = (a - x)^2 + b\left(y - x^2\right)^2 \tag{2.1}$$

with $a = 1$ and $b = 1$ is a popular test function and shall be used to illustrate a single-objective optimization problem with x and y being the design variables and $f(x,y)$ being the objective. When restricting the range of the input variables $x \in [-2, 2]$ and $y \in [-1, 3]$ and normalizing the function to its maximum value within this range, i.e., $f(-2, -1) = 34$, it can be written in normalized form with $u \in [0, 1]$ and $v \in [0, 1]$

$$g(u, v) = \frac{1}{34}\left[(3 - 4u)^2 + \left((4v - 1) - (4u - 2)^2\right)^2\right] \tag{2.2}$$

Figure 2.8 shows multiple surrogates with the analytically determined global minimum at $g(0.75, 0.5) = 0$, indicated by a green point. The global minimum associated with each surrogate is marked by a red point. For both sampling methods a good approximation can be observed for 15 and more samples. The actual positions u_{min} and v_{min} for the predicted global optima are given in Fig. 2.9. Comparing the



	5	10	15	20	analytical
Sobol u_min	1.0	0.0	0.7812	0.7451	0.75
Sobol v_min	0.8996	1.0	0.5469	0.4887	0.5
Sobol opt	-0.0003	-0.2114	0.0005	0.0001	0.0
LHS u_min	1.0	0.7488	0.7594	0.7598	0.75
LHS v_min	0.3712	0.6495	0.5208	0.5220	0.5
LHS opt	-0.0366	-0.0105	-0.0001	-0.0005	0.0

Fig. 2.9 Predicted optima and their positions based on *Sobol* and *LHS* sampling for different sample sizes. (Note, that LHS, as opposed to Sobol sampling does not offer the added benefit of repeatability and hence, the outcome for another run might differ slightly)

obtained optima for 15 and 20 LHS samples, one can observe that more samples do not necessarily result in a more accurate approximation.

Considering the low gradient of the chosen benchmark function in the optimal region, both data sets yield rather satisfactory approximations. (For comparison, to determine the positions u_{min} and v_{min} as well as the functional value of the optimum found by running a T-Search algorithm starting from $u = 0$ and $v = 0$ would require more than 120 designs until a similarly good solution is obtained. In addition, the knowledge derived from a data set stemming from an exploitation will be clustered near the optimal design point and, hence, will not allow for a reasonable approximation in the remaining design space).

2.3.3.4 Model Generation

Within CAESES and the present implementation, the generation of a surrogate always refers to a model that will predict just one evaluation based on a set of at least two design variables. Therefore, all the necessary input needed to trigger a model generation via *Surfpack*, which is part of the DAKOTA software toolkit, is available in CAESES in the form of a results table containing the sampling designs. All it takes is a custom export that writes out these data in the appropriate file format. Next, a template file is written to specify the type of model that shall be generated along with the previously prepared data set. It is then merely a matter of triggering an external executable that performs the necessary calculations in batch-mode and returns a model file.

As can be seen from Fig. 2.10, all of these steps were conveniently wrapped into a CAESES feature (here in CAESES 4.4), enabling the design engineer to apply the technique with just a few clicks. The only input arguments that need to be given by the user are the type of model one wishes to generate, the design variables and evaluation of interest ("Response Index") as well as the table containing the corresponding training data. Out of the different model types that are offered within *Surfpack*, the current implementation offers *Kriging, ANN* and second as well as third order polynomials.

2.3.3.5 Evaluation and Visualization

Similar to the generation of various models, the evaluation of an existing model file can be conveniently wrapped within a CAESES feature. To improve usability both feature definitions were packaged as sub-features and, hence, their in- and outputs are automatically linked; this means that a previously generated model file will be directly available for evaluation within the project (see input argument *"Surrogate"* in Fig. 2.10).

For the evaluation of one or multiple designs a data file is written, too. Furthermore, a template file pointing to the data as well as to the model which shall be used for prediction needs to be created. Again, from within the same feature, DAKOTA's *Surfpack* is called in batch-mode. The obtained response is subsequently written into an additional file.

For only one evaluation at a time, all it takes for CAESES is to wait for this file to appear and read in the predicted response. For multiple simultaneous evaluations, an array of responses can be read in from a single *Surfpack* computation. By evaluating two series of design variables with all their permutations of interest, keeping the remaining design variables constant, this procedure allows to conveniently visualize

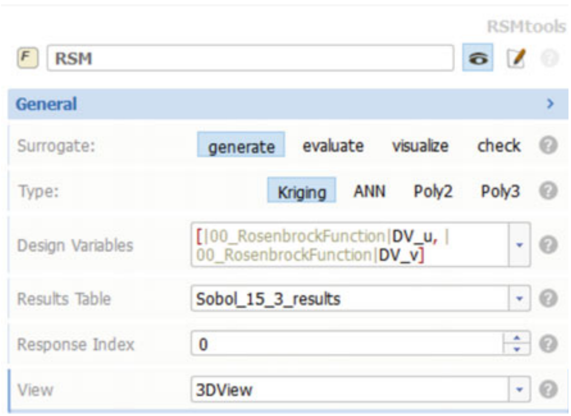
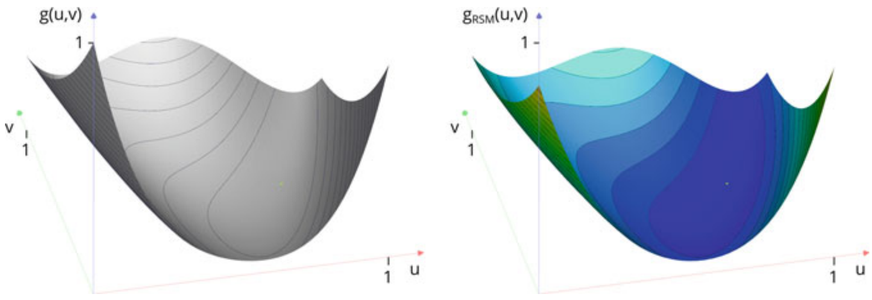


Fig. 2.10 Input arguments of the CAESES feature for generation, evaluation, visualization and cross-validation of the surrogate



(a) Original Rosenbrock function

(b) Approximation of the Rosenbrock function based on a Sobol with 15 samples using a Kriging model (same perspective as (A))

Fig. 2.11 Comparison of original Rosenbrock function and an associated surrogate

the surrogate in three-dimensions via the use of an interpolation surface. This is illustrated for the Rosenbrock function in Fig. 2.11.

2.3.3.6 Cross Validation

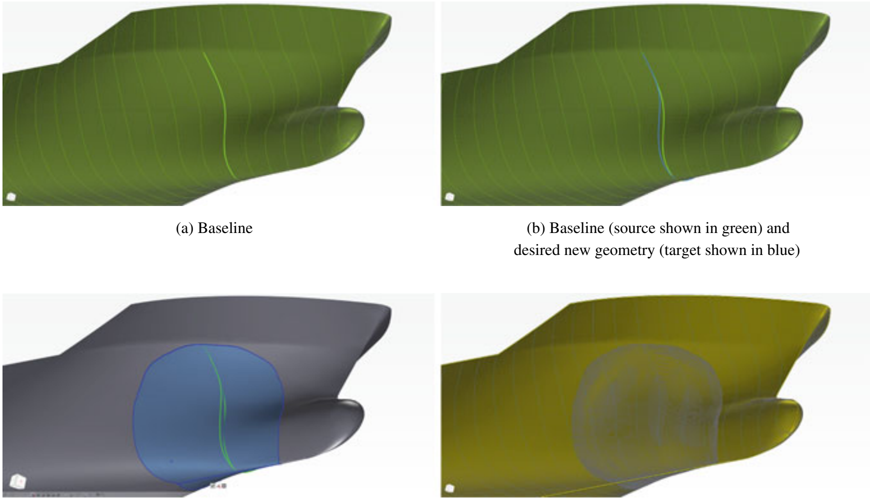
To judge the quality of a surrogate, a *k*-fold cross-validation (Fushiki 2011) has been implemented. The available result pool containing *n* designs is hereby split into *k* subsets, each of which contain *n*-*k* designs. For each subset, a model of the desired type is generated and evaluated at the remaining *k* design points. The coefficient of prognosis (CoP) is then calculated as

$$CoP = 1 - \frac{\sum_{i=1}^{n} (g - g_{RSM})^2}{\sum_{i=1}^{n} \left(g - \frac{\sum_{i=1}^{n} g}{n}\right)^2} \tag{2.3}$$

For the surrogate shown in Fig. 2.11, the maximum coefficient of prognosis of a threefold cross validation equals $CoP_{max} = 0.9506$. For a Kriging model it follows, that the actual CoP when using the entire result pool of 15 will be even higher. However, it should be noted that a higher CoP does not necessarily mean that any point within the design space will be predicted with a higher accuracy. Also the CoP is not necessarily higher for larger sample sizes as could be seen from Fig. 2.9.

2.3.4 Further Partially-Parametric Modeling

In order to enable less experienced engineers to more easily and quickly introduce high-quality changes in geometry, in particular to hull forms, the broad range of partially-parametric modeling approaches already available within CAESES was



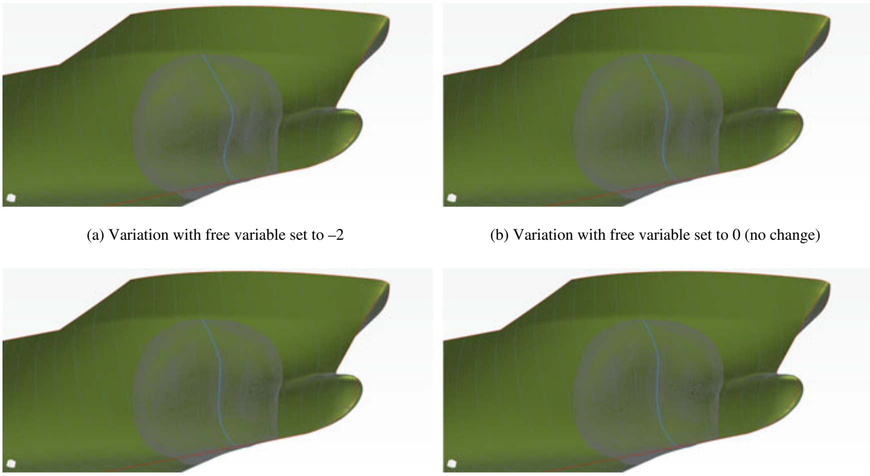
(a) Baseline

(b) Baseline (source shown in green) and desired new geometry (target shown in blue)

(c) Selection of region within which modifications are applied

(d) Tessellation and refinement for subsequent modification

Fig. 2.12 Set-up of a partially-parametric modeling approach using RBF



(a) Variation with free variable set to –2

(b) Variation with free variable set to 0 (no change)

(c) Variation with free variable set to +2

(d) Variation with free variable set to +3

Fig. 2.13 Application of a partially-parametric modeling approach using RBF

further extended. A new Radial Basis Function (RBF) approach was developed which allows the selection of regions to be modified interactively and to evoke changes to a baseline by means of source and target geometry. Figures 2.12 and 2.13 illustrate the set-up and the modification for a representative hull form given as a tessellated geometry (here by importing an stl-file to CAESES). Details of the RBF approach, following (Botsch and Kobbelt 2005), are elaborated in Table 2.2.

Table 2.2 Radial Basis Function approach

CAESES supports both discrete (trimeshes) and continuous (NURBS) geometries as baselines for RBF based deformations. The set-up for both kinds of geometries differs in the details but the underlying principle is the same and the usage is quite similar. In principle, a geometry can undergo more than one transformation. One such transformation is called an "RBF region"
First, the user needs to define an area of the geometry that may be freely deformed by the algorithm. (In the case of discrete geometry this can be done within CAESES using a newly created paint tool that allows for painting areas onto the geometry, while in the case of continuous geometry the user may select faces from the Boundary Representation that will be subject to the freeform deformation.) The area that was marked in this manner is treated (and called) the "support region", while the rest of the geometry is regarded as the "fixed region" as it will not be a part of the deformation
Once the support region is marked, the user needs to select a shape characteristic, the so-called "source", inside that region and specify what that shape should look like, i.e., how it should be transformed, establishing the so-called "target". Both the source and the target need to be supplied by the user, forming the creative part of the partially-parametric model. The support region will then be deformed by the algorithm in a way that ensures a tangent-continuous transition to the fixed region
Features (shape characteristics) that may be selected as source and target geometries are: • a point inside the support region that will be translated to a target location; • a collection of triangles that may be translated, rotated and scaled to a new location (discrete geometry only); • a curve on the geometry that is mapped to a target curve somewhere in space; • a sub-surface of the geometry that is mapped to a target surface in space (NUBRS geometry only)
To calculate the space deformation that governs the deformation of the support region, Radial Basis Functions (RBF) of the form $\phi_i(\boldsymbol{x}) = \lvert(\boldsymbol{x}\text{-}\boldsymbol{c}_i)^3\rvert$ are used. Here $\boldsymbol{x}$ is any point for which a deformation is to be calculated and the $\boldsymbol{c}_i$ are the centres of the RBF-points that are sampled from the boundary area of the fixed region and points sampled from the sources and targets defined by the user. For each centre $\boldsymbol{c}_i$ a basis function ϕ_i is assigned for which the algorithm needs to calculate an associated weight w_i. The space deformation to determine the new position of a point $\boldsymbol{x}$ can then be calculated as $\boldsymbol{d}(\boldsymbol{x}) = \sum \boldsymbol{w}_i\phi_i(\boldsymbol{x}) + \boldsymbol{p}(\boldsymbol{x})$ (summed over all centres $\boldsymbol{c}_i$), with $\boldsymbol{p}(\boldsymbol{x})$ being a trivariate quadratic polynomial.
To calculate the weights, a symmetric system of linear equations needs to be solved. Depending on how dense the point sampling from the "fixed region" and from the desired features is, the system of equations can become very large and, consequently, is computationally expensive to solve. To remedy this an incremental version of the QR factorization using Householder reflections was implemented to solve the system. Once the weights are known, the support region can be transformed.

(continued)

Table 2.2 (continued)

CAESES supports both discrete (trimeshes) and continuous (NURBS) geometries as baselines for RBF based deformations. The set-up for both kinds of geometries differs in the details but the underlying principle is the same and the usage is quite similar. In principle, a geometry can undergo more than one transformation. One such transformation is called an "RBF region"
This is where the major differences in the transformation of discrete geometry and continuous geometry come into play: For discrete geometry (trimeshes) the deformation can be directly applied to all vertices in the support region. In addition, the transformation can be used to refine the given input mesh so as to realize smoother modifications. Also, since a space deformation is defined, the changes are not limited to points that lie on the actual surface. Furthermore, within CAESES the application of "RBF regions" on discrete geometry was realized as an additive transformation, which means that a point to be modified may be part of different, possibly overlapping RBF regions. Its new position is then determined by the sum of all transformations, enabling very complex modifications. For continuous geometry (NURBS) the transformations are applied to the vertices of the affected surface(s). A surface's control polyhedron is refined until a very close NURBS approximation is reached. Then the transformation is applied. Afterwards the polyhedron is reduced again without deviating beyond a user defined tolerance.

2.4 Additional Means of Integration

2.4.1 Integration via COM

The standard connection between CAESES and any external simulation tool via template files was discussed in (Harries and Abt 2019). This type of connection is very flexible and independent of the operating system and, hence, is available for both Windows® or Linux™. Quite frequently, however, statistical data, auxiliary computations, estimates and quick checks (e.g. on the basis of previous design work or literature surveys) are compiled and run within Microsoft Excel. To support data exchange with Excel there is an integration mechanism within CAESES built on the COM-interface under Windows®, allowing to utilize Excel as an additional simulation tool.

In principle, any cell within an Excel-file can be addressed either to write data to or to extract data from (bidirectional data exchange). This allows a design team to formulate analyses, built parametric models (e.g. for costs and weight) and formulate company-specific relationships between data (e.g. from heuristics) within a spreadsheet—as is often done already—and still include this "knowledge" in a complex synthesis model. Maintenance of the data within the spreadsheet can then be done outside the synthesis model (and does not require an update of the integration unless the cells for data exchange, as identified via their row and column numbers, are modified).

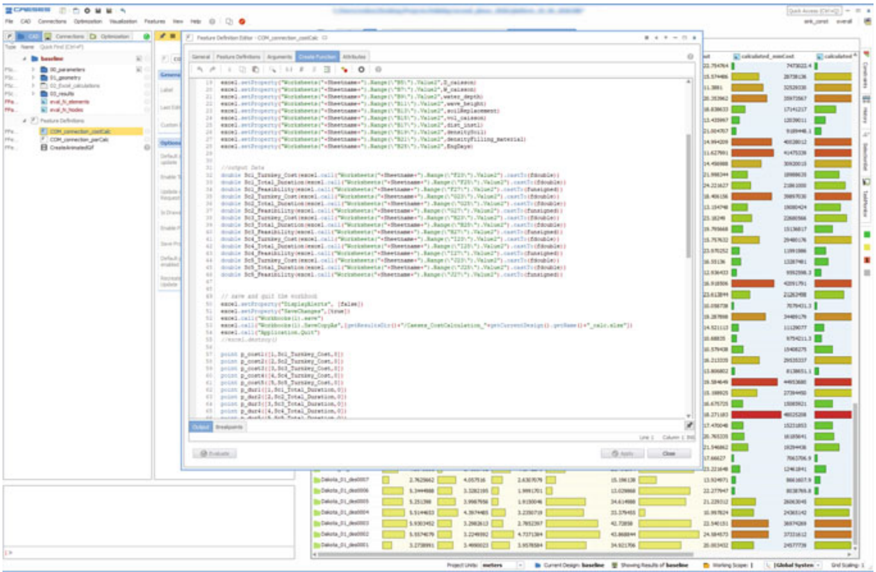


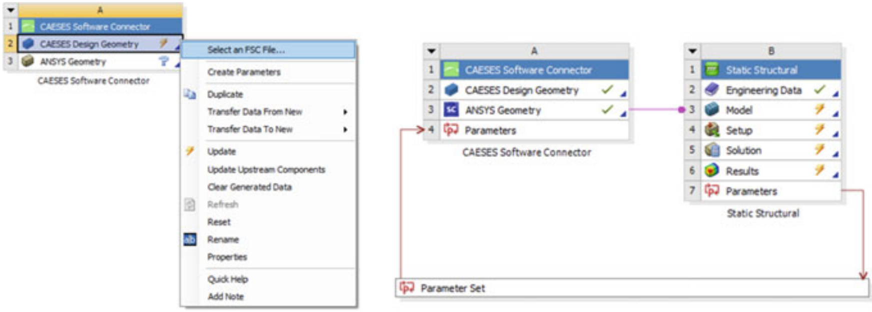
Fig. 2.14 Excerpt of CAESES feature for the connection to Excel (AC Offshore Platform)

Figure 2.14 shows an excerpt of a feature within CAESES with which to connect to Excel in the context of the application case of the design of an offshore platform. Within this AC, an Excel spreadsheet was developed that determines project costs (as an objective), the estimated duration for platform installation and an overall feasibility (as a constraint).

A more elaborate explanation about integration via COM can be found in (Abt et al. 2009). Further adaptations, maintenance and improvements were realized within the scope of the HOLISHIP project.

2.4.2 *CAESES and ANSYS Workbench*

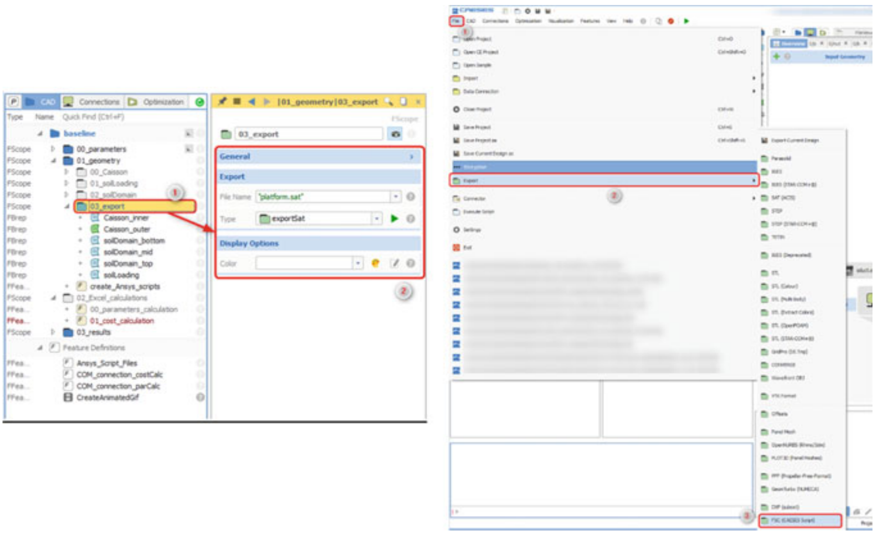
For the same AC of an offshore platform, an additional type of connection was needed, namely a smooth connection between CAESES and the ANSYS Workbench, with ANSYS Finite Element Analysis (FEA) being one of the market leaders in structural design. Building on the existing collaboration between ANSYS and FRIENDSHIP SYSTEMS, two interfaces could be established to support data exchange between CAESES and the ANSYS Workbench: (i) The ANSYS Workbench is run from CAESES as the controlling entity (i.e., the PIDO) and (ii) CAESES becomes available within the ANSYS workbench. While the former regards the ANSYS Workbench as yet another tool run in batch-mode, the latter offers CAESES parametrics



(a) Selection of a CAESES FSC file (for batch-mode execution)

(b) Link between an "ANSYS Geometry" and a component that processes geometry

Fig. 2.15 Integration of CAESES® within the ANSYS Workbench (AC Offshore Platform)



(a) Selection of objects to be exported

(b) Creation of a CAESES script file for the Workbench

Fig. 2.16 Integration of CAESES within the ANSYS Workbench (AC Offshore Platform)

and geometry generation for the Workbench as a plug-in (or component), further increasing the scope of multi-lateral integration.[3]

Figures 2.15 and 2.16 illustrate the integration within the ANSYS Workbench. Here, CAESES itself is executed in batch-mode (on the basis of an FSC file, i.e., a CAESES script file, see Fig. 2.15a). Within the AC Offshore Platform this approach

[3]In this context it should be noted that the ANSYS Workbench is a very flexible integration platform in its own right and hence, similar to what has been discussed, this additional connection increases the scope of applicability.

was utilized to compute with ANSYS FEA the maximum deformation under gravitational loads, under ice loads and under wave loads for a set of platform geometries (caisson) and seabed configurations (soil), see Fig. 2.15b.

2.4.3 Integration via XML

Within CAESES, tools can also be integrated on the basis of data exchange via XML files. This type of integration is typically used (and favoured) by tool developers that can freely decide on the format of their input and output files and that opt for XML syntax to combine human readability with easy maintenance.[4]

The XML integration in CAESES is based on a custom document type definition (DTD) provided by FRIENDSHIP SYSTEMS. This DTD defines all usable datatypes for both input and output, enabling the tool developer to complement (or, alternatively, even to replace) the existing input and output files by file formats following standard XML syntax. As soon as this has been done—which represents the major work load encountered—the tool provider sets up a so-called CAESES Definition which contains all possible input data. This can be readily done by using the GUI of CAESES itself.

Figure 2.17 shows parts of the so-called XFFL file for MARIN's flow code RAPID for illustration, RAPID being a nonlinear potential flow code for wave resistance computation. Figure 2.18 illustrates the definition for RAPID in the object tree of CAESES along with one of the entries, here the Froude number, in the object editor. Entries can be added or deleted and all necessary attributes like name, type, default value, number of occurrences etc. can be set interactively. Furthermore, CAESES Definitions can be structured in groups and sub-groups.

A CAESES Definition is saved in an XML file by the tool developer and then directly supplied to the users. This means that tailored versions of a tool, new features and changes can be distributed throughout a tool's user community without any need of involvement of FRIENDSHIP SYSTEMS. See also (Abt et al. 2009) for details. As with the COM interface, further adaptations, maintenance and improvements were realized within the scope of the HOLISHIP project.

2.4.4 Cross-Platform Integration of Tools

Tool integration as needed to build synthesis models does not only face the challenge of having to bring together separate tools from different providers with non-homogeneous inputs and outputs, disparate data storage, non-harmonized nomenclature etc. but also that not all tools can be made available on a single computer

[4]This situation is different to that of a pure software user who, commonly, has neither influence on any of the file formats nor on their syntax and semantics.

```xml
<?xml version="1.0" encoding="UTF-8" ?>
<!DOCTYPE xffl>
<xffl name="caseRapidDef01" >
  <FDouble name="FroudeNumber" >
    <value>0.3</value>
  </FDouble>
  <FDouble name="WaterDepth" >
    <value>50</value>
  </FDouble>
  <FInteger name="NumberOfStrips" >
    <value>37</value>
  </FInteger>
  <Group name="RapidInput" >
    <FDouble name="InitialSinkage" >
      <value>0</value>
    </FDouble>
    <FDouble name="InitialTrim" >
      <value>0</value>
    </FDouble>
    <FBool name="FixSinkageAndTrim" >
      <value>true</value>
    </FBool>
  </Group>
  <Group name="FreeSurfaceInput" >
    <FDouble name="ExtendAhead" >
      <value>1</value>
    </FDouble>
    <FDouble name="ExtendAstern" >
```

Fig. 2.17 Excerpt of XFFL file for MARIN's RAPID code

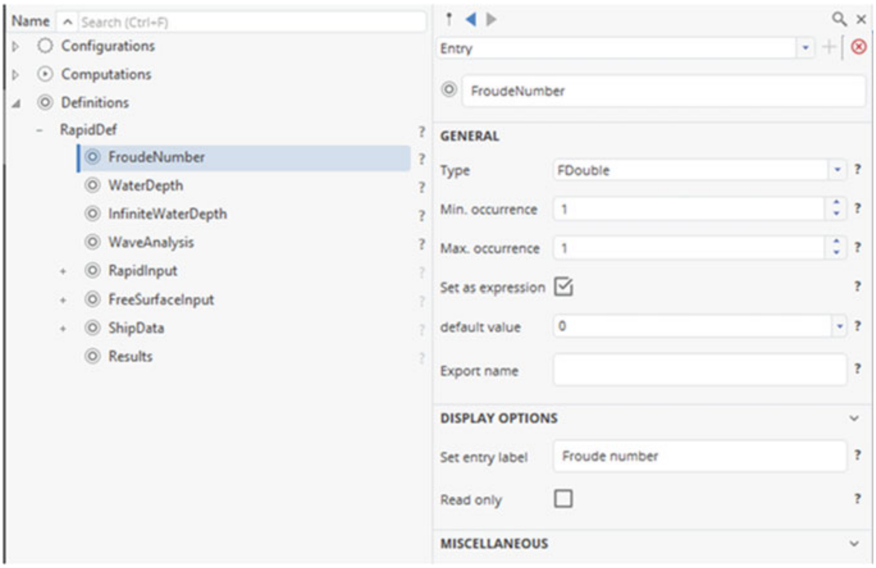


Fig. 2.18 Definition within CAESES®

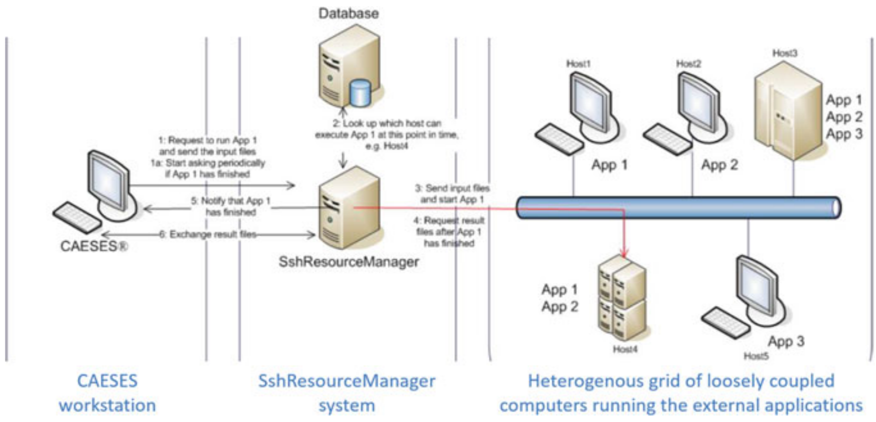


Fig. 2.19 CAESES resource manager for usage of tools across platforms and on different computers

or even within the same operating system. One way to circumvent this problem is to utilize surrogates as discussed in Sect. 2.3.3. An additional means of bridging the gap between computers and/or operating systems is to use CAESES' resource management capabilities.

As shown in Fig. 2.19 different apps—i.e., applications, meaning simulation tools and/or other integration platforms—can be accessed by a CAESES instance via the so-called SshResourceManager that can trigger and communicate with computers, may they run under Windows® or under Linux™, which are administered within one (local) network or within a virtual private network (VPN). This then enables, for instance, a design engineer to run CAESES on his or her personal computer, say under Windows®, and make use of a simulation tool that was installed and for which a license was provided on a more powerful Linux™ workstation (or on an HPC). It also supports the utilization of various computers for resource-intensive simulations overnight and over weekends when these computers would usually not be needed for interactive work. Furthermore, it can be put to use to run a tool remotely that is only installed on a colleague's computer and to which concurrent access cannot be provided easily.

2.5 Selected Connections and Collaboration

The main strategy behind the development of CAESES® and of HOLISHIP in general was not to attempt to introduce yet another monolithic system. Rather, the approach was to flexibly connect tools as they are needed for solving challenging design tasks. CAESES allows communication with stand-alone simulation tools either in a one-to-one relationship or in a one-to-*m* synthesis model (see again Figs. 2.1, 2.2, 2.3 and 2.4) with m being the number of tools connected. In addition, CAESES as the chosen integration platform can collaborate with Computer Aided Engineering systems that represent platforms themselves.

Several CAE systems were utilized within the scope of HOLISHIP's application cases, e.g. the ANSYS Workbench (see above) from ANSYS, CADMATIC from Elomatic, NAPA Ship Design and NAPA Steel from NAPA OY and the Remote Component Environment (RCE) from DLR. The primary motivation for this was and continues to be that the engineering environments found in industry are rather diverse and that, depending on experience, available soft- and hardware, partners involved, the design task to undertake etc. a number of tools, be it for the reason of utilizing best-of-class or just the tools at hand, need to be brought together. If a CAE system then already has connections to other tools the key advantage of collaboration between platforms is obvious, i.e., an integration need not be replicated but integrating systems and/or frameworks can cascade and exchange data from one system to the other.[5]

Some of the connections and collaborations shall be highlighted here with reference for further reading.

2.5.1 CAESES and CADMATIC

Figures 2.20 and 2.21 are taken from the application case of the design of a double-ended ferry. As discussed in detail in Harries et al. (2019) CAESES and CADMATIC exchange data that relate to the hull form and the inner structure. CADMATIC utilizes the current hull geometry to map a parametric model for decks, bulkheads etc. to generate an estimate of steel weight. When changing the hull form the inner structure is automatically adapted so that a considerable range of design variants can be taken into account.

The full elaboration of the design task, the optimization, including hydrodynamics and considerations for batteries, a hybrid and a conventional drive system, along with results are given by the task leader, Elomatic, in (Jokinen et al. 2020, and Chap. 12 of this book).

2.5.2 CAESES and NAPA Steel

Figure 2.22 is taken from the application case of the design of a RoPAX ferry (AC RoPAX). It shows the imported data of the steel structure set up for the RoPAX ferry (design Alpha). Here, CAESES allows filtering of data for viewing and examination.

[5]Moreover, the direct connection of tools that CAESES communicates with is not prohibited. In other words, if two tools that are integrated in a synthesis model require direct data exchange that can be accommodated, too.

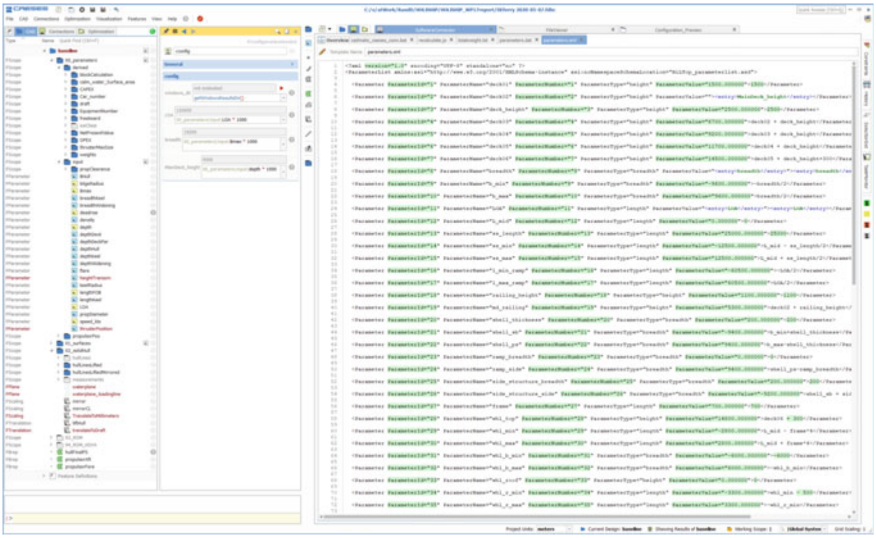


Fig. 2.20 Coupling of CAESES and CADMATIC (AC Double-Ended Ferry)

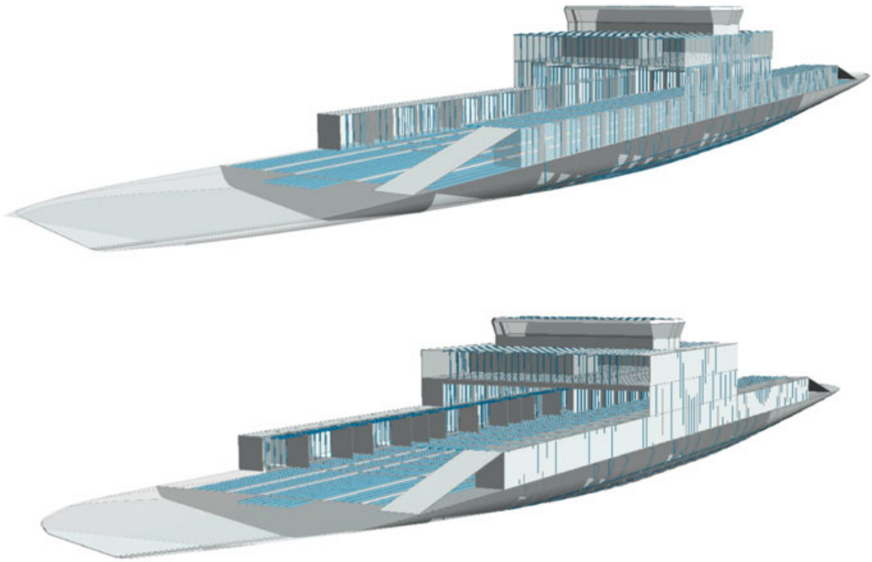
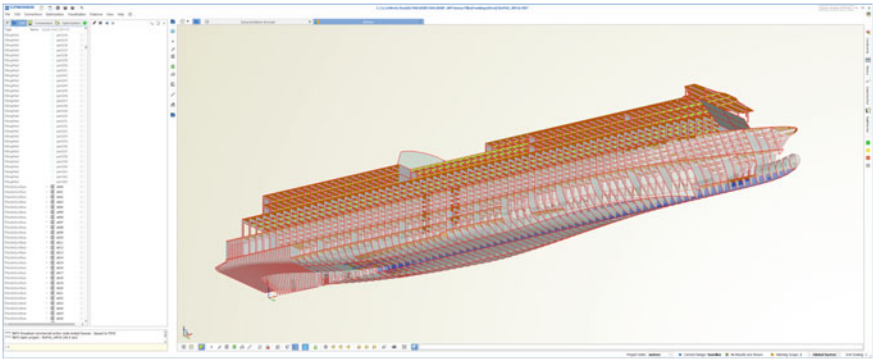
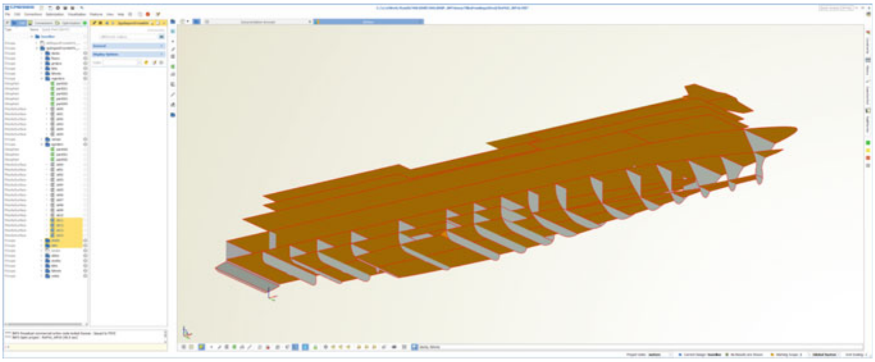


Fig. 2.21 Two variants of a parametric model for steel weight analysis within CADMATIC as triggered via CAESES (AC Double-Ended Ferry)



(a) Import from NAPA Steel (with plates of outer shell set as non-visible)



(b) Filters set to visualize decks and bulkheads

Fig. 2.22 Import from NAPA Steel (AC RoPAX)

2.5.3 CAESES and Shipbuilder

Figure 2.23 is taken from the application case of the design of a Multi-purpose Ocean Vessel (MPOV) (AC MPOV by the Naval Group, see Chap. 6 of this book). It displays the data imported from a general arrangement (GA) of blocks, representing rooms, compartments and important functional areas and volumes as defined within Shipbuilder by Sirehna. Details are described in (Le Néna et al. 2020). The data imported from the GA helps to adjust the hull shape or, alternatively, to check if the blocks fit the geometry and to identify which blocks may need adjustments (e.g. cut-aways, tapering, resizing, relocation etc.).

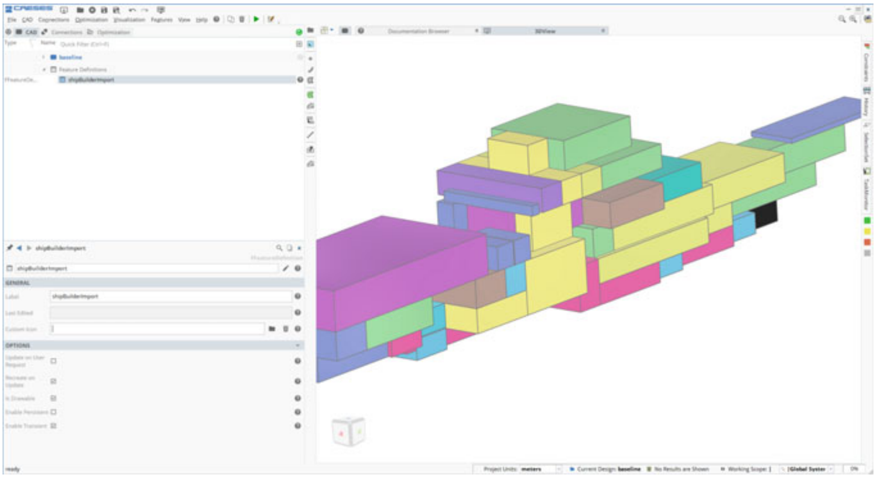


Fig. 2.23 Import of blocks in CAESES (AC MPOV)

2.6 Outlook

2.6.1 Version Control

It needs to be noted that CAESES even though versatile and flexible as a parametric modelling system (CAD) and as a process integration and design optimization environment (PIDO), respectively, has the inherent limitation of not being a product life-cycle management system (PLM). A PLM system would offer roles, access rights, version control, check-out and check-in of data, unified and long-term data storage etc. This is not the purpose of CAESES and, when developments started in 2004, was not part of its roadmap. Consequently, in order to elevate integration, coworking, concurrent engineering, collaboration between team members and also across company boundaries to another level, an additional PLM layer would be required. This was beyond the purpose of the HOLISHIP activities. Nonetheless, it would be worthwhile to pursue this topic, even though it has to be addressed with considerable effort within a yet to be defined new R&D project.

2.6.2 Marketplace

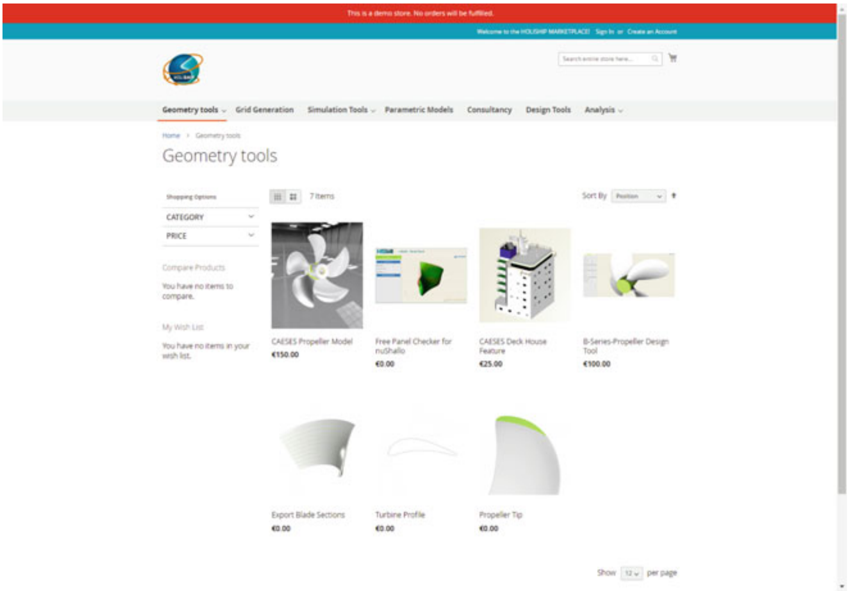
Complementing the holistic approach to ship design and the development of integration platform(s) within HOLISHIP, further ideas were proposed and studied, namely how to enable access to tools of various origin at a wider range, not only for partners of HOLISHIP but for the broader maritime community.

A first prototype of a web-based marketplace was realized on the basis of MAGENTO, a platform for B2B (and possibly also B2C) commerce. Figure 2.24 gives an impression. In principle, such a marketplace can offer tools, services, consultancy for design and simulation, quality assurance and can bring together teams beyond traditional company and academic boundaries. Two examples tasks are described in Table 2.3.

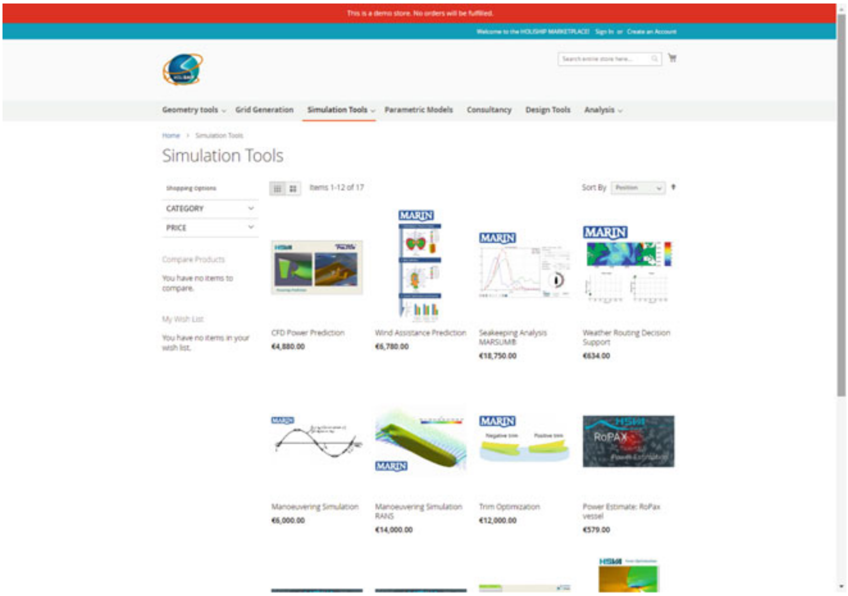
2.7 Conclusions

The purpose of integration and collaboration is to create synthesis models that comprise the most important drivers, i.e., the key aspects, when working on a specific design task. Since key aspects and the way they are determined differ depending on the design stage, the actual design task and the available resources an ad-hoc assembly of tools and systems as well as of dedicated parametric models and surrogates are proposed. The approach showed its validity and versatility when brought to life and put to use for challenging applications, namely the design of twin-screw passenger ferries of different size (RoPAX), the development of an Offshore Supply Vessel (OSV) for safe crane operations under dynamic positioning, the concept and contract design of a Multi-Purpose Ocean Vessel (MPOV) for safety and security as well as search-and-rescue in European waters, the design of a double-ended ferry (DE-ferry) with electric (alternatively hybrid and conventional) propulsion, the design and installation of a gravity-based offshore platform for shallow waters and, moreover, the retrofitting of a bulk-carrier and a container ship already in operation. As can be readily appreciated neither the design challenges nor the synthesis models for these application cases are the same nor are the parties involved or the interests they pursue.

Setting up suitable synthesis models takes time as well as the expertise and cooperation of several partners. Presently, this may still call for too much effort and may yet take too much time for daily practise when working on standard designs. Nevertheless, once synthesis models are available they can be employed to run sophisticated optimisation campaigns in order to generate valuable and new insight. This then leads to cutting-edge and even to rather ingenious designs which yields a competitive advantage in a commercially challenging economy. In particular if non-standard solutions are required the potential gain merits the effort. Furthermore, with each new integration and with more experience gained, the speed of setting-up synthesis models and the benefit of utilizing them for simulation-driven design increases.

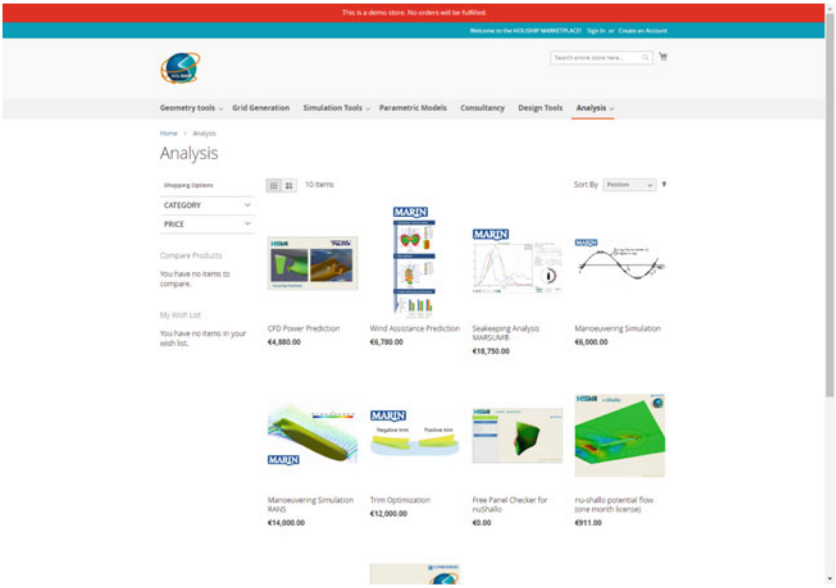


(a) Possible way to offer geometry tools
(N.B. Prices are not consolidated; they are purely given for illustration purposes)

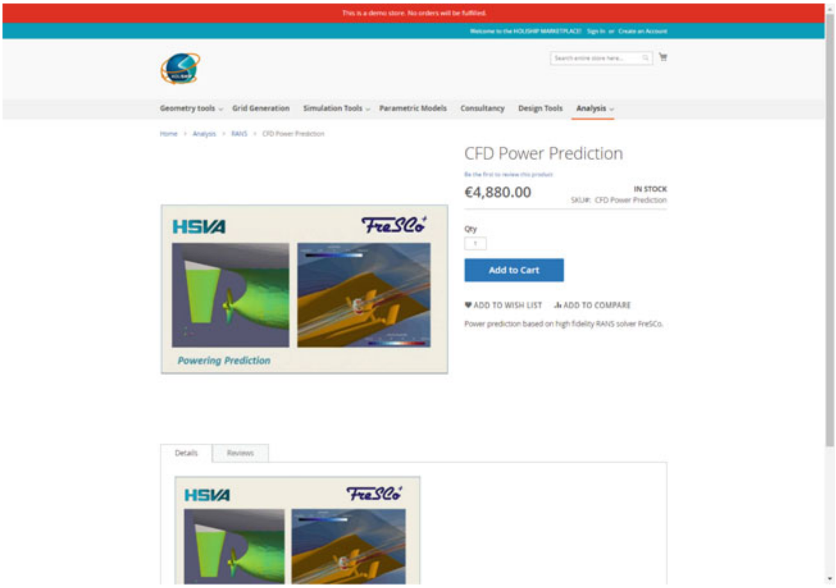


(b) Possible way to offer simulation tools
(N.B. Prices are not consolidated; they are purely given for illustration purposes)

Fig. 2.24 Screen shots from a first mock-up of a potential HOLISHIP marketplace (note that this is an outlook and all prices shown are purely fictitious and are given just for illustration)



(C) Possible way to offer analysis tools
(N.B. Prices are not consolidated; they are purely given for illustration purposes)



(D) Possible way to offer specialized CFD power prediction
(N.B. Prices are not consolidated; they are purely given for illustration purposes)

Fig. 2.24 (continued)

Table 2.3 Exemplary description of tasks and solution approaches for a possible marketplace on the basis of HOLISHIP (outlook)

Description: “My current design still requires an improved bulbous bow for a given operational profile. The lines are established. However, the bulb region just aft of the forward perpendicular, the lengths and volume of the bulb can still be changed We would need the improved design within the next five days in order to decide on the engine and freeze the lines” (a) Task description: Bulbous bow optimization	Solution via the HOLISHIP marketplace 1. The ordering company uploads several perspective views of its hull form along with a task definition and the description of the operational profile 2. It invites users of the marketplace to make an offer (price and time of delivery) within a certain time frame 3. It then selects its favorite offer and uploads the hull geometry to a secure area of the marketplace (e.g. STL-file, iges-file, CAESES project) 4. The service provider that runs the project starts the optimization work 5. While work is in progress certain data such as optimization history can already be accessed by the ordering company; selected variants can be downloaded for further investigations 6. The service provider and the ordering company discuss results in a virtual meeting (e.g. GoToMeeting) offered via the marketplace 7. Upon finishing the project invoicing is done automatically via the marketplace (e.g. PayPal, standard invoicing by automatically sending documents to all parties involved) (b) Solution approach for (a)
Description: “As a design team we are working on a new design which is supposed to be a SWATH. We have not yet worked on any SWATH of similar size nor can we find or access reliable data for resistance and propulsion We would need data for resistance at the design speed and one lower speed by the end of next week. So far we only have preliminary lines and estimates of the main dimensions” (c) Task description: Numerical hull series	Solution via the HOLISHIP marketplace 1. The ordering company uploads a sketch of its design along with a definition of the task 2. It invites users of the marketplace to make an offer (price and time of delivery) within a certain time frame 3. It then selects the service provider(s) • The fastest and most economic solution is a service by two partners that work together • One partner will provide a parametric SWATH model while the second partner will run the CFD analyses to build a surrogate model 4. The first service provider develops a parametric model in CAESES® within three days. The parametric model is made available to the ordering company via a WebApp 5. The ordering company uses the WebApp to study the model and give feedback 6. The CFD provider already uses a baseline geometry from the parametric model for setting up the CFD computations 7. Based on a slightly modified parametric model all three partners discuss the details for the numerical series in a virtual meeting (e.g. GoToMeeting) offered via the marketplace 8. The CFD provider runs the Design-of-Experiment over several days and provides the data for the surrogate model 9. While work is in progress certain data such as wave heights, pressure distribution, streamlines can already be accessed by the ordering company; selected variants can be downloaded for further investigations 10. Service providers and ordering company discuss final results in a virtual meeting 11. Upon finishing the project invoicing is done automatically via the marketplace (e.g. PayPal, standard invoicing by automatically sending documents to all parties involved) (d) Solution approach for (c)

Acknowledgements The authors like to say thank you very much to both the development team and the PreSales&Support team at FRIENDSHIP SYSTEMS. The contributions to this report by Erik Bergmann, Ceyhan Erdem, Stefan Wunderlich and Heinrich von Zadow shall be thankfully acknowledged in particular. Furthermore, the editorial effort put in by Aimilia Alisafaki (NTUA) shall be thanked for very warmly.

Finally and very importantly, the authors would like to express their very special thanks to the leaders of the consortium—Dr. Jochen Marzi (HSVA) and Prof. Dr. Apostolos Papanikolaou (HSVA/NTUA)—for their relentless efforts for and excellent project management of HOLISHIP.

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Chapter 3
Design and Operation of an Offshore Support Vessel

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Abstract Offshore Service Vessels (OSV) are utilized for demanding offshore operations often under challenging conditions, e.g. Anchor Handling Tug Supply vessel (AHTS) supporting offshore drilling rigs and Offshore Construction Vessels performing subsea installation. The OSV case in the HOLISHIP project has addressed

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A. Papanikolaou (ed.), *A Holistic Approach to Ship Design*,
https://doi.org/10.1007/978-3-030-71091-0_3

both these vessel concepts with the main focus on power system optimization based on the operational profile for the vessel. Regarded as highly specialized vessels, OSV design requires the synchronization of several of disciplines. Thus, a holistic approach, considering Key Performance Indices (KPIs) for several disciplines, was developed and utilized from a conceptual design level to the power system concept verification. Sub-optimization of each module for different KPIs without taking into account the interaction between the modules does not necessarily lead to an optimized overall performance of the vessel and a holistic approach design is highly likely to be beneficial. At the early design stage of a vessel, important parameters are defined having a huge impact on the performance of the vessel according to the KPIs. Changing these parameters at a later stage in the design process is difficult and requires a considerable effort from the multidisciplinary design team. This Chapter presents the holistic design of the OSV application case from main dimension determination to power system design, optimization and verification. Significant improvements for selected KPIs have been obtained comparing the optimized concept with the baseline vessel. The design optimization methods developed here are already being used in other research and commercial projects proving increase efficiency in the early design stage. The methods for virtual verification using dynamic simulations are being further developed and used in other research projects.

Keywords OSV · CAESES · COSSMOS · Holistic ship design · MPSET · Power system optimization · Ship emissions · RAM analysis · Risk based analysis

Abbreviations

AC	Alternating (electric) Current
AHC	Active Heave Compensated
AHTS	Anchor Handling Tug Supply
BMS	Battery Management System
BuDa	Bubble Diagram (architecture diagram tool of SIREHNA)
C++	Object-oriented computer-programming language
CAESES	CAE System Empowering Simulation
CAPEX	CAPital EXpenditures/EXpenses
COSSMOS	Complex Ship Machinery Systems Modelling and Simulation (software developed by DNV-GL)
CPCP	Controllable Pitch
DC	Direct (electric) Current
DG	Diesel Generator

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DP	Dynamic Positioning
ESS	Energy Storage System
FMI	Functional Mockup Interface
FMU	Functional Mockup Units
GMt_0	Initial transversal Metacentric Height
GNSS	Global Navigation Satellite Systems
GRIF	GRaphical Interface for reliability Forecasting (RAM tool by Satodev)
GZ	Righting arm distance when heeled
HOLISHIP	HOLIstic optimisation of SHIP design and operation for life cycle (EU H2020 project)
HC	Heavy Consumer
Hs	Significant wave height
IMO	International Maritime Organization
KM	Distance from Keel to Metacentric point
KPI	Key Performance Indicators
LCB	Longitudinal Centre of Buoyancy
LCF	Longitudinal Centre of Flotation
LCPA	Life Cycle Performance Analysis
LOA	Length Over All
MBB	Main Bus Bar
MPSET	Marine Power System Evaluation (tool of KONGSBERG)
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
NMVOC	Non-Methane Volatile organic Compound
NOx	Nitrogen Oxide
OPEX	OPerational EXpenes
OSV	Offshore Service Vessel
PM	Particulate Matter, total suspended particles
PMS	Power Management System
RAM	Reliability, Availability and Maintainability
RAO	Response Amplitude Operator
SAR	System Architecture and Requirements (tool of SIREHNA)
SC	Sensitivity Case
SHIPFLOW	Ship Flow resistance calculation (software by FLOWTECH)
ShipX	ShipX Workbench Simulation (software by SINTEF)
SFOC	Specific Fuel Oil Consumption
SLD	Single Line Diagram
TSP	Total Suspended Particles
UT	Ulstein Trading
VERES	VEssel RESponse program (ShipX plug-in of SINTEF)
VEPOST	VEssel POST-processing program (ShipX plug-in of SINTEF)

3.1 Introduction

Offshore Service Vessels (OSV) are utilized for demanding offshore operations often under challenging conditions. The OSV case studies in the HOLISHIP project focused on two different OSV vessel types; an AHTS supporting offshore drilling rigs and an offshore construction vessel performing subsea lifting operations. These vessel types provide different criticalities in vessel and system design. The AHTS has complex power systems operating with a wide power demand range. This vessel type was also used as reference vessel in the development of the power system evaluation tools as reported in Chapter 13 (Torben et al. 2019) of the first volume of Holiship Book (Papanikolaou 2019).

The mission of the vessel under this application case is to perform subsea installation of heavy modules in ultra-deep waters using an active heave compensated (AHC) crane. Therefore, the main purpose of the vessel is to transport the heavy module from shore to the installation site and, subsequently, to serve as a stable platform for the lifting operations over the side of the vessel using the subsea crane of fibre rope or steel wire rope. The type of wire has direct impact on the weight distribution of the operation and thus lead to different optimal vessel size solutions. The aim is to find the combination of vessel size for each crane type capable of performing the mission at the lowest possible cost considering both capital and operational expenses (CAPEX and OPEX).

This application case presents an interesting design optimization challenge involving all naval architecture disciplines to showcase the possibilities of the HOLISHIP principles and the capabilities of the developed design optimization tools. The overall design optimization process consists of three distinct phases of optimization and verification with increasing level of detail (Table 3.1). Four post-processing parts will be linking the three phases together.

The three phases are connected through a post-processing work area, where input required, and output generated is collected and results are analysed. Figure 3.1, shows a schematic representation of the three phases, their tools, and how these are connected via the post-processing work area.

Table 3.1 The three phases of design optimization

Phase	Description
1	High-level evaluation of main dimensions of the vessel
2	Evaluation of power system, RAM (Reliability, availability, maintainability) and life cycle analysis
3	Verification

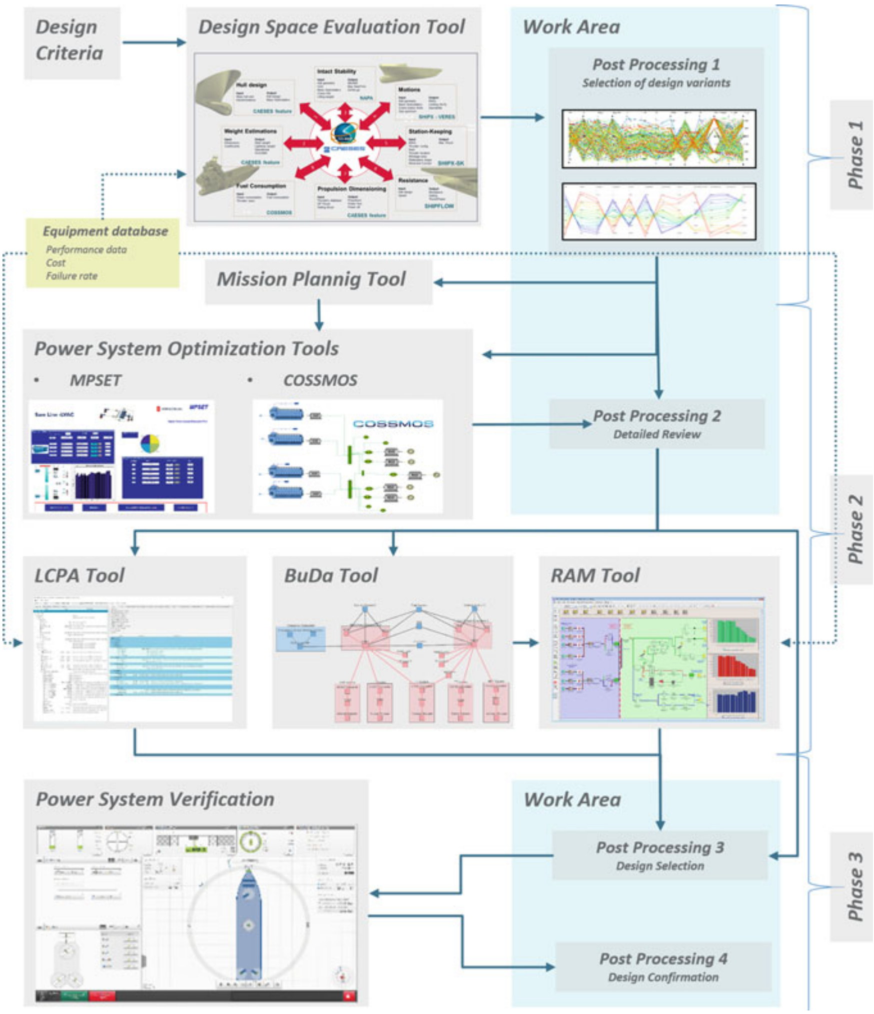

Fig. 3.1 Representation of the tools used through the design phases

3.2 Phase 1—High Level Conceptual Design

As part of the HOLISHIP project, Kongsberg Maritime has teamed up with Friendship Systems (developer of CAESES), SINTEF Ocean and DNV-GL to establish an integration platform for the various design tools on this early design phase of the OSV. Phase 1 is a high-level evaluation of main dimensions of the vessel and the propulsion units based on the variation of several design parameters, a set boundary conditions and criteria, and a handful of calculation tools presented in Fig. 3.2. The

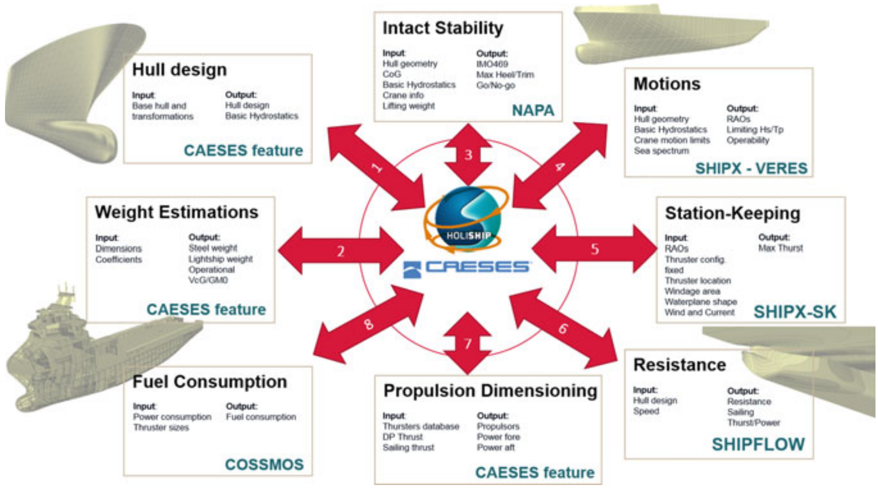

Fig. 3.2 Coupled design disciplines and tools in Phase 1

Table 3.2 High level conceptual design summary

Phase 1	Power system concept verification
Objective	Multi-disciplinary optimization of an OSV vessel
Input	Operational task and a baseline vessel
Method	Parametric intercoupling of each design discipline/tool
Output	Vessel main dimension and propulsion units size

result of this evaluation feeds basic vessel design parameters of a feasible concept to Phase 2 and Phase 3 (Table 3.2).

The output of Phase 1 is dependent on a collection of inputs resulting from an operational scenario that the vessel must fulfil. These can be summarized as:

- 1,300 m^2 of flat deck cargo area,
- 6,000 m^2 of accommodation and living spaces above main deck,
- 4,500 tonnes of deadweight capacity,
- Initial frozen transversal metacentric height (GMt_0) of 1.75 m during a stationary crane lifting operation,
- Station-keeping capability (DP2, Dynamic Positioning class 2) up to 3.5 m Hs (significant wave height), 12.5 m/s wind and 2 m/s current, at 30° heading angle,
- 13 kn of economical forward sailing speed in calm waters,
- Operational profile 40% DP, 40% sailing and 20% harbour,
- Propulsion units composed by 2 aft azimuthal thrusters, 2 forward tunnel thrusters and 1 retractable azimuthal forward thruster.

Additionally, a comparison between two types of crane was performed, a fibre-wire type crane, weighting 200 tonnes, and a steel-wire crane, weighting 500 tonnes, both able to lift 250 tonnes of cargo.

3.2.1 Multi-disciplinary Design Space

An alternative overview and more detailed understanding of the design process outlined in Fig. 3.2 is through the diagram in Fig. 3.3. It includes all required inputs, to all performed computations, constrains and KPIs utilized to choose an optimal design candidate to be studied in further detail during phases 2 and 3.

The first step towards the multi-disciplinary design optimization is to prepare a baseline design, which was obtained from KONGSBERG's UT 7623 (Ulstein Trading) OSV concept design, and set-up transformations relevant to the design process: main dimensions and sailing optimization possibilities such as local deformations and Lackenby shift (a longitudinal based Cartesian shift of the section area curve, maintaining vessel's displacement constant). From the transformed geometry, hydrostatics parameters are extracted, such as KM (height of the Metacentre from Keel), wetted surface, LCB (Longitudinal Centre of Buoyancy), LCF (Longitudinal Centre of Floatation) and displacement. This stage was solely performed in CAESES, with extra attention given to geometry robustness with applied transformations, ensuring reliable results of the subsequently calculations.

The second step performed was a loading condition estimation. Considering the accommodation and cargo area required, different arrangements depending on the main dimensions of the vessel, especially on the number of forward accommodation decks, thus vertical centre of gravity estimation. In order to obtain a fair comparison between all design candidates, an *FBrent* engine (one dimensional minimization algorithm) in CAESES is executed to adjust the operational draught such as the vessel's deadweight is 4,500 tonnes, creating already the first design dependency connection. The type of crane utilized for the operation is also of importance, as they have different weights and weight distribution. Utilizing previous similar vessels weight and centre of gravity estimations, constants are applied to the design variant and important KPIs are obtained from this stage: lightship weight, operation's vertical centre of gravity and GMt_0 (Initial transversal Metacentric height). These are essential, as they might constrain subsequently calculations, avoiding the calculation of unfeasible design candidates.

The third discipline evaluated was intact stability, calculating IMO 469 requirements which, in summary, are a list of minimum required hydrostatic values of a heeled ship without any hull damage. With a custom written feature in CAESES, a watertight description of the hull is heeled up to 60° in order to plot the GZ (righting arm distance between the centre of buoyancy and gravity) curve of the design candidate. In parallel, the hull and required parameters are imported into NAPA (Naval

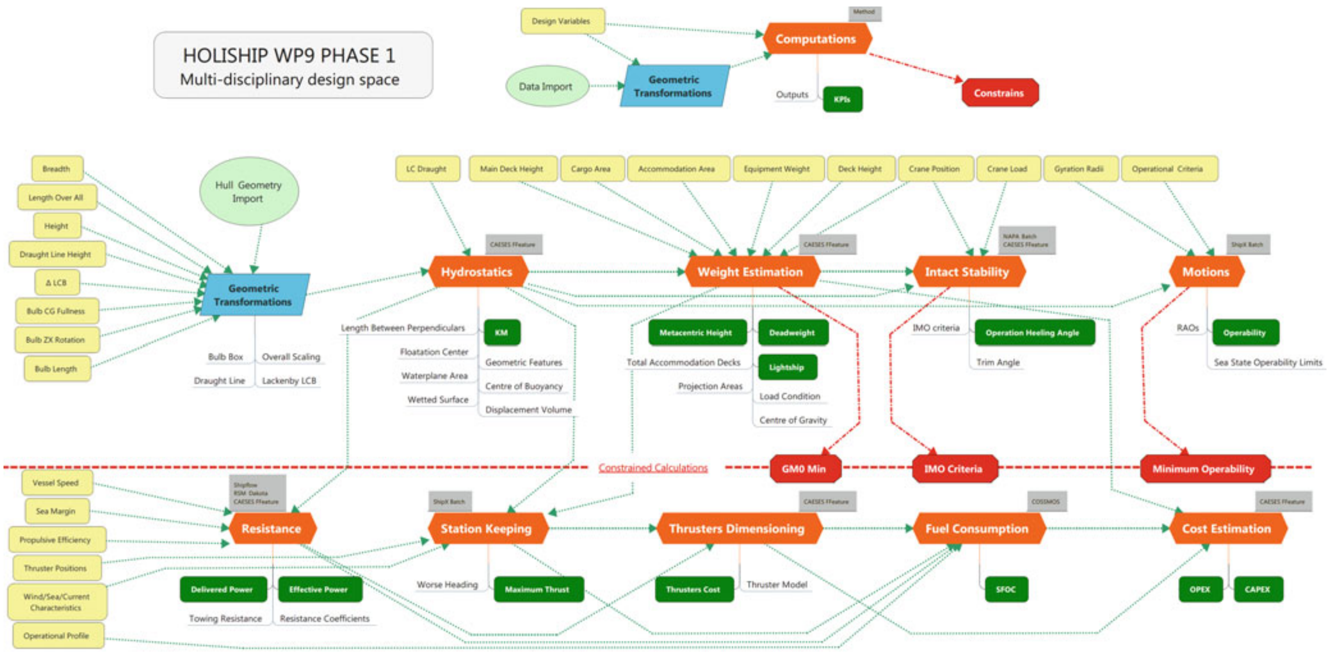

Fig. 3.3 Parameters, computations, constrains and KPIs in Phase 1

Architectural Package) and a lateral drop-load calculation is performed, returning the maximum heeling angle of the vessel in case of a fully loaded crane. From this calculation step, a second constraint of passed or failed IMO stability criteria is created and applied to subsequent steps.

Seakeeping is the fourth discipline integrated into the main core of software tools used for the simulation of operation in CAESES. The vessel's sections, hydrostatics parameters, bilge keel position and anti-rolling tank characteristics are imported to SINTEF Ocean's ShipX VERES toolbox that is integrated in CAESES; VERES is a potential, strip theory based tool that can calculate ship motions and global loads in waves, including short term statistics, long term statistics and operability. With the result files from VERES, ShipX's post-processor module (VEPOST) is executed and the vessel's operability is estimated based on a generic North Sea scatter diagram, crane operational limits as: maximum vertical crane tip displacement of 2.4 m and vertical velocity of 1.5 m/s. Additionally, RAOs (Response Amplitude Operators) are plotted in CAESES, monitoring magnitude and position (wave period) of motion responses for each vessel design variant.

Following Fig. 3.2, a steady-state dynamic positioning operation was simulated with another plug-in of SINTEF Ocean's ShipX workbench, the ShipX—Station Keeping. The results from station keeping analysis are of paramount importance with respect to dimensioning, positioning and usage of the force generators on the vessel. The vessel calculated in this study project has 2 identical aft located azimuthal thrusters, 2 identical forward tunnel thrusters and an additional forward azimuthal swing-up thruster. The station keeping calculation uses the RAOs file from VERES, frontal and lateral windage areas, waterline shape, wind and current vessel shape coefficients (obtained from KONGSBERG's UT design database), and returns the thrust required at each thruster to maintain position at a 3.5 m Hs, 12.5 wind and 2 m/s current sea condition, all coinciding at a heading angle of 30°. For dimensioning purposes of the thrusters, the DP2 failure mode returns the highest thrust required. This mode is a simulation of a switchboard failure, which is the worst case scenario of a fault in a single component failure. This will result in the shutdown of one aft-thruster and one tunnel thruster simultaneously. For this reason, two station-keeping simulations were performed for each design variant; one for intact condition, no failure, for fuel consumption estimations; and a failure DP2 mode, for maximum thrust estimation and thruster size dimensioning.

For fuel consumption estimations, resistance and propulsion calculation are also required and were included as the sixth discipline. Unfortunately, the precise calculation of calm water resistance is somewhat still time consuming with current CFD tools (between 1 and 2 h for each design variant). Thus, an empirical model for full scale resistance estimation (based on Holtrop-Mennen) was adapted to match the baseline vessel resistance estimated with CFD computations, including designs on the edge of the defined design space. The wave resistance component was calculated by use of SHIPFLOW, being able to optimize the vessel's wave pattern in calm waters with the transformations created on the first step. Addressing the computational time required when quick design variants evaluations are to be performed, the design space was pre-calculated and a response surface was created (*surrogate modelling*) and utilized to return the lowest achievable wave resistance component for that design variant.

The simplified cost estimation in phase 1 for relative comparison of design variants was divided in two parts. CAPEX considers propulsors costs and the lightship cost (steel, outfitting and standard equipment). OPEX cost considers fuel consumption estimations only. The lightship weight is used to estimate building cost and makes up to 90% of the CAPEX cost in this project example. Thus, reducing the vessel's dimensions is essential for CAPEX reduction. Thruster model size is also relevant, being dimensioned from the maximum input thrust loads (DP/DP2 or sailing conditions). The fuel consumption estimations were performed by a batch version of the COSSMOS software tool of DNV GL created for this study case. In this stage of design, it uses a fixed power system configuration and a simplified operational profile composed of 40% transit sailing at 13 kn, 40% of DP operation (intact mode) and 20% at harbour. It calculates yearly fuel consumption for four different engines (the B32:40L6A, B32:40L8A, C25:33L8A and C25:33L9A from Bergen Engines).

3.2.2 Post-processing 1—Holistic Design Optimization and Results

For benchmarking purposes, the baseline vessel design of a subsea construction vessel, KONGSBERG's UT 7623 design, 123.7 m LOA (Length Over All), 23 m beam, 6.5 m design draught, with the same offshore crane capability was used.

The first approach to the optimization was to perform a permutation investigation of the design space (from 86 to 130 m LOA, and from 22 to 25 m breadth) and observe how the KPIs behave. First results proved GMt_0 being the limiting criteria and constraining the execution of further parameters calculation. When comparing results for the two types of cranes, the higher centre of gravity of the steel wire crane type results in fewer designs with GMt_0 criteria satisfied. In other words, for the same task, a steel-wire crane vessel type requires a larger beam dimension (from 0.6 m for a 130 m LOA OSV up to 0.9 m for an 86 m LOA vessel).

In order to eliminate problems with stability issues and avoid that unfeasible designs are calculated, another *FBrent* algorithm was applied to find the smallest beam for a given LOA that satisfies intact stability criteria. This step addition basically resulted in the Pareto curve of minimal vessel size for the optimization problem faced. Reviewing these results showed that windage areas vary with vessel main dimensions, due to the required accommodation and cargo area, and influence the forces during station-keeping operation. A shorter and wider vessel yields smaller lateral windage area, which result in less thrust required during DP operations, lower thruster sizes and thus lower fuel consumption. Basically, when shorter and wider, the dimensioning of the propulsors are guided by the towing resistance, whilst when long and narrower, the windage area defines the thrust required for the DP operation. Therefore, the balance of these two fuel consumption factors results in the optimal sizing of a vessel for this type of mission.

The chosen design to be further developed in phases 2 and 3 of the Holiship OSV case study came to be a 91.5 m LOA, 23.8 m beam and 7.4 m draught vessel with the fibre-wire crane variant. Its main KPIs (relative to baseline vessel) are: 94.8% of lightship cost (CAPEX) and 93.7% of fuel consumption compared to the baseline vessel.

Last but not least, the difference in required breadth to satisfy intact stability in both wire type variants (designed to execute the same task) decreases the potential reduction in both fuel consumption and CAPEX by approximately 0.4%.

3.3 Phase 2—Power System Concept Design and Optimization

A typical power system of an OSV is made up of multiple power sources, accompanied or not by an Energy Storage System (ESS), a hybrid solution. An essential step in the design of the power system is, besides finding the single best solution for each component, to optimize and make these components work optimally together (in the holistic sense). A detailed evaluation of the system in every operational task is needed to find the best overall solution.

Hybrid systems and batteries indicate significant benefits when used for receiving the peak demands, allowing the rest of the power converters to operate at constant loading. This capability has positive impact on reliability and energy efficiency, which need to be quantified and assessed in order to support decision making towards the final configuration setup of the vessel. The quantification of the hybrid system performance is therefore essential to demonstrate savings and reliability benefits. These results provide essential feedback to risk assessment methods and tools, as not only qualitative information is provided, but also quantitative understanding on the integrated system behaviour. Phase 2 objectives, methodology, inputs and outputs are summarized in Table 3.3.

3.3.1 Operational Profile

An operational profile gives a quantitative description of the vessel's tasks and the power requirements in these. The operational profiling tool from SINTEF Ocean (Gymir) can simulate the vessel's operation in its intended mission, defined by the mission requirements. This will give indications of time spent in various tasks, such as sailing, dynamic positioning, towing, port-stay, etc. Further, environmental factors

Table 3.3 Power system concept design and optimization

Phase 2	Power system concept design and Optimization
Objective	Optimization of power system based on operational profile Selection of power system architecture and control strategy Sizing and configuration of energy sources Perform high-level RAM analysis
Input	Operational profile Thruster specification
Method	Tools for evaluation of power system performance RAM analysis tool
Output	Optimized configuration and control based on fuel consumption Statistics for reliability, availability and maintainability

(sea state, wind condition, sea/air temperature and so on) are significant for what mode is used to accomplish the task (speed, power consumption, vessel motions, etc.) and might change the duration or even cancel the task. Estimation of time consumed in each task, modes and weather profiles is here referred to as the operational profile.

In traditional weather routing tools, the main focus generally lies on optimizing the route with respect to a weather forecast, and less effort is put into the vessel model, and hence, the analysis of the profile is limited. In contrary to the typical weather routing tools, Gymir can be used for optimization purposes in the early design phase by combining the basic hydrodynamic properties of the vessel (e.g. on the basis of statistical data) and weather data from various digital data services (e.g. metocean data). With sailing patterns of the vessel, the tool calculates varieties of the KPIs, such as: time spent for different tasks; the modes applied to accomplish the tasks; weather encountered while accomplishing tasks; and power consumed.

The operational profile chosen for Phase 2 is presented in Table 3.4. The task consists of harbour, transit, standby and dynamic positioning operations. The latter three have been split up into two weather conditions. Each task is specified with loads for each individual thruster, heavy consumers, hotel load, as well as relative allocated time. Each task also has a set of requirements and can only operate in certain predefined modes. For example, dynamic positioning requires power redundancy due to a possible scenario of component failure.

In addition, two engine-limiting cases have been added—one with full thrust to the main thrusters, and one simulating a worst case fault within DP2—the loss of a main switchboard. This is done to make sure the engines can handle these tasks if needed. These two tasks were not assigned any time in our given operational profile. The thruster models and specifications are given in Table 3.5.

Table 3.4 The vessel's operational profile

#	Operational task	Relative time	Hotel (kW)	HC[a] (kW)	2 × Main azimuth thrusters (kW)		2 × Tunnel thrusters (kW)		Forward thruster (kW)
1	Harbour	20%	300	–	–	–	–	–	–
2	Transit 11 knots	10%	500	–	1,121	1,121	-	–	–
3	Transit 13 knots	10%	500	–	1,400	1,400	-	–	–
4	Standby calm[b] weather	20%	500	–	442	438	186	183	272
5	Standby harsh[c] weather	10%	500	–	567	541	406	396	1,034
6	DP2 calm[b] weather	20%	500	500	442	438	186	183	272
7	DP2 harsh[c] weather	10%	500	500	567	541	406	396	1,034
8	Full power to main thrusters	–	500	–	2,470	2,470	–	–	–
9	DP2 failure with max crane load	–	500	1,000	798	-	1,097	-	966

[a]Crane (heavy consumer)
[b]Wind = 5 m/s, current = 1 m/s.
[c]Wind = 12.5 m/s, current = 2 m/s.

Table 3.5 Thruster sizes and their nominal power and motor speed

Type	Model	Nominal power (kW)	Motor speed (rpm)
Main (azimuth) thrusters	2 × US 255 P30 CP	2 × 2,470	750–1,800
Tunnel thrusters	TT2400-CP	2 × 1,150	980–1,190
Forward (swing-up) thruster	TCNS 92/62–220	2,000	1,800

3.3.2 Power System Evaluation

Today, finding the best solution for a vessel's power system is often done manually and the chosen engine configuration is not necessarily the optimal one. For this application case we have used the Marine Power System Evaluation Tool (MPSET) from Kongsberg Maritime. It is a MATLAB based tool designed to automatically evaluate different power system configurations, reducing calculation time, as well as the likelihood of human errors.

The overall concept of MPSET is presented in this section of the application showcase. That is, to simulate every possible power system setup within its given constraints and provide the user with the optimum configurations. Through its Simulink toolsets, MPSET simulates every component of the vessel's power system, and builds up a blueprint model. With the vessel's operational profile and power criteria as inputs, MPSET uses a (2 + 1)-step loop for its program logic: overall power architecture, engine configuration, and task simulations (shown in Fig. 3.4).

3.3.2.1 Main Architectures Selection

The first step performed in MPSET is choosing the overall power system architecture. This task is done manually. The user can choose between four overall engine philosophy principles: two pure diesel-electric configurations based on Alternated Current (AC) or Direct Current (DC) for the Main Bus Bars (MBB) and two solutions combining mechanical propulsion and diesel electric engines. All of these configurations can also include energy storage systems (batteries). For Phase 2, only diesel-electric configurations, with and without ESS were considered, resulting in four different evaluations of the main power system architectures. Their single line diagrams (SLDs) are shown in Fig. 3.5.

Choosing an AC or DC power architecture impacts how the engines are configured. For AC setups using 50 or 60 Hz on the MBB, the generators and engines (generator sets) run at a fixed speed (fixed rpm). For propulsion engines and diesel-electric engines connected to a DC setup the engines can operate at variable speed, potentially

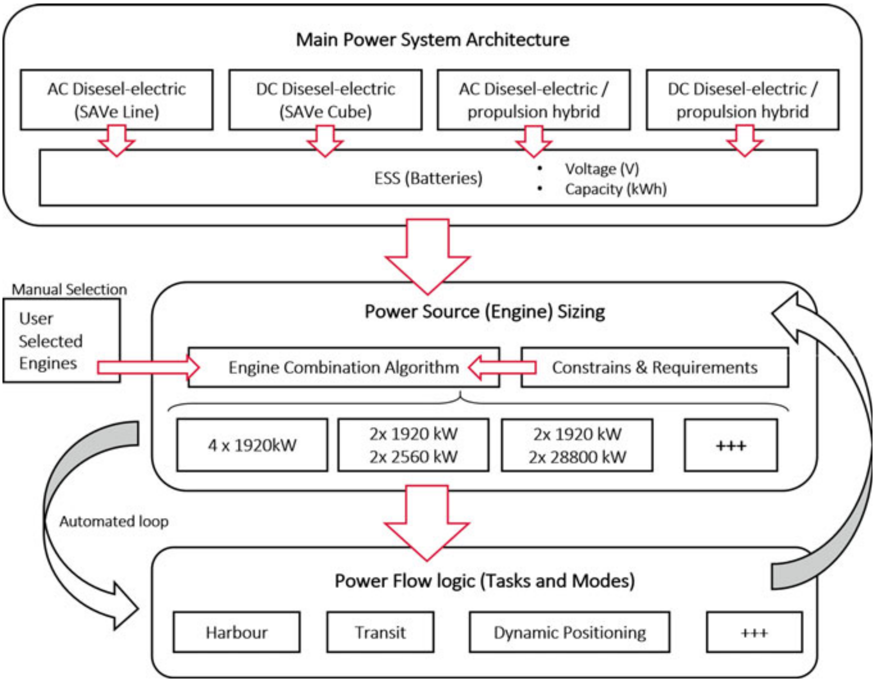

Fig. 3.4 Program logic for MPSET

improving fuel efficiency, especially in low-loads scenarios. The benefits of variable-speed engines are discussed in (Holmefjord et al. 2020).

After an AC or DC power system architecture is selected by the user, an ESS (typically batteries) can be included. For certain vessels this option can significantly reduce both fuel consumption and required engine sizes. The battery capacity (in kWh) and voltage is selected by the user. An automated algorithm for the ESS capacity is not yet included in MPSET. MPSET also allows for shore-connected power supply. An upper limit for this connection can be set.

3.3.2.2 Power Source (Engine) Sizing

The next step is to find the best configuration for the engines. Based on a library of different models and sizes for these, the user can then choose which should be included in the evaluation. The library also contains specific fuel oil consumption (SFOC) for both fixed-speed engines and variable-speed engines for each engine. For variable-speed engines, MPSET uses an optimal line for load versus rpm. The engine library is then screened to remove all options which does not fulfil requirements for the selected operational profile and architecture.

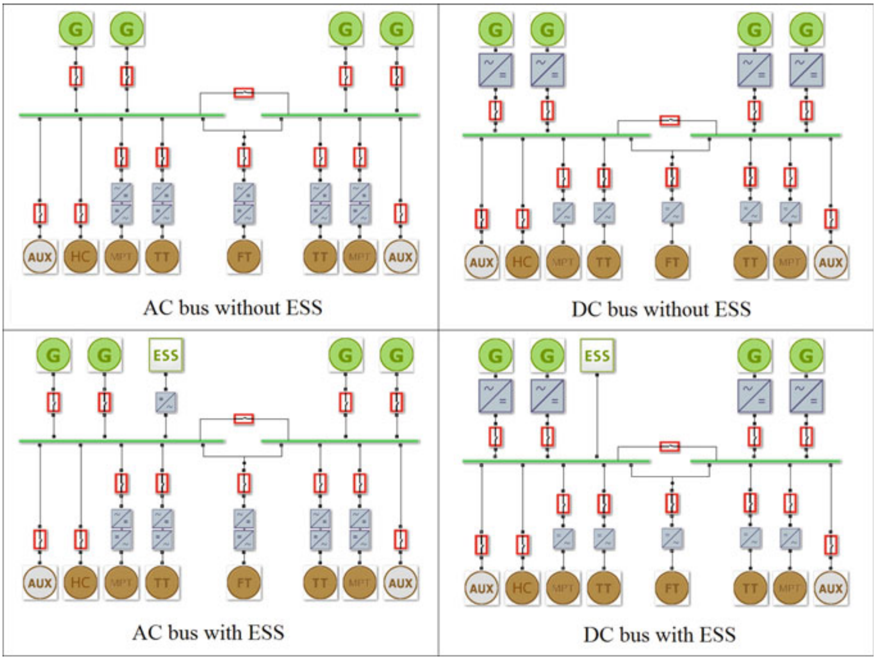

Fig. 3.5 The four main architectures evaluated for Phase 2. G = generator set, ESS = energy storage system, HC = heavy consumer (crane), MPT = main propulsion thruster, TT = tunnel thruster, FT = forward thruster, AUX = hotel load.

Once this is done, MPSET will create a matrix with remaining engines for all possible configurations. Here, MPSET checks one more constraint, namely the relative engine sizes between the largest and smallest engines. This relationship cannot exceed a pre-set ratio (default is 3). MPSET will then evaluate all the valid configurations.

In our operational profile the power consumption is quite high for DP2 operations in harsh weather (wind speed of 12.5 and current of 2 m/s). The vessel must be able to keep position, the thruster system deliver needed thrust and the power system deliver needed power in case of worst case single failure, which would be the loss of the starboard or port side main switchboard. Without an ESS, the engines are limited to run at maximum 40% of their max continuous rating, such that they can take over the load from a failing engine(s) if necessary. This requirement in DP2 will result in much larger required engine sizes for setups without ESS installed.

3.3.2.3 Power Flow Logic (Tasks and Modes)

The third step of MPSET is to simulate the power system configurations with the ships operational profile. Each task given in the operational profile can be simulated. For some operations, different power management modes are possible, and like the engine configuration option, all possible modes will be evaluated. For this application study we have only evaluated a single default mode for each task. MPSET will calculate the fuel consumption, emissions, and engine running hours for engine combination, task and mode, using physical-based models in Simulink. This will be done by every valid engine configuration.

3.3.3 Application Case Results

For this application case we have looked at different generator sets from Bergen Engines and MTU—all running on diesel. Only 60 Hz frequency were considered for the fixed-speed AC configurations. For the 4 main architectures, up to 7 different engine candidates were considered, resulting in different 92 total combinations. The results, ordered based on minimum fuel consumption are given in Fig. 3.6. The emission models for MPSET are linear functions of the fuel consumption, and will thus rank in the same order.

The recommended engine configuration for each of the four architectures are listed in Table 3.6.

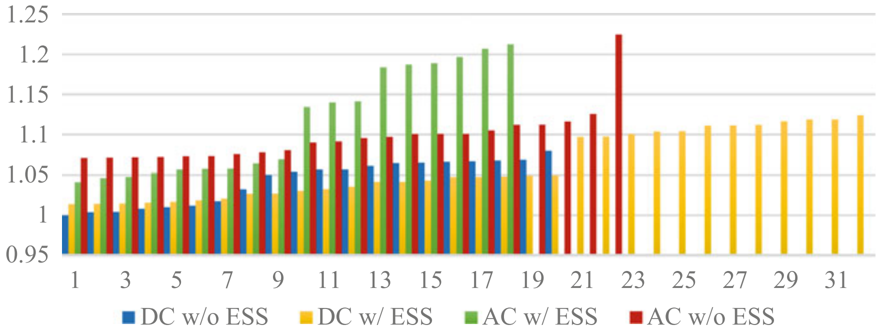

Fig. 3.6 Relative fuel consumption of the 92 (20 + 32 + 18 + 22) different engine configurations from all four main architectural topologies (shown in different colour tones)

Table 3.6 Comparison between the four evaluated architectures

Rank	Architecture	DG1 (kW)	DG2 (kW)	DG3 (kW)	DG4 (kW)	Daily SFOC (tonnes)	365 days SFOC (tonnes)	Relative %
1	DC w/o ESS	3,600	2,665	3,600	2,665	11.71	4,275.57	100
2	DC w/ ESS	2,000	2,000	2,000	2,000	11.88	4,335.01	101.4
3	AC w/ ESS	1,920	1,920	1,920	1,920	12.19	4,450.83	104.1
4	AC w/o ESS	3,840	3,840	3,840	3,840	12.54	4,578.17	107.1

Our evaluation shows large differences in fuel consumption between the different power architectures, with the DC-variable-speed engine setup without ESS coming out on top with the six best engine combinations. These are slightly better than the ESS variant. The two AC variants falls 4% and 7% behind in fuel consumption, respectively.

For the observant reader, the fact that the non-ESS variant comes out better than the one with ESS installed seems a bit odd, and do require some explanation. This is due to the good fuel efficiency, even at relatively low load, of the six cylindered 3,600 kW B33:45L6P engines. This is the smallest variant of this series, and is considered too big for our ESS variant evaluation. It should be noted that disregarding this exclusion, and running the same engine setup with ESS, this comes out as the best option (<1% better). The small change in specific fuel consumption at different loads is true for all variable-speed engines, and another reason why the adding an ESS has limited effect here. We should note, however, that the SFOC numbers used in MPSET were not yet confirmed at the time of this printing. Once we have more accurate data, we expect the specific fuel consumption at low loads to rise for our variable-speed engines as well.

For fixed-speed AC-setups, the optimal power load window for fuel consumption is smaller than for variable-speed DC setups, as is confirmed by our evaluation. This also has a greater impact for our AC-setup without ESS, where larger, and in many ways oversized engines, increases the space between the optimal power load windows even further (see Mo and Guidi 2018 for more information on this topic). The emissions for our optimal AC configuration with ESS are shown in Table 3.7 and, specified by operational task in Table 3.8. This table showing the fuel-consumption and emissions, is one of several auto-generated tables created by MPSET after a simulation.

3.3.4 Risk Based Analysis

DNV GL COSSMOS is a generic modelling framework for Complex Ship Machinery Systems Modelling and Simulation (COSSMOS). It is in-house development by DNV GL and contains a wide list of models of ship machinery systems (Dimopoulos et al. 2014), capable to be connected on system level to simulate integrated ship machinery systems. DNV GL COSSMOS was used in the present case study to compare the predicted performance for the machinery system, as estimated with MPSET in the context of model-to-model check for the case with and without batteries. The model was further used to perform a risk-based analysis of the operational performance of one of the hybrid system configurations presented in Table 3.6, presented in detailed in Chap. 9 of this book.

The hybrid system with batteries was also modelled in DNV GL COSSMOS (Fig. 3.7). The assumed total battery capacity is 1,920 kWh, equivalent to deliver the nominal engine throughput for 1 h.

Table 3.7 Detailed MPSET result table for recommended option for the AC with ESS, 4 × 1,920 kW engines

	SFOC (tonnes)	Total NOx Emission (tonnes)	Total NMVOC[a] Emission (tonnes)	Total TSP PM2.5 + 10[b] Emission (tonnes)	Total CO_2 emission (tonnes)	Total SOx emission (tonnes)
Daily	12.194	0.646	0.061	0.038	38.655	0.012
365 days	4,450.827	235.894	22.254	13.798	14,109.123	4.451
345 days	4,206.946	222.968	21.035	13.042	13,336.020	4.207

[a]Non-methane volatile organic compound
[b]Total suspended particles, particulate matter (diameter < 2.5 & 10 μm)

Table 3.8 MPSET results of hybrid system performance at the prospective OSV operating modes, AC with ESS, 4 × 1,920 kW engines

Operational Task[a]	Active Generators (on/off)				Daily SFOC (tonnes)	345 days SFOC (tonnes)
	DG1	DG2	DG3	DG4		
1	On	Off	Off	Off	0.3580	123.50
2	On	Off	On	Off	1.3571	468.18
3	On	on	On	Off	1.6644	574.20
4	On	Off	On	Off	2.1014	724.99
5	On	On	On	Off	1.7403	600.39
6	On	Off	On	Off	2.5263	871.58
7	On	on	On	Off	1.9597	676.11
Total	–	– lePara>	–	–	11.7072	4038.95

[a]Operational Tasks can be consulted in Table 3.4

The system performance was evaluated and compared to MPSET results for the assumed operating modes of the OSV (Table 3.4). The same Battery Management System (BMS) and Power Management System (PMS) strategies as implemented in MPSET were adopted. In particular, the PMS is as for the baseline case and the BMS is for using the battery as spinning reserve. The same assumptions for the annual operating hours were considered. Results are presented in Table 3.9 and can be directly compared with results obtained from MPSET, Table 3.8.

Table 3.10 refers to the use of battery at ON/OFF mode. Total vessel consumption per year is estimated at 4,077.5 tonnes (battery ON/OFF at harbour) to 4,113.3 tonnes (battery at spinning reserve mode). Compared to MPSET, DNV GL COSSMOS delivers results for the engine production and system losses at the same order of magnitude, with mean relative difference of 1%. Compared to baseline (without batteries), the hybrid system yields energy efficiency improvement of 2 to 8% per mode (where the battery is used as spinning reserve) and 3.7 to 4.5% in total.

Potential use of the battery at ON/OFF mode at harbour can bring efficiency improvement of 26%, accounting for less 35 tonnes of fuel per year. This benefit comes with the drawback of increased battery cycling that affects maintenance negatively. The reason causing this observation is the fact that, at baseline conditions, the harbour engine load is 17% accounting for a specific fuel consumption of 263 gr/kWh, compared to the value of 187 gr/kWh at 77% engine load and including consumptions for engine pumps.

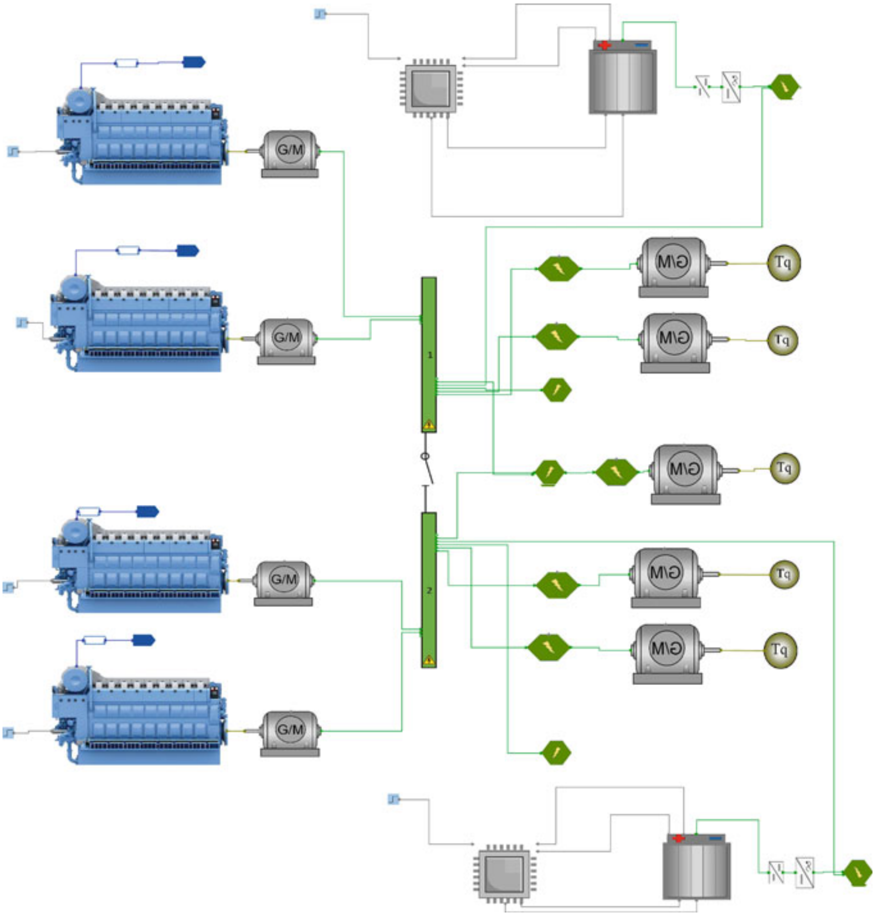

Fig. 3.7 Hybrid OSV machinery system (with batteries) modelled in DNV GL COSSMOS

This aggregated level of assessment is only a demonstration of the benefits of the hybrid system. In order to monitor the actual benefits, the simulations need to evaluate the savings from using the hybrid system at peak shaving mode. A study on this is included in Chapter 9 of this book.

3.3.5 Post Processing 2—Power System Results

Once the software-based power system evaluation has been completed for Phase 2, the project enters its second post-processing stage, where the following decision shall be taken:

Table 3.9 COSSMOS results of hybrid system performance at the prospective OSV operating modes, battery is used for spinning reserve only

Operational Task[a]	Engine loading [%]				Daily SFOC [tonnes]	345 days SFOC [tonne]	Relative to w/o ESS [%]
	DG1 (%)	DG2 (%)	DG3 (%)	DG4 (%)			
1	0	0	0	17	0.388	133.91	0
2	0	81	0	8	1.390	479.49	0
3	0	65	65	65	1.691	583.27	0
4	0	60	0	60	2.118	730.86	8
5	0	68	68	68	1.777	613.18	4
6	74	0	74	0	2.556	881.95	5
7	0	78	78	78	2.002	690.60	2
8	80	80	80	80	–	–	–
9	75	75	75	75	Fuel tonnes per charging: 0.22 Time per charging: 0.6 hrs		
Total	–	–	–	–	11.922	4113.26	–

[a]Operational Tasks can be consulted in Table 3.4

Table 3.10 COSSMOS results of hybrid system performance at the prospective OSV operating modes, battery is used at ON/OFF state

Operational Task[a]	Engine loading [%]				Fuel [tonnes per day]	Fuel [tonnes per annum]	Relative to w/o ESS [%]
	DG1 (%)	DG2 (%)	DG3 (%)	DG4 (%)			
1	0	0	0	77[b]	0.284	98.14	26%
2	0	81	0	81	1.411	486.74	–
3	0	65	65	65	1.706	588.41	–

[a]Operational Tasks can be consulted in Table 3.4
[b]When in operation

- Selection of power system architecture,
- Selection of type and size of engines,
- Selection of size and performance of energy storage system (kWh and kW),
- Selection of power management strategy to be used for different operational modes.

  Several factors needs to be taken into consideration when the selection of the architecture is made:
- Fuel consumption and emission: From the MPSET simulations, the DC alternatives have the lowest fuel consumption with a potential of 4% reduction without ESS and 3% reduction with ESS compared to the AC alternatives with and without ESS. DC systems can use variable-speed engines and combined with controllable pitch (CP) thrusters the engines can be operated at high efficiency even at

low power demands. Functionality for CP was not yet available in MPSET, thus the results for the DC alternatives are conservative. With variable speed and CP thrusters, the additional gain of ESS on fuel consumption is limited. The reason that the DC without ESS came out with the lowest fuel consumption in the analysis is related to the possibility to select an engine with very high efficiency.
- CAPEX of AC versus DC: DC system comes with a higher CAPEX due to additional frequency converters for the generators.
- CAPEX with and without ESS: ESS allows for selection of smaller engines when used as spinning reserve, however there is a significant additional cost of the ESS that must be considered.
- Maintenance and spare parts: From a maintenance and spare parts point of view, it is an advantage to have four identical engines.
- Operational margins/risk: ESS can be used both as spinning reserve allowing for operation with fewer engines running and peak shaving allowing for design and operations with smaller dynamic margins.

Based on a combined expert assessment of the four alternative architectures, it was decided to focus on the AC system with ESS. There were several alternatives with only small increases in fuel consumption, but the alternative with lowest fuel consumption was based on four identical 1,920 kW engines (C25:33L6A). It was decided to focus on this alternative for the COSSMOS analysis and the RAM second part of Phase 2.

There is no automated functionality procedure for the battery sizing in MPSET at the time of this study, so this was a manual user input. From a spinning reserve point of view, the power rating was selected to be the same as for one engine, i.e. at least 1,920 kW. For peak shaving of transient loads, a power rating of +/- 600 kW was simulated by COSSMOS. The power rating is considered sufficient for both spinning reserve with loss of one engine and peak shaving. For spinning reserve with loss of two engines, the 1,920 kW power rating is not sufficient for the specified conditions and operation with more engines must be considered.

The strategy for load dependant starting and stopping generators was included in the simulations for both MPSET and COSSMOS. Equal load sharing between running engines on a switchboard was used. Three different ESS strategies were evaluated in the COSSMOS simulations (spinning reserve, peak shaving and on/off), while only spinning reserve was considered in the MPSET simulations.

Spinning reserve is applicable for all modes and is enabling operation with less engines running in standby and DP2 operation. This reduces both fuel consumption and running hours when comparing AC system with and without ESS.

Peak shaving was considered for standby and DP2 operations in addition to spinning reserve. This allows engines to operate at a constant load. The benefit from this was simulated by COSSMOS and showed an efficiency increase of 5% compared to AC system without ESS and three engines running and 12% compared to AC system without battery and 4 engines running. On/off was considered for harbour mode with the potential of reducing the fuel consumption by 26% in this mode. The actual reductions in fuel consumption is 34 tonnes per year for this case. The fact that this reduction is made in harbour makes it especially attractive when considering local pollution. In summary, the input to the second part of Phase 2 was concluded to be the following system:

- AC bus with ESS,
- Four C25:33L6A engines with a power rating of 1,920 kW,
- ESS power rating: 1,920 kW,
- ESS capacity: 2,000 kWh,
- Power management strategy,
- On/off for harbour mode,
- Spinning reserve for all modes,
- Spinning reserve and peak shaving for stand-by and DP2,
- Load dependant starting and stopping of engines when applicable,
- Equal load sharing between running engines on a switchboard.

3.3.6 System Architecture and Requirements

BuDa is the system architecture diagram tool developed in the frame of the Holiship project by SIREHNA, as part of the System Architecture and Requirements (SAR) management tool. Ship design is a complex endeavour characterized by the diversity of the technical domains involved, the distribution of the work across several teams, and many asynchronous iterations. The role of the SAR tool is to support heterogeneous, distributed, asynchronous ship design activities to ensure that the requirements of the customer are met at the end of the design process. Therefore, BuDa fits in the activities workflow:

- After the system performance assessment activities: the MPSET and COSSMOS tools are focusing on modelling and simulation of a ships power system in terms of energy, to evaluate performance characteristics;
- BuDa takes over from the defined detailed architecture to ease the data link to the RAM analysis, and to perform the initial qualitative RAM analysis. Overall, qualitative reliability and fault resilience analysis is performed. The BuDa tool is used to prepare and optimize the analysis performed subsequently;
- Before the detailed RAM analysis activities in which quantitative reliability is performed. The GRIF tool is used, based on the results and the scope defined previously in BuDa.

Overall, qualitative reliability and fault resilience analysis has been performed using both the SLD (Single Line Diagram) for AC bus with ESS and the operational profile as inputs.

The system architecture was modelled in BuDa and its concept of *functional chain* was used to define and outline the scope of the system on which the detailed RAM analysis shall be performed (active components), depending the operating modes (DP2, harbour) of the operational profile. This was later used by the detailed qualitative RAM activities.

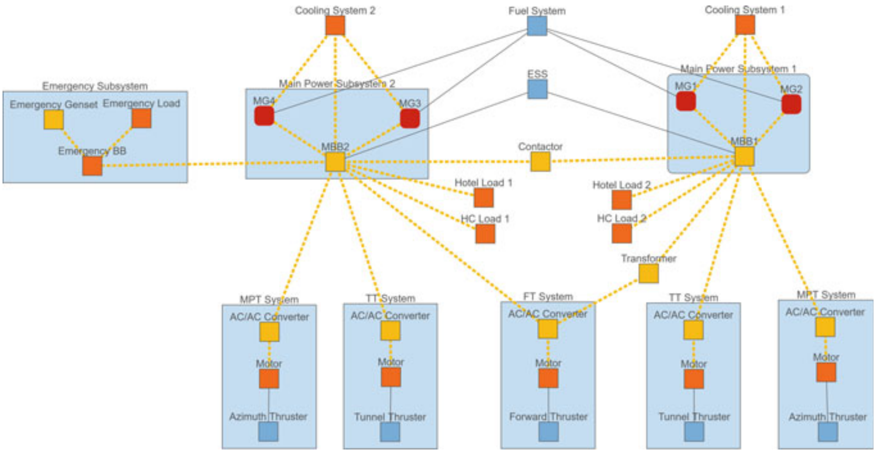

Fig. 3.8 BuDa representation of the fault propagation for harbour and transit modes

Complementary, qualitative consistency checks were performed: this required to define the electrical network for distribution, producers and consumers. Some failure of the producers was introduced (red-rounded main generator (MG) blocks in the figure below) and impact (failure of the consumers: orange square blocks) was analysed with the *fault propagation* function of the tool. Fault propagation for harbour and transit mode was addressed as shown in Fig. 3.8, and reassure on the level of reliability of the system while operating in those modes. For instance, all the MG producers have to be faulty for consumers to be faulty: that is, say in case of the failure of the 4 MG sets (producers: red blocks), all the consumers (thrusters motors, hotel loads—orange colour blocks) are impacted and no more supplied. The yellow doted lines illustrate the link between the cause (failure) and the consequence (loss of supply).

BuDa targets to improve RAM analysis activities by reducing the scope of studies and focusing on the necessary and seemed to succeed to that objective. In addition, it has allowed two technical domains to communicate and finally agree on which part of the electrical system shall be part of the RAM analysis. A more seamless tool integration, which was not addressed, could be added in the future, as well as automating qualitative architecture consistency checks.

3.3.7 RAM Analysis

Reliability, availability and maintainability analysis simulates the configuration, operation, failure, repair and maintenance of all equipment included in the system or a vessel. 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 & logistics and operational profile. The outputs determine the operational performance of the system or vessel over the vessel's life cycle.

RAM modelling is part of the HOLISHIP project in order to evaluate the performance of power system architecture developed so far in terms of reliability and availability, i.e. exposure of risk.

The outputs of RAM simulation are used as an input to evaluate the OPEX related to equipment failures and maintenance based on the association of the number of failures and repairs, quantity of maintenance activities (planned or unplanned), maintenance mobilizations performed during the life cycle and running time of each equipment.

More specifically, the RAM analysis for this application case were performed by Bureau Veritas with the following objectives:

- To create the RAM model of the power supply system selected for the OSV to reflect the power generation and power distribution configuration and its reliability performance
- To understand reliability bottleneck/advantage of different designs
- To understand constraints and limiting factors for availability in different operational modes
- To assist the HOLISHIP team in assessing opportunities to improve the performance of the power distribution and power generation systems
- To provide input data in term of system unavailability, equipment reliability and maintainability in view of the subsequent life cycle cost analysis for OPEX calculations.

The scope of this study covers the operating procedures and equipment of the selected power system for the application case. As the focus of this RAM project is to test the methodology described in Holiship Book 1 (Papanikolaou 2019) with a study case, a simplified RAM model of the power system is enough to highlight the findings for an easy interpretation of results.

The BuDa tool defined the system configuration and functional links between equipment for each vessel operational mode, i.e. which equipment are required to be running and those that are in standby-mode (redundancy). Therefore, the impact of equipment failures on the system performance and in the vessel's mission, could be accessed. This was done by visualizing the functional effects of equipment single point failures on the system. It was also possible to quickly highlight all the possible causes (equipment failures) that can lead to the loss of mission capability for each operational mode.

Therefore, the analysis is based on a simplified structure of the power supply system that has been modelled in the BuDa tool as presented in Fig. 3.9. It shows the highlighted RAM scope for the DP2 mode. The architecture on which the RAM analysis was performed is composed of the blocks (electrical components) and links (electrical cables) highlighted in pink. The components which are not part of the

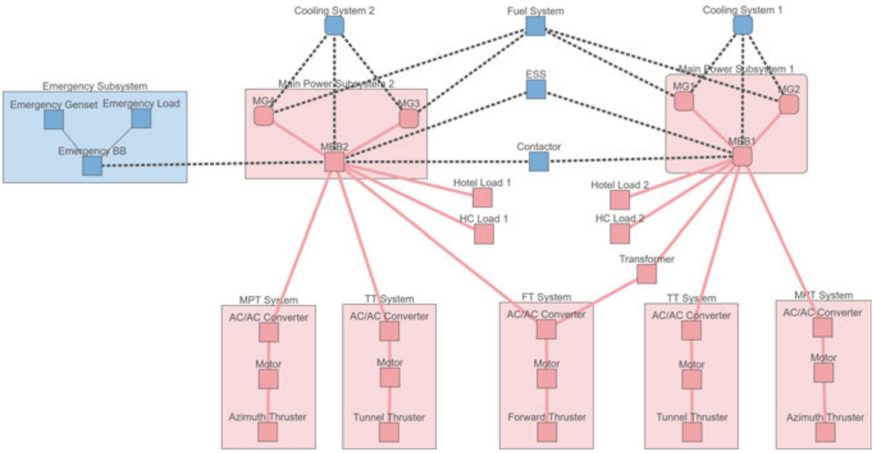

Fig. 3.9 Simplified power system configuration in BuDa

RAM analysis are coloured in blue, while components which are part of the RAM analysis are highlighted in pink. The dashed lines allow to identify blocks that were not active (or not assessed) in this mode.

The RAM software GRIF developed by Satodev (subsidiary of TOTAL) is used to undertake this RAM project. GRIF software is a Monte Carlo based RAM modelling allowing simulating global behaviour of multi-functional systems by constructing Petri-Nets representation that enables analysing systems with high level of complexity. GRIF also allows a precise simulation of system behaviour with regards to the propagation of its equipment failure and to identify which failure combination leads to a particular situation.

In order to establish average results and confidence levels, the RAM analysis was performed considering 10 days as a mission cycle for 10 years as the system life. A mission is considered accomplished when the DP2 operation is performed with success.

Table 3.11 presents the result of overall ship reliability and operational availability and Table 3.12 the average of failures per equipment for a period of 10 years. The

Table 3.11 RAM Overall results

Operations events	OSV application case
N° of potential missions in 10 years (A)	365.00
N° of missions effectively started in 10 years (B)	370.08
N° of DP2 accomplished with success (C)	324.16
Ship reliability (C/B)	87.59%
Ship operational availability (C/A)	88.81%

Table 3.12 Number of equipment failures in 10 years operation, per equipment type

Equipment type	Total number of failures	Contribution (%)
Main generators	37.27	71.8
Main switchboards	3.89	7.5
Bus tie	0.02	0.0
Propulsion motor frequency converters	0.89	1.7
Thruster motor frequency converters	0.96	1.9
Propulsion motors	4.34	8.4
Thruster motors	4.54	8.7
Transformer	0.00	0.0

latter can be used to identify the equipment that contribute the most to power system failure and ship performance, allowing the project team to focus on the area with largest improvement potential.

Other relevant RAM outputs are also calculated in order to build the cost model in terms of revenues and OPEX for life cycle cost analysis, they are:

- Number of missions performed with success
- Mission losses
- Equipment repairs
- Number of rescue with tug boats
- Time spent at port under repair
- Main generators running hours.

Two Scenario Cases (SCs) were performed. The first SC consists in considering the effect of the ESS implementation in the power system to the reliability of the main generators. The second scenario case (SC2), in addition to SC1 set-up, presents results in case the loss of main generators redundancy is acceptable for DP2 operations. A sensitivity analysis of main generator reliability was performed taking into consideration an increase from 1 to 10 times more than that was considered in the base case.

The ESS is used to provide extra power and cover other power generators when more power is required during a limited period of time. This allows stabilising the load of the main engines during the operations and avoiding exposition to extra degradation due to load variations.

Figure 3.10 shows that both ship reliability and availability increase with main generator reliability enhancement. However, the curves seem to trend asymptotically, i.e. whenever the increase of reliability of the main generator increases, the ship reliability and availability will not exceed a certain limit. This limit for the ship reliability is around 92.5% and for the ship availability is around 94.0%. It means that the ship performance would increase around 5% if main engines never fail. The remaining loss of performance is due to the failure of other equipment included in

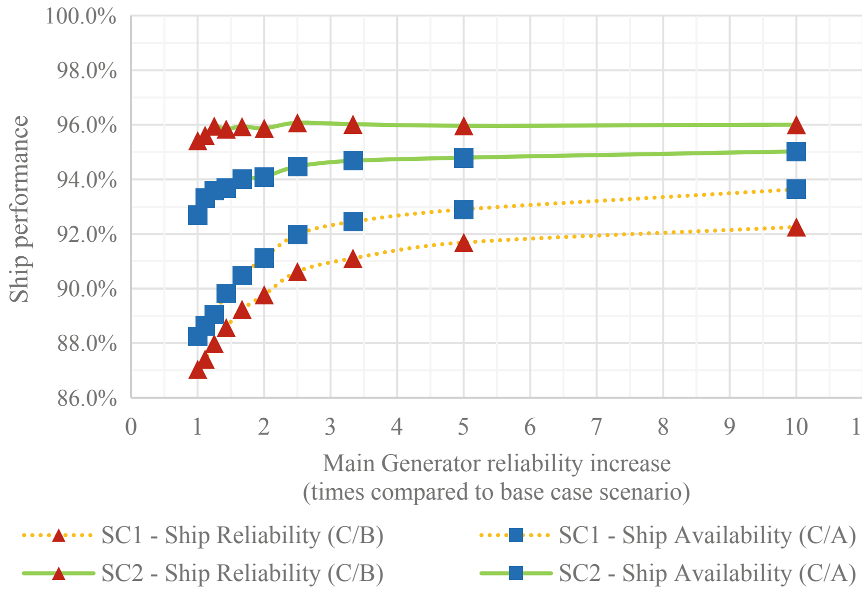

Fig. 3.10 Ship performance evolution with main generator reliability increase

the power system. Additionally, ship reliability and availability indicators present better values (up to 7%) in SC2 than in SC1. This is explained by the fact that less few DP2 operations are cancelled due to the failure of one unique main generator as it is the case in the SC1.

As for SC1, both ship reliability and availability increase with main generator reliability enhancement. However curves in SC2 are closer to the asymptotic limits than they are in SC1. The maximum ship reliability and availability in SC2 are approximately 96.0% and 95%, respectively. It means that the ship reliability would increase by up to 2% and ship availability would increase by up to 0.5% in case main engines never fail.

Finally, the result of the two sensitivity cases could be used as a support to analysis and understand: what would be the minimum level of reliability that main generators need to achieve in order to make ESS implementation worth doing for the case that loss of main generator redundancy is tolerated in DP2 mode.

3.3.8 Post Processing 3—Linking Phases 2 and 3

The RAM analysis performed for the selected power system was considered as good basis for performing further analysis and design optimization in a detailed design phase, including:

- Performing criticality analysis based on statistics of mission losses and equipment repair and identify potential design changes,
- The results highlighted the MG as the most critical equipment to focus on.

The selected system from the performance analysis included an ESS. This was based on quantitative assessment of fuel consumption and emissions, indicative assessment of CAPEX and OPEX and analysis of dynamic loads. The RAM analysis further supports inclusion of an ESS from both a reliability and availability perspective. It also provided information that can be used in life cycle cost analysis and a business case in terms of:

- Number of not accomplished missions. This represents loss of revenue.
- Number and type of equipment failure. Equipment repair cost including tug assist, service engineers, spare parts and harbour cost.
- Contractual penalties that may happen or be avoided due to down time specified in specific contracts.

3.4 Phase 3—Power System Concept Verification

The objective of Phase 3 was to verify the power system concept resulting from the optimization process in Phase 2. Note that Phase 2 optimization was based on average power consumption, and the power fluctuation due to wave dynamics was therefore not captured in that case.

The verification was performed by exposing the power system to dynamic loadings in a critical operational scenario. The operational scenario used is a subsea lifting operation using an active heave compensated crane and a vessel operating in DP mode in harsh weather conditions. The biggest consumers in this operation were the thrusters and crane winch, in particular when operating at or close to the maximum environmental condition. In order to simulate a realistic power load profile in waves, the vessel and environmental effects were simulated in six degrees-of-freedom simulations, and an industrial DP system was used to control the vessel such that realistic thruster loads were created. The power flow to and from the winch motor/generator was simulated based on vessel motion. In addition, the simulator was also interfaced to an industrial PMS. The PMS controls and protects the power system, and it was therefore important to verify that the PMS was performing well with this power system.

Besides the interaction between the simulated vessel components and control systems, signals could be manipulated in the simulator to evaluate failure cases and the response of control systems to these failures (software-in-the-loop testing). Phase 3 is summarized in Table 3.13.

Table 3.13 Power system concept verification

Phase 3	Power system concept verification
Objective	Verification of power system performance in critical operational scenarios including fault situations Testing of power management strategies Optimization of power system based on realistic load profile
Input	Technical specifications from Phase 1 and 2 Definition of operational scenarios including fault situations Design variables for power system optimization (e.g. PMS strategies, energy storage elements)
Method	Dynamic simulation of vessel in realistic environment performing critical operational scenarios Iteration of dynamic simulation to test options and further optimize the power system based on dynamic performance
Output	Dynamic loading of engines and generator sets Performance of various PMS strategies, energy storage sizes etc. KPI's in dynamic conditions Updated technical specifications based on power system optimization for dynamic load profile

3.4.1 Integrated Simulation Setup

A simplified overview of the simulator is shown in Fig. 3.11. The simulator was assembled with components from different internal Kongsberg Maritime product simulators and some custom-made components. The components were developed in

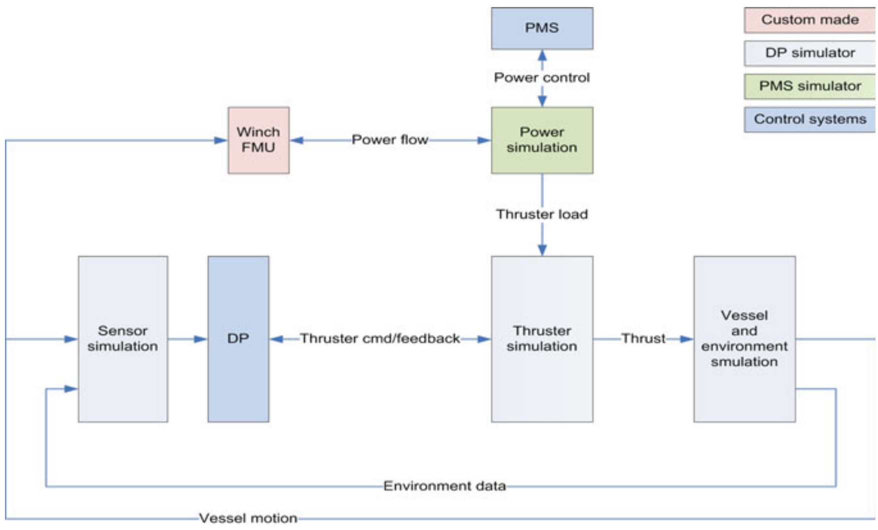

Fig. 3.11 Simplified overall simulation setup

C++, but the simulation framework supports Functional Mockup Interface (FMI) and can therefore also import Functional Mockup Units (FMUs) exported from different simulation tools. In this setup, the winch component is an FMU. The reason for using components from internal product simulators is that the interfaces with the respective control system were already in place, reducing interfacing work considerably.

3.4.2 Simulation Components

The motions of the vessel were modelled in 6 degrees-of-freedom (DOF), with rigid body, hydrodynamic and hydrostatic components. The wave forces were simulated based on a wave field with irregular waves generated for a JONSWAP North Sea spectrum, while current and wind were modelled using current and wind coefficients in relevant areas. Environmental condition direction was compromised by the average direction and a fast-varying component. Wind and current speeds also have an average speed, as well as a gust component. Thruster forces were calculated from thrust input from each thruster model, taking into account the location and angle of the thrusters. The model was made for zero-speed operations.

Classic DP position references and sensors were modelled with realistic error profiles. This includes Global Navigation Satellite Systems (GNSS), hydro-acoustic systems, relative positioning systems, gyro-compass (heading sensor), vertical reference systems (roll, pitch and heave measurements).

The vessel has two aft-azimuthal main thrusters, one azimuthal thruster and two tunnels in the bow. The thruster models were based on thruster performance curves (combinatory curves) that calculate power and thrust based on RPM and pitch input.

The winch model included both a physical winch model and a simplified winch controller performing active winch compensation. This motion, together with a specified fixed crane load, was used to calculate the power flow to and from the winch as the vessel moved up and down in the waves.

The DP system in this setup was an industrial DP system which has been proven in many deliveries to subsea vessels. The DP system is an important part of the simulation setup since it is required to create a realistic thruster load profile. Using an industrial DP gave confidence in the results of the simulations.

The PMS used in the setup was also an industrial control system that included battery management. The main relevant functionalities of the PMS that were used in this work are the automatic start and stop of energy producers, blackout recovery system and ESS operation control.

3.4.3 Simulation Cases

Several simulation cases were run to verify the concept vessel design. The vessel was designed to operate in environmental conditions with winds up to 12.5 m/s,

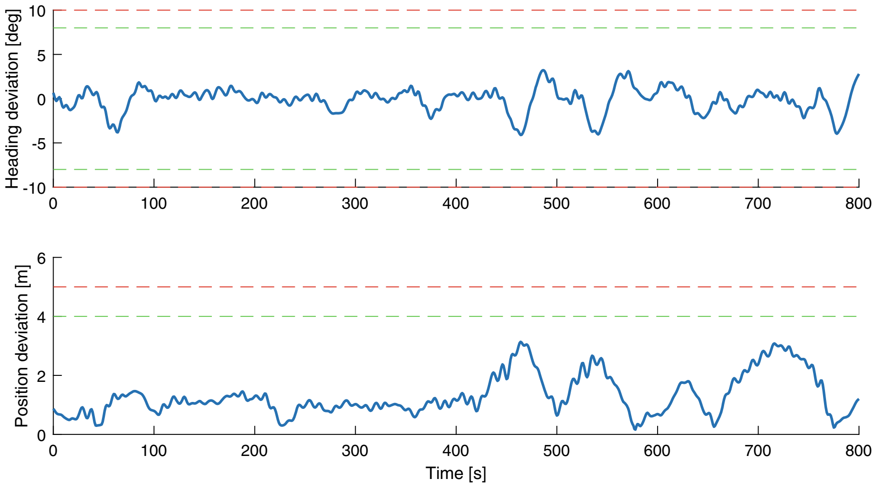

Fig. 3.12 Heading and position deviation at 30° heading

currents up to 2 m/s and waves up to 3.5 m Hs. For this simulation the maximum environmental conditions were assumed acting co-linearly and coming from north.

3.4.3.1 Vessel Heading at 30°

The first simulation case aligned the vessel to 30° relative to the environmental conditions. Figure 3.12 shows that the control system is capable of utilizing the existing thrust and power to keep the vessel position and heading close to the desired setpoint.

By operating at its designed setpoint, with maximum operational condition, it is expected that the vessel power usage approaches its maximum capacity after worst case failure, without saturation happening. This can be seen in Fig. 3.13, as the total power usage of one bus is close to its maximum output (3840 kW without considering the ESS capacity). The same can be interpreted to the propulsion system and concluded that there is enough room to accommodate failures before saturation occurs.

3.4.3.2 Vessel Heading at 90°

In this simulation, the vessel was initially aligned with the environmental conditions, and at 100 s a command is issued to turn 90° clockwise. The positioning and heading deviation are shown in Fig. 3.14, clearly presenting that the vessel was unable to keep its positioning.

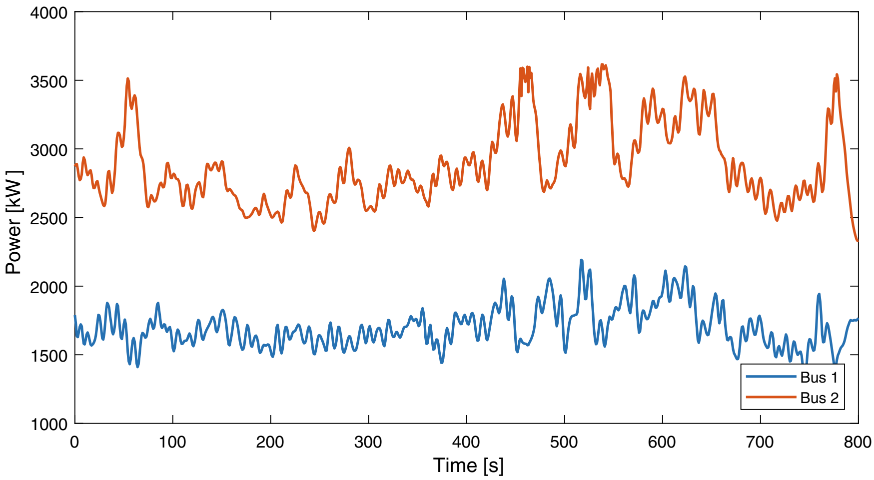

Fig. 3.13 Bus power consumption at 30° heading

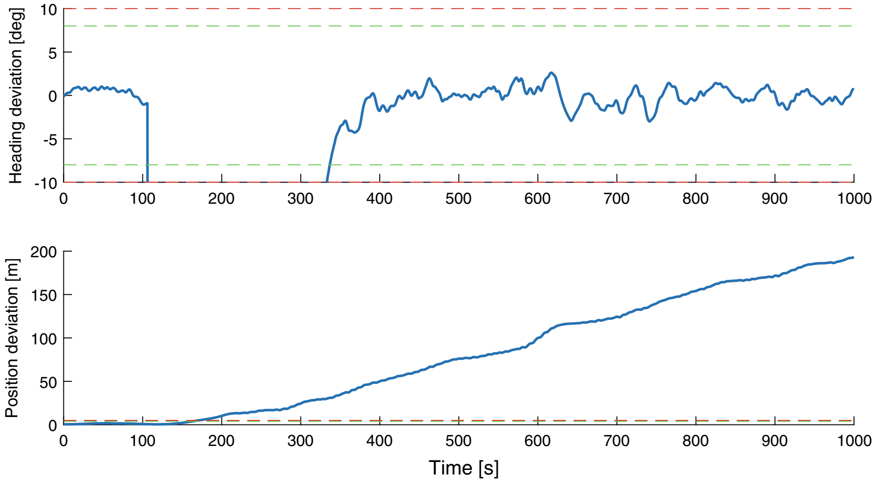

Fig. 3.14 Heading and position deviation at 90° heading

The vessel drifts out of the position due to saturation of the power plant, as shown in Fig. 3.15, and lack of available thrust on the propulsion system, as shown in Fig. 3.16.

The fact that the vessel is unable to keep position outside the design condition indicates that the vessel is not over dimensioned for its design point.

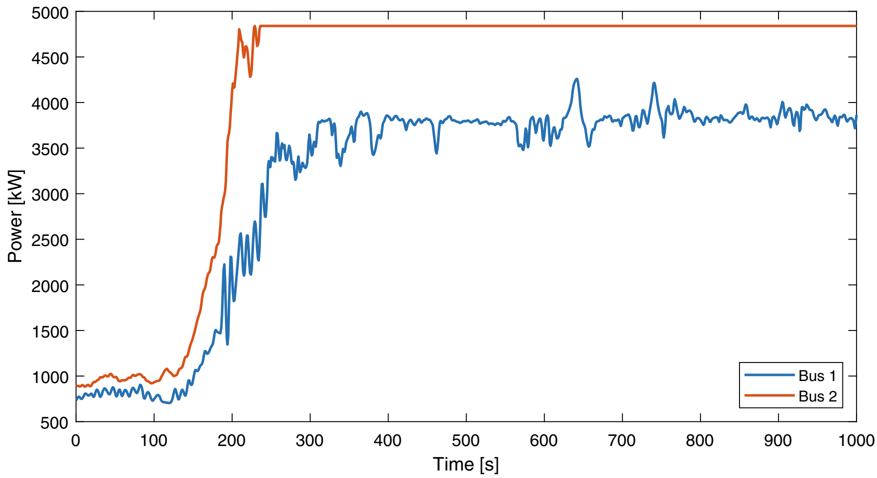

Fig. 3.15 Bus power consumption at 90° heading

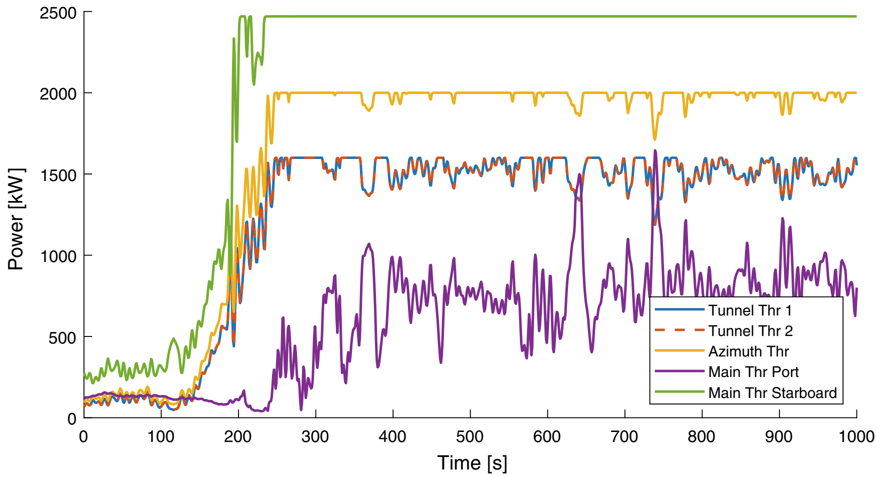

Fig. 3.16 Thruster power consumption at 90° heading

3.4.3.3 Blackout of Half the Switchboard

Assuming a blackout of one MBB, the simulation was performed for about 1,500 s before the fault was introduced. For clarity, in this section we only display a section of 1,000 s, with the fault inserted in the middle of the time interval.

For this simulation case, one of the two buses suffered from a blackout, which is the worst single component failure. The vessel heading leads to environment conditions inciding from an angle of 30°, which is the maximum heading deviation from the environmental conditions on which the vessel is designed to operate.

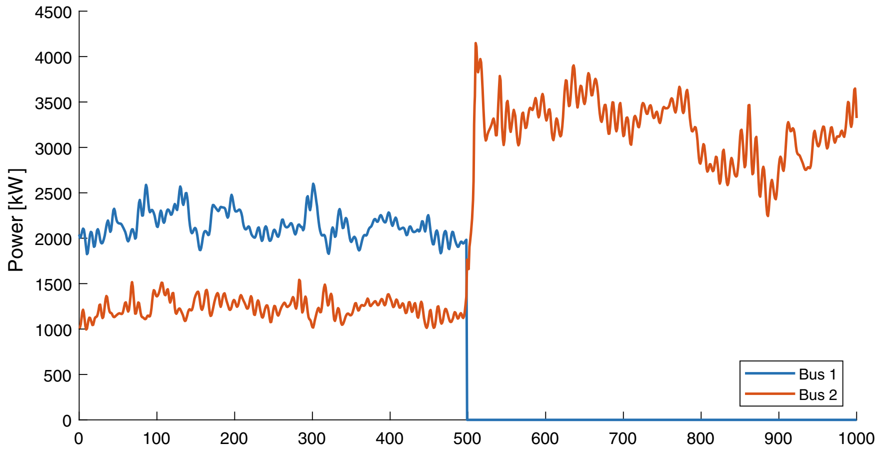

Fig. 3.17 Bus power output before and after blackout

Due to the incidence angle not being zero, the power consumption over both buses was not equal, and the bus that provided power to the port side thruster deployed more energy to the system. Figure 3.17 shows the power consumption on buses 1 and 2, the total power consumption.

The vessel shows that it is in a stable position and heading before and after the failure. Shortly after the blackout event, the vessel heading deviated more than before the blackout event, due to the sudden loss of propulsion and automatic thrust reallocation and direction adjustment of the remaining propulsors. Figure 3.18 shows that the heading is rather stable and peaking close to 5, while position is kept within 2 m and indicates that the propulsion and power system designed in phases 1 and 2 meet DP2 criteria for 30° heading.

3.4.4 Post Processing 4—Dynamic Design Confirmation

Phase 3 of the OSV vessel design has verified the combination of the designed vessel in phase 1 and the power system in phase 2. The creation of the time domain simulations were successfully performed at Kongsberg's bridge simulator, including blackout recovery, automatic start-up and shutdown of generators due to variations on power demand, performance verification during station-keeping operations and single component failure of a generator, a main thruster unit and a blackout of half the switchboard (DP2 class criteria).

In Sect. 3.4.3 it was shown that the vessel design is capable of withstanding the maximum environmental conditions for which it is designed to operate. The worst case failure analysis, blackout of one MBB, shows that the vessel is stable after the

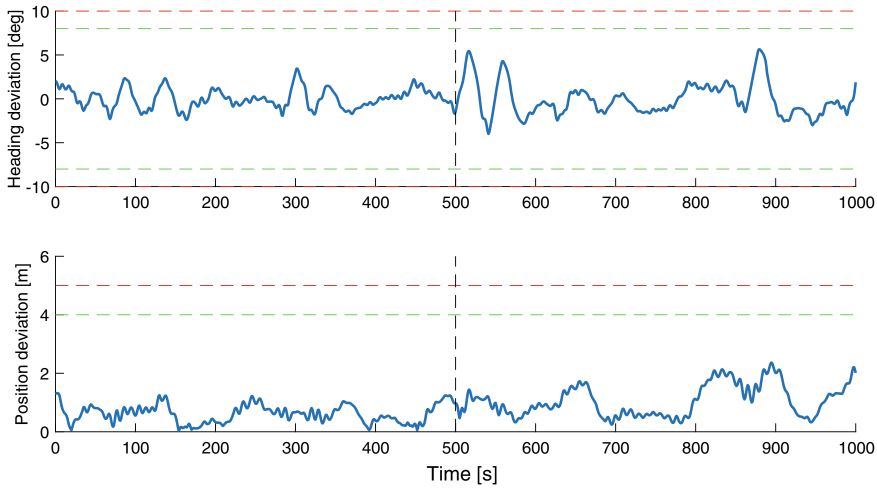

Fig. 3.18 DP system setpoint deviation before and after bus blackout

worst case failure, but the heading fluctuates a bit more. It is also possible to attest that the design of the power system is satisfactory for the given propulsion demand, since the buses are saturated in cases where the thrusters are saturated as well, meaning that a step up in the engine and ESS size would not provide any practical benefit to the vessel dynamic capabilities. It can therefore be concluded that the design provides sufficient capability for DP2 operations under the specified conditions.

If the results had shown lack of capability for the design condition, we would have to go back to phase 1 and make adjustments to the vessel design with the newfound knowledge that the propulsion and power system is not capable of handling the design conditions, or re-consider the requirements for capability.

3.5 Conclusions

At an early design stage, an innovative holistic and integrated design, optimization and verification method has been demonstrated of a conceptual design of an OSV vessel based on customer functional requirements, regulatory and technical constraints and multiple KPIs. With special dedication to a complex power systems design, the application case is tightly linked to the tools and methods developed in WP5, including fuel cost, emissions and maintenance requirements, as well as, virtual testing and demonstration using a dynamic simulations platform. By exploring a much larger design space within the limited time and budget (usually available at an early design stage), the application case has demonstrated the potential of the HOLISHIP design concept. Furthermore, significant improvements for selected KPIs has been obtained comparing the optimized concept with the baseline vessel.

The design procedure executed in this application case is not intended to replace the need for experienced naval architects and domain experts, but rather providing them with supporting tools to assist in identifying and verifying an optimized design. In addition, the method increases quality of the design at an early stage, avoiding costly modifications in later stage of the contractual design and construction process of the vessel. When it comes to further work, there are still potential to further develop the tools and the methodology of the connection between phases, with fully automation of the process, for example.

The design optimization methods developed in the HOLISHIP project are already being used by the lead beneficiary Kongsberg Maritime of WP9 in other research projects like the EU funded project NEXUS (design and optimization of a SOV for offshore wind farms) and commercial projects proving increase efficiency in the early design stage. The methods for virtual verification using dynamic simulations are being further developed and used in other research projects including the EU funded projects NEXUS (Demonstration and verification of operational concepts) and AUTOSHIP (verification of control systems for autonomous vessels).

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Satodev (2020). *GRIF—GRaphiques Interactifs pour la Fiabilité.*

Sintef Ocean (2020). *ShipX*—ShipX Workbench (Version 3.1).

Sintef Ocean (2020). *VERES*—ShipX VEssel RESponse program (Version 4.09.7).

Sintef Ocean (2020). *VEPOST*—ShipX VEssel POSTprocessing program (Version 4.09.17).

Sintef Ocean (2020). *Station Keeping*—ShipX Station Keeping program (Version 6.1.4).

Sirehna (2018). *BuDa*—Bubble Diagram

Sirehna (2020). *SAR*—System Architecture and Requirements.

Software name	Acrynom description	Developer	Year	Version
COSSMOS	COmplex Ship Systems MOdelling and Simulation	DNV-GL	2018	

(continued)

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Software name	Acrynom description	Developer	Year	Version
SHIPFLOW	Shipflow	Flowtech	2018	6.4.01
CAESES	CAE System Empowering Simulation	Friendship Systems AG	2020	4.4.2
MPSET	Marine Power System Evaluation Tool on Matlab Simulink	Kongsberg Maritime	2020	Beta
MATLAB	Matlab Simulink	MathWorks	2018	2018b
NAPA	Naval Architectural Package	NAPA Group	2018	2018.3
GRIF	*GRaphiques Interactifs pour la Fiabilité*	Satodev	2020	
ShipX	ShipX Workbench	Sintef Ocean	2020	3.1
ShipX VERES Plug-In	ShipX VEssel RESponse program	Sintef Ocean	2020	4.09.7
ShipX VEPOST Plug-In	ShipX VEssel POSTprocessing program	Sintef Ocean	2020	4.09.17
ShipX Station Keeping Plug-In	ShipX Station Keeping program	Sintef Ocean	2020	6.1.4
BuDa	Bubble Diagram (system architecture tool)	Sirehna	2018	
SAR	System Architecture and Requirements	Sirehna	2020	

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- Digitalization of maritime control systems

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Engine room configuration assessment for LNG newbuilding project.

Digitalization of services.

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M.Sc. in Computational Mechanics from the School of Chemical Engineers of the same University.

2 years in the Laboratory of Marine Engines of the School of Naval Architects and Marine Engineers (NTUA).

Technical projects during the academic and military periods.

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Ph.D. in Mechanical Engineering, National Technical University of Athens, Greece.

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10 years in DNV GL Maritime Research & Development and Advisory.

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Chapter 4
Development of a Tool for the Assessment of Lightweight Bulkheads and Decks Made of Composite Materials

Arthur-Hans Thellmann, Tim Schouwer, Wibke Mayland, and Santiago Ferrer Mur

Abstract This chapter deals with the development of methods and tools for the concept structural design of lightweight decks and bulkheads of cruise ships by use of composite materials. This task of the HOLISHIP project dealt with the development of a decision-support solution for the assessment of decks and bulkheads that may be replaced by composite materials. For this purpose, an Excel-based tool was developed, which is optimising the inspected structural design with respect to cost and weight. This chapter explains how this solution was developed. Various designs are explored and tested, while test results are presented and conclusive remarks are made after each completed milestone.

Keywords Lightweight structure · Composite materials · FRP · Cruise vessel · Outfitting · Accommodation · Cost

Abbreviations

AC	Application Case
AC	Air Conditioning

This chapter quotes the "Public Report of Cruise Vessel Deliverable D10.1" of the HOLISHIP project, funded by the EU under the European Union's Horizon 2020 research and innovation programme under the grant agreement No. 689074.

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A. Papanikolaou (ed.), *A Holistic Approach to Ship Design*,
https://doi.org/10.1007/978-3-030-71091-0_4

CABIN	TNO Software Tool
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAESES®	CAE System Empowering Simulation (Friendship Systems Software
CCT	Cost Calculation Tool
CMT	Center of Maritime Technologies gGmbH
CRN	Comfort Rating Number
FEM	Finite Element Method
FRP	Fibre-Reinforced Polymers
HOLISHIP	HOLIstic optimisation of SHIP design and operation for lifecycle
IMO	International Maritime Organization
PE	Polyethylene
PET	Polyethylene Terephthalate
PIR	Polyisocyanurate
R'w	Apparent Sound Reduction Index
Rw	Sound Reduction Index
SME	Small and Medium-Sized Enterprises

4.1 Introduction

4.1.1 Design Challenges of Cruise Vessels

Cruise vessels are highly complex ships including a high level of outfitting for ship functions, high owner requirements towards design and performance as well as challenging operational conditions. These vessels are built by large and often specialized shipyards in Europe, supported by a wide range of SME suppliers.

Cruise vessels are traditionally designed and manufactured out of steel material. The material is robust, and both design and production processes are well established. Since the shipbuilding industry faces the challenge of reducing both emissions and costs, the use of lightweight materials is becoming increasingly important. While lightweight materials—especially aluminium—have a long history in shipbuilding, dating back to the 1950s, there is great potential for integrating fibre-reinforced polymers (FRP) into cruise ships. FRP can help to reduce mass in weight critical areas of the ship. However, the use of such lightweight construction materials not only affects the weight, but also leads to different mechanical and fire protection properties, as well as altered noise and vibration behaviour. It may be necessary to adapt the surrounding design to some extent when replacing steel by FRP in specific components. Production processes need to be adapted from the steel process when integrating FRP into the ship design. Last but not least, the cost of material and process will be influenced.

Generally, when considering lightweight materials in cruise vessels, the goal is to use them only in areas and components where it leads to improvements in the technical and/or economic performance of the ship. Hence, the designer needs to be able to compare and evaluate different aspects such as design integration, noise and vibration as well as cost and producibility of designs using conventional metals like steel or aluminium and fibre-reinforced polymers. Since the use of lightweight materials affects many aspects of design and process, it has to be addressed in the design right from the start. The different material behaviours, design options as well as production aspects have to be considered and harmonized. Thus, in order to decide whether the use of lightweight materials is a good choice for a certain component, the ship designer must be able to compare the economic and technical performance of a steel design to a lightweight design in the early design phases.

4.1.2 Objectives of the Application Case

The Cruise Vessel Application Case focuses on the integration of fibre-reinforced polymers (FRP) for a SOLAS passenger vessel. Specifically, a structure on the sundeck of a cruise vessel is being investigated (see Sect. 4.2 for more details of the application case). At this position (upper decks) it is especially critical to have increased weight—since the centre of gravity is shifted upwards, the ship becomes less stable due to the reduction of the transversal metacentric height (GM_T) and draft problems can occur. Hence, it is of great importance to save weight in this area. Therefore, the possibility to replace the conventional materials (steel, aluminium) by fibre-reinforced materials is investigated.

For this application case, the first objective is to investigate the design integration of FRP components considering owner, class, and yard requirements as well as elaborating different design cases. The second objective is to assess the noise and vibration behaviour of the new materials. The third objective is to develop a tool to compare the producibility and cost of different design options including retrofitting and advanced outfitting aspects and to apply it to the sun deck application case.

4.2 Design Integration

4.2.1 Introduction to Design Integration

When changes are made to an existing design with an established process, design integration needs to be considered. This means addressing the integration of a new design aspect or component, which may involve a material change, into the existing shipyard process.

The approach here is to intervene as early as possible in the shipbuilding phase in order to be able to react to necessary subsequent changes. The phases/milestones of the ship design process are explained in more detail in Sect. 4.4. In this context, a scenario is described, which is intended to explain the integration more detailed.

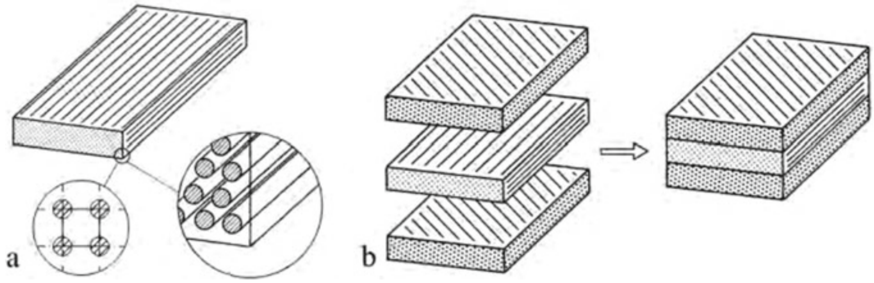

Fig. 4.1 **a** Unidirectional layer, here with square fibre packing **b** Multi-layer composite consisting of individual layers bonded together (Schürmann 2007)

This chapter also looks at the conventional steel solution and the advantages of replacing it with composite materials. Furthermore, the individual requirements that play an important role in the integration of a new material on a cruise ship according to SOLAS regulations are considered. SOLAS is the abbreviation for Safety Of Life At Sea. It contains rules and guidelines that should lead to the safe production of a ship.

Below is a brief introduction to the topic of fibre composites and the advantages they offer. Afterwards it is described what the results of the project goal are and what challenges have to be overcome.

Composites are materials, which consists of at least two different components. They combine the positive properties of the different materials. They usually consist of reinforcement fibres and a matrix surrounding them, see Fig. 4.1. Fibre composite materials are characterised by the fact that the fibres are mainly responsible for the stiffness and strength of the part while the matrix has to keep them in place and distributes the internal stresses between the load bearing fibres and at the same time protecting them from environmental impacts. Since the fibres mainly determine the mechanical properties of the composite material, their orientation is decisive for the mechanical performance of the later component.

It is well known that fibre-reinforced polymers are ideally suited for lightweight constructions. In the last decades, many applications in the aerospace and automotive industries have proven their suitability. However, to benefit the most from the use of composites, the design needs to be adapted to the specific material behaviour. To exploit the full potential of fibre composites, it is not sufficient to replace the material while keeping the design. The design of the component and the material properties define each other when using composites. Since the goal of the WP10 was to provide the designer a tool to compare the cost and benefits of different materials and design options in a very early design phase, without too much effort of looking into specific composite details, it was not feasible to generate an optimal composite design at this design phase though. Instead, the focus was set to taking the first step for the introduction of this new material group in the cruise shipbuilding industry and showing the potential of composites in comparison to standard materials by using the developed tool. While not changing the overall design of the application case (spatial geometry etc.) the design was kept and scaled to a unit cell panel, able to compare the influence of the different material approaches. To exploit the maximum potential of a lightweight approach, the design of the complete surrounding structure (room geometry etc.) has to be changed.

The goal of this study is to give the designer an estimation of the benefit of integrating composite materials in large structural panels, such as walls (bulkheads) and decks. As there are currently no composite materials on the market that meet all regulations and guidelines (especially IMO FTP Code) necessary for the approval process for SOLAS cruise ships, the first step was to work with composite panels with fictitious material properties, but foreseeing the option to complement the database as soon as suitable panels are available.

Currently, the conventional material for production is steel. As soon as the ship becomes weight critical (due to draft or damage stability requirements), the usual practice is to change the materials. This means that steel is replaced by aluminium, wherever possible. The procedure is described in more detail in Sect. 4.2.4. For the realization of the project, the already built cruise ship "Norwegian Gem" (see Fig. 4.2) was chosen, because it had the conditions that would require a change of material. The application case refers to the upper decks of the cruise ship.

In this chapter, first of all the Application Case (AC) is described in more detail in Sect. 4.2.2. This includes the initial situation and the adjustments required to achieve a successful result at the end of the project. In order to meet the objectives, the requirements of the classification society, shipping company and shipyard must be met. These are described in Sect. 4.2.3. In Sect. 4.2.4, the typical design phases of the shipyard are described. In Sect. 4.2.5, the different design options that have been investigated in this study are presented.

Fig. 4.2 Cruise vessel "Norwegian Gem"

4.2.2 Application Case Cruise Vessel

This application case was selected to be representative for the future application area of the developed tool. The tool should automatically provide information about which walls and decks can be replaced by using composite materials. The selection should be made in compliance with and in consideration of the characteristics, such as fire protection classes, ship specific requirements as noise & vibration characteristics and mechanical requirements.

In the case of the *Norwegian Gem*, it was determined prior to the start of the detail design phase that the ship could become weight critical. This was the reason to consider making the cruise ship lighter without removing accommodation areas from the ship or making them smaller. The design phases of a ship until completion are explained in more detail in Sect. 4.2.4. As the ship's centre of gravity got critical, the upper deck structures were considered for replacement, and it was analysed how and where an economic reduction in weight could be achieved. For the application case a deckhouse on the sundeck of the cruise ship "Norwegian Gem" was chosen, which was originally intended to be made of steel. A picture and a 3D CAD model of the application case are shown in Fig. 4.3 and in addition a technical drawing in Fig. 4.4. The structure consists of a deckhouse with several rooms of different use categories on deck 14 as well as on deck 15 of the ship. The structures of the deckhouse to be analysed can be categorized either as deck panels or as bulkheads. This and the fact that a material change had been made, makes this application a good example for the tool to be developed.

As can be seen in the figures (see Figs. 4.3 and 4.4), the geometry is complex due to bevels and recesses. Due to this fact, the CAD model of the application case was adapted and only plane structures are considered as the input structures for the assessment. This modification simplifies just the input and has no negative influence on the output of the tool, because mainly plane structures are found to be suitable for the use of FRP. These plane deck and wall structures can be found in a very huge amount on a cruise ship.

For a better view, Fig. 4.5 shows a side view of deck 14. On this drawing, the rooms of the application case are shown with information on the space category and fire protection classes according to SOLAS. The red-circled numbers indicate the

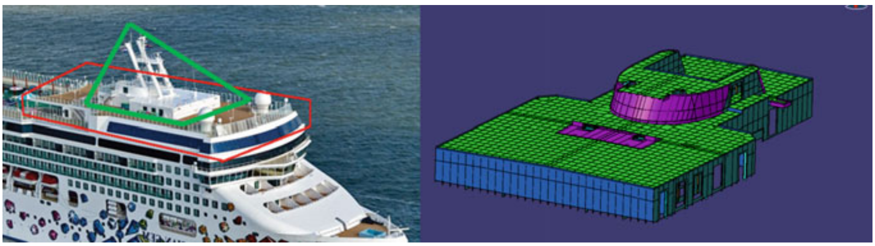

Fig. 4.3 Real application case and 3D-CAD model

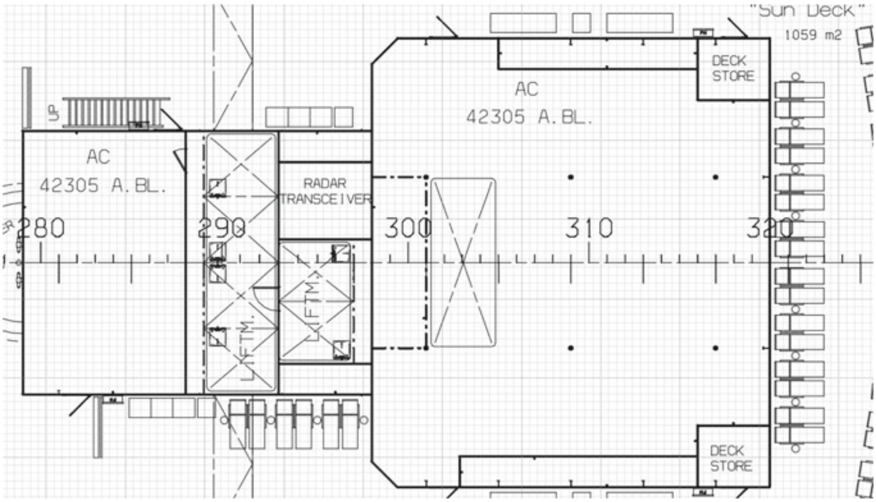

Fig. 4.4 Top down view of Deck 14: technical drawing with area names AC (Air Conditioning)

space category according to the SOLAS listed in Table 4.1. In combination with the neighbouring area, the insulation for the fire protection can be determined.

For example, the right air conditioning room in Fig. 4.5 is marked with a 10 and thus is a tank, void or auxiliary machinery space with little or no fire risk (see Table 4.1). The adjoining space on the top left marked with a 5 is an open deck space.

Table 4.1 Description of spaces for fire classification according to SOLAS

Description according to SOLAS 2014 Ch. II-2 Reg. 9-2.2.3	
1	Control stations
2	Stairways
3	Corridors
4	Evacuation stations and external escape routes
5	Open deck spaces
6	Accommodation spaces of minor fire risk
7	Accommodation spaces of moderate fire risk
8	Accommodation spaces of greater fire risk
9	Sanitary and similar spaces
10	Tanks, voids and auxiliary machinery spaces having little or no fire risk
11	Auxiliary machinery spaces, cargo spaces, cargo and other oil tanks and other similar spaces of moderate fire risk
12	Machinery spaces and main galleys
13	Store-rooms, workshops, pantries, etc
14	Other spaces in which flammable liquids are stowed

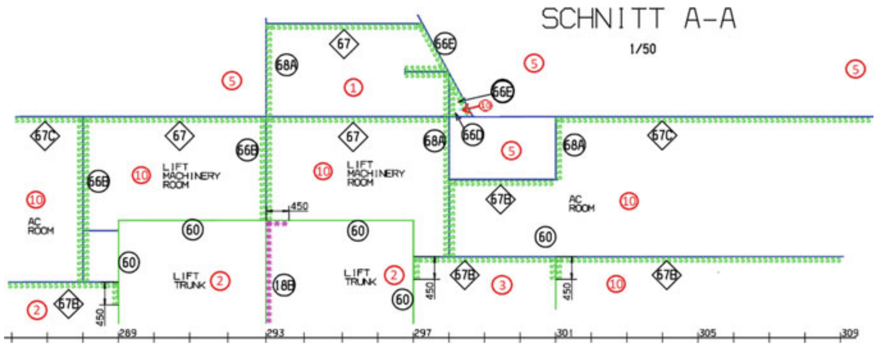

Fig. 4.5 Side view of Deck 14: technical drawing with area names AC Room (Air Conditioning Room)

The space categories of these adjoining rooms can be used to determine the correct fire integrity class for the wall connecting the rooms. To do so, it is important to distinguish between bulkheads and decks, because SOLAS defines different fire categories for bulkheads and decks as shown in Tables 4.2 and 4.3. In our example, the vertical separation is defined as bulkheads and the horizontal separation as decks. For the wall between the air conditioning room and the open deck space, the fire protection class A0 is determined from Table 4.2 by choosing the entry to space number 5 and 10. For bulkheads, the matrix is symmetric, i.e. the definition of the fire category only depends on the combination space categories on both sides of the

Table 4.2 SOLAS matrix for fire classification—bulkheads

Bulkheads not bounding either main vertical zones or horizontal zones														
Spaces	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	B0	A0	A0	A0	A0	A60	A60	A60	A0	A0	A60	A60	A60	A60
2		A0	A0	A0	A0	A0	A15	A15	A0	A0	A15	A30	A15	A30
3			B15	A60	A0	B15	B15	B15	B15	A0	A15	A30	A0	A30
4					A0	A60	A60	A60	A0	A0	A60	A60	A60	A60
5						A0	A0	A0	A0	A0	A0	A0	A0	A0
6						B0	B0	B0	C	A0	A0	A30	A0	A30
7							B0	B0	C	A0	A15	A60	A15	A60
8								B0	C	A0	A30	A60	A15	A60
9									C	A0	A0	A0	A0	A0
10										A0	A0	A0	A0	A0
11											A0	A0	A0	A15
12												A0	A0	A60
13													A0	A0
14														A30

Table 4.3 SOLAS matrix for fire classification—decks

Decks not forming steps in main vertical zones nor bounding horizontal zones														
Spaces	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	A30	A30	A15	A0	A0	A0	A15	A30	A0	A0	A0	A60	A0	A60
2	A0	A0	A0	A0	A0	A0	A0	A0	A0	A0	A0	A30	A0	A30
3	A15	A0	A0	A60	A0	A0	A15	A15	A0	A0	A0	A30	A0	A30
4	A0	A0	A0	A0		A0	A0	A0	A0	A0	A0	A0	A0	A0
5	A0	A0	A0	A0		A0	A0	A0	A0	A0	A0	A0	A0	A0
6	A60	A15	A0	A60	A0	A0	A0	A0	A0	A0	A0	A0	A0	A0
7	A60	A15	A15	A60	A0	A0	A15	A15	A0	A0	A0	A0	A0	A0
8	A60	A15	A15	A60	A0	A15	A15	A30	A0	A0	A0	A0	A0	A0
9	A0	A0	A0	A0	A0	A0	A0	A0	A0	A0	A0	A0	A0	A0
10	A0	A0	A0	A0	A0	A0	A0	A0	A0	A0	A0	A0	A0	A0
11	A60	A60	A60	A60	A0	A0	A15	A30	A0	A0	A0	A0	A0	A30
12	A60	A60	A60	A60	A0	A60	A60	A60	A0	A0	A30	A30	A0	A60
13	A60	A30	A15	A60	A0	A15	A30	A30	A0	A0	A0	A0	A0	A0
14	A60	A60	A60	A60	A0	A30	A60	A60	A0	A0	A0	A0	A0	A0

wall, but it does not matter which space category is on which side of the wall. For decks, the fire risk of two adjoining spaces also depends on the information which of the rooms of below since this influences the fire spreading behaviour. Hence the matrix for decks in Table 4.3 is not symmetric. For the application case, the conservative approach was taken to always use to higher category where they differ.

In Fig. 4.6, a top view of the application case on deck 15 is shown. This depicts

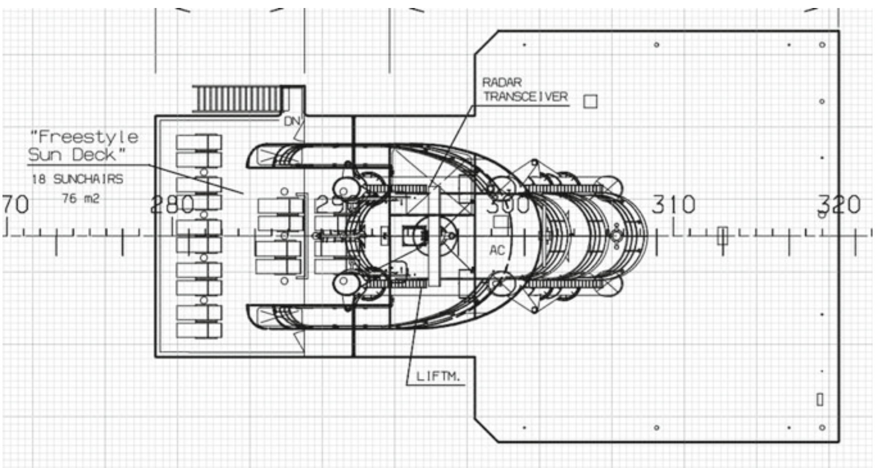

Fig. 4.6 Deck 15 technical drawing (AC)

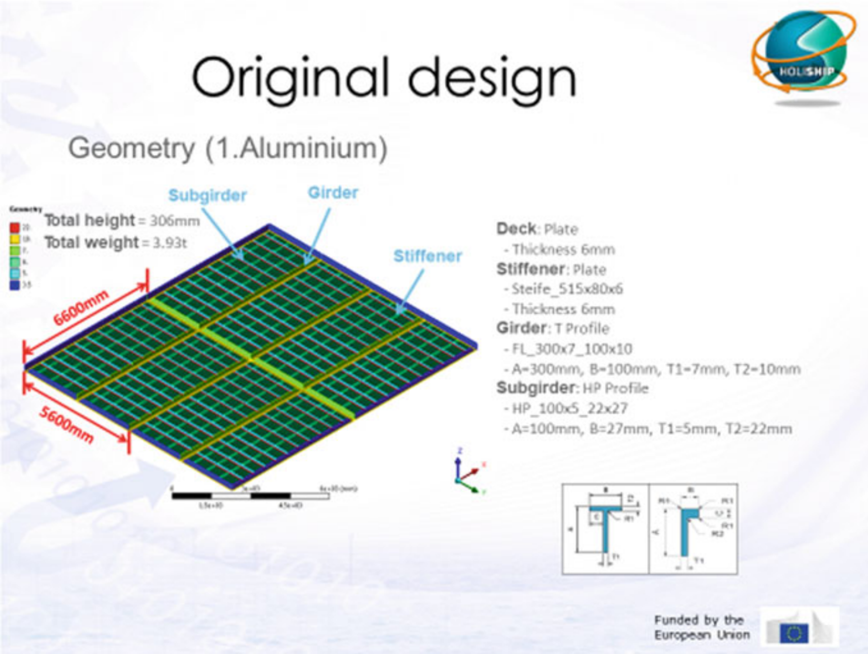

Fig. 4.7 Original panel design

a mast mounted on the deckhouse on sun deck and has sloping geometries.

By adjusting the geometry to plane elements, the panel to be examined looks like in Fig. 4.7, but care was taken to keep the arrangement of the girder, subgirder and stiffener. Furthermore, the size of the panel corresponds to the actual size of a panels of the deckhouse. The dimensions of the profiles were also maintained. In this way, an investigation can take place as close to reality as possible and the results obtained are meaningful.

4.2.2.1 Fields of Application and Improvements

Fibre composite materials are intended to be used everywhere in cruise ships as soon as they meet all necessary requirements, which are explained in more detail in Sect. 4.2.3. This is not yet the case, as products on the market for example do not cover all necessary fire categories and comply with the non-combustible requirements stated in SOLAS. Theoretically, however, it is already possible that fibre-reinforced composites can replace conventional steel in areas even with the highest fire protection (A60) and acoustic requirements. Expecting that new materials will meet these requirements and will be available in the near future or changes in the rules will be made with the aim of a more performance based criteria instead of definition based ones, which is the current status for the permitted materials for bulkheads and deck structures. The work for this application case could only be carried out with this assumption and combining already known values with best guesses for unknown properties for composite panels. However, there are areas in the ship where it is not foreseeable that in the near future a deviation from steel as the constructing material will be allowed. Examples of these spaces are load-bearing structures capable to contribute to the global strength of the ship and main fire zone barriers. Further areas are defined in the SOLAS guidelines.

The main objectives for a change of material are to save weight and costs. By saving weight, the cruise ship consumes less fuel and therefore lowers the emissions. Another benefit of saving weight is being able to increase the number of cabins on the ship and thus generating a higher revenue. For the application case, costs will need to be compared to the use of aluminium since this is the current option to decrease the weight of structures when the weight becomes critical. Compared to steel, aluminium is more expensive and complex to handle. This is due to the joint between the aluminium structures the steel structure of the ship, which can only be achieved by using special explosive cladding. The use of fibre composites usually implies higher costs as well, but if fibre composite materials will be applied in a serial application, it is quite possible that they could become competitive.

For the use of composite structures, there are plenty of possible applications on a ship. It is conceivable to initially "only" build stores and galleys made of fibre composite material. The next step could be to continue manufacturing cabins. First, the necessary composite panels are created and calculated purely theoretically, as there are no ready to use products on the market yet. Research is already being conducted on usable products and it appears that suitable products will be available in the near future. In order to be able to act quickly and safely, an Excel-based tool is being developed which can provide automated information about whether a material change can be carried out in a particular area and how economical this is. A detailed description of the tool can be found in Sect. 4.4.5.

In order to cover further requirements that go beyond this application case, a few examples are given which should also be taken into account. On one hand, concepts have to be worked out how to proceed with structures with recesses. In doing so, the recording of the geometry and the dimensions play an important role. If geometries made of composite should have interruptions, an exact proof for the preservation of the required structural properties has to be provided to avoid an early failure. Furthermore, slopes or arcs must be considered. Although it is somewhat more complex to calculate these, these shapes are often found in ships. For the current application, an optimization regarding weight reduction is aimed at, but this only refers to the constant profile geometry. In this project, the walls and decks should have the same stiffness as the aluminium ones, to be able to compare the weight of the variants. These results can be found in Sect. 4.2.5 and refer to the comparison of aluminium to steel and composite as material.

In the next section, an overview will be given of the requirements, laws and guidelines, which must be complied with in order for composites to be applied as a material for a wall or deck. The SOLAS regulations of the International Maritime Organization (IMO) are described more in detail, as they play a decisive role in the construction of a cruise ship. These regulations are reflected in the class requirements, and apply to ship-owners and the shipyard.

4.2.3 Owner, Class and Yard Requirements

In the following, the essential requirements of the class, the ship-owner and the shipyard are explained.

4.2.3.1 Class Requirements

The class or classification society draws up technical guidelines for the design and construction of ships and issues them as construction rules. Building regulations contain, for example, strength calculations for the design and dimensioning of shipbuilding structures.

Classification societies monitor and document compliance with these guidelines when building a new ship and then issue it with a so-called class. The class is an assessment of seaworthiness and is the basis for ship and cargo insurance as well as for trading ships.

Today there are twelve internationally recognized classification societies worldwide:

- American Bureau of Shipping (ABS), USA.
- Bureau Veritas (BV), France.
- China Classification Society (CCS), China.
- DNV GL, emerged from Det Norske Veritas and Germanischer Lloyd, Norway/Germany.
- Hrvatski Registar Brodova (CRS), Croatia.
- Indian Register of Shipping (IRS), India.
- Korean Register of Shipping (KRS), Korea.
- Lloyd's Register of Shipping (LRS), England.
- Nippon Kaiji Kyōkai (NK), Japan.
- Polski Rejestr Statków (PRS), Poland.
- Registro Italiano Navale (RINA), Italy.
- Maritime Register of Shipping (RS), Russia.

The requirements, such as structural properties for the application, are therefore determined by the classification society.

For the requirements for fire protection noise & vibration, however, the guidelines are the responsibility of SOLAS. The SOLAS (Safety Of Life At Sea) regulation contains many rules and restrictions to be applied with when building a ship. However, the most important ones for the project are those of fire classification, design properties and noise & vibration. The fire characteristics are determined by the class. More specifically, Chapter II-2 "Fire protection, fire detection and fire extinction" is the relevant SOLAS part that needs to be considered. It includes detailed fire safety provisions for all ships and specific measures for passenger ships, cargo ships and tankers.

They include the following principles:

– Division of the ship into main and vertical zones by thermal and structural boundaries.
– Separation of accommodation spaces from the remainder of the ship by thermal and structural boundaries.
– Restricted use of combustible materials; detection of any fire in the zone of origin.
– Containment and extinction of any fire in the space of origin.
– Protection of the means of escape or of access for fire-fighting purposes.
– Ready availability of fire-extinguishing appliances.
– Minimization of the possibility of ignition of flammable cargo vapour.

Composites should be integrated on cruise vessels considering SOLAS guidelines. The biggest challenge here is to meet the specified fire protection classes. FRP may only be used in compliance with certain requirements, which would be:

- For an area with fire class A60, the average temperature increase must not exceed 140 °C and the maximum temperature increase must not exceed 180 °C for 60 min. In addition, neither fire must not spread to other areas for 60 min.
- It is similar for A30, A15 and A0, except that the temperatures here must be maintained for 30, 15 and 0 min respectively. However, here too the requirement is that the fire does not spread to other areas for 60 min.
- There are areas with the fire classes B15 and B0. Here is the difference to fire class A that the maximum temperature of 225 °C must not be exceeded and the fire must not spread within 30 min.
- A wall with fire class C, does not have to meet any special requirements in terms of fire protection. In a standard cruise ship, there are no areas with this fire class.

These are summarized in Tables 4.4 and 4.5.

In the application case, the design characteristics refer to the loads and dimensions. For example, point loads can occur on a wall because a television is installed at this

Table 4.4 Fire class information for A

Fire class	Average temperature increase ≤140 °C (min)	Maximum temperature increase ≤180 °C (min)	Preventing passage (min)
A60	60	60	60
A30	30	30	60
A15	15	15	60
A0	–	–	60

Table 4.5 Fire class information for B & C

Fire class	Average temperature increase ≤140 °C (min)	Maximum temperature increase ≤225 °C (min)	Preventing passage (min)
B15	15	15	30
B0	–	–	30
C	–	–	–

point. However, it is also possible that two cabins are located directly next to each other and therefore the maximum depth of a wall must be observed.

Another reason for a minimum distance of two cabins can be noise & vibration. There are many areas on a cruise ship and some of them are exclusively for crew members and others are only for passengers. Since the goal is to maintain the highest level of comfort, there are clear guidelines on how much noise is allowed. However, this depends on areas and categories. Table 4.6 lists the areas that lead to so-called sound insulation indexes. The Comfort Rating Number (CRN) determines the level of well-being with regard to sound reduction. There are three categories 1, 2 and 3, whereby 1 is the highest rated category. This means that noise reduction is highest in this category and lowest in category 3. The three different categories are listed in Tables 4.7, 4.8 and 4.9. The values in these matrices are given in decibel dB. The higher the dB value, the higher the noise suppression.

Since the position of the room relatively to the wall or deck is not important, the "Sound insulation indexes for passenger areas" is symmetrical, thus it has no influence whether to start with the columns or rows to get the required sound insulation value of the surrounding bulkheads. As an example, we can take the areas 6 and 4, which are next to each other. If we now look at Category 1 in Table 4.7 on the left side of row 6 and column 4, we get the result of 38 dB. The same result is obtained if row 4 and column 6 are selected. The reading direction is therefore independent of each other (Tables 4.8 and 4.9).

Table 4.6 Space types for sound insulation

Space types for sound insulation according to DNV-GL	
1	Crew cabin or hospital
2	Crew corridor
3	Crew mess room, recreation room, public spaces or entertainment areas
4	Passenger cabin standard grade
5	Passenger cabin top grade
6	Passenger corridor
7	Passenger mess room, recreation room or public spaces
8	Passenger entertainment area

Table 4.7 Sound insulation indexes for CRN 1

Sound insulation indexes for passenger area with CRN 1								
Spaces (DNV-GL)	1	2	3	4	5	6	7	8
1	38	37	50					
2	37							
3	50							
4				41	46	38	51	65
5				46	46	41	56	65
6				38	41			
7				51	56			
8				65	65			

Table 4.8 Sound insulation indexes for CRN 2

Sound insulation indexes for passenger and crew area with CRN 2								
Spaces (DNV-GL)	1	2	3	4	5	6	7	8
1	35	32	47					
2	32							
3	47							
4				38	43	35	48	62
5				43	43	39	53	62
6				35	39			
7				48	53			
8				62	62			

Table 4.9 Sound insulation indexes for CRN 3

Sound insulation indexes for passenger and crew area with CRN 3								
Spaces (DNV-GL)	1	2	3	4	5	6	7	8
1	32	28	42					
2	28							
3	42							
4				35	40	33	45	60
5				40	40	37	50	60
6				33	37			
7				45	50			
8				60	60			

4.2.3.2 Owner Requirements

The shipping company is the shipyard's customer and orders the cruise ship. The ship is built in close cooperation according to the wishes of the ship-owner and rules and regulations of the classification society. The shipyard assesses the feasibility of the project in compliance with all guidelines and safety standards.

It is particularly important for the ship-owner to stand out from the competition, which is why many cruise ships have a unique selling point. This and, of course, the excursion destinations, are intended to increase the market shares of the specific ship. On the *Norwegian Gem*, two highlights for example are a climbing wall on the upper deck (see Fig. 4.8) and the Crystal Atrium with a very large screen on which games can also be played.

Otherwise, the requirements of the shipping companies are often identical. Typical requirements are a long life-cycle of the cruise ship, modern appearance, innovative technologies on board, many passenger cabins and ample space to be filled with the specific wishes of the customer. Furthermore, the appearance must be attractive and the technology must be in perfect condition. With this application case, all requirements are covered at least partially. Since FRP's do not corrode, they require less maintenance and therefore do not need to be replaced as often. The modern appearance is of course a matter of opinion, but composite material gives completely new design possibilities. Composite materials also are innovative technologies, because they have an enormous potential. There are many different combination and manufacturing possibilities, each of which is tailored to its intended use. More cabins and more space can be created, because the ship becomes lighter and it would be possible to implement more decks.

Fig. 4.8 Climbing wall on the Norwegian Gem (Source: TMN / Norwegian Cruise Line)

4.2.3.3 Yard Requirements

Roughly speaking, the shipyard's mission is to fulfil the customer's wishes, but with due regard to the laws and regulations. The aim of the shipyard is also to give its customers individuality and to gain a head start over competitors through unique knowhow. Therefore, the shipyard is constantly developing new solutions and concepts to increase effectiveness and sustainability. For this reason, the shipyard has its own standard (the "Werft Standard" of Meyer Werft GmbH & Co. KG). All requirements, laws and guidelines are observed or exceeded by the shipyards' demands.

Production Aspects

An essential part of the introduction of composites is the consideration of the production aspects. Thus, it must be ensured that the value-added chain is maintained for the most part. At present, MEYER WERFT has one of the largest and most modern panel production facilities in the world. Of course, the competences at the yard are currently set on the production of steel panels and not on composite ones. Therefore, the composite panels would initially have to be purchased (as soon as the availability is assured). However, as soon as a fibre composite material has proven to be suitable, fulfils all the safety, comfort and design requirements, and is established on cruise ships, the next consideration would be to set up a production facility for fibre composites.

At the moment, it is often difficult to react to short-term changes from the customer. Often new planning and calculations have to be performed to react on these developments during the ship development process. It becomes very complicated when changing or moving areas. This requires new calculations for the centre of gravity of the ship, but also the consideration of cables and piping. In many cases "hot work", like welding or burning, is no longer allowed when the ship is at an advanced stage of construction, which can lead to a lot of work even for minor changes e.g. something as trivial as burning an opening for cables. All neighbouring and surrounding areas are then inspected and evaluated. This can lead to the consequence that an adjacent area in which the hot work is to be carried out must be dismantled partly in order to minimize the risk of fire. With a composite wall this case could be avoided, because it can be cut without the need of hot work. Of course, the necessary structural properties must still be available.

4.2.4 Design Phases

In this section, the design phases are explained. To illustrate the process, a short scenario of what the work might look like using the results from this project is described. For a better understanding, the application case is chosen in the example.

After the rough details for the pre-contract phase have been clarified with the customer, the contract is signed and the following steps on the ship development process can be initiated. In this early stage for the preliminary weight prediction and stability calculations steel is used as the building material for all structural elements. Due to changes of the ship's design or of some areas, the ship might become weight-critical and under certain circumstances, the vessel stability might get critical if the centre of gravity shifts upwards. One of the possible countermeasures to increase the ship's stability is a change of the material of free-standing deckhouses on the upper decks, for example. An alternative material for the to be assessed structures would be aluminium, even if the substitution of steel with aluminium is expensive, since the connection between steel and aluminium is more complex by using explosive plating by specialist companies for example. Also the insulation of the aluminium structure to get the required fire classification has to be considered. Another possibility, which is currently in the focus of interest, is to use composites instead of steel or aluminium. The tool developed in this project is aimed to help at the decision which material is most suitable in respect to the specific requirements. With this tool the designer can quickly compare steel, aluminium and composite, determine costs, production time, and weight savings.

In order to benefit from the tool, it needs to be carefully considered at which point of the design process the tool ought to be used. It was a particular challenge to find a suitable shipyard process in which sufficient information on the ship areas was available and at the same time, sufficient flexibility was available to be able to react to short-term planning changes. Accordingly, the tool had to be developed based on the available information at this point of the process.

For this purpose, it was first necessary to know all processes and milestones of a ship. These are recorded in a so-called ship development process (SEP). This process is very comprehensive and describes the development of a cruise ship from kick off to delivery. It was clear that the tool should be integrated as early as possible in the design process, since the later changes appear the more expensive they will get. So the first milestones were examined more closely.

After careful research, the point within the ship development process is positioned after milestone B "Feasibility & Functions defined", because at this stage of the construction process there is sufficient data to obtain a weighted statement from the tool and the construction process is still not so far advanced that a change would not be possible anymore. In this phase the tasks of the contractor are defined and an agreement is reached with the buyer. A general arrangement plan is aligned and a block plan is created. Final orders are then sent out.

4.2.5 Conclusions to Design Integration

Analysing the design integration for this application case provides a good foundation for gaining an edge over the competition when a composite material is approved and established on cruise ships.

As there are no composite panels on the market yet, fictitious assumptions for the tool input of the composite panels had to be made, which were then used for calculations and the assessment of the design. This often made it difficult to make the topic tangible for everyone. For this reason, the chosen panels were previously created with common materials. This made it possible to work with meaningful values.

A further hurdle was the integration into the shipyard process. Unfortunately, it is often the case that many decisions are based on experience, which is especially true in the pre-contract phase. Therefore, it was often difficult to get a reasonable statement about which results are available at what point in time in the ship development process. It is often the case that rough areas of the ship are planned, but without detailed values. Therefore, it is not unusual that during the development of a ship areas are relocated, redesigned or simply replaced.

Nevertheless, the composite selection tool developed on basis of these information can provide great added value for the engineer in a very early stage and indicates a direction what the influences of different material alternatives may result in. Because it is used where decisions about the material can still be reconsidered and with the stored figures, a statement can be made easily and quickly about how effective it might be to change the material of certain components.

4.3 Noise and Vibration

4.3.1 Introduction to Noise and Vibration

An important development in ship and seagoing structures is the application of non-conventional materials including synthetic materials and fibre reinforced polymer (FRP) materials with the aim of reducing structural weight, reducing building costs and combining functional properties (e.g. structural support and sound/ vibration isolation). Accommodation and workspaces on board cruise ships are subject to stringent noise and vibration requirements. This not only holds for the interior noise level inside a cabin, but also to the noise transmission of one cabin to the adjacent one. Noise and vibration prediction calculations enable nowadays the designer or ship builder to foresee already in an early design stage if these noise requirements can be met or if additional countermeasures are needed. For this purpose appropriate acoustic and dynamic assessment methods and tools are required. In this section the transfer of airborne and structure-borne sound and the damping of structural vibrations of composite structures are discussed.

4.3.2 Sound Reduction Index for Typical Sandwich Compositions

For the present application case of HOLISHIP, the frequency dependent transmission loss and the resulting weighted sound reduction index have been calculated for a targeted sandwich panel layout, see Fig. 4.9. The skin panels are glass-fibre reinforced resin (density 2000 kg/m^3). The low stiffness of an additional mass layer in between skin panel and core has been neglected and the mass included by increasing

	GFRP Panels	Core materials					
		1. PIR foam	2.PUR foam	3.Balsawood	4.PET foam	5.PE foam	6.PVC foam
Young's modulus E [MPa]	2e4	6.4	0.5	2e3	60	37	50
Density ρ [kg/m³]	2200*	33	35	82	100	96	90
Geometrical properties							
t_p [mm]	4-8-16	-					
t_c [mm]	-	50-100-200					
l [mm]	2,650**						
b [mm]	3,750						

* Density of FRP panels includes additional mass of mass layer

** Standardized laboratory dimensions

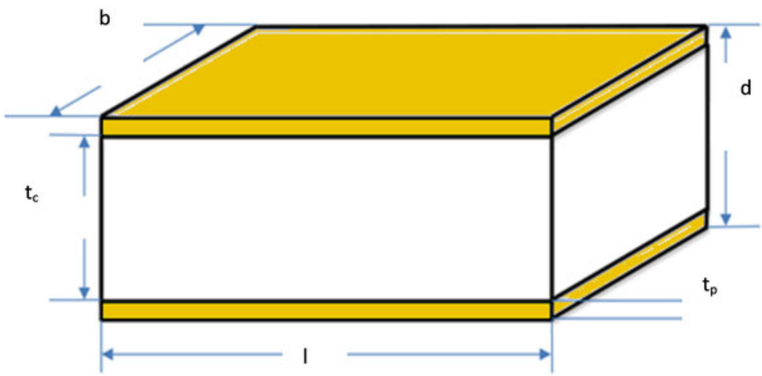

Fig. 4.9 List of the studied sandwich compositions and material properties

skin layer density. Several core materials have been studied, see Fig. 4.9. Some are foam materials, like polyisocyanurate (PIR) which is typically used for rigid thermal insulation. Balsawood is a common core material but much stiffer and heavier. Not all core materials will have the correct fire-retardant properties. The PET and PE foams are known to have fire resistance. The Young's modulus of all cores is much smaller than of the skin panels.

The damping loss factors of the material are not specified. For this exercise, they were taken from database and literature values found for FRP and foam-like materials, typically 0.1–0.2. The damping loss factor of the core material governs the sound insulation at the core resonance frequency. To illustrate the sensitivity of the loss factor, the resulting R_W value is increased by 3 dB if the loss factor is doubled.

In addition, geometrical and material properties have been changed to study the sensitivity of these parameters on the R'W value. For this purpose, an existing calculation model for sound insulation of composite building structures is used (see Gerretsen 1991). This is a model to simulate laboratory test. This means no flanking sound path, direct transmission through the panels only. Also, the sound field is diffuse, which means that sound waves reach the panel from all directions.

As a start, the effect of skin thickness is tested, by halving and doubling the layer thickness, see Table 4.10. As this directly affects the mass per unit area, insulation increases for increased thickness and consequently R_W value increases, see left Fig. 4.10. Additionally, the core resonance decreases for increased skin mass, which is favourable for the high frequency insulation.

Next, the core layer is changed by halving core thickness and halving core density, both resulting in the same total mass properties. The effect on R_W is only small, 0–1 dB. Insulation performance can be substantially improved by selecting a softer and thicker core material. This forces the core resonance frequency down, see centre Fig. 4.10. In this example, a foam core is used with equal density but much lower Young's modulus. It results in an increase of R_W of 7 dB.

The 4 mm layer attached to the FRP skins is quite light. Replacing the layer by heavier rubber layers (density 1300 kg/m^3) with equal thickness can increase the R_W value by 5 dB.

Table 4.10 Sandwich compositions and corresponding calculated weighted sound reduction index

Model	Modification	Total mass (kg/m^2)	Core resonance (Hz)	R_W in dB
1	Baseline	19	822	30
2	Doubling panel thickness	37	583	37
3	Halving panel thickness	11	1125	27
4	Halving core thickness	18	1166	31
5	Halving core material density	18	825	30
6	Carbon fibres (E-modulus 3 times higher)	19	1162	30
7	Rubber layer infill	28	679	35
8	Soft and thick core	24	117	37

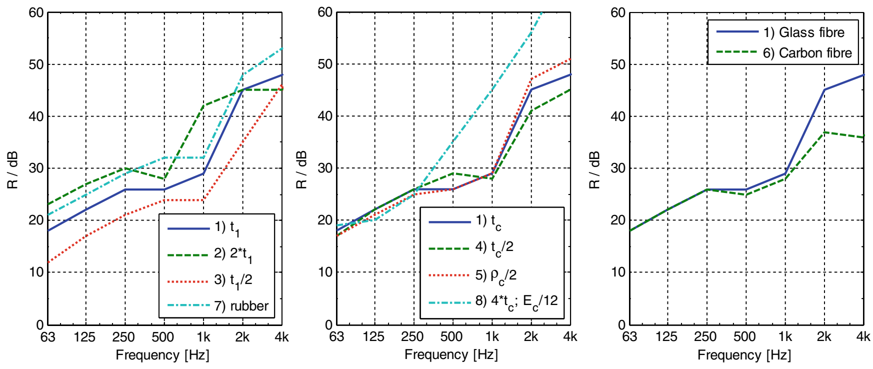

Fig. 4.10 Calculated sound insulation R for various sandwich designs in third-octave bands

Finally, the skin stiffness was changed by using carbon fibres instead of glass fibres. This results in an increase of the Young's modulus by a factor 3 and a longitudinal wave speed equal to that of aluminium. Since the mass is kept constant, effects can only be seen in the stiffness controlled high frequency range. Due to the stiffening the coincidence frequency, the frequency for which bending wavelength in the panel is equal to wavelength in air, decreases. This high frequency affect has no impact on the R_W value.

A validation of the transmission loss and corresponding R_W value prediction on a prototype sandwich panel in a building acoustics laboratory is recommended (see Dym & Lang 1983).

4.3.3 Simplified Design Tool

A simplified version of the acoustic model to assess the R_W value in an early design stage was implemented in the developed Excel tool see Fig. 4.11. The material properties of the skin and core materials can be entered, and the insulation index is estimated. From the spectrum the R_W value is calculated. High frequency coincidence effects are not implemented.

4.3.4 Attenuation of Structure-Borne Sound

Experimental analysis on a hybrid steel/composite ship structure showed a clear potential of hybrid superstructures in the attenuation of structure-borne sound in vertical direction (along deck transitions) (see de Regt 1981). It is much higher for a hybrid steel/FRP deck transition then for steel/steel. This is due to steel/FRP joints

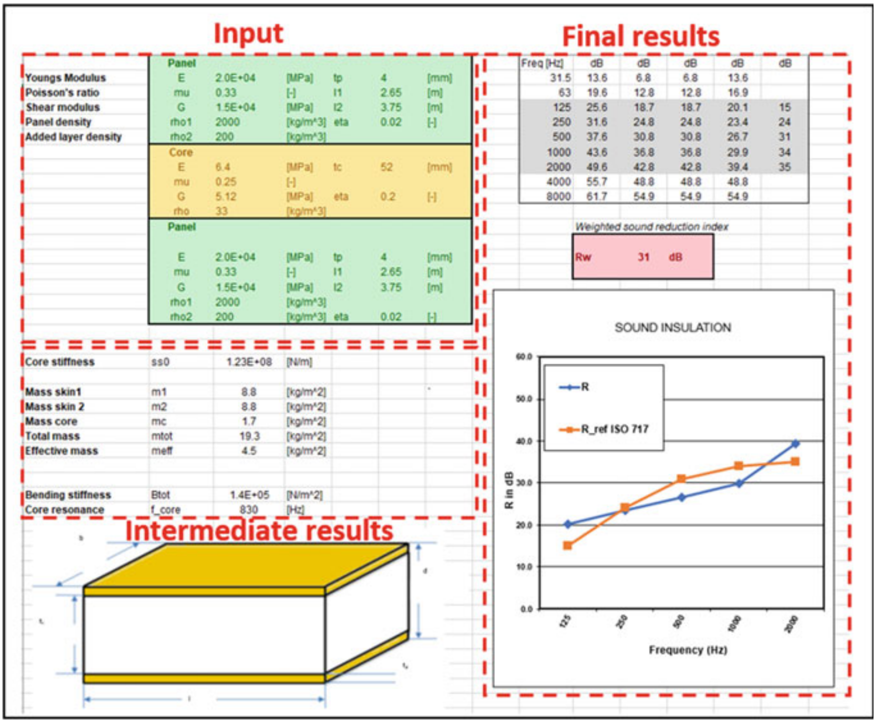

Fig. 4.11 Overview of the R_W Excel sheet

and interfaces introducing impedance mismatches. In horizontal directions (in-plane deck), no substantial differences with a steel reference case was observed.

4.3.5 Vibration Damping

Dynamic analysis on the same hybrid steel/composite ship structure showed that composite decks and bulkheads feature structural damping ratios ζ in the range of 4 to 7% of critical damping, as opposed to steel deck/ bulkhead structures where these values tend to lie below 1%. Hence dynamic amplification factors for composite structures range from 7.1 to 12.5, whereas for steel structures they are at least 50. Also composite structures seem to have a tendency towards a lower number of natural frequency and associated mode shapes in the frequency range of interest (0–30 Hz) compared to steel structures.

4.3.6 Conclusions to Noise and Vibration

The calculation results have shown that meeting stringent acoustic requirements with light-weight sandwich panels is not straightforward. The structural requirements to save weight by application of light-weight composite panels seems in conflict with the acoustic requirements.

Especially in the frequency range which is important for speech and music, the panel mass governs the sound transmission. The stiffness of the panel mainly affects the high frequency transmission. From this perspective the insulation of a partition panel can be improved by:

- Increasing thickness of skin panels;
- Adding additional layers.

However, there is a way to gain more benefit from a sandwich panel: the core resonance should be as low as possible. This can be achieved by selecting a low stiffness core layer (low Young's modulus in combination with high core thickness) in combination with a high skin layer mass.

4.4 Producibility, Retrofitting, Advanced Outfitting and Cost

4.4.1 Introduction to Producibility, Retrofitting, Advanced Outfitting and Cost

Ship designers need to be able assess the feasibility of a FRP design compared to a conventional steel or aluminium design in the early design phase. This includes evaluating whether a new design can fulfil owner, class and yards requirements as described in Sect. 4.2.3 and assessing the impact on noise and vibration behaviour as described in Sect. 4.3. Additionally, cost and producibility of a new design are important selection criteria that need to be considered. Within this study, it was investigated how replacing a steel or aluminium design by a FRP design for the application case affects cost and producibility aspects. A tool for the assessment of cost and producibility as well as the feasibility regarding fire safety was developed and used to compare different designs for the application case. Since it is common to have small design changes in later stages of the production process of a cruise vessel, the ability of a new design to accommodate to such changes is also considered.

In this chapter, first relevant aspects regarding producibility, retrofitting and advanced outfitting are discussed. The methodology to determine costs for different design options is explained. Subsequently, the tool for the assessment of different designs and material choices is presented and applied to the application case.

4.4.2 Producibility

When new design alternatives are considered, usually the initial focus is on technical feasibility regarding design and classification criteria. If a design is considered feasible with respect to these aspects, the next important question is whether this design can be produced and integrated in the existing production process—i.e. to assess the producibility—and whether this can be done at a reasonable price. If a design is producible in general, different parameters such as geometric parameters may influence whether the production process can be implemented easily or is of a more complex nature.

In the early design phase, there is limited information available to assess producibility of different design alternatives. Since there is, however, the need to evaluate different design alternatives at this stage, a producibility assessment tool was developed based on a relatively simple dimensionless producibility score system elaborated in Work Package 4 of the HOLISHIP project. Utility functions are derived in particular for geometrical variation of the different parameter of stiffener panels. The tool demonstrates, that such parameter variations can be assessed well using such utility functions. The concept of this application case is to replace the existing aluminium deckhouse structure with panels and beam structures made of composite. For the concept of using available composite panels for the alternative design assessing producibility is reduced to assessing the assembly process of the panels to the steel ship structure including considering accessibility for the assembly and possible joining methods.

It should be noted that the exact implementation of the production process affects the cost of different designs (see Sect. 4.4.5). Hence, there is potential for optimizing costs by optimizing the production process. However, based on the information in the early design method, it is impossible to already include an optimized process. But it should be kept in mind when comparing costs that there is further potential for cost reduction of the alternative design, whereas the process for the current design usually is already optimized with respect to costs.

4.4.3 Retrofitting

Retrofitting is an important aspect in shipbuilding, especially in cruise liner and yacht markets, as the trends evolve fast with respect to integrated technologies, required equipment and interior fashion.

When retrofitting involves the installation of either heavy devices directly bolted to the bulkheads and decks, special considerations need to be taken into account if a composite sandwich type construction is involved. In that case, there are three main effects to be considered: out-of-plane and in-plane buckling due to the weight of the device, compression loads due to the fastening of the device, and bearing loads again due to the weight of the device. Buckling loads exceeding the design load of the panel might require re-dimensioning for higher stiffness, normally with thicker cores for weight optimization. Compression loads are a crucial design parameter for the core material. An increased compression load might require local re-dimensioning of the core, normally selecting a high-density core of the same type. Bearing loads act transversely to the fibres and normally require local reinforcements of $\pm 45°$ plies. Another possibility would be that the device is fastened with wood-type screws in which case special considerations need to be taken concerning the sandwich core.

Penetrations introduce different design considerations related to fire resistance and pre/post-processing. The fire division category must to be maintained also with penetrations. This can be easily achieved if this is already considered in the design phase, but will need special care in case of repair and retrofitting. On the other side, penetrations would need special considerations when they are done on humid or weather-exposed areas, where it must be ensured that the core of the sandwich remains watertight at any time.

The tool is ready to integrate data for retrofitting as the assessment procedure is the same as for the preliminary design phase, which is explained in more detail in Sect. 4.4.6. The input will give information about the required fire division categories as well as sound insulation. The tool will then check if the requirements are achieved with the available panels configured in the panel catalogue. At this point, the panel catalogue should be updated with the new design considerations of the retrofitting, and the new panel reference list can be compared with the same references of the original list, knowing in this way which bulkheads and decks need to be post-processed. The format of the panel catalogue including update buttons for new panels is shown in Fig. 4.12.

4.4.4 Costs

The early determination of costs and cost drivers in the production of shipbuilding elements increases the probability of meeting planned budgets and thus leads to profitable success in shipbuilding. Based on a reference panel of the project partner Meyer Werft, a cost calculation tool (CCT) was developed in order to make suitable statements about the production costs of a shipbuilding panel made of different materials.

4.4.5 Composite Selection Tool

4.4.5.1 Tool Description

Since it has been theoretically proven that significant weight savings can be achieved in classic shipbuilding by using future composite materials, a tool is developed which performs an assessment to determine whether the use of composite materials is suitable.

	A60				
	Panel 1A60C	Panel 2A60C	Panel 3A60C	Panel 4A60C	Panel 5A60C
	Plate 1A60C	Plate 2A60C	Plate 3A60C	Plate 4A60C	Plate 5A60C
	Update plate	Update plate	Update plate	Update plate	Update plate
σ_t	107	126	126	126	107
σ_c	107	126	126	126	107
t_{lam}	1.5	8	3	8	1.5
t_{core}	15	50	20	50	15
τ_{core}	1.45	1.45	1.45	1.45	1.45
t_{eq}	12.2	52.8	20.3	52.8	12.2
E_{eq}	1.21E+04	1.16E+04	1.19E+04	1.16E+04	1.21E+04
	Stiffener 1A60C	Stiffener 2A60C	Stiffener 3A60C	Stiffener 4A60C	Stiffener 5A60C
	Update stiffener	Update stiffener	Update stiffener	Update stiffener	Update stiffener
S	825	0	825	0	825
σ_t	460	0	280	0	126
σ_c	460	0	280	0	126
τ	266	0	162	0	68
$y_{stiffener}$	58	0	136	0	173
y_{plate}	22	0	22	0	22
GA	7.34E+06	0.00E+00	2.26E+07	0.00E+00	8.48E+06
EI	2.90E+11	0.00E+00	6.73E+11	0.00E+00	1.40E+12
I	2.99E+06	0.00E+00	2.23E+07	0.00E+00	7.24E+07
Support	Simple	Simple	Simple	Simple	Simple
m	17	43	23	43	22.7
SI	60	60	60	60	60
Cost	50	40	55	40	60

Fig. 4.12 Composite panel group in the panel catalogue

The assessment procedure implemented in the tool is elaborated in the following steps:

1. The user provides an input file containing information on the deck and bulkhead panels that are to be assessed. This includes geometric dimensions, current material, weight, and existing fire division category. Additionally, the user can define parameters defining structural and insulation requirements and has the option to define fire division categories manually as well. These input variables are shown in Fig. 4.13. For example, the user can define the maximum allowable deflection, relevant safety factors, or the sound insulation level according to its crn (comfort rating number). Subsequently, the user has the choice of optimizing either weight or cost. The tool has been integrated into the HOLISHIP CAESES® design platform.

2. With this input information, the tool will start the assessment of each panel. During the assessment procedure, the tool evaluates whether it is feasible to replace the original panel by a pre-defined selection of alternative panels defined in a panel catalogue. This panel catalogue contains a selection of aluminium and FRP panels as well as material data for steel panels. As explained in Sect. 4.4.3,

Input variables and optimisation box

Structural	Maximum relative deflection general (%)	0.5%
	Maximum relative deflection plates (%)	1.5%
	Maximum absolute deflection (mm)	50
	Safety Factor for bending	3
	Safety Factor for shear	3
	Safety Factor for deflection	2
	Ship rule length (m)	300

insulation	Crew areas insulation crn level	2
	Passenger areas insulation crn level	1

Input	Fire division given in input? (otherwise, fire zones need to be specified)	YES
	Highest fire division category allowed with composite	A0
	Highest fire division category allowed with aluminum	A0

Import data

Optimize for weight

Optimize for cost

Fig. 4.13 Input variables in the "cockpit" sheet of the tool

the panel catalogue can be updated by the user at any time e.g. if new materials become available on the market.
Assessment of the feasibility of the alternative panels is based on the compliance of different design parameters to class, owner, and yard requirements. Specifically, three aspects are evaluated subsequently in the assessment procedure (each containing a few sub-criteria for compliance):

a. Compliance of fire division class,
b. Compliance of structural requirements,
c. Compliance of sound insulation requirements.

3. The results of the panel assessment are presented in the "report" sheet.
This sheet serves as a simplified visual summary, allowing the designer to get a quick overview of the compliance assessment for each panel. As shown in Fig. 4.14, the designer will be able to see for all selection criteria whether compliance can be achieved using the alternative panels from the panel catalogue

FeatureName	Type	Fire category	[redacted]	Panel type	Fire category compliance	Plate deflection compliance	Plate bending strength compliance	Plate shear strength compliance	Stiffener deflection compliance	Stiffener bending strength compliance	Stiffener shear compliance	Sound insulation compliance	Panel 1	Panel 2	Panel 3	Panel 4	Panel 5
LW_1_D14	BULKHEAD	A0		A0 Composite	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
LW_2_D14	BULKHEAD	A0		A0 Composite	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
LW_3_D14	BULKHEAD	HEAT		HEAT Composite	YES	YES	YES	YES	YES	YES	YES	NO	NO	NO	NO	NO	NO
LW_4_D14	BULKHEAD	HEAT		HEAT Composite	YES	YES	YES	YES	YES	YES	YES	NO	NO	NO	NO	NO	NO
LW_5_D14	BULKHEAD	A0		A0 Composite	YES	YES	YES	YES	YES	YES	YES	NO	NO	NO	NO	NO	NO
LW_6_D14	BULKHEAD	A0		A0 Composite	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
LW_7_D14	BULKHEAD	A0		A0 Composite	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
LW_8_D14	BULKHEAD	A0		A0 Composite	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
LW_9_D14	BULKHEAD	A0		A0 Composite	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
LW_10_D14	BULKHEAD	A0		A0 Composite	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
LW_11_D14	BULKHEAD	A0		A0 Composite	YES	YES	YES	YES	YES	YES	YES	NO	NO	NO	NO	NO	NO

Fig. 4.14 Compliance summary in the “report” sheet

(where green means panel complies, red does not comply). These results help the designer understand where the problems can be and introduce changes in the panel catalogue accordingly, e.g. if most FRP panels in the panel catalogue fail to achieve compliance of the fire division class it is promising to look for different materials with better fire properties, if fire division achieves compliance but sound insulation requirements are generally not achieved then there is potential in finding materials with better sound insulation properties.

4. The last step is the weight and cost optimization algorithm. This algorithm is implemented in the "results" sheet and will select the best available option from the panels that where identified to be technical feasible in the previous step. Depending on the optimization criteria selected by the designer, the algorithm selects the cheapest or the lightest available option out of all technically feasible panels. In the result table (Fig. 4.15), for each panel the optimal selected material (aluminium or composite) is displayed together with the according optimal panel, i.e. out of several different composite panels with different mechanical properties and weight and cost in the panel catalogue the result table specifically identifies the best composite panel if composite is the best choice. For this optimal panel, the new cost and weight is determined and compared to the original cost and weight. If none of the alternative panels are feasible, the original material will be selected.
5. An overview of the results is given in the result area of the "cockpit" sheet as shown in Fig. 4.16. The designer can see at one glance how many panels were analysed and for how many panels a replacement of the original panel by an alternative panel of the panel catalogue can reduce weight as well as which total weight savings can be achieved at which cost. The graphic results also display failure type distribution, giving a clear information on the suitability of the panel catalogue for the considered application.

4.4.5.2 Integration in CAESES®

This section describes the workflow performed to create the "Tool Input File" that is generated by CAESES® and consumed by the "Composite Selection Tool".

Workflow

The procedure starts with the user importing an input geometry in CAESES® (see Fig. 4.17). The input geometry is preferred to be an stp/step or ascii file type where some of the naming arguments are preserved and transferred directly into CAESES®.

In CAESES®, a so called "Feature Definition" has been created. After having imported the geometry in CAESES®, the user needs to specify the scope that contains the imported geometry. The created feature includes the necessary commands to evaluate the panels within the scope. The panels are checked initially for their type (Bulkhead, Deck, Column) and then are used for detecting the existing rooms and floors. As a result, a plan view of the rooms and floors is created below the existing imported geometry where the user is requested to assign the room functionalities (Fig. 4.18).

FeatureName	Required fire division	Selected material	Panel reference	Surface cost (€/m²)	Original cost	Cost (€)	Cost delta (€)	Surface mass (kg/m²)	Original weight	Weight (kg)	Weight delta (kg)
LW_1_D14	A0	Composite	Panel 1A0C	50	392.9625	785.925	392.9625	17	1100.295	267.2145	-833.0805
LW_2_D14	A0	Composite	Panel 1A0C	50	392.9625	785.925	392.9625	17	1100.295	267.2145	-833.0805
LW_3_D14	HEAT	Aluminum	Panel 1HEA	40	449.1	718.56	269.46	60	1257.48	1077.84	-179.64
LW_4_D14	HEAT	Aluminum	Panel 1HEA	40	449.1	718.56	269.46	60	1257.48	1077.84	-179.64
LW_5_D14	A0	Aluminum	Panel 1A0A	40	212.075	339.32	127.245	60	593.81	508.98	-84.83
LW_6_D14	A0	Composite	Panel 1A0C	50	212.075	424.15	212.075	17	593.81	144.211	-449.599
LW_7_D14	A0	Composite	Panel 1A0C	50	212.075	424.15	212.075	17	593.81	144.211	-449.599
LW_8_D14	A0	Composite	Panel 1A0C	50	87.325	174.65	87.325	17	244.51	59.381	-185.129
LW_9_D14	A0	Composite	Panel 1A0C	50	130.9875	261.975	130.9875	17	366.765	89.0715	-277.6935
LW_10_D14	A0	Composite	Panel 1A0C	50	130.9875	261.975	130.9875	17	366.765	89.0715	-277.6935
LW_11_D14	A0	Original	Original A0	25	87.325	87.325	0	70	244.51	244.51	0

Fig. 4.15 Results table

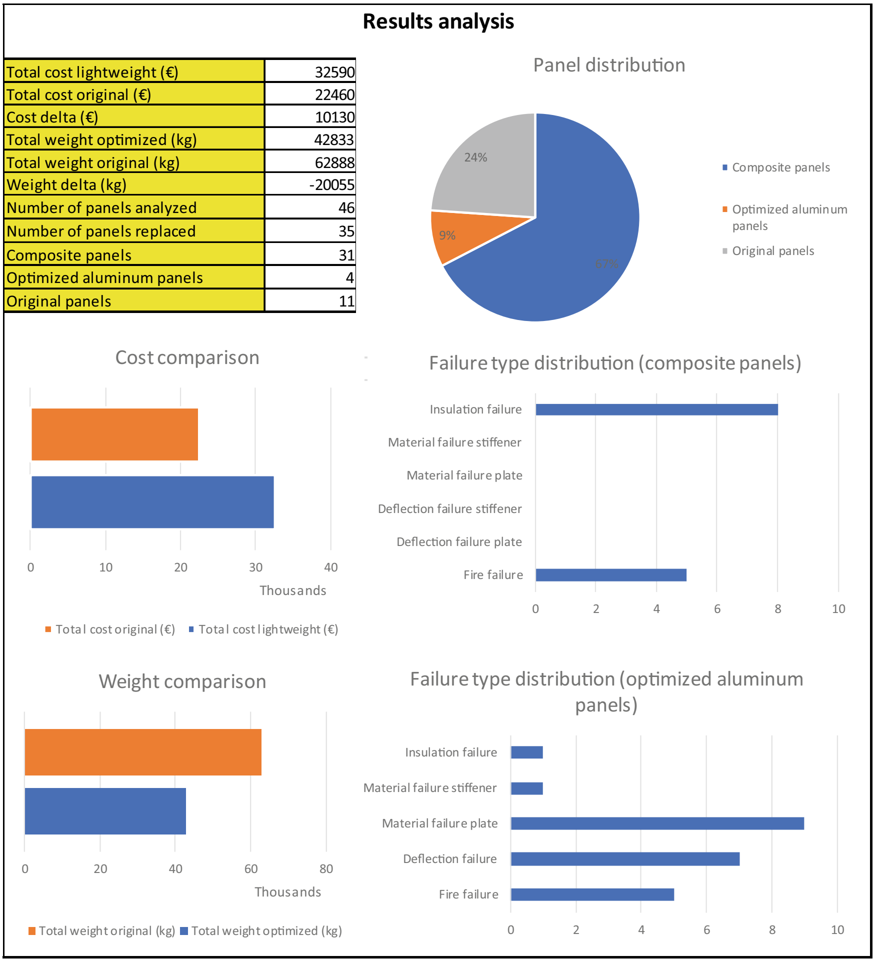

Fig. 4.16 Results analysis box

Fig. 4.17 Workflow of CST Tool integration into the CAESES® platform

When this step is performed, the panels are sorted with respect to their dimensions (Long Dimension, Short Dimension, Thickness, Area) and fire category (A15, A30, A60, etc.) (Fig. 4.19).

The final stage before the initiation of the Composite Selection Tool would be the input file creation step. All obtained data from the panels is written into an input file which would be consumed by the Composite Selection Tool (Fig. 4.20).

Having run the Composite Selection Tool using the CAESES® provided input file, the user should be having the information of the assigned material to each panel. This data is brought back into CAESES® where the panels are renamed and coloured with respect to their assigned material, ready to be exported for further use.

4.4.5.3 Application of the Tool

The present application case used in this study the uppermost superstructure on a cruise liner which is currently built in aluminium. The aim of the tool, in that case, will be to provide information on whether it is possible to replace partially the original aluminium construction by composite plates or by aluminium plates with optimized properties. To do so, first, the panel catalogue has been updated with the data derived from the analyses conducted by SMILE FEM (see Sect. 4.2.2). This study compared several types of composite sandwich panels with or without local stiffening members, either of composite, aluminium, or steel. Pure aluminium and steel panels were also compared. The relevant strength and stiffness data were obtained, and the panel catalogue was updated with 5 composite panel types and 1 optimized aluminium panel type. In Fig. 4.15, the data for these considered composite panels are shown:

- Panel 1A60C: thin composite sandwich with steel stiffeners,
- Panel 2A60C: thick composite sandwich panel without stiffeners,
- Panel 3A60C: thin composite sandwich panel with aluminium stiffeners,
- Panel 4A60C: thick composite sandwich panel without stiffeners to set different sound insulation or increased strength if needed,
- Panel 5A60C: thin composite sandwich panel with pultruded composite stiffeners.

The shipyard provided an input data sheet with a suitable structure including data of all bulkheads and decks of the superstructure of the application case. The fire division category was set to a potentially applicable A0 and the optimization algorithm was set to optimization for the lowest weight. The results for the application case are displayed in Fig. 4.16.

It can be seen that there is a potential benefit for weight savings by replacing 76% of the assessed panels by either composite panels (67%) or optimized aluminium panels (9%). A significant weight saving of almost 30% can be achieved with this replacement, but only at an increased cost of approximately 45%. In general, this means that the pre-selected panels in the panel catalogue are well-suited for the requirements of this application case. For most panels, a replacement is technically feasible. Where this is not the case, the failure type distribution shows that for the considered composite panels, compliance with structural criteria such as material and deflection is achieved for all panels. For some panels, however, compliance with fire and insulation criteria cannot be achieved. Aluminium on the other hand more often was not selected due to failing to meet material or deflection criteria.

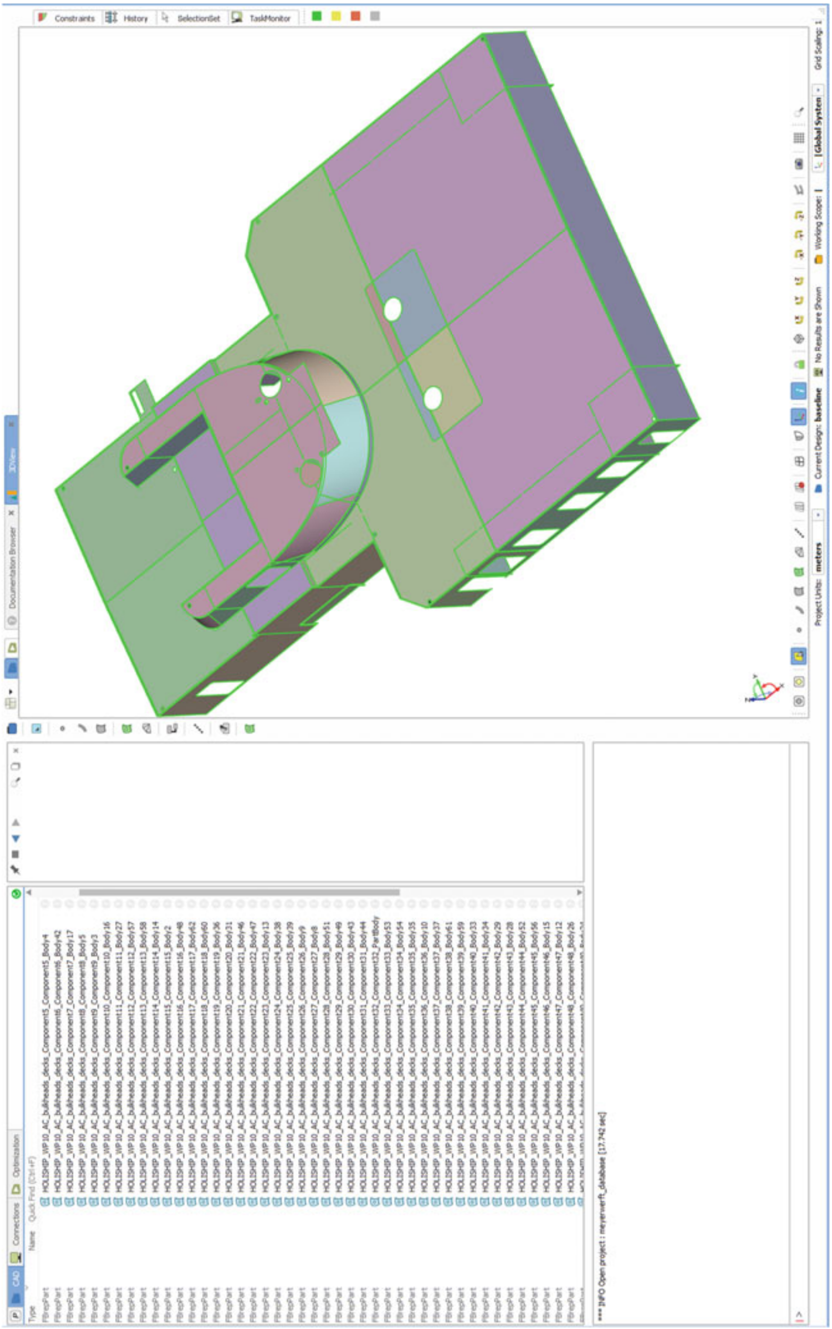

Fig. 4.18 Application case model in CAESES®

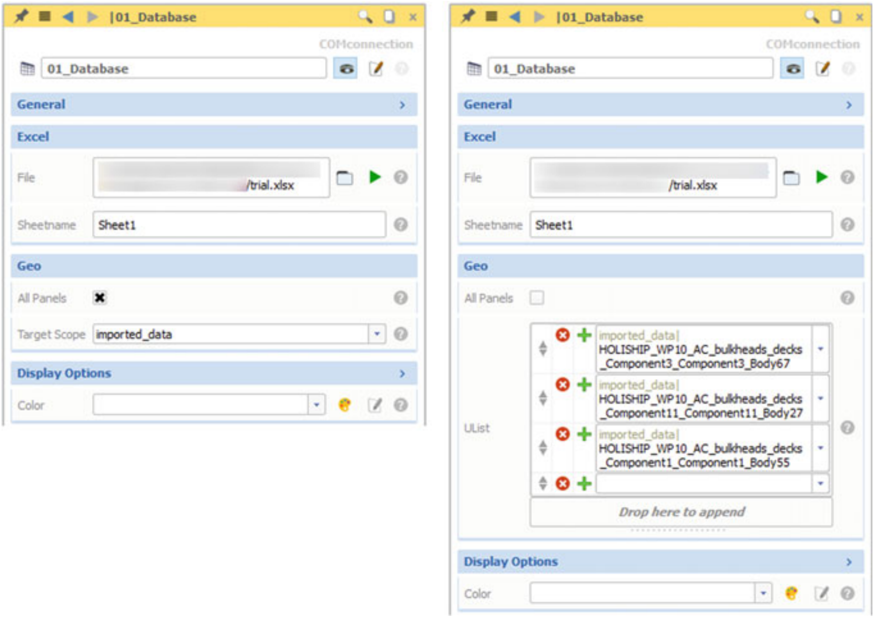

Fig. 4.19 Room functionality assignment in CAESES®

If the optimization algorithm would be set for cost optimization, the aluminium option will be dominant as the cost of the panels is set lower in the panel catalogue compared to composite panels, although the result would be a heavier structure. This option would also give the possibility to replace 76% of the bulkheads and decks.

To determine the best solution regarding to both cost and weight, the user can decide on different strategies. The approach suiting the current needs of Meyer Werft is to set a maximum allowable percent increase for costs. Since this is a typical two objectives optimisation, it is also possible to modify the tool and to implement another decision support method available to rationally decide about the best option.

In general, the results depend on some assumptions made in the early design stage. Hence, if the designer assesses this result, he should be aware that the real costs and weight savings, when using composites, might differ to some degree in the end. However, the results also well demonstrate that the designer can get a good idea of the weight savings potential, and the shipyard has a basis to decide if the option to reduce weight at this increased costs should be pursued further or not in the design process.

The present approach to replace a steel or aluminium construction 1:1 by composite materials does not take advantage of all possible benefits of composite materials, but it is a first step to introduce composite materials in the shipbuilding design process. There is still potential to further optimize the use of composites,

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1	FZ	FeatureName	Type	SubType	Category	Material	Thickness	Area (m2)	Weight (kg)	Cover mat	Cover are	Facing ma	Long dimension	Short dimension (	OP Worki	SC side A	SC side B	SI side A	SI side B	Passenger area? (Y/N)	
2	491 EU1 DK33 -	LW_L6_0_2235.1	BULKHEAD	Plate	A60	U SeaProt	70	4,76	18,6592		4,76	Aluminiur	2600	2600	5	2	8	1	1	y	
3	491 EU1 DK33 -	QW_#64_-1700_3	BULKHEAD	Plate	A60	U SeaProt	70	3,36	13,1712		3,36	Aluminiur	5100	2500	5	3	5	1	1	y	
4	491 EU1 DK33 -	LW_L8_0_6202.2	BULKHEAD	Plate	A60	U SeaProt	70	1,26	4,9392		1,26	Aluminiur	3500	1500	5	8	9	1	1	y	
5	491 EU1 DK33 -	LW_L8_0_6202.3	BULKHEAD	Plate	A60	U SeaProt	70	1,26	4,9392		1,26	Aluminiur	4300	1800	5	11	4	1	1	n	
6	491 EU1 DK33 -	LW_L8_0_6202.4	BULKHEAD	Plate	A60	U SeaProt	70	1,26	4,9392		1,26	Aluminiur	2600	2600	5	2	14	1	1	n	
7	491 EU1 DK33 -	LW_L8_0_6202.5	BULKHEAD	Plate	A60	U SeaProt	70	1,26	4,9392		1,26	Aluminiur	5100	2500	5	10	2	6	1	n	
8	491 EU1 DK33 -	LW_L8_0_6202.5	BULKHEAD	Plate	A60	U SeaProt	70	3,752	14,70784		3,752	Aluminiur	3500	1500	5	7	9	8	8	y	
9	491 EU1 DK33 -	LW_L8_0_6202.6	BULKHEAD	Plate	A60	U SeaProt	70	5,04	19,7568		5,04	Aluminiur	4300	1800	5	4	6	5	6	n	
10	491 EU1 DK33 -	LW_L8_0_6202.7	BULKHEAD	Plate	A60	U SeaProt	50	2,8	12,04		2,8	Aluminiur	2600	2600	5	5	7			y	
11	491 EU1 DK33 -	LW_L-8_0_6359.2	BULKHEAD	Plate	A60	U SeaProt	70	1,26	4,9392		1,26	Aluminiur	4300	1800	5	7	8	3	5	n	
12	491 EU1 DK33 -	LW_L-8_0_6359.3	BULKHEAD	Plate	A60	U SeaProt	70	1,26	4,9392		1,26	Aluminiur	2600	2600	5	2	8	8	4	y	
13	491 EU1 DK33 -	QW_#64_0_1344.1	BULKHEAD	Plate	A60	U SeaProt	70	1,26	4,9392		1,26	Aluminiur	5100	2500	5	3	5	1	4	n	
14	491 EU1 DK33 -	LW_CL_0_2736.1	BULKHEAD	Plate	A60	U SeaProt	70	1,26	4,9392		1,26	Aluminiur	3500	1500	5	5	3	2	2	y	
15	491 EU1 DK33 -	LW_CL_0_2736.2	BULKHEAD	Plate	A60	U SeaProt	70	1,26	4,9392		1,26	Aluminiur	4300	1800	5	11	4	3		n	
16	491 EU1 DK33 -	QW_#64_0_1340.1	BULKHEAD	Plate	A60	U SeaProt	70	1,26	4,9392		1,26	Aluminiur	2600	2600	5	7	6			n	
17	491 EU1 DK33 -	QW_#60_-1000_2.	BULKHEAD	Plate	A60	U SeaProt	70	1,26	4,9392		1,26	Aluminiur	5100	2500	5	6	8			n	
18	491 EU1 DK33 -	QW_#60_-1000_2.	BULKHEAD	Plate	A60	U SeaProt	50	1,26	5,418		1,26	Aluminiur	3500	1500	5	7	2			y	
19	491 EU1 DK33 -	QW_#60_0_737.1	BULKHEAD	Plate	A60	U SeaProt	70	1,05975	4,15422		1,05975	Aluminiur	4300	1800	5	3	7	1	4	y	

Fig. 4.20 "Tool Input File" generated by CAESES®

reducing mainly logistic, production and material costs. Also, using the tool continuously in the shipyard will increase the data basis and allow the user to make more precise estimations in the future.

4.4.6 Conclusions to Producibility, Retrofitting, Advanced Outfitting and Cost

The composite selection tool (CST) developed herein serves the need of the shipyard to have a tool which can be used in the preliminary design stage in the most practical way. Since it was developed together with the shipyard, it takes into account not only the type of information that is available at this stage, but is also considering the data structure of the shipyard. In general, the input data needed to assess the composite panels would, however, be the same for any other shipyard. Hence, the tool could be used by other shipyards as well without any changes if the input data is provided in the exact same format. It has been developed with simple approaches and doing some compromises and assumptions as it has to be flexible tool, with the potential of analysing sets of many thousands of panels sometimes, even as part of an iterative process.

It is important to remark that the aim of the tool is not to provide final design parameters, because there is not enough information available at the early design stage to do so, so none of the modules have been developed with the aim to give detailed final design values. The calculations are based on simplifications which will serve the target of the tool of giving a global estimation with the highest possible accuracy. With respect to the application case, the results are based on a simple first comparative study where the designs of the composite panels can still be further improved. The design of highly optimized composite structures needs a very different approach than the classical isotropic plate-composed structures used in shipbuilding. Composite materials have significantly increased costs in comparison with steel or aluminium, but give the possibility to provide highly optimized topologies where each structure element has his customized properties. The application of this tool can only provide results for a given set of panels and is the first step in integrating composite materials. To benefit most from the use of composites, the ship designer needs to determine the most convenient way to design and produce those panels. This is a key to get the most interesting results from the tool for future applications.

The cost comparison tool developed in this work package implements a methodology to determine the costs of production processes for different materials. This gives the designer the option to compare costs by following a clearly structured process. Since process details for steel are at this point better known, cost estimates are more precise than for the composite process. Hence there is a need to study costs and the integration of composite construction techniques in the entire value chain of the yard in more detail.

Both the composite selection tool and the cost comparison tool enable the designer to evaluate the benefits and costs of different design options today already. The shipyard can maximize the benefit of both tools, however, by continually increasing the data basis in the future.

4.5 Overall Conclusions

Different aspects need to be considered when integrating FRP (fibre-reinforced polymers) into a SOLAS passenger vessel. Applying a new material is only possible if owner, class and yard requirements are fulfilled. An analysis of the requirements showed that the use of composites could contribute to meeting owner and yard requirements such as using innovative technologies. The use of composite structures particularly has great potential to support the objective of saving weight in critical areas. With increasing ship sizes, weight becomes critical more often especially in upper decks. The biggest challenge concerning the requirements today lies in meeting class requirements specifically for fire protection. There are currently no composite panels on the market that can fulfil all class requirements. It is however, expected that suitable materials and components will be available in the market in the near future.

For a smooth design integration, it is essential to choose the right timing for design changes within the design process. If a new design aspect or component is introduced at a very late stage, integrating it into the production will be more challenging and costly than when changes are made at an early stage. However, at an early stage available information on design details is limited, so the decision of whether or not to replace steel by composite or aluminium cannot consider all aspects that could be used to compare more elaborated design options. For the application case, a suitable milestone in the design phase was identified and the tool was developed for the use at this stage.

Another challenging aspect is the design philosophy when composite materials are introduced into a passenger vessel that is traditionally designed of metal. The greatest benefit of using composite materials can be achieved when a design is specifically tailored to composite material behaviour. This would, however, require detailed analyses and bigger changes in the complete design and production process, thus raising the hurdle for the shipyard to consider composite materials at all. Thus, to take the first step of integrating fibre-reinforced composites, the strategy is to replace existing steel or aluminium structures almost 1–1. This obviously still leaves further potential to obtain benefits from the use of composite materials in future designs. Within this strategy, there is still some degree of freedom to implement different design options for the considered panels such as varying stiffener spacing. These were analysed and the best option was identified.

Aside from structural properties, fire safety, and design integration, the noise and vibration behaviour of a new material is essential, effecting comfort of passenger and crew as well as possibly influencing the structural behaviour of the ship. The analysis of vibration behaviour showed that composite decks and bulkheads feature structural damping ratios ζ in the range of 4–7% of critical damping, as opposed to steel deck/ bulkhead structures where these values tend to lie below 1%. Hence dynamic amplification factors for composite structures range from 7.1 to 12.5, whereas for steel structures they are at least 50. Also composite structures seem to have a tendency towards a lower number of natural frequency and associated mode shapes in the frequency range of interest (0–30 Hz) compared to steel structures. Regarding acoustics, experimental results showed a clear potential of hybrid superstructures in the attenuation of structure-borne sound in vertical direction (along deck transitions). In horizontal directions (in-plane deck), no substantial differences with a steel reference case was observed. For the airborne sound transmission through sandwich panels, meeting stringent acoustic requirements with light-weight sandwich panels is not straightforward. By selecting a low stiffness core layer in combination with a high skin layer mass, the insulation performance of sandwich panels can be improved.

For the assessment of different material options, a cost tool (CCT) and a composite selection tool (CST) were developed. The cost tool is based on a detailed analysis of different process steps for the different materials. One challenge here is that the process for steel is known in detail and is optimized, while composite panels would be purchased from supplies in the first step and subsequently a process would need to be established first. Hence, the degree of available information on actual cost is more detailed for steel at this point. The methodology provided in the tool can, however, be easily applied by the shipyard to update cost estimates when knew information on the composite costs becomes available. The composite selection tool is based on comparing requirements to a catalogue of pre-selected aluminium and composite panels. The current selection is based on some assumed material properties, but the user at any point can easily update the panel catalogue in time.

Input and output of the tool was determined to suit the shipyards data structures and requirements and to be easily integrated into the CAESES® platform. A use by other shipyards would be possible without any modifications if input data is provided in the same format. Application to the present application case showed that it can be applied as intended and gives the designer a quick overview of how much weight savings can be achieved at which price when replacing aluminium panels by composite panels, if this is technically feasible. The results are based on some assumptions relating to cost, material properties etc. but in general they seem reasonable, with a potential for some weight savings at a higher cost. The tool also gives the designer an easy way to see how the panel catalogue can be improved by showing the failure distribution for the panels. To get the most use out of the tool in the future, it is essential for the shipyard to continue to extend the data basis for costs and available materials and their properties.

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Chapter 5
Design for Maintainability of a Research Vessel's Engine Room

Chiara Notaro, Paola Gualeni, Matteo Maggioncalda, and Carlo Cau

Abstract The Life Cycle Performance Assessment (LCPA) Tool developed in the first phase of the HOLISHIP project (Maggioncalda et al. 2018) was tested in the herein presented application case dealing with the "Design for Maintainability of a Research Vessel's Engine Room". In this relation, we further developed the methods for the estimation of the operational and maintenance costs of a Research Vessel, by using a structured and flexible tool capable of evaluating the investment, operational and maintenance costs for different engine room configurations and of identifying the best solution for elaboration at the design stage (*design for maintainability*). The engine room space optimisation and accessibility were also evaluated by use of a developed 3D digital mock-up, enabling the assessment of the potential impact on maintenance costs in relation to the clearance space around the machinery and their compliance with specific requirements. After a general introduction to the topic provided in Sect. 5.1 of the chapter, Sect. 5.2 describes the reference vessel used in this Application Case, with a focus on the main characteristics of the propulsion system and electric power generation. Section 5.3, besides an overview of the standard maintenance techniques, describes the implementation of the Mean Time Between Maintenance (MTBM) in the LCPA tool, based on the best working point of an engine. Section 5.4 identifies the alternative solutions for the propulsion layout, proposed with respect to the base configuration, while analysing the obtained LCPA results in terms of economic and environmental Key Performance Indicators (KPIs).

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A. Papanikolaou (ed.), *A Holistic Approach to Ship Design*,
https://doi.org/10.1007/978-3-030-71091-0_5

Finally, Sect. 5.5 presents the results of further investigations on ship design for maintainability by using the digital mockup of a 3D model of the engine room and focusing on accessibility analysis.

Keywords Design for maintainability · Maintenance costs · Engine room maintenance · Digital mock-up · Maintainability Index

Abbreviations

AC	Application Case
AUV	Autonomous Underwater Vehicle
BIM	Building Information Modelling
BLD	Building Cost
CODELOD	COmbined Diesel and Electric Or Diesel
D-level	Depot level
DMU	Digital Mock Up
I-level	Intermediate level
KPI	Key Performance Indicators
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCPA	Life Cycle Performance Assessment
LORA	Level Of Repair Analysis
M&R	Maintenance and Repair
MCR	Maximum Continuous Rating
MI	Maintainability Index
MRT	Mean Repair Time
MTBM	Mean Time Between Maintenance
MTBM'	Corrected Mean Time Between Maintenance
O-level	Operational level
OPEX	Operational Expenditures
PTO	Power Take Off
ROV	Remotely Operated Vehicle
SE	System Engineering
UAV	Unmanned Aerial Vehicle
WBS	Work Breakdown Structure

5.1 Introduction

In the first phase of the HOLISHIP project, an innovative LCPA (Life Cycle Performance Assessment) tool, that combines the LCC (Life Cycle Costing) and LCA

(Life Cycle Assessment), was developed: this design tool permits, in a comparative perspective, the evaluation of various design alternatives over ship's life cycle while considering in parallel both design and operational issues. Different ship configurations or system layouts can be compared and optimised in terms of pre-selected Key Performance Indicators (KPIs) used for the calculation of the LCPA Index (Maggioncalda et al. 2018). The KPIs modelled in the tool represent building and operational costs, as well as environmental impact, and play a fundamental role in the decision-making process towards the selection of the best design solution.

The present Application Case is dedicated to the further development of estimation methods for the operational and maintenance costs of a Research Vessel, defining, in particular, a structured and flexible tool capable of evaluating maintenance costs for different engine room configurations. The LCPA tool has been extended to include refined Maintenance and Repair (M&R) costs based on realistic maintenance plans and specific tasks, thus overcoming earlier empirical formulations. The improved LCPA tool has been applied to a ship type characterized by different working scenarios, with a specific focus on its propulsion system. Engine room space optimisation and accessibility have also been evaluated through the development of a digital mock-up, enabling to assess the potential interference between different systems and components for maintenance applications, while using a newly defined Maintainability Index (MI).

5.2 The Research Vessel

This section describes the main features of the reference vessel used in this Application Case, with a focus on the propulsion system and its auxiliaries. A description of the vessel's electric balance and its operational profile is provided as well. A general overview of the ship propulsion system and ship power demand is also provided. These data have been used for reference in the following assessment of maintenance costs among different design solutions (Sects. 5.4 and 5.5).

5.2.1 Main Features of the Ship

The application platform is based on a typical research vessel designed by Fincantieri that ensures versatile performances on possibly scheduled research activities and working scenarios in the sea, i.e. an oceanographic ship. These specialized types of vessels are designed and equipped to navigate to the far reaches of the globe. They can conduct research on the sea's behaviour; analysing temperature gradients and sea's chemical composition; carrying out biological investigations, measurement of bottom topography and more.

Requirements for an oceanographic ship are driven by the user and the type of mission to be carried out. However, survey actions or researches have a common scientific base. The scientific facilities on oceanographic ships consist of laboratories, open deck areas, accommodations, storage spaces for scientific equipment and supplies, scientific gear such as winches, lifting frames and cranes, ROVs (Remotely Operated Vehicle) and AUVs (Autonomous Underwater Vehicle), disposal of moon pool and diver's equipment. For these reasons, in order to obtain the highest scientific return, the vessel should be versatile, providing at the same time the maximum amount of available space for scientific facilities.

The overall characteristics of a research vessel will be determined by its use/mission, which will identify the carried equipment, the specialized personnel and the required speed/range. The type of equipment will strictly depend on the type of mission to be accomplished. These can be physical and chemical activities, biological investigations, environmental monitoring or marine geological and geophysical researches.

The herein studied vessel can be classified as a so-called "General-Purpose Research Vessel" that typically includes the classical oceanographic ships previously described. This ship has laboratories and equipment suitable for two or more studies in the physical, chemical, biological and geological areas. Main dimensions and performances are described in Table 5.1.

The study vessel has various capabilities, such as working far from operating bases, accommodation of large scientific spaces for multi-disciplinary studies, materials collection on-site, acoustic support systems ranging from multi-channel seismic to Doppler profilers and hydrophones. All scientific laboratories, technical areas and motion-critical spaces, in general, are located closer to amidships, here above deck 2 at 5.5 m from keel line. Accommodations for scientists, technicians and crew members are located on deck 3 at 8.4 m. The navigation bridge is arranged on the last upper deck at 19.4 m from keel line and allows visibility to both aft and forward working areas.

A rendering image of the vessel is shown in Fig. 5.1. An UAV about to land on the deck of the vessel is visible, as part of the equipment of the ship (aft working zone).

Table 5.1 Main dimensions and performances

Characteristic	Value	Units
Length over all	94	m
Length between perpendiculars	84	m
Beam	16.6	m
Depth	8.5	m
Full load displacement	3600	t
Maximum Draft	5.5	m
Cruise Speed	13	kn
Max Speed	17	kn
Range	3000	Nm

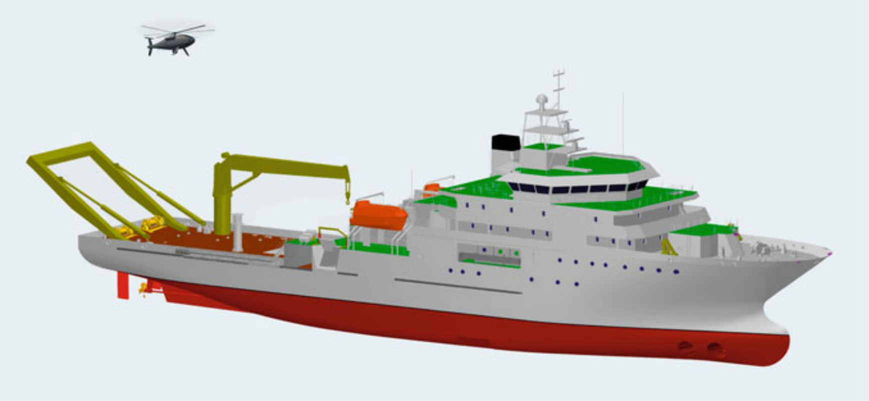

Fig. 5.1 Rendering of the Research Vessel used for AC3

The deck equipment suite is distinguished by a crane able to reach any portion of the large aft deck working area and offers support for both shallow and deep-diving submersibles and unmanned seafloor scientific systems. Large coring/drawling winches and dedicated trawling winches are installed in the large aft working area.

Fuel tanks, lubricant oil tanks, ballast tanks, grey and black water tanks, fresh water tanks and other small various tanks are mainly located in the double bottom, while the engine room and the auxiliary spaces are arranged on deck 1 at 1.5 m from keel line, at midship.

The vessel's operational profile strongly influences the design decision process and analysis.

As a research vessel, the ship will be optimised to work at two different speed ranges: low speeds during the manoeuvre and oceanographic operations (typically from 0 to 8 knots) and high speeds during shift operation at design or maximum speed (from 12 to 17 knots). Figure 5.2 shows the operational profiles of the ship.

The percentages refer to 165 days operation/year when the ship is operating at sea. In the remaining 150 days/year the ship is considered in the harbour and the remaining 50 days/year in drydock or not operational. In this scenario the 10% of working life (16 days) is spent at 0–5 kn; 35% (58 days) is spent at 6–8 kn in research operations; 5% (8 days in total) at 9–11 kn during speed transient phases; 35% (58 days) is spent at 12–14 kn at design speed; 15% (25 days) at maximum speed. All future considerations here will be based on this particular operating scenario.

In order to define the maintenance model inside the LCPA tool, i.e. comparing different design options, the first step is to define how the vessel's propulsion system works at different speeds and then to identify possible design alternatives to satisfy the operational profile most efficiently. These alternatives will be identified throughout the elements listed below (associated with different Work Breakdown Structures or WBS):

– Main Diesel Propulsion Engines (WBS 233).

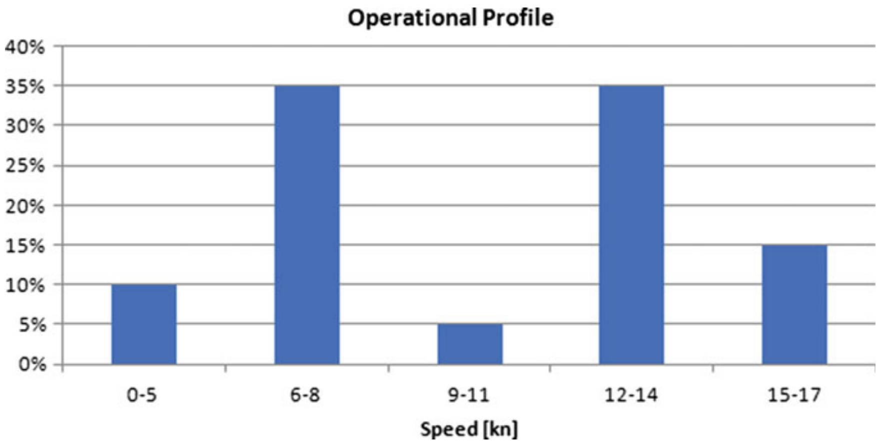

Fig. 5.2 Reference vessel operational profile

- Electric Motors (WBS 235).
- Gearboxes (WBS 241).
- Shaft Lines and Bearings (WBS 243 and 244).
- Engines sea-water cooling system (WBS 256).
- Fuel supply system (WBS 261).
- Diesel gen-sets (WBS 311).
- Emergency Diesel gen-set (WBS 312).
- HVAC system (WBS 514).
- Compressed Air System (WBS 551).

The flexibility of the LCPA tool structure ensures the readily implementation of new WBS systems.

5.2.2 Propulsion Layout—Reference Design

The vessel is equipped, in its original configuration, with two independent shaft lines, each provided with the main diesel engine, a small electric motor, a gearbox and a controllable pitch propeller. Mechanical and electrical items work together in the propulsion train, optimizing the ship's propulsion efficiency and providing the right amount of power delivery to the propeller in any operating scenario. The combination of mechanical power, delivered by diesel engines, and electrical power, provided by electrical motors, assures a broad operational capability with high efficiency.

This hybrid propulsion system works as a CODELOD (COmbined Diesel and ELectric Or Diesel) where electric motors are used for low speeds (up 8 kn), and propulsion diesel engines are instead used for high speeds (from 9 to 17 kn). Electric power generation at 400 V and 50 Hz, in all operating conditions, is ensured by 3 independent diesel generators connected to the main distribution grid. The emergency power generation is delivered on a dedicated diesel generator, located in a different small engine room. A simple functional sketch of the propulsion and electrical generation layout is shown in Fig. 5.3. Figure 5.4 shows how these items are installed onboard in a top view of the vessel engine room. The ship is also

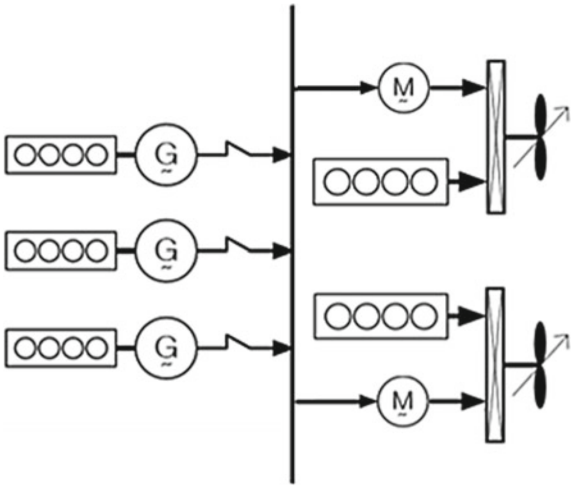

Fig. 5.3 Hybrid propulsion layout (S0)

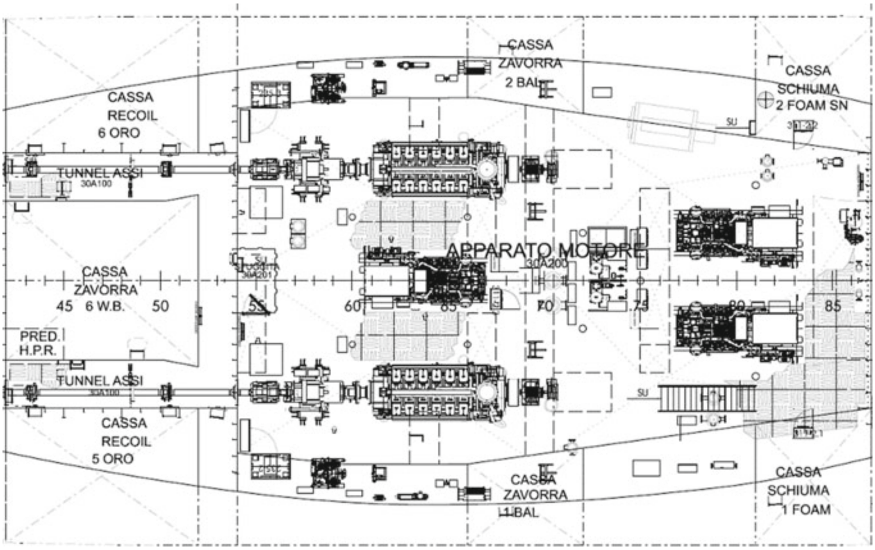

Fig. 5.4 Engine Room layout

provided with a stern thruster and two “flat type” rudders to ensure the required manoeuvrability features. The steering gear is arranged in a single aft room.

The description of the main propulsion items of the base configuration S0 is provided in the following Fig. 5.3, whereas the alternative configurations are elaborated in Sect. 5.4.

Main Propulsion Engines

The 2 main propulsion engines of the vessel are typical 4 strokes diesel engines with supercharger and direct fuel injection. The super charge is ensured by a turbo-compressor driven by the engine’s exhaust gases. The 2 diesel engines installed onboard can supply an MCR power output of 2289 kW.

Electric Propulsion Engines

Additionally, the vessel is propelled by two electric motors (hybrid system), one for each propulsion line, to increase energy efficiency in the range of low speeds. The motors are directly connected to a gearbox with a transmission rate of 10. The two e-motors are of the synchronous type with squirrel cage. They can supply a maximum power output of 250 kW at 1500 rpm and an electric output at 400 V at 50 Hz.

Each electric motor can be used from zero speed operation till the vessel is operating at low speed. The switch-on of the electric propulsion and switch-off of the mechanical one is automatically mastered and managed by the propulsion control system.

Diesel Gen-sets

The electricity generation onboard is ensured by 3 gen-sets located in the main engine room. The electric power produced onboard is mainly used for the payload services (that include accommodation services but also scientific equipment power demand) and for the electric propulsion at low speed as well.

The gen-sets can produce 650 kWe each, at 1500 rpm, with an electric output at 400 V at 60 Hz. The gen-set consists of a 4 strokes diesel engine with direct fuel injection connected to an electric alternator. The manufacturer assumes two main working profiles for the gen-sets:

– a variable load service, with a mean power output (calculated on 350 h of working time) up to 75% of the maximum power output;
– a continuous service, with a 100% of power output. Overload is not allowed.

By the international rules, an emergency gen-set with a power output of 200 kWe at 400 V and 50 Hz is installed onboard, outside of the main engine room.

5.2.3 Power Demand

The term propulsion system (as we considered it in this work) is not only referring to the power required to propel the ship, which is generated by the two main diesel engines and two small electric motors, but it takes also into account the entire electric energy demand. The electrical power associated to this demand includes not only the needs of the electric propulsion motors but also of the bow or stern thrusters, of the auxiliary propulsion systems, of hotel loads and of the scientific equipment. In the original vessel configuration, this power demand is ensured by three diesel gen-sets (please refer to Fig. 5.3) that satisfy the total electrical power demand in all operative ship conditions. Thus, the total power demand is satisfied by a set of Main Propulsion Diesel Engines and of Diesel Generators as elaborated for the different versions of the alternative design configurations (see Sect. 5.4).

5.3 Maintenance Cost Assessment

5.3.1 Maintenance Strategies

Different maintenance techniques were developed in recent years in order to better preserve propulsion system's functionality over ship's life cycle, minimising the failure rate and downtime. These techniques are summarised in the following listed categories.

– **Corrective maintenance**: the operator intervenes, when a failure occurs, switching off the system and performing maintenance with economic implication that can be more or less significant.
  This approach assumes that costs sustained for downtime and repairs, in case of a fault, are lower than the investment required for keeping a maintenance program. This strategy may be cost-effective until catastrophic faults occur.
– **Scheduled preventive maintenance**: the manufacturer provides a so-called Mean Time Between Maintenance (MTBM) plan that is the best working time range for which a maintenance action has to be performed in order to prevent system's failure or performance degradation.
  In this way, an operator can plan the maintenance services to minimise the impact on working hours and so on costs and profits. The maintenance cycles are planned according to the need to take the device out of service. The incidence of operating failures is reduced.
  In a complex system with more sub-systems that work together to complete a task, this method can be a better way to plan the maintenance operations.
– **Performance-based maintenance**: it is based on the response analysis of multiple sensors mounted on the system in order to measure actual working parameters like temperature, pressure, fluid levels and more.
  Measured values are automatically compared with average values and performance indexes generated by prediction models. Maintenance is carried out when some indicators give the signal that the equipment is deteriorating and the likelihood of failure is increasing.

This strategy, in the long term, could allow a drastic reduction in maintenance costs, thereby minimising the occurrence of serious faults.

Within the design assessment of the present application case, the scheduled preventive maintenance is assumed best complying with the adopted maintenance policy. It is based on the development of maintenance prediction models, where the designer can evaluate the performance of alternative configurations and link maintenance costs and time. Preventive maintenance is known related to a semi-deterministic model; it provides a direct way to compare different layout and operational profiles at an early design stage. The primary information needed to set up a scheduled maintenance approach could be obtained from manufacturer's manuals and shipyard's experience. A model based on a performance-based maintenance, on the other side, requires an extensive database of performance data to be set up by designers, which is almost useless in the first design phase when information level is low, and the design evolves continuously.

5.3.2 Maintenance Costs Evaluation, Tool Development

During the early design stage, one of the essential steps that strongly influences the next decisions is to define the ship operational profile as much as possible, and consequently, a propulsion system typology that meets the needs. Moreover, the propulsion systems strongly affect the ships final building cost and costs are linked to operational activity during the whole product life. From what above, the maintenance prediction tool has been developed with a specific focus on propulsion systems to evaluate the best configuration among some proposed alternative propulsion layouts. Due to the vast number of systems and sub-systems installed, the complex connections between them and the massive amount of required information, it is necessary further to reduce the domain of investigation in this development phase.

The maintenance costs evaluation model adopted in this application case is based on the scheduled preventive maintenance and the MTBM value. Once the ship type has been fixed, and after the identification of some alternative design configurations that satisfy the main owner's requirements (i.e. speed, range, operational profiles, maneuverability, environmental and efficiency performance), the following considerations can be applied:

– the system's complexity, the significant number of sub-systems and the single components installed in each assessed layout impose to choose a robust and structured procedure to evaluate the maintenance actions and related costs over the ship's life cycle.
  From the builder point of view, the best practice would be to use the so-called Work Breakdown Structure, defined as a hierarchical and incremental decomposition of a project/system into smaller components.
  Following a tree structure for the system or its subsystems, which are iteratively evaluated, a higher detail level can be achieved by breaking up complex systems

into less complex ones, and so on. This top-down structure allows to identify the elements by a single code number and to decide the ones useful in the analysis for the fixed detail level.

- For each selected system or sub-system, the designer can choose maintenance tasks to be included or excluded from the analysis, according to the level of detail and data availability.
- An MTBM value is required to model every maintenance task selected for the analysis, expressed in working hours or years. The MTBM of an asset is the average length of operating time between one maintenance action and the next one, and it is usually based on a conservative stochastic distribution (Weibull distribution). Although it could be supposed that the MTBM is a conservative value, if a system or item works outside of its optimal working point for few hours, it is reasonable to assume that the MTBM value can be reduced.
- When defining alternative configurations, it is essential to define the system's working point. For example, considering a diesel propulsion engine, it is necessary to define its actual working condition expressed in term of MCR percentage and actual working hours. Thus, the off-design working condition can be estimated together with is effects on the MTBM value delivered by the manufacturer. By combining off-design functioning hours and the corresponding power percentage, it is possible to create a dimensionless corrective coefficient to update the actual maintenance plan and its impact on maintenance costs.

This concept has been implemented in a developed MTBM assessment tool that is elaborated below. The MTBM is expressed through by Eq. (5.1), which has been obtained through a "trial and error process" based on the real yard data provided for the specific design to be assessed:

$$\mathrm{MTBM}' = \mathrm{MTBM} - \frac{1}{\mathrm{h_T}} \cdot \left[\sum_i \mathrm{h}_{\mathrm{ACT}_i} \cdot \frac{(\mathrm{P}_{\mathrm{T}_i} - \mathrm{P}_{\mathrm{ACT}_i})}{\mathrm{P}_{\mathrm{T}_i}} \right] \cdot \mathrm{MTBM} \tag{5.1}$$

where: "MTBM'" is the new corrected, effective value of MTBW; "MTBM" is the original manufacturer's value assigned to MTBM; "$\mathrm{h_{ACT}}$" is the number of effective off-design working hours; "$\mathrm{h_T}$" is the number of total effective working hours in one year; "$\mathrm{P_T}$" is the power corresponding to the optimal working point; "$\mathrm{P_{ACT}}$" is the actual power; "i" is the operational scenario considered, i.e. navigation at 13 kn or navigation at 8 kn. This type of formulation can be applied to the diesel engines for electricity generation or propulsion.

If $\mathrm{P_{ACT}}$ and $\mathrm{P_T}$ are equal, the engine works at its best and MTBM = MTBM'. The same result is obtained if $\mathrm{h_{ACT}} = 0$, i.e. the engine is in its best working point. This formulation has an application domain from 20 to 50% of MCR engine's power: if an engine works above the 50% of its MCR the corrective formula is not necessary; at the same time, for MCR less of 20% the formula is not recommended.

- The next step requires to consider for each maintenance task the person-hours required to perform the maintenance task and their relevant costs (in €/h). All

these values will be combined in order to calculate a total cost amount for each single analysed task over the life cycle. Spare parts will also be included in the cost assessment for each task assumed in the tool.
– Once the main system's actual working hours and the ship's life cycle (in years) are inserted, the tool calculates the number of maintenance action (times) during the whole life cycle (for each task), and the LCPA tool determines life cycle total costs.

The tool provides all this information in order to have a general overview of maintenance-related costs over the ship life cycle, with graphical and tabular results.

5.4 Comparison Among Different Design Solutions

Starting from the same base configuration S0, described in Sect. 5.2.2, it is possible to develop and assess few alternative propulsion layouts aiming to achieve a more efficient system layout that uses the system components/items in a better way than the original one, with possible advantages in building and operating costs, including all maintenance actions. Three alternatives configurations S1, S2 and S3 have been considered: they were designed focusing on a reduction in WBS working hours and/or maintenance costs.

5.4.1 Design Alternative S1—Power Take-Off

The first alternative layout S1 shown in Fig. 5.5 proposes the introduction of a Power Take Off (PTO) in the original propulsion system. In particular, the PTO is supplied

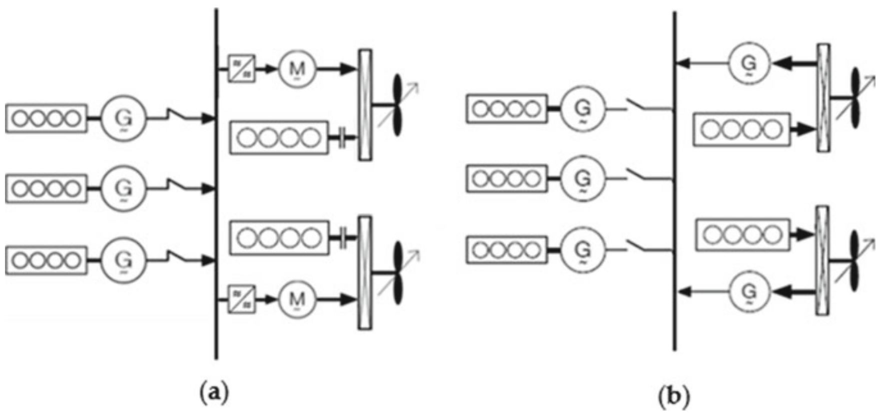

Fig. 5.5 Alternative configuration layout S1 (and S2)

by the main propulsion Diesel with the double aim to reduce the working hours of one or more diesel gen-sets, and to achieve a better working point both in diesel engines and the gen-sets (compared to the original layout S0). Engines' power size is the same as for the reference vessel and the PTO is active only from 9 to 17 kn; up to 8 kn the configuration works exactly as the original one.

5.4.2 Design Alternative S2—Power Take-Off with Higher Power Size

The second alternative layout S2 has taken into account the introduction of a higher power size PTO and, also, a higher power size for gen-sets in order to obtain a good item working point. This solution could be identified as an evolution of the S1, with the main aim to reduce to zero the number of gen-sets used during the navigation phase. Thus, the configuration layout is the same as defined for S1 and differs only for the items size and working point. Figure 5.4 represents the system layout also for S2 configuration. This design alternative increases the electric motors' size (also used as PTO) from 250 to 390 kW and gen-sets size from 650 to 850 kW. This option permits to satisfy the total amount of power demand in navigation phase using the PTO only.

5.4.3 Design Alternative S3—Full Electric

The third alternative layout S3 considers a completely changed layout through the introduction of a full electric propulsion: a comparison between the hybrid propulsion (S1, S2) and full electric propulsion (S3) from a maintenance perspective, should be interesting. Instead of the two main diesel engines, two main electric motors of 1800 kW each were installed, which are supported by four diesel gen-sets of 1150 kW each. This configuration ensures high power flexibility, thus it is not necessary to divide the speed range as done before. For the entire range of 1–17 kn, the total electrical power demand will be satisfied by a variable number of gen-sets, regulated by on board automated control system. The electrical motors are only used as main propulsion engines: a PTO is not considered in this configuration.

This design alternative (shown in Fig. 5.6) could be an optimal choice for ships that have special environmental requests, such as a research vessel, and need a large amount of electric power available during the operational phases.

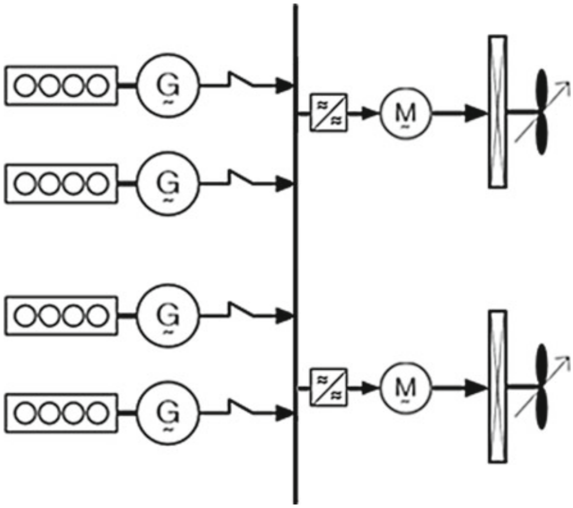

Fig. 5.6 Alternative configuration layout S3

5.4.4 Results of Calculations with LCPA Tool Applied to Different Configurations

Using the LCPA tool previously developed within HOLISHIP project (Gualeni et al. 2019), the design configurations defined in Sects. 5.4.1, 5.4.2 and 5.4.3 were compared to evaluate their life cycle performances. Building costs, OPEX and Maintenance and Repair costs were used as LCC KPIs, while CO2, SOx and NOx emissions were also considered in order to compare the environmental impact of the assessed design configurations. The output of an LCPA analysis is influenced by the KPIs and their relevance in the calculation, which is represented by a weight assigned to each KPI. In fact, a LCPA analysis strictly depends on ship owner's and operator's economic and environmental priorities that are reflected in the used KPIs and their weights.

Table 5.2 shows the KPIs results obtained from the LCC assessment for the design configurations S1, S2 and S3.

As expected, more complex design solutions, such as S2 and S3, have a higher building cost compared to the reference design. On the other hand, OPEX and Maintenance Costs are lower, due to a better overall efficiency and lower maintenance costs of the installed systems.

Table 5.2 LCC assessment of S1, S2 and S3: KPIs comparison

KPI coefficients	Reference ship S0	Solution S1	Solution S2	Solution S3	KPI weight
1. BLD	1.00	0.90	0.60	0.00	0.3
3. OPEX	0.00	1.00	0.98	0.51	0.3
4. M&R	0.21	0.00	1.00	0.60	0.4

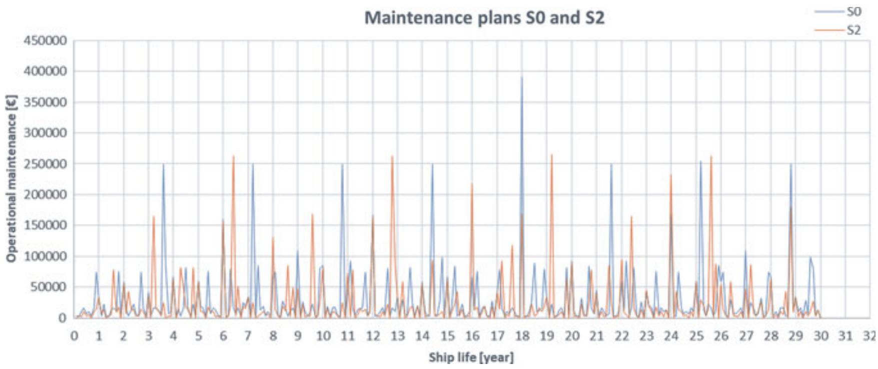

Fig. 5.7 Example of maintenance costs comparison (S0 and S2)

In particular, Fig. 5.7 provides an example of a comparison of maintenance costs over the life cycle of two design configurations, previously identified as S0 and S2. Maintenance cost peaks varies depending on systems running hours and operational profiles. Ship owners can use these graphs to forecast and plan major maintenance activities during the vessel's life cycle.

The results already presented in Table 5.2 are shown in a spider graph format in Fig. 5.8.

From the LCC perspective, as shown in Table 5.3, S2 proves itself as the best solution, due, in particular, to the very low maintenance costs thanks to the reduced running hours and better working points of the main engines and diesel generators. Nonetheless, due to the extensive use of PTO to propel the vessel at lower speeds, fuel consumption is higher compared to the other solutions, therefore the

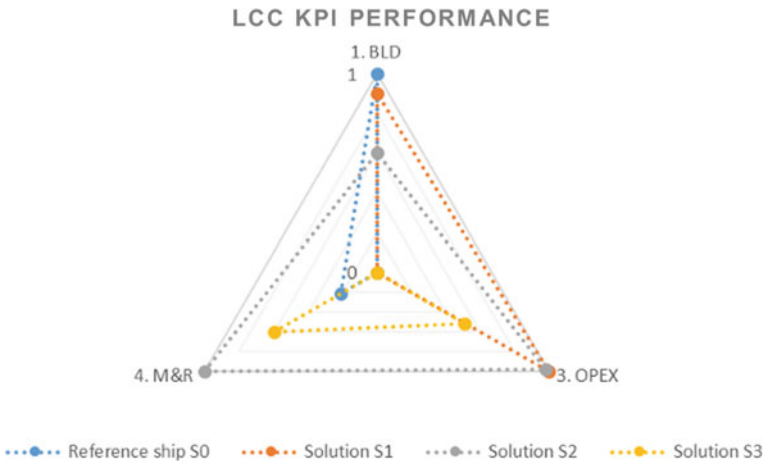

Fig. 5.8 LCC KPI performance of design configurations

Table 5.3 LCPA comparison

Final Indexes	Reference ship S0	Solution S1	Solution S2	Solution S3	Index weight
LCC Index	0.63	0.57	0.82	0.48	0.5
LCA Index	0.64	1.00	0.00	0.78	0.5
LCPA Index	0.63	0.79	0.41	0.63	–

LCA performance of this vessel is the worst among the three design alternatives analyzed.

For what regards S3, a full electric propulsion configuration (Sect. 5.4.3) represents an average solution in terms of both LCA and LCC. However, this LCPA model assumes that all design configurations satisfy the minimum design requirements requested by the ship owner; in case of a full electric configuration, the high flexibility of this solution, the lower noise and the zero toxic gas emissions should be also taken into account in the design selection process.

Considering this particular case study, S1, with introduction of PTO to propel vessel at varying speeds (manoeuvring condition), proves itself as the best solution in terms of LCPA analysis. In this specific case, a lower overall fuel consumption provides lower OPEX and better LCA performances, which counterbalances the higher maintenance cost of this solution.

5.5 Design for Maintainability: The Digital Mock-Up

5.5.1 The Digital Mock up: A Ship Engine Room Application

A 2D representation of the layout of arrangements is the traditional approach in many engineering field and manufacturing activities, supporting the integration of details and for the performance prediction activity during the design phase. However, the recent increased availability of extensive computational capability has enabled a superior level of representation with the use of 3D modelling mock-ups, especially in case of complex systems. Virtual reality and digital twins are a near future asset that will renew the approach to ship design and construction, enabling a strong focus on life cycle domain (Arrichiello and Gualeni 2020).

The "Digital Mock Up" (DMU) has been exploited in the definition of assembling/disassembling procedures and pathway and/or interference evaluation of engineering systems (Avallone et al. 2001; Kaun 2002; Zachmann and de Sa 2001). In this perspective, the issue of ship "design for maintainability" is a perfect subject to evaluate the great potential of DMU.

The maintainability costs are an important part of the ship OPEX costs and they largely depend on decisions taken during the ship design and on the quality of production process. The 3D representation is a fundamental support to foresee the ship during the operational life and this has a particular relevance when the technical spaces of the ships are concerned: in the engine room, for example, several systems are closely integrated, both functionally and spatially, and are supposed to undergo maintenance activity along the ship's life.

The issue of geometry overlapping and lack of space has implications in terms action feasibility and time increment in relation with possible handling difficulties among different items and components under maintenance; ergonomic issues are of outstanding importance as well.

In this section an application case has been developed, with reference to the engine room of the research vessel described in Sect. 5.2. To this purpose a DMU has been created, characterized by the reasonable level of detail, compatible with the aim of the foreseen activity in this application. It represents a 3D model functional to carry out evaluations enabling the implementation of a methodology, developed on purpose. The proper balance between the level of details and the size of the parts to be modelled by a DMU is a very important element, since it is going to have an influence on the cost/benefit balance of the digital asset.

In the investigated case, a more detailed definition has been given to the parts of the engine room that are going to be analyzed for the practical application. The engine room taken into consideration is the one of the ship analyzed in the previous paragraphs and the definition of the digital mock-up has been initiated from the traditional 2D drawing (i.e. see Fig. 5.4) as provided usually by shipyards during the design phase. The 3D model used for the digital mock-up is shown in Fig. 5.9.

The length of the engine room is nearly 20 m and it is positioned amidships, where the ship in provided with a double bottom, consumables and ballast tanks at the ship's sides. Vertically, there are two decks involved: the engine room is actually a unique space of 6 m height, where the upper deck is just a partial horizontal structure. The average engine room breadth is around 13 m.

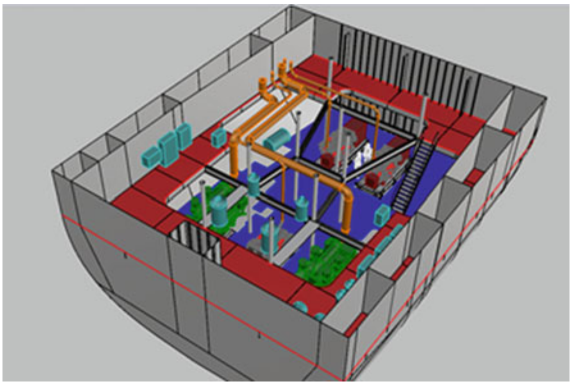

Fig. 5.9. 3D model of the ship's engine room used for the digital mock up

5.5.2 An Innovative Design Approach for Maintainability

Maintainability is a quality that can be embedded into the design process in order to guarantee that the maintenance activity is carried out efficiently (time/cost versus system availability) and safely (DoD US 1997; Dlugokecki and Hepinstall 2014).

Moreover, "design for maintainability" entails the capability of a life-cycle perspective, i.e. the ability to foresee the future operational activity of the ship, in order to take better decisions on the system to be installed onboard, considering also implications on the maintenance policy. Within the wide and complex topic of "design for maintainability" the concept of systems and sub-systems accessibility is a central point. This is always a critical issue, but more and more for special types of ships, naval ships, research vessels and mega-yachts, where the space available particularly in the engine room is very much limited and full of systems and equipment.

In the following, a methodology to rationally define the arrangements of the engine room and take decisions during the design stage, based on the accessibility issue, is delineated.

Two aspects have been considered, one has to do with the geometrical interference and compatibility between the item under maintenance and the special context around. The second aspect can be defined as an ergonomic aspect and it takes into consideration the physical interference and comfort between the maintenance operator and the space where he/she is supposed to work.

They have been modelled separately by means of two parameters:

1. parameter **i**: representative of the "item based" space
2. parameter **h**: representative of the "human based" space

A third aspect, represented by the parameter **c**, has been considered as well, i.e. in relation with the complexity of the maintenance activity that is to be carried out. In fact, this element can play a significant role when defining the actual space that is needed in order to carry out an efficient maintenance execution. Each of the parameters described above will be better detailed in the following paragraphs.

Subsequently, a comprehensive **Maintainability Index (MI)** can be defined (further detailed as well in a following paragraph) in order to characterize comprehensively a design configuration, as expressed by Eq. (5.2):

$$MI = i^3 + h^3 + c^2 \tag{5.2}$$

Each parameter i, h and c can range from 1 to 3 with the significance:

- 1 → acceptable
- 2 → intermediate
- 3 → critical.

This approach is simple but effective in typical design situations, where the level of details is not always much advanced.

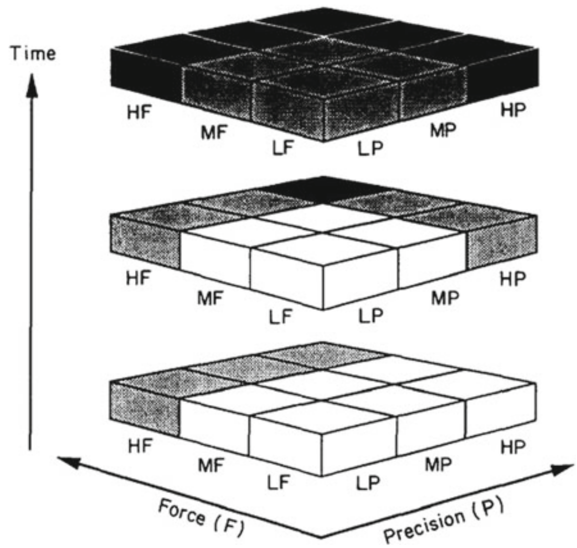

Fig. 5.10 The McCumber Cube (McCumber 1991)

From the above formulation, the index MI can be classified in three main categories and takes the following values:

- $3 \leq MI \leq 17 \rightarrow$ acceptable
- $18 \leq MI \leq 37 \rightarrow$ intermediate
- $39 \leq MI \leq 63 \rightarrow$ critical.

The knowledge that can be globally derived from combined elements, as defined by the introduced parameters and which are very different in nature and implications, can be logically and graphically characterized with reference to the so called "Cube model" or "McCumber Cube" (McCumber 1991), initially developed in the computer science field and then applied to several other fields.

The Cube model has also been exploited for ergonomic studies (Sperling et al. 1993) where on the three axis the parameters force, precision and time have been considered (Fig. 5.10). This model, with appropriate adaptation, will be extensively used in the following paragraphs.

5.5.2.1 The Item Based Space

The **i** "item based" space is an index meant to measure the available space to dismantle an item intended for maintenance The suitable clearance is usually indicated by the item supplier and this indication, provided together with the maintenance necessary procedures, is very relevant especially in complex context like a ship engine room. The point is that only the shipyard is able to take into account the possible problems of physical interference that can arise during the operational life of the ship and that are to be addressed already in the ship design phase. Actually, the equipment suppliers assume that the "clearance clash" is always guaranteed but this cannot be the case from time to time. The term "clearance clash" is derived from the BIM (Building Information Modelling) context and it describes a situation where two objects do not physically interfere but their proximity is such that the assembling and disassembling activity might result very difficult if not nearly impossible.

In order to develop a comprehensive approach where to model this issue the "item based" space has been identified and it is defined, as already mentioned, as the necessary space to extract and move items for maintenance activity. The item-based space index has been formulated as a parameter representative of the characteristic dimension of the item size.

As already mentioned, the value of this index can range from 1 to 3 with the following significance:

- 1 → acceptable
- 2 → intermediate
- 3 → critical.

Identifying with **D** [mm] the characteristic dimension and with **S** [mm] the available space, the following ranking is applied:

- 1 (fully acceptable) when the available space around the item is $\mathbf{S} \geq 3^*\mathbf{D}$
- 2, 5 (intermediate) when the available space around the item is $\mathbf{S} = \mathbf{D}$
- 3 (critical) when the available space around the item is $\mathbf{S} = 0,8 * \mathbf{D}$.

Intermediate values of **I** (item based space) relevant to available space such as ($0,8^*\mathbf{D} < \mathbf{S} < \mathbf{D}$; $\mathbf{D} < \mathbf{S} < 3^*\mathbf{D}$) are found by interpolation. In case the available space is $\mathbf{S} < 0,8 * \mathbf{D}$, the situation is deemed as not acceptable.

In order to better clarify the D and S parameters, an example is given in Fig. 5.11.

Figure 5.12 provides an overview of acceptability ranges for the item based space index.

5.5.2.2 The Human Based Space

The human based space is aimed to measure the available space for the access and the permanence of human operators within a specified area in order to carry out maintenance activity and, therefore, is representative of a Human Factor aspect.

Of course, this huge topic has to deal also with a safety perspective, but in this case we are making reference to the ergonomic aspect specifically for maintenance.

Some classification societies have developed guidelines on this topic:

– *Guidelines for the design of the means of access for inspection, maintenance and operation of commercial Ships* (BV 2008);
– *Guidance notes on the application of ergonomics to marine system* (ABS 2013).

Both these documents suggest minimum dimensions for accessibility in some specific ship areas, derived from anthropometric data of standard populations.

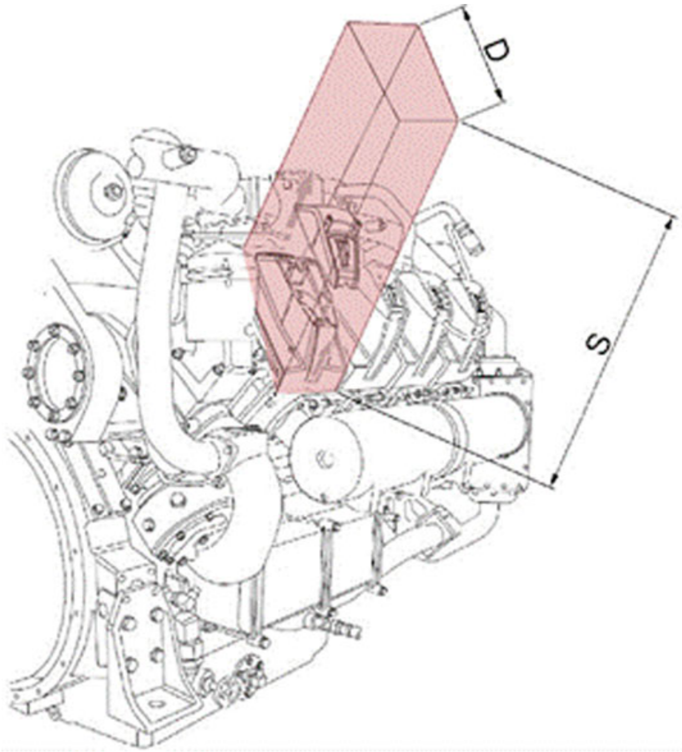

Fig. 5.11 The definition of D and S parameters

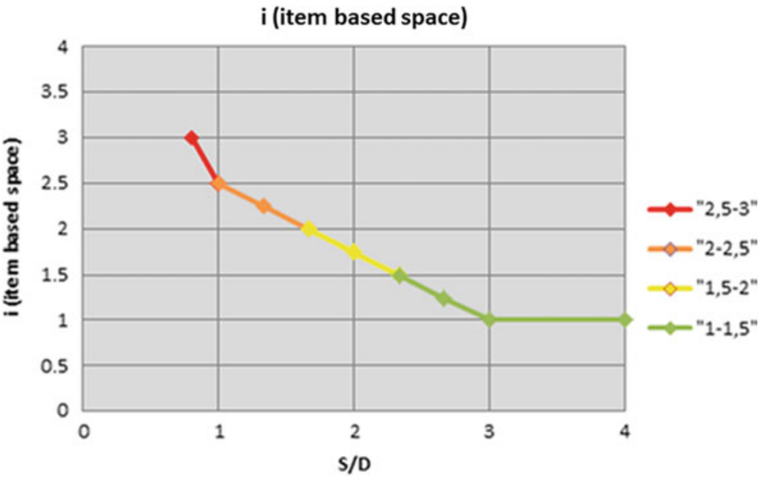

Fig. 5.12 Values of i item based space index with reference to S/D

This kind of documents together with some others have been used to derive the dimensional requirements in terms of available spaces around an equipment/system to allow human accessibility for maintenance.

In particular, requirements in terms of available height "**H**" and available width "**W**" have been defined. **H** is defined vertically from the flooring and **W** is defined horizontally from the surface of the equipment/system body. These two distances are to be defined in significant sections around the machinery under investigation and are used to formulate and calculate the index "**h**".

Minimum distances have been identified as:

- **H** $\geq$ 1600 mm
- **W** $\geq$ 600 mm.

As far as the minimum requirement in terms of height the value has been derived from (Zhigang et al. 2019) where it is put in evidence that, in case in a specific area the height is lower than 1800 mm, it is likely the personnel bend down and if the height is lower than 1600 mm people needs to squat. In this perspective the stoop walking height area is identified within the height interval between 1600–1800 mm. As a further contribution, IMO/IACS select 1600 mm as the minimum walkways height onboard, so it is something that is considered acceptable for a reasonable short time but not the ideal situation that has been defined correspondent to 2000 mm that allows a comfortable upright position for a person characterized by an height relevant to the 95^{th} percentile of a north European males population (ABS 2013) and it is in line with requirements of 2020 mm requested by Bureau Veritas (BV 2008).

The same approach has been followed for the identification of the **W** ranges and 680 mm together with 600 mm have been identified as the intermediate and critical scenario respectively.

As a consequence, the 1–3 values necessary for the formulation of the approach have been assigned with the following scheme:

- **H** = 1600 mm $\rightarrow$ 3
- **H** = 1800 mm $\rightarrow$ 1,5
- **H** = 2000 mm $\rightarrow$ 1
- **W** = 600 mm $\rightarrow$ 3
- **W** = 680 mm $\rightarrow$ 2
- **W** = 1000 mm $\rightarrow$ 1.

Values within intervals (1600 < **H** < 1800; 1800 < **H** < 2000; 600 < **W** < 680; 680 < **W** < 1000) are computed by linear interpolation.

Dimensional requirements in this case are to be considered as couples, since a free volume for comfortable activity is to be guaranteed for the operator. The "human space volume" is represented in Fig. 5.13 as the union of all the appropriate sections.

The **h** index is calculated as the average between **H** and **W,** as expressed by Eq. (5.3):

$$\boldsymbol{h} = \frac{score\,(H) + score\,(w)}{2} \tag{5.3}$$

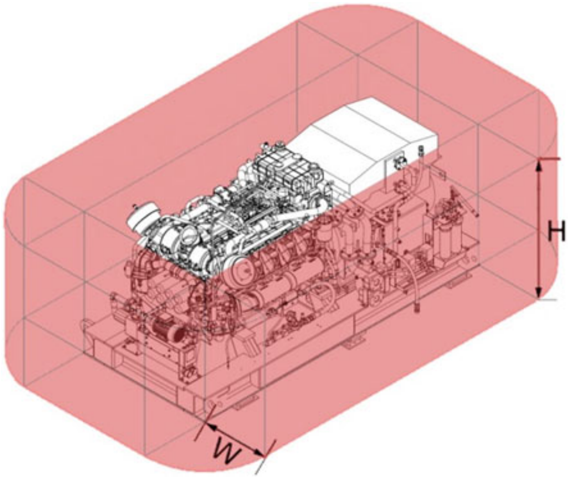

Fig. 5.13 Representation of parameters W and H for h index evaluation

In line with the approach followed for **i** (item based) and in order to provide some flexibility to the proposed tool, situations not compliant with the minimum requirements are modelled as well, to the extent of 80% of the minimum requirement: therefore, situations are modelled as well up to a width of W = 0.8*600 mm = 480 mm.

The worst score (3) is attributed to **h** (human based) when the available width **W** is within the range form 480 and 600 mm, whatever is the available height **H**.

When **W** is lower than 480 mm the configuration is simply not acceptable, since the following inequalities can be expressed:

- 480 < **W** < 600 → h = 3
- **W** < 480 → not acceptable for maintenance activity.

The same is applied in case the minimum requirement in terms of height is not complied with and in this case the limiting value is 1500 mm: below this threshold the situation is not deemed as acceptable for maintenance activity.

A score of 3 is applied for **h** (human based) when 1500 < **H** < 1600, whatever is the coupled available width W. In this case 1500 mm has been selected from ABS regulations which define 1500 mm as the "Kneeling Work height".

In line with the **i** index after the interpolation an approximation to obtain rounded numbers is necessary and also for **h** a graphical representation has been used (Fig. 5.14) putting in evidence 4 values ranges as a more detailed information with respect to the approximation activity.

5.5.2.3 Complexity

The complexity of the maintenance operation might appear as something vague and of difficult evaluation. Nevertheless, the forecasted complexity of the operation, the

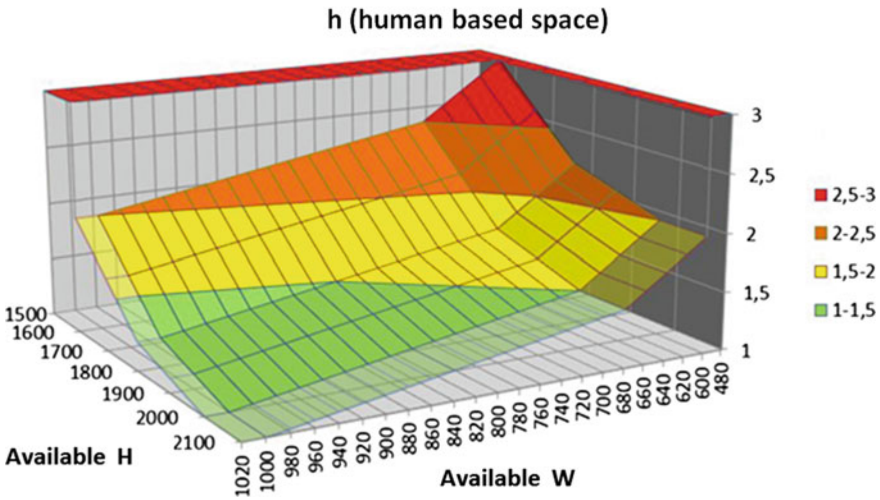

Fig. 5.14 Values of i item based space index with reference to S/D

necessary competence and the implied safety and risk issues are usually included in the maintenance manuals. A definition in classes or levels for the previously mentioned characteristics of maintenance is applied in several fields. The common approach is to express complexity as low-medium-height (or first, second, third level) and therefore very suitable for the kind of paradigm at the base of the proposed methodology. In the aeronautical field, three classes are defined: Operational level (O-level), Intermediate level (I-level) and Depot level (D-level). This last classification had to do with the Level of Repair Analysis (LORA) (Gutin et al. 2005), a methodology applied to investigate maintainability policies in a cost/effectiveness perspective.

The index **c**, which is a representative of the complexity of the maintenance operation, is a very wide concept that needs to be associated both with the needed competency and the criticality of the situation.

In the proposed methodology the aim is to define it as a parameter that is able to better represent the feasibility of a maintenance activity when it is combined with the necessary item based on space represented by **i** and the human based space represented by **h.**

For the purpose of this application, **c** has been treated as independent from the other two parameter **i** and **h**, and its level has been derived from manufacturer's maintenance manual. It is recognized, however, that **c** could be also defined as dependent on **i** and **h** and this matter can be subject of further investigations.

In the application case that will be elaborated later, reference is made to the classification of operational complexity, indicated in the maintenance manual of a Diesel Generator, by means of letters A, B, C, D, E, F, G.

The index **c** therefore has been defined as follows:

- A, B → **c** = 1
- C, D → **c** = 2
- E, F, G → **c** = 3.

5.5.2.4 Calculation of the Maintainability Index MI

The maintainability index MI has been already defined as a combination of the three indexes **i, h, c** with the formulation expressed by Eq. (5.2).

The raise to a power is introduced to enhance the penalization of situations described by a value > 1. In particular, the "**c**" index is squared (differently from **i** and **h** that are in the cube power) to point out that, as mentioned in Sect. 5.5.2.3, complexity is assumed as independent from **i** and **h**, and therefore cannot be managed acting on different design features and layouts; its value has been derived by the maintenance manual and, therefore, it is more relevant to the system itself under maintenance.

The whole range of possible scenarios and relevant MI values is given in Table 5.4, where it is evident that 18 different values of MI can be identified.

The same values can be evaluated with the formulation based on combination with repetition calculus given by the following Eq. (5.4):

$$\sum_{c=1}^{3} C^r_{k,n_c} = \binom{n+k-1}{k}_c = \sum_{c=1}^{3} \left(\frac{(n+k-1)!}{k! * (n-1)!} \right)_c \tag{5.4}$$

In our case $k = 2$ and $n = 3$ (with "c" is the complexity index), so that (5.4) gives the following result:

$$\sum_{c=1}^{3} C^r_{2,3_c} = \sum_{c=1}^{3} \binom{3+2-1}{2}_c = \sum_{c=1}^{3} \left(\frac{(3+2-1)!}{2! * (3-1)!} \right)_c = 18 \tag{5.5}$$

The cube model is an effective tool with graphical representation, especially when a green-yellow–red color logic is assumed, as represented in Fig. 5.15.

Based on this methodology, a further step can be also introduced, enabling the translation of the MI index value in possible increment of time for maintenance, as an impact of a design solution on operation costs.

Due to lack of data availability in this area, assumptions have been formulated based on experts' know-how in order to pursue this task. In case real data from the field become available, this procedure can be easily updated.

The Mean Repair Time (MRT), that is usually known, has to be multiplied by a coefficient expressed in Eq. 5.6:

$$R_{MTR} = \frac{\sqrt[2,6]{MI}}{\left(\sqrt[2,6]{MI}\right)_{113}} \tag{5.6}$$

Table 5.4 MI range of values

i or h	h or i	c	i^3 or h^3	h^3 or i^3	c^2	MI
1	1	1	1	1	1	3
1	1	2	1	1	4	6
1	2	1	1	8	1	10
1	1	3	1	1	9	11
1	2	2	1	8	4	13
2	2	1	8	8	1	17
1	2	3	1	8	9	18
2	2	2	8	8	4	20
2	2	3	8	8	9	25
1	3	1	1	27	1	29
1	3	2	1	27	4	32
2	3	1	8	27	1	36
1	3	3	1	27	9	37
2	3	2	8	27	4	39
2	3	3	8	27	9	44
3	3	1	27	27	1	55
3	3	2	27	27	4	58
3	3	3	27	27	9	63

acceptable

intermediate

critical

The root of 2.6 has been identified by the average value of the three exponents and the value is normalized with respect to the scenario with **i** = 1, **h** = 1, **c** = 3.

In Table 5.5 the coefficient R_{MTR} is reported in relation to the MI value.

5.5.3 Application Case Study

As an application case, specific maintenance activities are identified for a Diesel Generator and the complexity “c” index is derived from the maintenance manual:

– Check of play valves/balance wheel, c = 1.

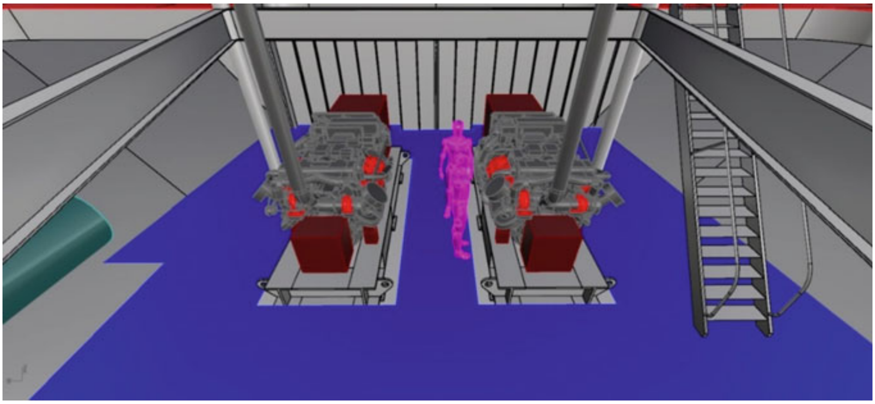

Fig. 5.15 Combinations of i and h indexes in the Cube model

- Replacement of injector, c = 2.
- Check/ replacement of turbocharger, c = 3.

The procedures for the "Check of play valves/balance wheel" and "Replacement of injector" both need the opening of the cylinder head and are characterized by the same **i** item based space and the **h** human based space; in these cases it is possible to observe the influence of the complexity index.

Two different layouts have been compared for the engine room of the model ship described in this chapter and they are represented in Fig. 5.16 (Layout 1) and Fig. 5.17 (Layout 2). Layout 1 is particularly favorable for maintenance activities.

The importance of a 3D mock-up representation in order to better appreciate at a glance the situation and to be able to derive quantitative values to support the comparison is evident.

In Layout 1 (Fig. 5.18) the situation is (always nearly) acceptable for a maintenance activity around the generator. In the Layout 2 (Figs. 5.19, 5.20 and 5.21) the situation is quite critical in the space between the generators (as shown in particular by Fig. 5.21).

In Tables 5.6 and 5.7 results are reported with reference to the investigated different scenarios of the application case.

Layout 2 is definitely much more critical and almost not acceptable, in particular in the three cases where the requirement in terms of width relevant to index **h** (human based) is not sufficient, since **W** < 480 mm implying that **h** is not acceptable and therefore the solution is globally not acceptable.

Such result has generated the need for a further configuration identified as Layout 2-bis, obtained by pursuing the improvement of the index **h** (Fig. 5.22).

In Table 5.8 the results relevant to this new configuration are presented.

The new layout can be evaluated with the methodology and its better suitability for maintenance operations can be evidenced.

Table 5.5 Values of time correction factor in relation to i, h, c combinations

i or h	h or i	c	MI	$\sqrt[2,6]{MI}$	$R_{MTR} = \frac{\sqrt[2,6]{MI}}{\left(\sqrt[2,6]{MI}\right)_{113}}$
1	1	1	3	1,51	0,61
1	1	2	6	1,96	0,80
1	2	1	10	2,37	0,96
1	1	3	11	2,46	1,00
1	2	2	13	2,62	1,06
2	2	1	17	2,89	1,18
1	2	3	18	2,96	1,20
2	2	2	20	3,08	1,25
2	2	3	25	3,34	1,36
1	3	1	29	3,54	1,44
1	3	2	32	3,67	1,49
2	3	1	36	3,83	1,56
1	3	3	37	3,87	1,58
2	3	2	39	3,95	1,61
2	3	3	44	4,13	1,68
3	3	1	55	4,49	1,83
3	3	2	58	4,58	1,87
3	3	3	63	4,73	1,92

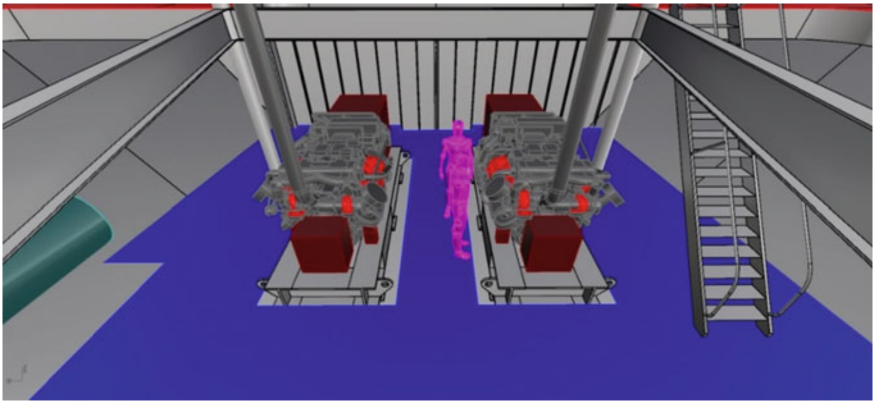

Fig. 5.16 Layout 1 for the engine room

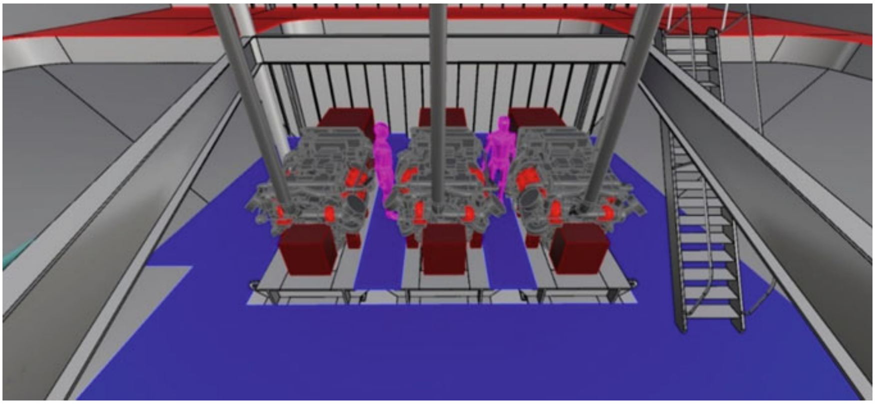

Fig. 5.17 Layout 2 for the engine room

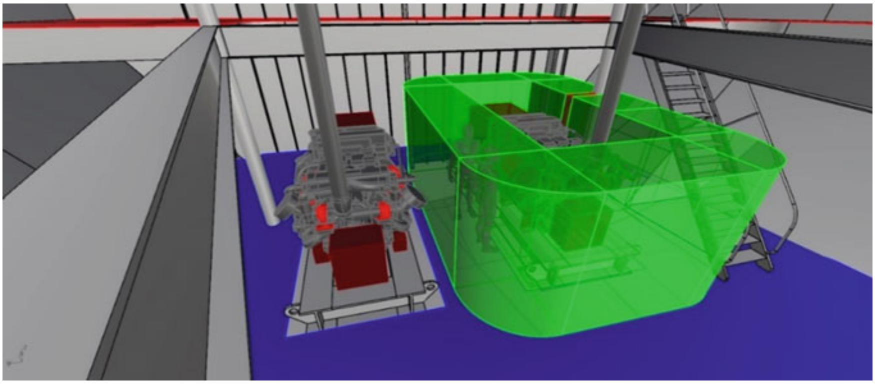

Fig. 5.18 Layout 1: human based space h

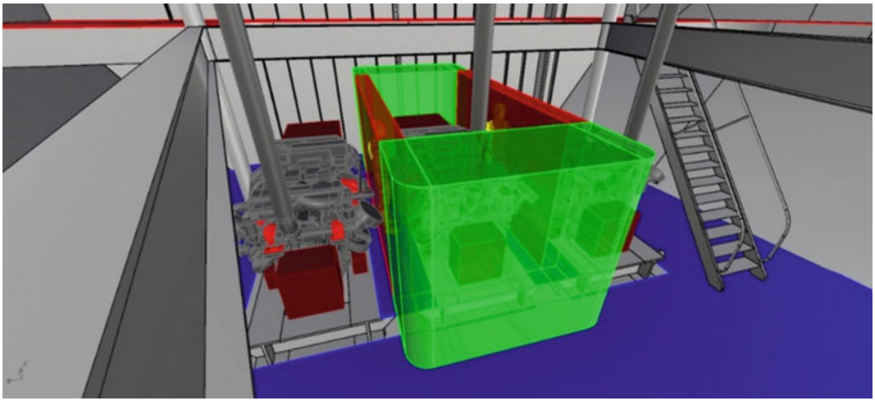

Fig. 5.19 Layout 2: human based space h for the central Diesel Generator

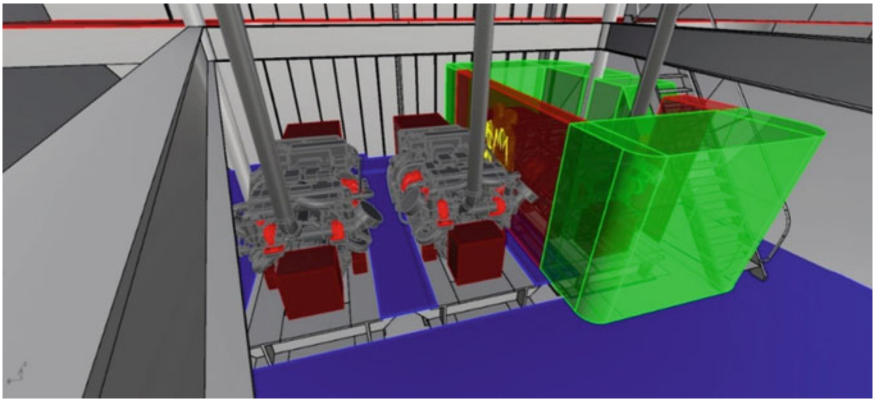

Fig. 5.20 Layout 2: human based space h for the lateral Diesel Generator

5.5.4 Final Considerations on the Methodology

A methodology has been proposed to assess different engine room layout configurations in terms of accessibility for maintenance. The McCumber Cube model has been assumed and three parameters namely **i** item-based space index, **h** human-based space index and **c** complexity index have been identified and combined. Finally, the definition of a procedure to translate the difficult accessibility in maintenance time increment has been proposed.

The importance to rely on digital mock-up in order to have an immediate qualitative perception of the situation and in order to directly derive quantitative information

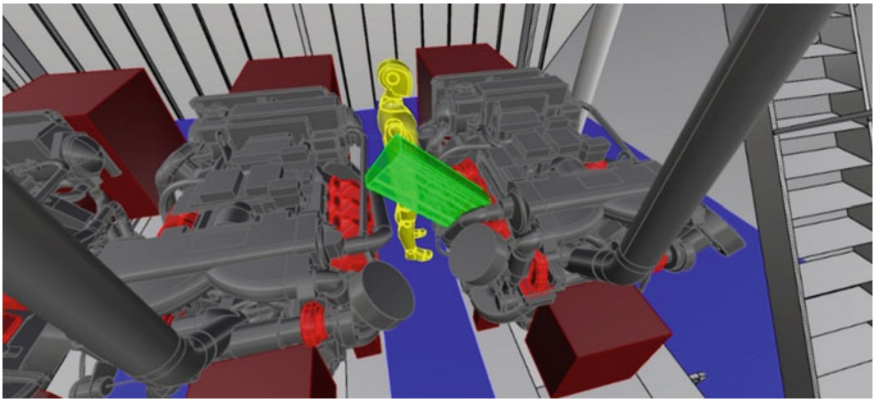

Fig. 5.21 Layout 2: human based space h for the lateral Diesel Generator (particular of body representation)

Table 5.6 Layout 1 results in terms of MI index calculations

Layout 1			
Maintenance operation	**Check of play valves/balance wheel**	**Replacement of injector**	**Check/ replacement of turbocharger**
D [mm] characteristic dimension	400	400	300
S [mm] available space	> 1200	> 1200	800
S/D	> 3	> 3	2.67
I (item based space)	1	1	1
H [mm] (human based available height)	>2000	>2000	>2000
W [mm] (human based available width)	875 (worst case)	875 (worst case)	>1000 (worst case)
h (human based space)	1	1	1
c (complexity)	1	2	3
MI (Maintainability Index)	3	6	11
$\mathbf{R_{MTR}}$ (increment time coefficient)	0,61	0,8	1

Table 5.7 Layout 2 results in terms of MI index calculations

Layout 2			
Maintenance operation	**Check of play valves/balance wheel**	**Replacement of injector**	**Check/ replacement of turbocharger**
D[mm]characteristic dimension	400	400	300
S [mm] available space	> 1200	> 1200	800
S/D	>3	>3	2,67
i (item based space)	1	1	1
H [mm] (human based available height)	>2000	>2000	>2000
W [mm] (human based available width)	350 (worst case)	350 (worst case)	235 (worst case)
h (human based space)	N/A	N/A	N/A
c (complexity)	1	2	3
MI (Maintainability Index)	N/A	N/A	N/A
R_{MTR} (increment time coefficient)	-	-	-

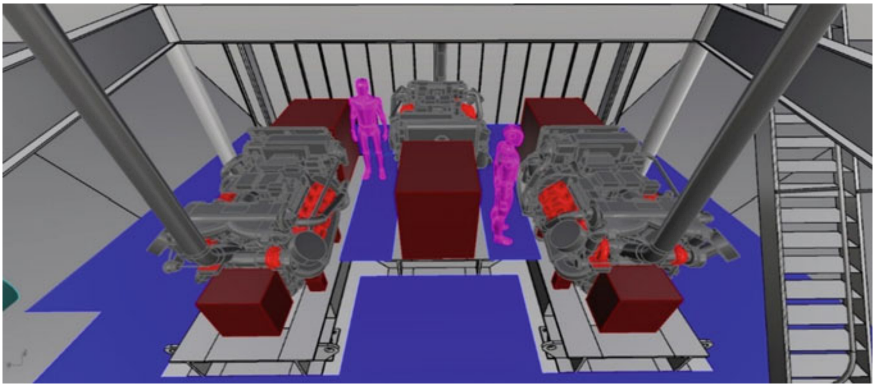

Fig. 5.22 Layout 2-bis: Diesel Generator arrangement

to be used in order to compare different solutions has been evidenced. A further integration between the proposed methodology and the digital mock-up can be developed in the perspective of a more automatic assessment of design decisions with respect to the maintenance costs.

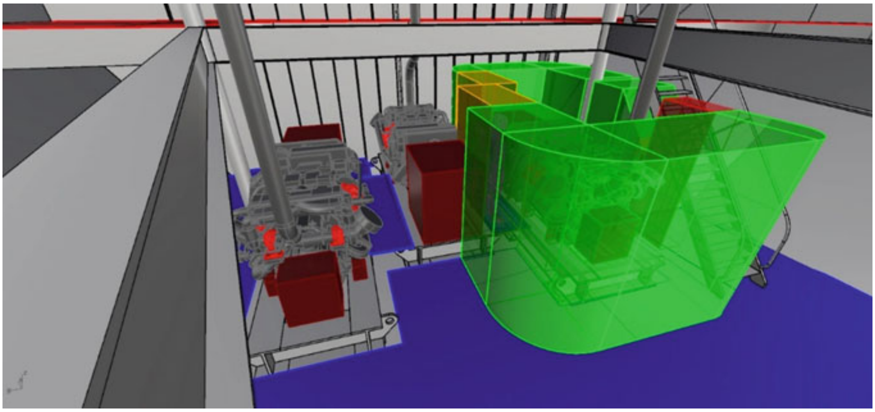

Fig. 5.23 Layout 2-bis: human based space h for the lateral Diesel Generator

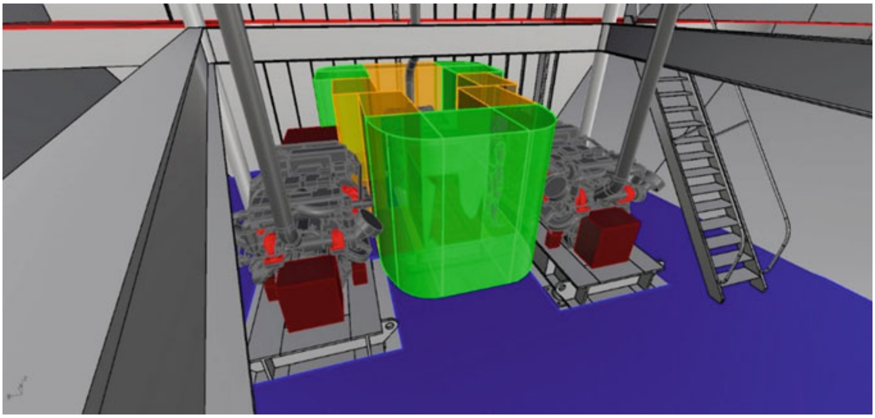

Fig. 5.24 Layout 2-bis: human based space h for the central Diesel Generator

5.6 Conclusions

Maintenance costs are one of the most important constituents of the operational costs. In a ship life-cycle design perspective, it is important to develop suitable methodologies and tools able to foresee ship performances compared with costs. To this regard, within the context of SE, the concept of "left shifting" suggests to identify and analyze operational issues since the early design phase. Among the most important topics is the understanding of how to account for maintenance costs in relation to the adopted energy systems solutions onboard and the impact of systems accessibility for maintenance in the engine room.

An application case has been dedicated to investigate maintenance cost estimations for a Research Vessel with reference to different power generation system

Table 5.8 Layout 2-bis results presented in terms of MI index calculations

Layout 2-bis			
Maintenance operation	**Check of play valves/balance wheel**	**Replacement of injector**	**Check/ replacement of turbocharger**
D [mm] characteristic dimension	400	400	300
S [mm] available space	> 1200	> 1200	800
S/D	>3	>3	2,67
i (item-based space)	1	1	1
H [mm] (human based available height)	>2000	>2000	>2000
W [mm] (human based available width)	635 (worse case)	635 (worse case)	>1000 (worse case)
h (human based space)	2	2	1
c (complexity)	1	2	3
MI (Maintainability Index)	10	13	11
R_{MTR} (increment time coefficient)	0,96	1,06	1

configurations. Since operational scenarios play an important role, assumptions have been made and different power need profiles have been defined in terms of ship's propulsion and other ship operational load demand.

Starting from the LCPA tool already described in HOLISHIP book Chap. 12, Vol. I, (Papanikolaou 2019) related to first phase of the HOLISHIP project, M&R costs have been modelled based on equipment running hours and actual working points, which are in some cases different form the ideal ones.

Three alternative engine room solutions S1, S2 and S3, besides the original one S0, have been identified and analyzed under the BLD, OPEX and M&R perspective by means of a quantitative approach, which is reliable on a comparative basis.

From the analysis of results, it appears evident that the best solution is very much close to the point of view of the stakeholders performing the assessment: this is particularly true when environmental considerations are introduced in the trade-off activity.

For some specific ship typologies, characterized by limited space for the engine room, the selection of the best energy system configuration is also influenced by the space available for maintenance during the operational life of the ship. The vessel selected for the AC belongs to this class (together with, for example, navy ships and mega yachts typically built in European shipyards) and, therefore, further attention has been payed to the accessibility of systems, influencing maintenance costs. A specific approach has been developed able to provide warnings and evidence of critical situations when comparing different engine room configurations.

The methodology is based both on necessary space and maintenance operational complexity. With reference to the space domain, attention has been payed to the item-based space and to ergonomic requirements. To this aim, a digital mock-up has been of fundamental importance both to provide the necessary information and to verify the solutions effectiveness. On the other side, this left-shifting operation had to rely on the availability of a significant amount of details and equipment information. The methodology has proven to be robust and reliable. The future availability of field data, which are selected and organized with the specific purpose of investigating the accessibility of equipments, will be very useful to further improve its validity.

Acknowledgements The authors gratefully acknowledge the noteworthy contribution of Andrea Musacchio with specific reference to Sect. 5.5, which is mainly based on his Master Thesis developed at UNIGE (La Spezia branch).

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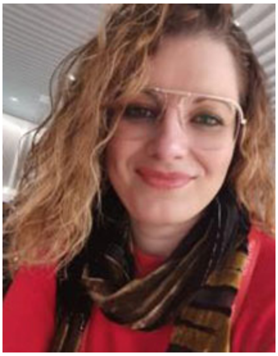

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Chapter 6
Design of a Multi-Purpose Ocean Vessel

Romain Le Néna, Julien Calvignac, and Alan Guégan

Abstract The fourth application case of the HOLISHIP project is the design of a Multi-Purpose Ocean Vessel with the support of the CAESES platform. A particular focus is given to early stages of ship design, to systems' architecture and to mission requirements by use of management software (s/w) tools developed in the first phase of the HOLISHIP project (Papanikolaou A Holistic Approach to Ship Design. Springer 2019). The Multi-Purpose Ocean Vessel is designed to address a large variety of missions, from patrol and surveillance to search and rescue or pollution fighting operations. The missions of such a vessel depend strongly on the range, the region of operation, and the type of operations the ship owner ultimately wants to perform. "Off-the-shelf" ship designs meeting this type of requirements require intensive re-work, when they are not excluded altogether. To deliver the best possible design, the naval architect needs to reach a balance between the many requirements expressed by the ship owner and the complexity of the ship systems' architecture. To achieve this aim, several variants need to be explored. In this chapter we present the design of a Multi-Purpose Ocean Vessel. We discuss the advantages of using "easy-to-use" early stage ship design tools combined with a more advanced, integrated CAD design platform, when exploring several variants. We also discuss the benefits of use of the architecture and requirements management tool SAR developed in HOLISHIP, in the context of complex ship design.

Keywords Holistic ship design · Multi-purpose offshore vessel · Sensitivity study · Systems engineering · Configuration management · Continuous integration · GITLAB · Architecture management tool · Evaluation of mission requirements · Scenario oriented design · Simulation driven design · Synthesis design tool

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A. Papanikolaou (ed.), *A Holistic Approach to Ship Design*,
https://doi.org/10.1007/978-3-030-71091-0_6

Abbreviations

Buda	Bubble Diagram
CAESES	Computer Aided Engineering System Empowering Simulation
CairnBuilder	Continuous integration tool (part of SAR management tool)
CAPEX	Capital expenditure
CI	Continuous Integration
CODAD	Combined Diesel and Diesel
CODLAD	Combined Electrical and Diesel
DAD	Diesel and Diesel
EEDI	Energy efficiency design index
GES	General Energy System of TNO
GITLAB	Open source Software development management tool
IMO	International Maritime Organisation
LCB	Longitudinal position of Centre of Buoyancy
LCC	Life cycle cost
LCPA	Life Cycle Performance Assessment
Lpp	Length between perpendiculars
MPOV	Multi-Purpose Ocean Vessel
OPEX	Operational Expenditure
PAX	Passengers
PBS	Product Breakdown Structure
PMT	Project Management Platform
RHIB	Rigid-Hulled Inflatable Boat
ROV	Remotely Operated Vehicle
SAR	System Architecture and Requirement tool of SIREHNA
SEASAFE	Stability calculation tool of Lloyds Register
ShipBuilder	General layout sketching tool (part of SAR management tool)
SimulationDesk	Simulation management tool (part of SAR management tool)
S&R	Search and Rescue
SS X	Sea State X
WP	Work package
VERES	Vessel Response tool of ShipX SINTEF
VEPOST	VERES Postprocessor tool of ShipX SINTEF

6.1 Introduction to the Design of a Multi-Purpose Ocean Vessel (MPOV)

The pre-contract design of a complex ship such as a MPOV can be divided into two major phases (see Fig. 6.1), namely the concept and the contract design phase that aim at delivering a contractual vessel offer with a consistent, consolidated and optimized ship design:

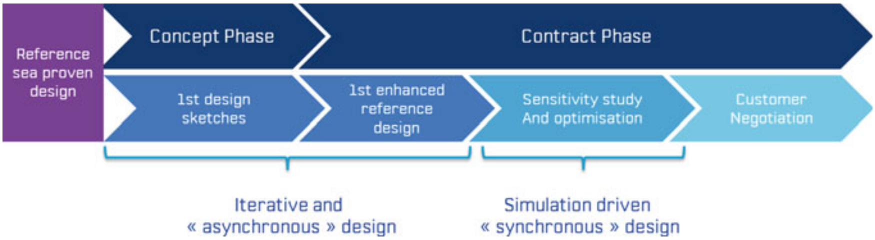

Fig. 6.1 Basic phases of the MPOV design process

- The general design of the ship is outlined during the *concept design* phase. This stage generally involves a small team of the yard—in our case, one naval architect and one system engineer. Operational scenarios and requirements are refined with the customer. System architecture principles are drawn and the preliminary characteristics and performances of the vessel are discussed. The management of customer requirements and the exploration of architecture variants are essential in the concept design phase, and we have chosen this phase as the main focus point to demonstrate the benefits of the developed SAR *System Architecture and Requirements management tool*.
- In the *contract design* phase, the main characteristics of the ship are consolidated and refined. This stage involves a more comprehensive team of technical experts. The aim is to secure performance and cost assessments to deliver the best possible technical and commercial offer. The design spiral loop originally introduced by Evans (1959) is the traditional way of reaching a converging design solution on both the technology and cost/economy side of the ship. The HOLISHIP CAESES® s/w platform offers a unique opportunity to speed up dramatically this iterative design process, and we discuss the benefits of an integrated evaluation platform for design optimization in the contract phase.

6.2 Exploration oF CONCEPT DesiGN Phase by Use of the SAR Tool

6.2.1 Description of the SAR Management Tool

A System architecture and Requirement Management tool called SAR has been developed in the first phase of the HOLISHIP project (Le Néna et al. 2019). The development of this tool was due to the following observations:

1. Ship owners' contractual requirements often lack specific contextual information, such as a description of the operational scenarios that the ship will actually serve.

2. Comprehensive and synthetic views of the architecture of the systems on-board complex ships are often missing, even if the architecture of each system or network is thoroughly described in dedicated electrical, cabling, piping, command & control tools.
3. Simulation data is often disconnected from design data. For instance, the main particulars of the ship might be adjusted to new operational needs without the hull resistance and powering evaluation being updated according to this evolution.

Over the course of the project, we realized that some needs of design would be better fulfilled by *specific applications*, while the need for drawing connections between different sources of information (and between systems in general) could be efficiently fulfilled by using standard *configuration management tools*.

The resulting System architecture and Requirement Management SAR tool is composed of several *services* or front end applications displayed in Fig. 6.2:

- **Scenarios**: operational scenarios can be described and managed with this tool. The evolution of scenarios over time can be tracked and traced to design requirements and variants. This tool answers the observation expressed in the first bullet point 1 above.
- System Architecture Diagram Tool (**BuDa**): BuDa is an architecture design and visualization tool designed to offer a sharp, clear systems architecture display. BuDa answers the needs from bullet point number 2.
- **Simulation Desk** enables the user to manage simulation data in connexion with design data, thanks to the connexion with the project's database managed in GITLAB. Simulation Desk targets bullet point 3.

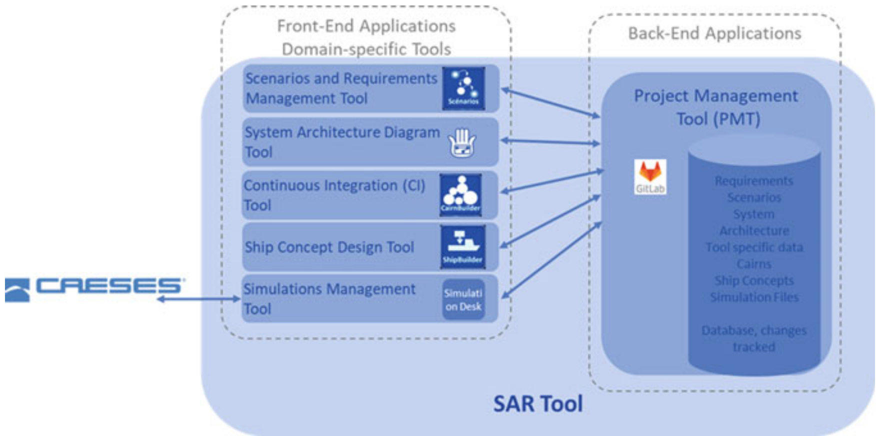

Fig. 6.2 Architecture of the SAR management tool. The SAR tool combines domain-specific applications (dashed rectangle on the left) and the standard configuration management (dashed rectangle on the right). The tool connects with the CAESES® platform through the simulation management tool

We resorted to a marketplace configuration management platform to ensure the connexion of the design and simulation data. GITLAB (Calvignac et al. 2019) is a widespread, friendly, efficient and free-to-use configuration management platform and we decided to develop connectors between our own design tools and GITLAB. We even took the opportunity to include one more tool to the SAR environment—the early stage design tool **ShipBuilder** developed in the first phase of the project.

The configuration management platform made a link between the various tools that we used. However, we felt the need to complement this with a "continuous integration" tool that we called **CairnBuilder** (Calvignac et al. 2019; Le Nena et al. 2020). This tool offers the possibility to any designer to group any data in a "Cairn", and to be informed in case any of this data changes during the design process. When, say, the displacement of the ship changes, the expert that has included the "displacement" in a cairn can re-evaluate the consistency of the other data he has included in the same cairn. By so doing, we offer an equivalent to the continuous integration (CI) capability that can be found in software configuration management environments, where "manual tests" (expert evaluation) play the role of automated tests that are run every time a new contribution is made to the source code in a software project. Accordingly, CairnBuilder is designated by "CI tool" in Fig. 6.2.

6.2.2 Main Activities of the Concept Phase

The following activities were performed to achieve the general design of the MPOV:

- Elicitation of stakeholder's needs: we defined the operational scenario and the basic requirements for the ship.
- Defining preliminary system architecture with respect to operational scenarios.
- Defining the payload for each operational scenario.
- Extrapolation of main characteristics from reference vessel by modifying the preliminary arrangement, functional volumes and weights.
- Checking the first concept with respect to the sea proven shipyard fleet.
- Defining the validation method for later stages by defining cairns and simulation workflows with SimulationDesk and CairnBuilder.

These steps are described in the sections that follow.

6.2.3 Scenario and Requirement Management

The first step of the concept phase is to build independent and descriptive operational scenarios. Defining the scenarios at the beginning of the design helps to clarify and contextualize the vessel operational needs, which will be useful to evaluate trade-offs between design options. For more information on using operational scenarios for the design of ships, please refer to Le Néna et al. (2019).

The following operational scenarios have been defined for the MPOV:

- Search and rescue an overloaded craft of migrants
- Surveillance of surrounding ship at EEZ
- Interception of a fast craft suspected of illicit activities
- Disperse pollution and investigate oil leakages
- Supply first necessity goods and rescue means to near shore disaster areas

These scenarios were used to define the main operational requirements such as, for instance, the ability to load a full ROV system including control command on deck, the ability to sail up to 26 knot in sea state 2, the ability to store a sufficient dispersant liquid volume or the ability to launch, operate and recover a ROV in sea state 3.

The scenarios and requirements have been described with the Scenarios SAR tool; they have been tranferred to the configuration management platform, for further configuration management purposes.

6.2.4 System Architecture Mapping

A standard Product Breakdown Structure (PBS) tool has been used as a base for defining the PBS of an MPOV that would comply with the operational scenarios and requirements previously defined. All the systems, sub-systems and components required for the MPOV have been identified at this stage and modelled in the systems architecture tool BuDa.

A BuDa model is a multi-physical and multiscale representation of the complex system architecture. In addition to the standard hierarchical representation of the PBS, BuDa enables the designer to navigate through the system architecture and its components via their physical interfaces. More details can be found in (Guégan et al. 2017).

Several propulsion models have been defined for the MPOV:

- CODAD with 2 diesel engines
- CODAD with 4 smaller diesel engines
- CODLAD with 2 electrical drive motors and 2 diesel engines

The BuDa model of the CODLAD architecture is displayed in Fig. 6.3. Oil and fuel networks are displayed in green, the electrical network is in pink, and mechanical power is transferred through the purple (starboard) and brown (portside) lines.

In this simplified model, all the components are represented, as well as all the functional links between them (electrical network, fuel oil piping, mechanical chains, etc.). This sketch can be the support for preliminary, qualitative functional and dysfunctional analysis (Corrignan et al. 2018).

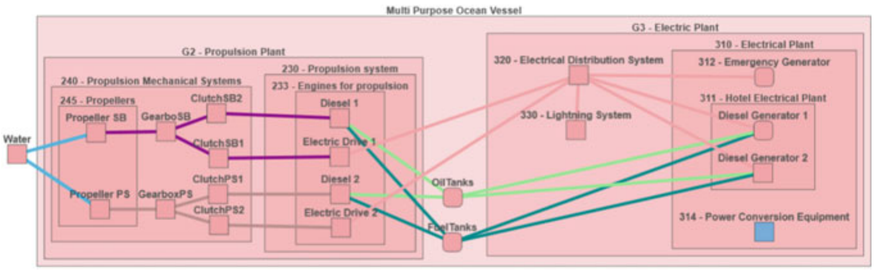

Fig. 6.3 CODLAD system architecture representation in BuDa

6.2.5 Preliminary Vessel Arrangement with ShipBuilder

The preliminary general arrangement of the vessel takes into account:

- the operational scenarios
- the preliminary system architecture
- the arrangement of an existing ship (reference design).

ShipBuilder is used to sketch up the initial design, preliminary arrangement and space reservation, by taking into account the main volumes and weight allocation.

The first step to define MPOV's general arrangement was to identify all deadweight on-board components (solids and liquids). For each operational scenario, assumptions were made on deadweight mass and volumes and the critical loading condition is identified.

Once the bill of mass and volumes has been drawn, the naval architect uses 3D functional blocs to build several consistent general arrangements. The naval architect is able to monitor the main particulars and weight distribution (lightweight and deadweight) of the vessel. All the systems needed to comply with the operational requirements shall be integrated in the design.

At this stage of the "concept phase" several preliminary sketches have been defined for several vessel arrangements and several propulsion architectures. The preliminary solutions have been assessed based only on qualitative functional and dysfunctional analysis, the experience of the naval architect and the comparison with the sea proven fleet data base.

Figure 6.4 gives the example of a preliminary general arrangement drawn with ShipBuilder. In this model, the yellow space is allocated to propulsion, the light green space is allocated to accommodation, purple spaces are dedicated to aviation, etc. All the functions and systems have been arranged in the vessel with the pre-allocated functional volumes and weight estimations. If some functions shall be adapted in a later stage (increasing number of PAX or increasing installed power, for instance) a preliminary volume extrapolation can be performed, whether globally, per room or per functionally allocated spaces.

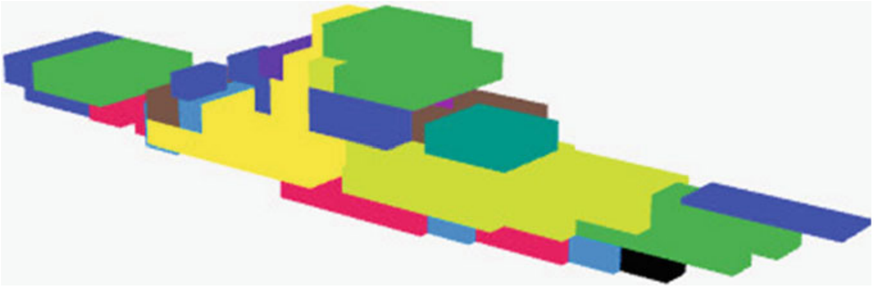

Fig. 6.4 First iteration on MPOV arrangement with ShipBuilder

6.2.6 SimulationDesk Experimentation

In the concept design phase, the frequency at which ship characteristics evolve is high. Many variants are explored, and even the main particulars of the ship are not settled.

It can be hard, in this moving context, to make sure that simulations are consistent with ship characteristics at all times. We have developed and tested a tool called SimulationDesk. This tool enables users to manage the configuration of the simulation data, of the ship data and their interrelations.

SimulationDesk users can create a list of "simulations". Each simulation has a name, a short text description, and list of URLs pointing to files related to the simulation. The users can link any file to any simulation, as long as the file has been stored on a GITLAB repository—which was the case in our MPOV application case.

Figure 6.5 shows the case of a propulsion power simulation. The simulation is run with the GES tool of TNO; all the input and output files are stored on the project's GITLAB repository and have been linked to *simulation 2_simulations_definition_GES* in SimulationDesk.

The author and last edit date of each file is displayed, which enables the user of SimulationDesk to know whether the simulation files are still consistent with the current state of the design. For instance, if *ges_configuration.bat* dates back to 26 days ago, like is the case in Fig. 6.5, and the propulsion power configuration has been changed from CODAD to CODLAD, then the simulation of the propulsive power is most probably wrong.

In its current version, SimulationDesk lacks versatility—only those files that have been committed to a GITLAB repository can be linked, for instance—but further developing the tool and extending its use should provide extremely beneficial to the management of early design phases, by enabling the design team to ensure the consistency of simulation and design data at all times.

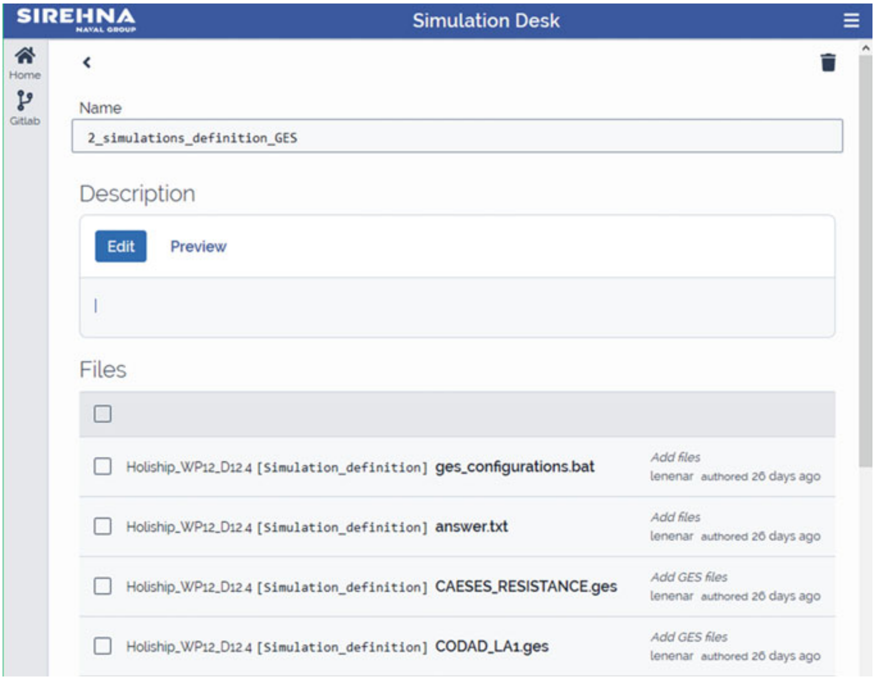

Fig. 6.5 Snapshot of SimulationDesk, showing a simulation event history with its name, text description (empty here) and related files with authoring data

6.2.7 CairnBuilder Principles and Experimentation

Ensuring the consistency of simulation data with design data is essential, but is part of the larger issue of the consistency of project data as a whole.

We extended the concepts initiated in SimulationDesk to the following general case:

- For a particular design subject, ship characteristics, customer requirements, simulation data, etc. should be consistent. E.g., hull characteristics and propulsion power should be consistent with a maximum speed requirement, in simulation conditions corresponding to a given sea state.
- These data are stored in different files on the GITLAB repository of the project. E.g., there can be Scenarios files, ShipBuilder models, SimulationDesk files…
- Each of these files is likely to change any time during the concept design phase, e.g. the propulsion configuration might change.
- How can a designer ensure that the changes he made to his own design files do not affect the global consistency of the design? e.g., if I change the propulsion configuration, will it still fit in the hull while ensuring the speed requirement?

- How can a designer make sure that the design that was consistent last week has not been weakened by some design change he is not aware of? e.g., is it still true that the propulsion power is enough to meet the speed requirement?

The last two questions may require some specific simulations, but the truly difficult task is to *keep track* of all the changes and the risk they create for the consistency of *multiple aspects* of the design—just to be able to ask these questions. We have developed a tool called CairnBuilder, which allows the users to link files together in what we call a Cairn—as a reference to the piles of stones built by hikers on mountain trails. A Cairn is a “pile” of objects that anyone can contribute to build, to make visible which objects contribute to a specific aspect of the design. For instance, in Fig. 6.6, Cairn 2 contains links to all the files that may affect energy efficiency. On the left of Fig. 6.6, the main interface with the list of cairns, and the “Set a reference commit” button that allows users to select the reference baseline. On the right, the content of a cairn: the list of the files that are linked to the cairn is given, with a red or green tag that says whether the file differs from the “reference commit”—or not.

In addition to SimulationDesk, where authoring data was displayed, CairnBuilder users can specify the configuration baseline against which the version of the files in the cairn shall be verified. This baseline is called the “reference commit”; each file in the cairn that differs from its version at the date of the reference commit is tagged in red—all other files are green.

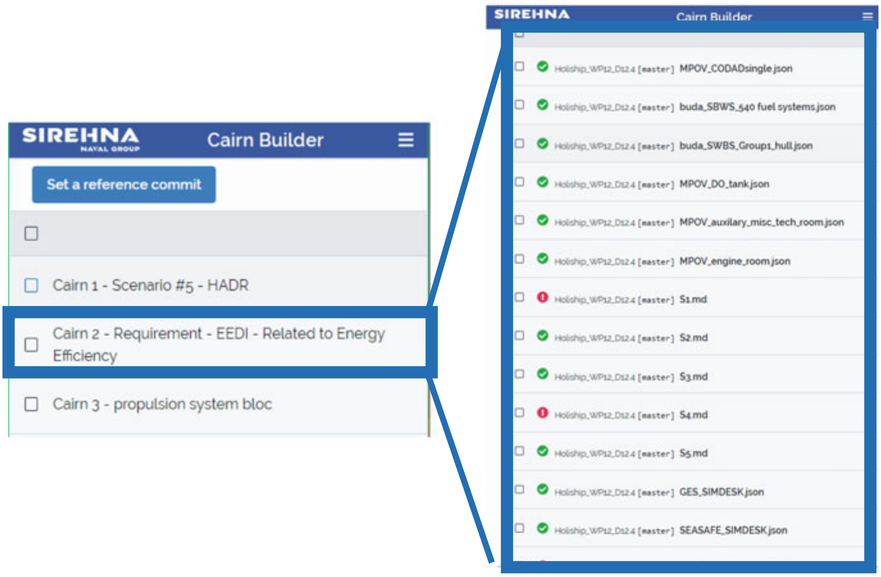

Fig. 6.6 Views of the CairnBuilder interface

Thanks to this, the user of CairnBuilder can see at a glance which files have changed since the last time they validated a certain aspect of the design—thus questioning the current validity of the design. They can also—and this is the nice case—have the guarantee that the validation they have performed sometime in the past is unchanged and still valid, when all the files in the cairn are green.

This is particularly useful to manage compliance, which was one of the goals of the second workpackage of the HOLISHIP project. A cairn can be built around each major requirement, to aggregate all the files that are needed to demonstrate the compliance; if the compliance of a cairn has been demonstrated once, it is guaranteed at all times as long as all the files in the cairn are green.

6.3 Exploration of Contract Design Phase by Use of CAESES® Platform

6.3.1 Contract Phase Steps in MPOV Design

The concept phase design outcomes lead to a first analysis of system architecture, operational needs and of main particulars, but it does not include complete simulations or enhanced numerical verifications.

In the following contract design phase, three steps have been identified (see Fig. 6.1):

1. The first step is to *consolidate an MPOV baseline design.* This baseline design is not optimized here, but it *shall be a feasible design point* with robust verification methods.
2. From this enhanced baseline design point, the second step can be implemented by using the HOLISHIP CAESES® platform. At this stage, simulations and associated s/w tools that are required to verify the main design performance can be connected to the CAESES® platform and a first hull definition modelled in 3D can be generated in fully parametrized. This new phase will enable the designer to perform *global sensitivity studies* and eventually local optimization runs to select one or more improved design points (Pareto front favoured designs) within the solution space explored.
3. In the following, the final step can be performed, by opening *a "negotiation phase" or "trade-off selection"*. The final design point can be selected with the feedback of the vessel stakeholders within the explored space by use of CAESES®. In that case the contract design phase ends and the final design point is elaborated in the light of operational scenarios defined in SAR management tool.

However, it might happen that despite the large range of solutions explored/discussed with the customer, some major modifications in the arrangement of requirements, not parametrized in CAESES®, will need to be taken into account (deep system or arrangement modifications for instance). In that case, the process shall be repeated from the concept phase on and arrangement sketches analysis involving the SAR management tool will be the starting point.

6.3.2 MPOV Baseline Definition

As described in the previous section, the first step of the contract design phase is to consolidate the MPOV performance assessment with dedicated simulations and verifications. This phase ends up with an enhanced reference design point, namely the baseline design for CAESES® model implementation.

Figures 6.7 and 6.8 hereafter give a 3D view of MPOV's external shape and the internals of the general arrangement:

In Fig. 6.8a, b, The MPOV's compartments are classified according to following four main functional categories:

- Mission spaces (green areas);
- Accommodation spaces (blue areas);
- Electrical and propulsion spaces (brown areas);
- Platform technical compartments (purple areas).

At this stage of the design, the baseline vessel integrates a DAD propulsion system which is quite heavy, non-flexible regarding the intended operational profile, but easier to install in a narrow vessel. With this configuration, the vessel can be 12,5m wide. For CODAD and CODLAD architecture, the vessel shall be minimum 13 m

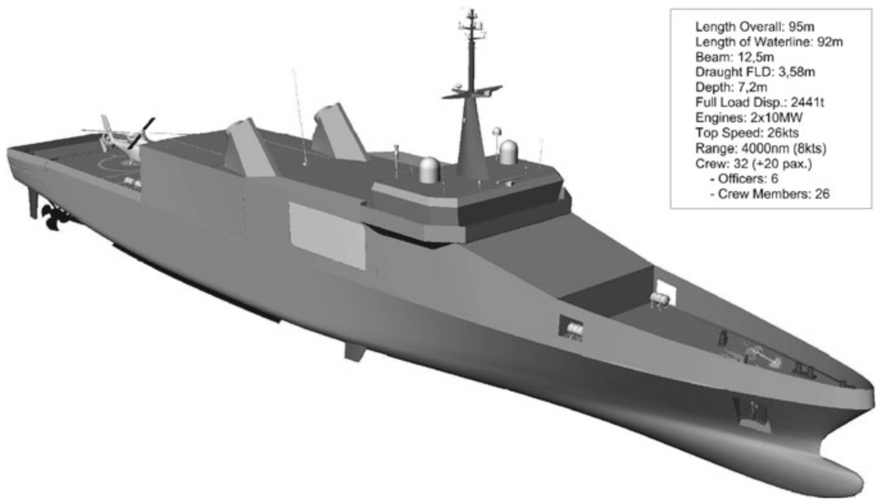

Fig. 6.7 3D external view of MPOV baseline design and main particulars

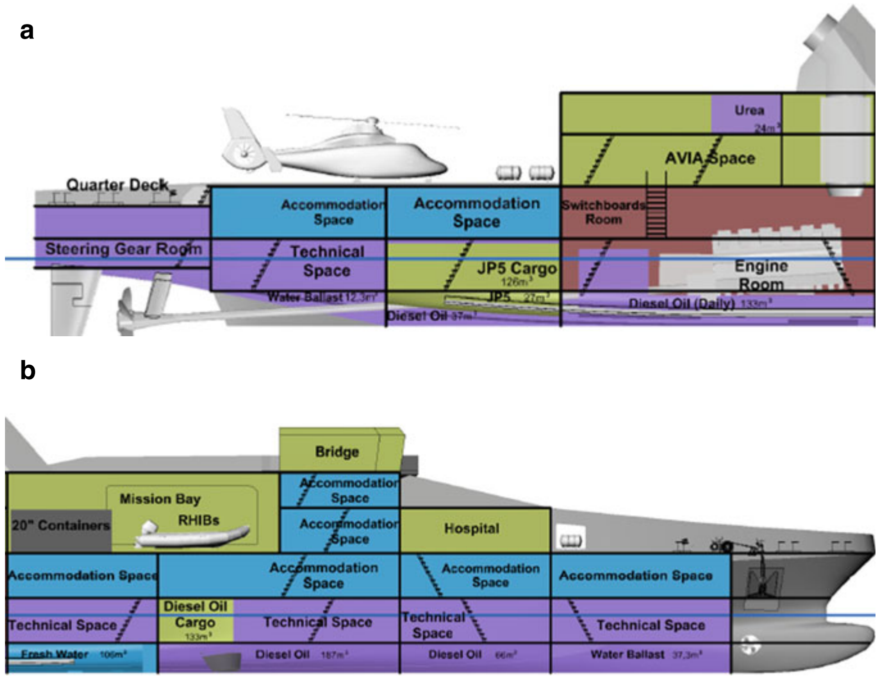

Fig. 6.8 **a** Internal arrangement of the MPOV vessel's aft part. **b** Internal arrangement of the MPOV vessel's fore part

wide, but the minimum depth remains unchanged. CODAD and CODLAD architectures were not taken into account at baseline design phase, however, and these options are simulated in sensitivity studies (see Sect. 6.4).

In this baseline design phase, a classical iterative design loop has been used to ensure that this baseline design is feasible. This first step brings to the designer a good understanding of critical performances. Moreover, it is also important to start the sensitivity study from a realistic point to avoid launching large calculations in a wide non-feasible space. The following activities are performed here for the MPOV baseline definition:

- General arrangement verification.
- First 3D hull model definition.
- Weight estimation check.
- Intact stability check including freeboard calculation and trim.
- Resistance assessment check.
- Propulsion architecture performance (power / speed)
- Seakeeping criteria check for comfort on-board and launching & recovery operations (Helicopter, RHIBs, and ROV).
- Structural cross section check
- Life Cycle cost first assessment.

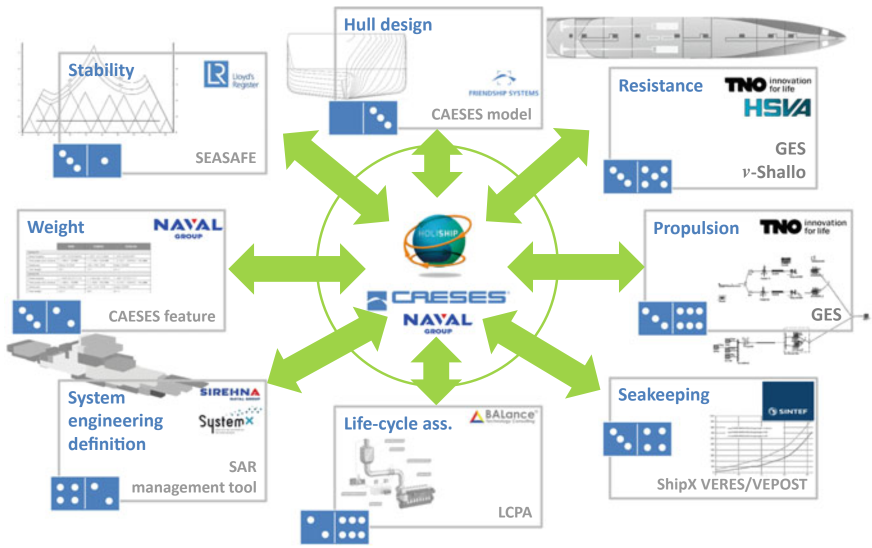

Fig. 6.9 MPOV CAESES® design synthesis model

- Rules analysis

6.3.3 *CAESES® Model Implementation*

Once the baseline design is defined, the designer can then implement the holistic design synthesis model of CAESES® in order to perform sensitivity and optimization studies. Figure 6.9 shows all simulation tools connected in the MPOV CAESES® platform model:

6.3.3.1 Fully Parametrized Hull Shape Implementation

The MPOV case study considers design variants generated by the following parametrized models:

- 3D hull global variations:
  - Lpp
  - Boa
  - Depth
  - Superstructure length and position
  - Cross section shape
  - Lackenby transformations i.e. shift of LCB or Cp value independent of displacement (Lackenby 1950).

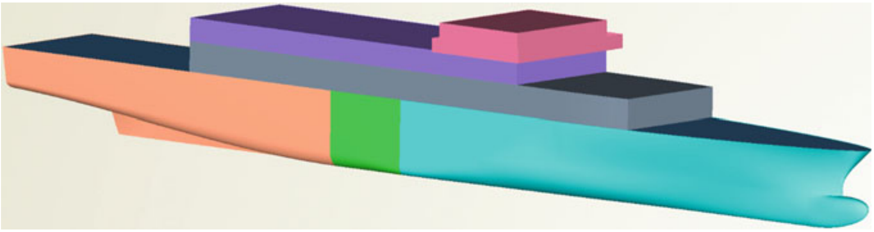

Fig. 6.10 MPOV 3D geometry parametric model

- 3D hull local variations:
  - bow shape including bulb,
  - Transom shape and bilge.
- System architecture: 6 propulsions variants are implemented with predefined models embedded in the GES software. Each predefined configuration is selected via a "configuration" number in CAESES® from 1 to 6. The installed power for each of the 6 configurations is around 20 MW. This value comes from the vessel baseline and the present sensitivity study does not imply variants on total installed power. However, it would have been possible to generate more predefined propulsive configurations from a database including variations on installed power.
- General arrangement: internal layout variants implemented in CAESES® for this application case are limited to volume constraints definition, induced by predefined propulsion system architectures and tank arrangement update with respect to main particulars.

The 3D hull parametrisation is based on points and curves definitions. Parameters are introduced throughout the process, which control the coordinates and angles of the points used to define the parametrised controlled curves. The latter are used to define the so-called meta-surfaces, which offer increased flexibility and detail in developing the hull surfaces (Harries et al. 2015). Figure 6.10 shows a screenshot of MPOV 3D model implemented in CAESES®.

6.3.3.2 Weight Estimation

A dedicated weight feature has been implemented in CAESES® to update the lightweight estimation in parametric form, taking into account standard empirical ratios and formulas. Involved ratios are independent, as much as possible, from displacement and draught, but they take into account, instead, values directly derived from length, beam, depth and hull form specific parameters. System configuration parameters are also taken into account here for weight estimation.

For each design variant, and each system configuration, the lightweight and eventually associated solid deadweight are updated within this feature.

Liquid deadweight and different loading conditions are defined with tank definition update in the employed stability tool SEASAFE.

6.3.3.3 Loading Condition Definition and Intact Stability Results

SEASAFE is a tool developed by Lloyds register in order to check intact and damage stability criteria. It has been connected with the CAESES® platform. Herein, only the intact stability features of SEASAFE are used.

With this connection in batch mode, the designer is able to update automatically the whole stability model and get back stability results for several loading conditions.

In particular, as per baseline design, loading conditions from scenarios 1 to 5 are implemented automatically from CAESES® to SEASAFE, while taking into account updated lightship values together with updated deadweight (liquid and solid).

The series of design steps implemented to run automatically in CAESES® are:

- Import baseline arrangement from ShipBuilder
- Cut all tanks with updated hull shape
- Modify the tank and hull definition in stripes definition as per SEASAFE format
- Update all inputs files for SEASAFE run in batch mode.
- Run SEASAFE intact stability calculations
- Get back results from SEASAFE outputs files

These steps are illustrated in Fig. 6.11.

For each design variant, intact criteria are checked here and the maximum allowed KG is compared to the loading conditions' KG. Output files automatically generated from SEASAFE comply with templates that CAESES® is able to read. Output values (displacement, hydrostatics, centre of gravity/buoyancy, free surface effects …) can be all reused in other simulations (propulsion, seakeeping, etc. …).

6.3.3.4 Seakeeping Criteria Check

In order to perform MPOV seakeeping analysis, some tools from SINTEF Ocean's hydrodynamic workbench ShipX were used. ShipX consists of many plug-ins, each one designed for a specific task. VERES is a plug-in in ShipX, which is based on potential, 2D strip seakeeping theory (Gerritsma and Beukelman 1972). It calculates ship motions and global loads, including short term statistics, long term statistics and operability. Moreover, in the post-processor of the code called VEPOST, short-term and long-term statistics and operability limiting boundaries and operability percentage can be calculated for various relevant limiting motion criteria.

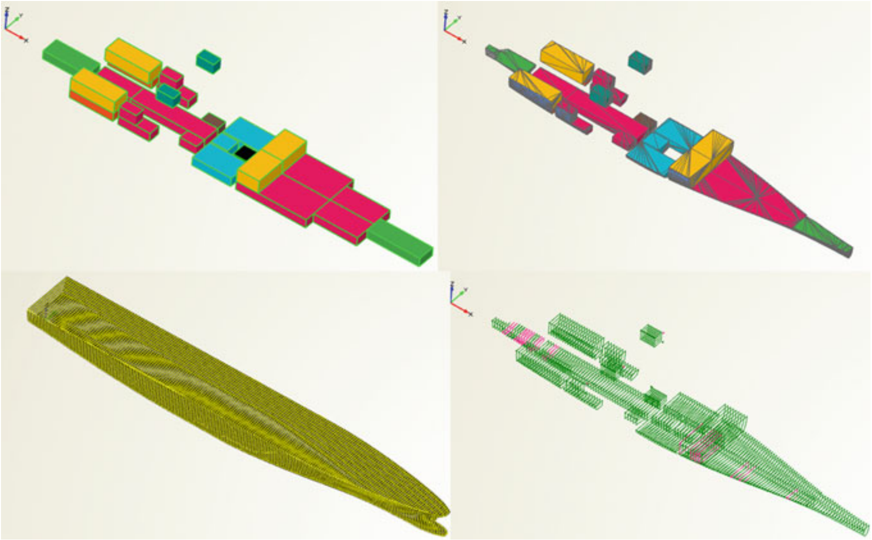

Fig. 6.11 SEASAFE tank and hull model generation in CAESES®

In the frame of the present application case, two connections have been implemented between CAESES® and ShipX VERES by SINTEF and Friendship Systems:

- One connection to VERES to estimate the vessel motions and RAOs.
- One connection to VEPOST (VERES postprocessor) to determine the compliance with specific operational criteria on specific predefined points on the ship.

Figure 6.12 shows typical outputs generated in batch mode by VEPOST and saved in CAESES®. In Fig. 6.12, all 18 criteria are checked for sea state 5, for 7 given ship speeds (from 0 to 26knots) and for all wave headings (0° to 180° each 45°). Two connectors are made in CAESES® to check criteria at sea state 4 and at sea state 5 (both including VEPOST and VERES).

In the end, the designer can check a percentage of operability over 90% at sea state 4 (among all criteria, all heading and all speeds) and an operability percentage over 80% for sea state 5.

6.3.3.5 Resistance & Powering Calculation

The purpose of the computer program GES developed by TNO is to facilitate, during the early-design stage of a naval vessel, comparisons of different systems for propulsion and electricity generation, concerning the values of important items such as:

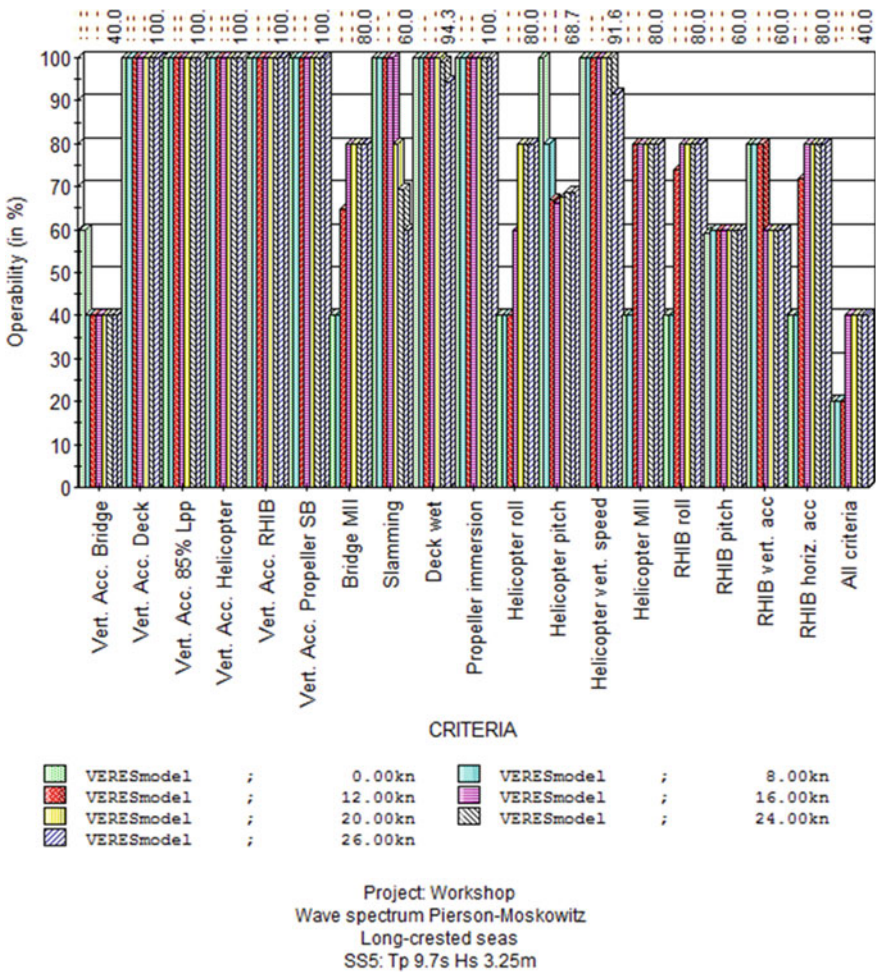

Fig. 6.12 Percentage of operability of one vessel variant by use of VERES with varying speed and wave heading (18 criteria) at SeaState 5

- Energy consumption and efficiency of the ship as a whole;
- Pollution through engine emissions;
- Dimensions of the installations (in view of required volume);
- Weight of installations.

The resistance calculation can be either obtained directly in GES with some statistical/empirical calculation method (Fung 1991) or imported from a dedicated software (e.g. the 3D panel code ν-Shallo of HSVA). The resistance calculation method and all inputs can be selected, generated and monitored via CAESES® platform.

The Fig. 6.13 shows the resistance and propulsion selection model in GES:

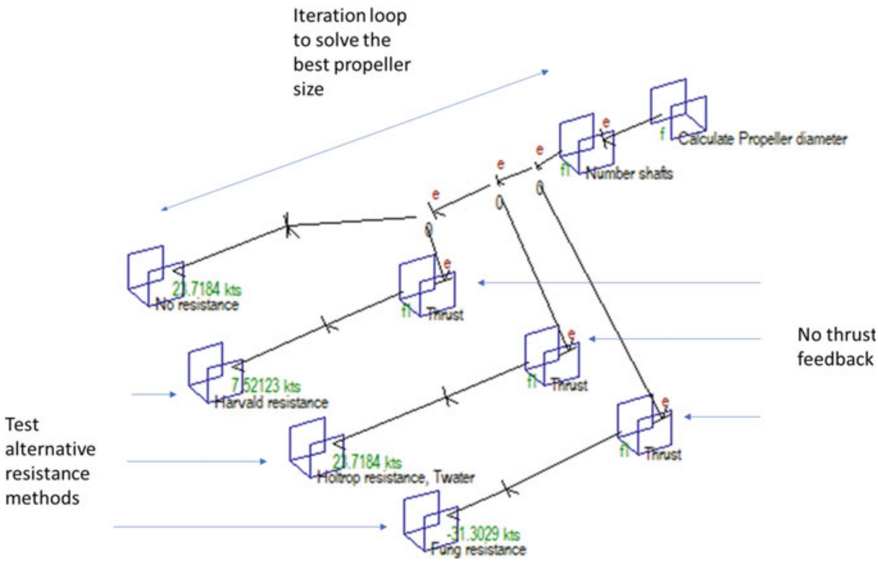

Fig. 6.13 Propeller selection model in GES depending on resistance calculation method

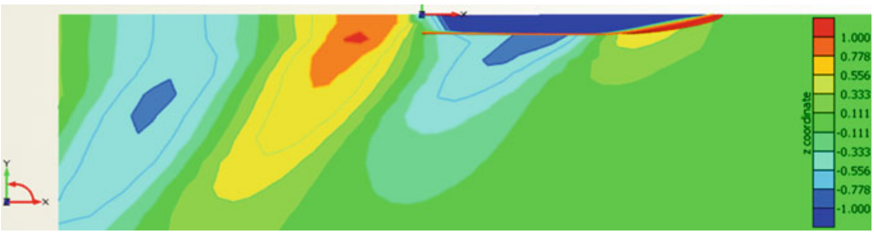

Fig. 6.14 Wave elevation results from ν-Shallo of HSVA for resistance calculation at 26knots

An external resistance calculation method from CAESES® can be also taken into account for the propeller selection in GES. For instance, ν-Shallo is a 3D panel code developed of HSVA, which is connected to CAESES. This tool is available for MPOV resistance calculation (see Fig. 6.14).

6.3.3.6 Propulsion Performance Assessment

Six alternative propulsion configurations are implemented in GES, two for each of three machinery architectures (DAD, CODAD and CODLAD). There is an option to select also different architectures from a Microsoft Access database, but this option has not been fully explored herein.

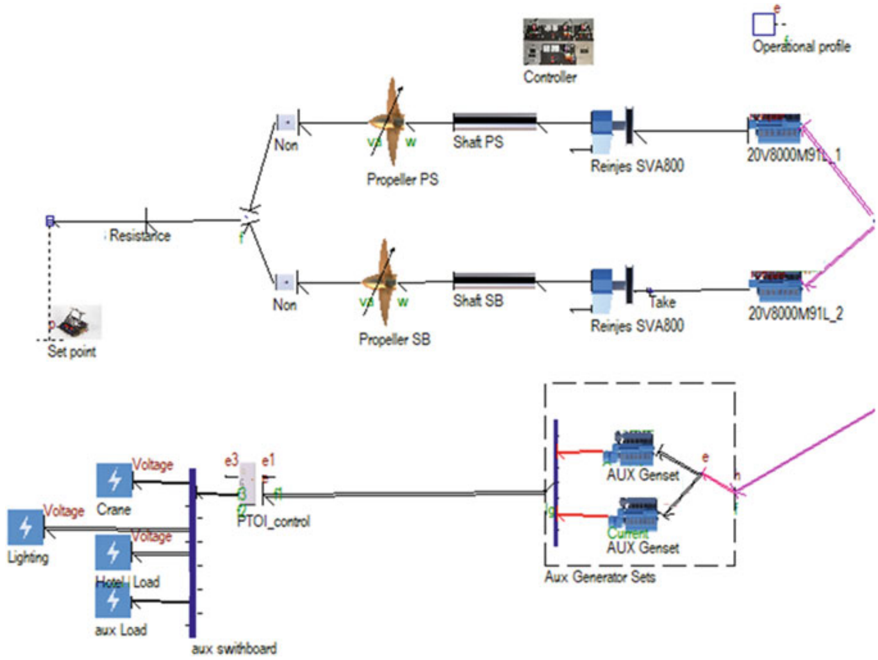

Fig. 6.15 DAD model for the machinery/propulsion of MPOV in GES

In the CAESES® model, once the resistance calculation method has been selected and ran, it is possible to select one of these 6 pre-defined machinery/propulsion configurations in order to assess the fuel consumption and few other KPIs. Figure 6.15 gives one example of a DAD propulsion model implemented in GES (Fig. 6.15).

The typical output values are then available from GES:

- Gas emissions: NOx, SOx, EEDI (Deltamarine 2011)
- Fuel consumption over a full operational profile (for 20 days missions as per operational scenario)
- Weight and volume of propulsion system
- Propeller definition
- Maximum speed

6.3.3.7 LCPA Model Connected to CAESES®

The MPOV vessel in not a commercial vessel thus, only OPEX, CAPEX and life cycle cost are herein taken into account.

Operating Expenditure (OPEX): The operating expenses result from the running costs a ship owner has carried in the frame of its business. Main elements of OPEX for a ship are (Stopford 2004):

- Operating cost (i.e. crew wages, management…)
- Voyage cost (i.e. fuel, port duties and fees…)
- Cargo handling cost
- Insurance cost
- Maintenance and Repair cost

Capital Expenditure (CAPEX): Capital expenditures are the funds that a ship owner has to invest to purchase a vessel from a shipyard to generate a potential profit. CAPEX are herein considered from a ship owner's perspective. However, it is easier to estimate the building cost from a shipyard-perspective with a parametric or a bottom-up estimation. The price for the ship-owner will generally differ from the actual building cost and depends on the present market-trend, when the contract is placed, which is in a certain way uncorrelated to the production cost (building cost) (Papanikolaou 2014; Maggionaclada et al. 2019).

For this reason, a coefficient 'r' is introduced in CAPEX calculations to consider this factor, which can be modified to market data and uncertainty.

CAPEX ship owner (€) = BLD Cost * r.

Building cost (BLD): It is the cost sustained by the shipyard to build the vessel. Effective cost estimation can be especially difficult in the early phases of a project, where only limited information regarding the construction cost is available. The shipyard has a very limited time to come up with a bid/tender to respond to a request for tender. In most cases, new building contracts are signed before the detailed design is completed. This is the reason why the shipyard experience in this kind of estimations is of critical importance (Maggionaclada et al. 2019).

For each main group of the lightweight (steel structure, machinery, electrical equipment, insulation, outfitting…) the associated building cost (BLD) has been implemented in CAESES®. For the structural cost:

BLD = Weight * (Cost per tons + hours per tons * cost per hours).

For the cost of large electrical equipment, of machinery and propulsion units, estimations are based on ratios taking into account kW power instead of vessel's weight (Papanikolaou 2014).

6.3.4 Holistic Sensitivity Study Results

In the frame of the MPOV application case, one variant of the design space exploration is detailed, elaborating how to identify a better design than the initial baseline design. The employed *design engine* performs a global sensitivity study on main hull dimension (L, B, D) and propulsion system configuration. For the purpose of this first sensitivity study on main dimensions, a statistical method (Fung 1991) is being used to calculate the resistance from GES as per enhanced reference design.

In the frame of this global sensitivity study, it has been chosen to generate 20 variants of length and beam for each of the 6 machinery/propulsion configurations (DAD, CODAD, CODLAD). The design engine generates here 120 design variants in total.

Objectives defined here are:

- OPEX,
- CAPEX,
- Life cycle cost over 10 years and over the whole vessel's life (30 years here)
- EEDI.

Constraints checked for each design variant are the following:

- Maximum speed > 26 knots.
- All intact stability criteria satisfied for 4 loading conditions.
- Percentage of operability regarding seakeeping criteria > 90% at SS4.
- Percentage of operability regarding seakeeping criteria > 80% at SS5.
- Breadth shall be above 13m for CODAD and CODLAD configuration.
- Maximum propeller diameter check depending on vessel minimum draft and beam.
- Trim check for each loading condition.
- Autonomy for 20 days mission satisfied.
- Numerical check for relevant 3D model generation.

First, regarding the 120 generated designs, Fig. 6.16 hereafter gives the distribution of design solutions' status.

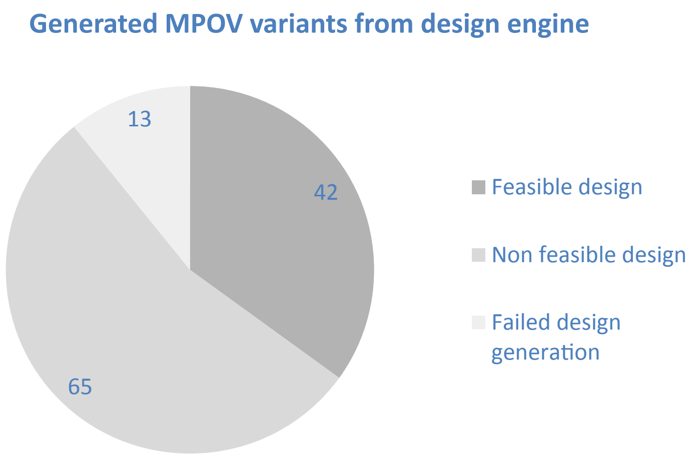

Fig. 6.16 Distribution of generated MPOV feasible and infeasible designs

Once the sensitivity study has been launched, CAESES® platform enables the naval architect to navigate in the design space with a whole range of visualisation solutions. Influence of length breadth and propulsion configuration can be discussed by enlightened visualisation features as shown on Fig. 6.17.

From the CAESES® results, the designer can select a new design point i.e. a new MPOV design. This selection shall be performed with a close understanding of operational scenarios, in good collaboration with the owner and end users.

The following Fig. 6.18 sorts all generated designs via a life cost evaluation (value 1 is the reference design here). If the customer wants to get the best life cycle cost (CO_LC_evo, i.e. LCC on 30 years) respecting all design constraints, the highlighted design (93) is the best trade-off.

If the customer prefers a low EEDI value beyond present rules' values, then another design may be selected. For instance, this will be design 17 (not in underneath screenshot).

Reading all operational scenarios, it appears that the maximum value of 26 knots is required only for pollution fighting. At this point, the customer may decide that this maximum speed critical value could be slightly decreased to get a better life cycle cost over 30 years. Then, design 51 might be selected.

The designer can then closer investigate that design 93 is indeed the best one. The naval architect and design team experts will access all results from individual simulations to check that all results are consistent.

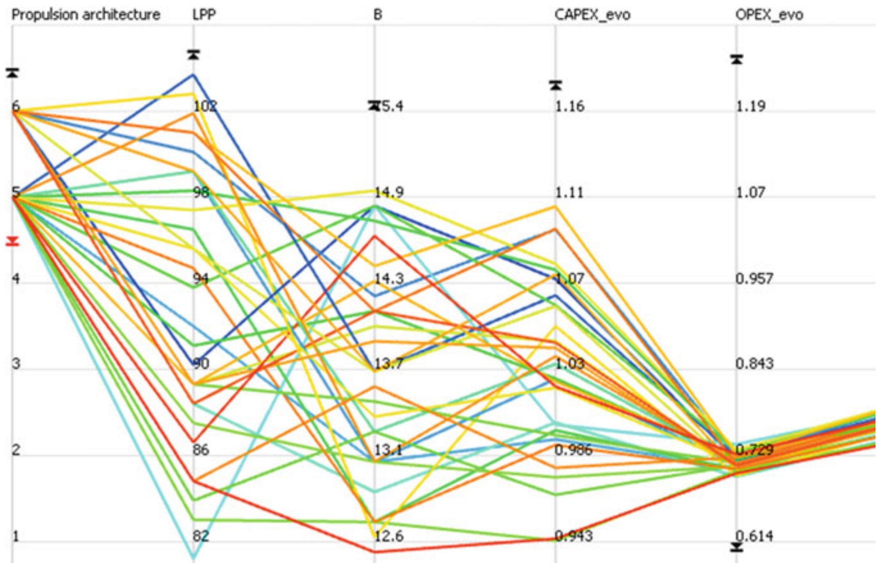

Fig. 6.17 Relationship between CODLAD feasible MPOV design parameters

	CO_10y_evo	CO_LC_evo	CAPEX_evo	OPEX_evo	EEDI_evo	Autonomy20days	Max_speed01
Dakota_09_des0007	0.80505036	0.7514758	0.94418851	0.70495248	1.1140239	0.65469876	26.1558
Dakota_09_des0048	0.80653678	0.75388759	0.94326852	0.70815457	1.1637251	0.66665758	25.59788
Dakota_09_des0081	0.82656256	0.75902192	1.0020105	0.70053316	1.0237211	0.60665933	26.25744
Dakota_09_des0051	0.82024404	0.76409744	0.96606683	0.71536084	1.1460876	0.64796112	25.375944
Dakota_09_des0046	0.82304323	0.76462094	0.97478263	0.71393525	1.0591753	0.62612182	25.92744
Dakota_09_des0015	0.8276914	0.76487311	0.99086019	0.71042298	0.94696813	0.58746794	27.334208
Dakota_09_des0064	0.83022206	0.76556313	0.99817629	0.70953629	0.92456574	0.57510238	27.83
Dakota_09_des0093	0.8298399	0.76677315	0.9936543	0.71210862	0.99540239	0.59295799	26.607416
Dakota_09_des0029	0.84695451	0.76877821	1.0500528	0.70117389	0.85413944	0.53157941	28.631592
Dakota_09_des0049	0.83436123	0.77222271	0.99576115	0.7183483	1.0337371	0.60584092	25.951728
Dakota_09_des0016	0.83199418	0.77519911	0.97950071	0.72589765	1.1892988	0.64693616	25.536456
Dakota_09_des0018	0.84902088	0.77581099	1.0392052	0.71245326	1.0184661	0.58326974	25.619968
Dakota_09_des0095	0.84474315	0.7758159	1.0237928	0.71612533	0.91067729	0.5550669	27.676616
Dakota_09_des0031	0.84428948	0.77688315	1.0193845	0.71849399	0.94924701	0.56911017	26.874408
Dakota_09_des0035	0.85634575	0.77793002	1.0600646	0.71011279	0.93086056	0.54899385	26.688904

Fig. 6.18 Design variants sorted with lower life cycle cost over 30 years

6.4 Conclusions

6.4.1 Concept Design Phase Achievements Including SAR Management Tool Experience

With reference to the *concept design phase*, the gained experience and the obtained benefits from the use of the SAR management tool are discussed. This tool was adapted to iterative exploration of design solutions with significant modifications. The SAR management tool includes features and techniques inspired from contemporary software developments, such as, for instance, *scenario oriented design, configuration management platform* (PMT and GITLAB use) and *continuous integration principles* (CairnBuilder)… Benefits of the use of the SAR design method were not quantified in terms of cost. However, services offered by SAR management tool are supporting the design team to handle design complexity and organizing activities with flexibility. In the end, the ultimate objective is to reduce design technical risks, to explore the huge design solution space and to speed up first exploratory designs. The numerous services of the SAR management tool have been explored and analysed, even if the benefits cannot be quantified at present early stage of usage.

6.4.2 Contract Design Phase Achievements Including CAESES® Platform Tool Experience

In the *contract design phase*, a holistic synchronous exploration is performed by use of the HOLISHIP CAESES® platform. The first step here was to consolidate the outcome of the concept design phase, by selecting one enhanced baseline design. This first reference design definition was performed with a classical iterative design loop (Sect. 6.3.2). A limited number of iterations has been performed here as the first objective was to supply reference data for the larger design exploration phase using CAESES®. From this point, a sensitivity study is conducted to reach another improved design point with a lower life cycle cost. The used CAESES® platform increases the contract design phase's efficiency with the high number of design variants taken into account within short time (see Sects. 6.3.3 and 6.3.4).

After the CAESES® sensitivity study, the adopted holistic model provides the naval architect with the opportunity to explore new system configurations and other main particulars. In the end, an improved design is discussed and selected. This new design point should request a critical review from a team of experts to ensure its reliability. However, the general methodology used can bring substantial benefits.

For this specific kind of vessel with many possible general arrangement configurations and system architectures, and a very strong dependency on the owner's needs, the space exploration is necessary during the concept design phase before building a fully parameterised model within CAESES®. This concept phase follows a classical iterative design method here, but it can be herein supported with the SAR management tool and by new s/w tool services inspired from recently introduced software design methodologies for instance.

For simpler types of ships, with standard internal layout or system configurations, the simulation driven approach used in CAESES® can lead to very quick contractual design optimisation (see other application cases, e.g. RoPAX design application case, chapter 11). Even for more complex vessels such as MPOV, the shipyard may consider developing a database of parametric models for all types of ships of potential interest and the associate different product lines. Compared to the classical design spiral method, this simulation option offers a clear and quick overview of the design space around the baseline design or reference design. The optimum point can be selected as basis for later design stages (i.e. detailed design phases).

Methods and tools discussed herein can be then a substantial advantage for a shipyard to offer competitive vessel designs within short lead time.

Acknowledgements All activities described in this chapter have been realized in close collaboration with several European partners including Balance, Epsilon Malta Ltd, FRIENDSHIP SYSTEMS, HSVA, IRT System X, Lloyd's Register, Naval Group, SINTEF, Sirehna, TNO and University of Strathclyde.

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Chapter 7
Virtual Vessel Framework for Merchant Ship Manoeuvring Operation

Patrick Hooijmans, Martin Th. van Hees, and Freek Verkerk

Abstract There is a need for prototyping in the shipping industry but the costs are too high. Numerical simulations can provide a solution for this. In order to use numerical simulations in prototyping, proper numerical tools for relevant components of various suppliers are needed, as well as a framework capable of coupling these tools. HOLISHIP proposes asolution by coupling the tools of various suppliers through the internet, where the tools remain on the server of the owning company, protecting the Intellectual Property Rights (I.P.R.), but providing limited, controlled access to the framework.In this chapter, after abrief introduction on the numerical models in Sect. 7.1, the next Sect. 7.2 describes the need for coupled simulations, what is required from atechnical point of view to achieve that.In Sect. 7.3 the use of simulations in concept design is elaborated, while in Sect. 7.4 the use of simulations in design verification is discussed. Section 7.5 provides insight into the available models, frameworks to perform coupled simulations.Some application , acase study are discussed in Sect. 7.6. Finally, Sect. 7.7 demonstrates the framework through an example application.The conclusions, way ahead are presented in Sect. 7.8.

Keywords Numerical Models · Virtual Vessel Framework · Interoperability · Prototype · High Fidelity Simulations · Low Fidelity Simulations · Multi Fidelity Simulations · Medium Fidelity Simulations · Design Verification

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A. Papanikolaou (ed.), *A Holistic Approach to Ship Design*,
https://doi.org/10.1007/978-3-030-71091-0_7

Abbreviations

API	Application Programming Interface
CEM	Concept Exploration Model
CFD	Computational Fluid Dynamics
CPACS	Common Parametric Aircraft Configuration Schema
CVM	Concept Variation Model
DLR	German Aerospace Center
FEM	Finite Element Method
GES	General Energy Systems
IPR	Intellectual Property Rights
RCE	Remote Component Environment
STEP	Standard for The Exchange of Product
VVF	Virtual Vessel Framework
XMF	EXtensible Modeling Framework
XML	EXtensible Markup Language
XSD	XML Schema Definition
UID	Unique IDentifier

7.1 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. Following these developments, the HOLISHIP project developed a Virtual Vessel Framework (VVF), called HOLISPEC/RCE, noting that RCE if a product development of DLR representing the German aviation industy.

The nature of ship design is different from aircraft design. Lead times are short, the possibility for innovations are 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 location 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, for e.g. hull lines optimisation, workability analysis, CFD calculations, etc. 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 mostly built in small series of only a couple of ships of the same design, compared 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 maritime 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 focused 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 simulation 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 an output; however, expertise is needed to judge the output. The VVF is therefore not only a framework connecting tools, but also a framework integrating 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 is 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 with a bridge simulator, the feel of the manoeuvring configuration can be tested apart from only the numerical evaluations.

In this chapter, Sect. 7.2 describes the need for coupled simulations and what is needed from a technical point of view to achieve that. In Sect. 7.3 the use of simulations in concept design is elaborated, while in Sect. 7.4 the use of simulations in design verification is discussed. Section 7.5 provides insight into the available models and frameworks to perform coupled simulations. Finally, Sect. 7.6 provides example applications.

7.2 Why Do We Need Coupled Simulations?

Ship design follows an iterative process of requirement definition, concept development, design verification and operational optimization and adaptation. 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, 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 maybe 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 console 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 enabling experts to be part of the simulation steps adding required expertise when necessary.

Last but not least, 3D modelling and spatial arrangement becomes of increasing importance with increasing fidelity and maturing design. A framework to incorporate all this 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:

1. To use and re-use existing tools and data from different sources
2. To arrange analysis, simulation and design into streamlined processes
3. To create processes that provide guidance and ease-of-use for complete chains of pre-processing, simulation and post-processing
4. 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. 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 (Fig. 7.1).

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

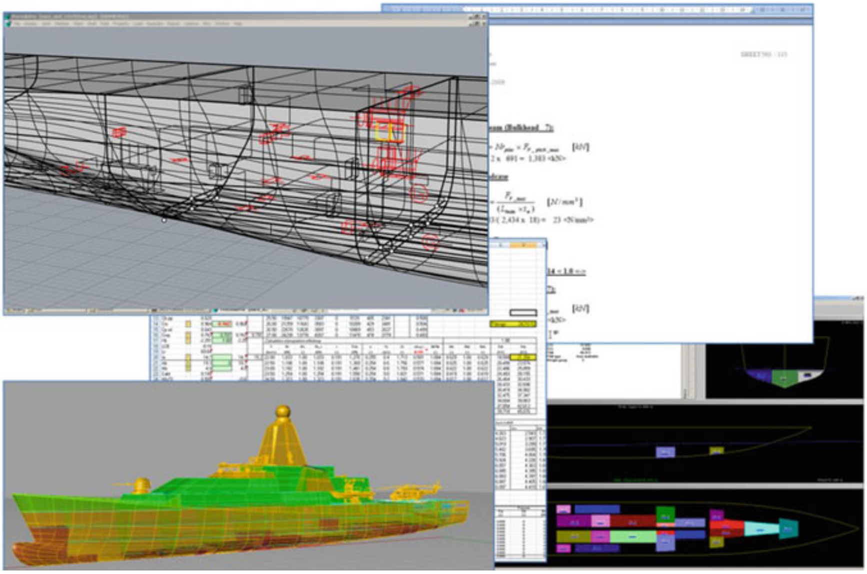

Fig. 7.1 Tools used in the early design stage

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 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 Microsoft's 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 QUASTOR 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 standardization already present in these frameworks, single interfaces between each of these frameworks and the VVF are considered feasible.

7.3 Simulations in Concept Design

7.3.1 Prelude

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 the 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.

7.3.2 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 practise, these tools are able to export geometric information in different formats, which can be used as input for 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 e.g. CAD and simulation tools. In Sect. 7.5.1 this is discussed in more depth. A relatively simple 'HOLISPEC' information model is proposed, which is tested in the following demonstration case.

7.4 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 organization. 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 for e.g. strength analysis and the performance assessment of propulsion and energy systems. Section 7.3 gives an example of ship systems in ship design that are created and verified by GES simulation.

7.5 Available Tools and Frameworks

7.5.1 RCE and CPACS

Within HOLISHIP, it is proposed to use the Remote Components Environment platform (RCE) 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. 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 in the aviation industry, cf. https://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, illustrated in Fig. 7.2. 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

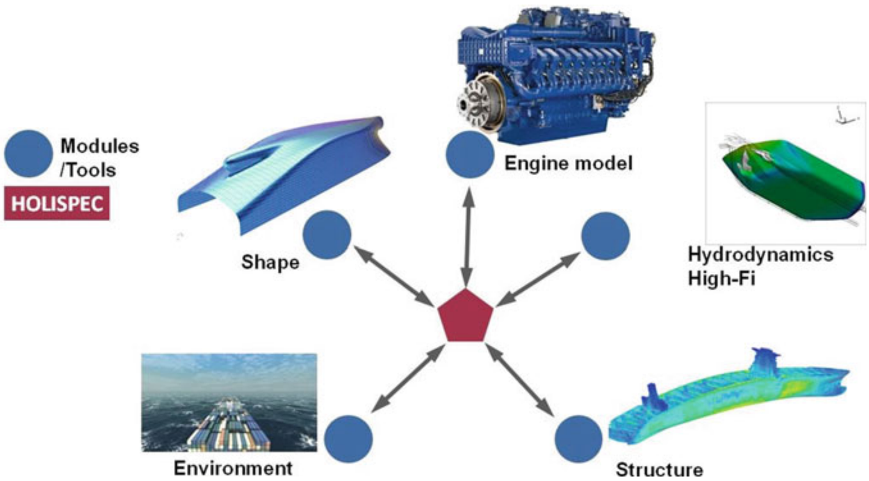

Fig. 7.2 Example of HOLISPEC/RCE use

- 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

Fig. 7.3 CPACS global structure

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 Fig. 7.3 the global structure of CPACS is presented.

7.5.2 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. Figure 7.4 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, the need is real. ISO 10,303 took 30 years to develop and is used in particular in the CAD community to exchange topological information in a neutral manner. The exchange of CAD data is a huge headache in the field, so ISO 10,303 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

```
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
```

Fig. 7.4 'Maritime CPACS' global structure proposal data". The STEP-file (ISO 10,303–21) 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). To name a few: compartment oriented, surface oriented, system oriented and function oriented, cost oriented, production and assembly oriented, etc. 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 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 e.g. inertia forces and moments in a crane foundation for which data has to be passed from hydrodynamics to structure. Another example are propeller forces and moments to calculate shaft loads and vibrations or as input moment and revolutions to a diesel engine model.

Analysis and simulation tools need varying sub sets 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 need information about components, maintenance, materials, cost factors, etc., so information partly originating from the design concept representation and partly from operational environment (the world). Hydrostatics and construction needs spatial information, switching between a surface-based and compartment-based views.

In Fig. 7.5 an information model is presented with the least possible number of types.

The blue rectangles represent '*Repository elements*' that can be declared once and used (referred to) many times. The orange rectangles represent '*Design elements*',

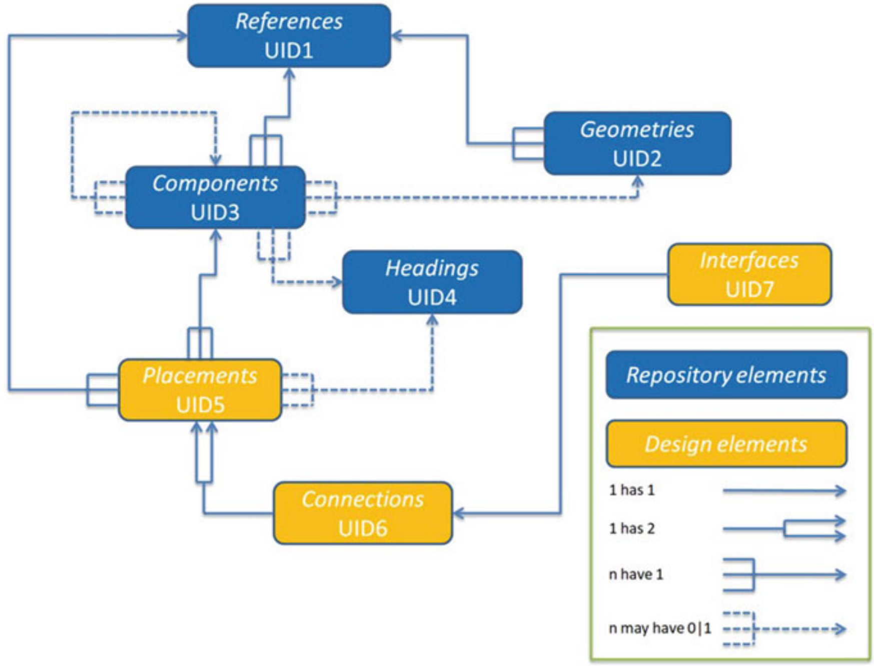

Fig. 7.5 HOLISPEC information model

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 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.

7.6 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.

7.6.1 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 multi-fidelity 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 has been created. For a selected ship two rudder configurations were designed. The hydrodynamic manoeuvring behaviour of both configurations were calculated using the HOLISPEC/RCE framework. By coupling these simulations to a bridge simulator, the human element is 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 zig-zag 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 were 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 not all components can be calculated in real time, use has been made of response surfaces. Figure 7.6 shows the simulation scheme for the HOLISHIP demonstration case.

A multi dimensional response surface of the manoeuvring coefficients was calculated for various speeds and rudder angles which are loaded in the bridge simulator.

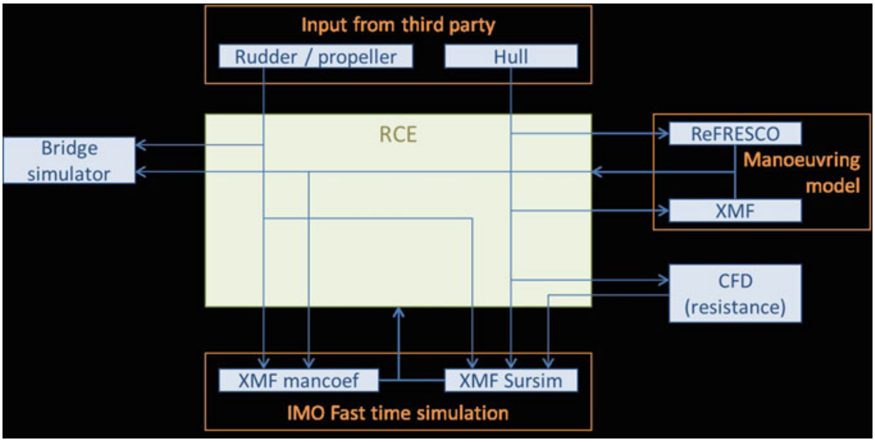

Fig. 7.6 Simulation flow for HOLISHIP demo

The speed—power relation is 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 are connected to the real time bridge simulator and the real time behaviour of the captain.

7.6.2 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. 7.5, 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 & simulation in TNO/GES.

GES (*G*eintegreerde *E*nergie *S*ystemen or General Energy Systems) 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, ULYSES, INOMANSHIP and POSEIDON.

Within HOLISHIP, data from the DAMEN Combi Freighter (Fig. 7.7) is used.

The internal arrangement is created in Rhino in the COSMOS workflow (*CO*mpositional *S*hip *MO*deling *S*cheme). COSMOS is based on a workflow which is

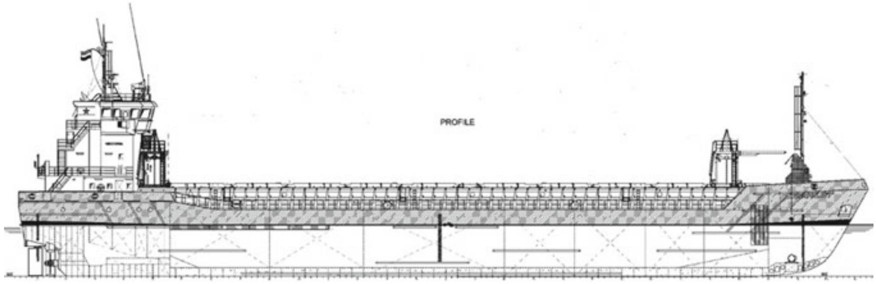

Fig. 7.7 DAMEN Combi Freighter 3850

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 2018) further details are provided. COSMOS provides a 3D design 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 modeling principles introduced in Sect. 7.5.2.

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 modeling of components by which working compositions are created. GES comprises an extensive library of system components and sub systems 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. 7.8, 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 behavior 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. 7.9. 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. 7.5.2.

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,

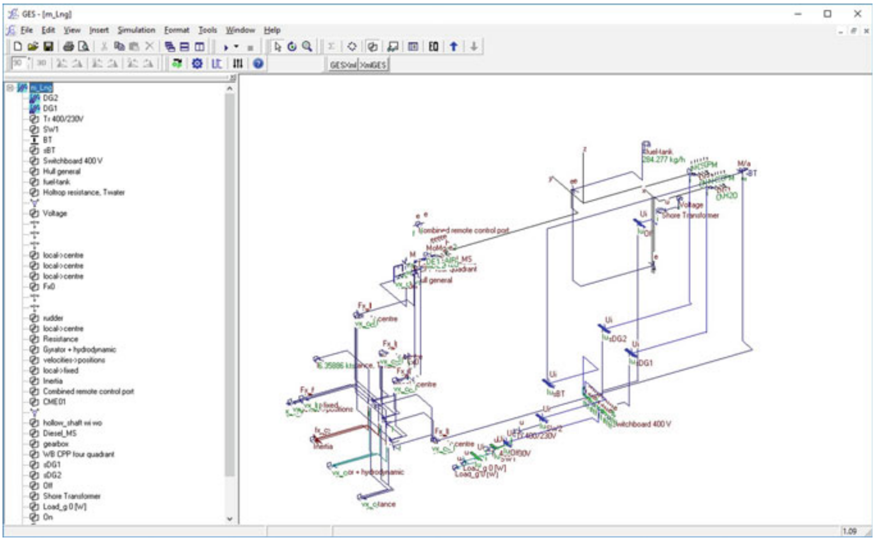

Fig. 7.8 Example GES model

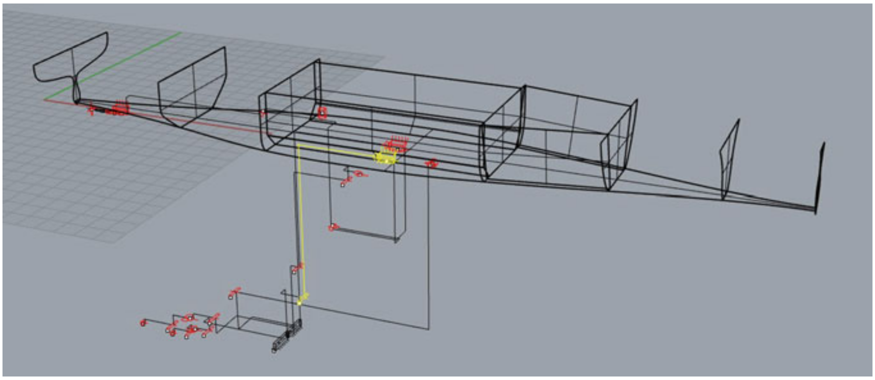

Fig. 7.9 GES model uploaded in COSMOS

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 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.

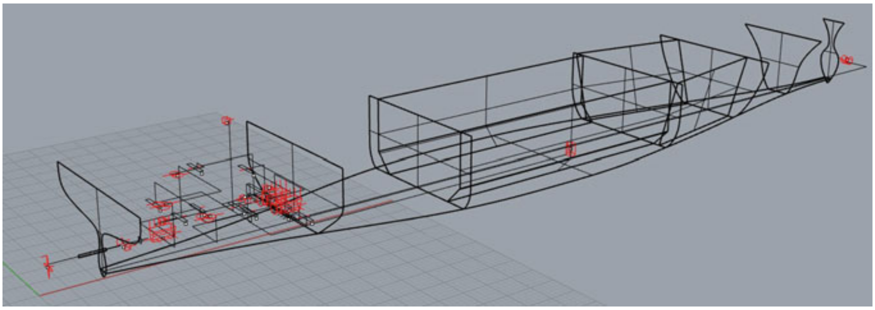

Fig. 7.10 Rearranged GES model uploaded in COSMOS

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 modeling 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 is 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. 7.9, 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 7.10 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 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 e.g. diesel and propulsor response which can be re-used in e.g. a bridge simulator to mimic an engine model. As each simulation model (sub system 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 modeling 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.

7.7 Virtual Vessel Framework: Demonstrator

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.

The AC demo merchant vessel is based on the Damen Combi Freighter 3850 series see also 86 (Table 7.1).

A half 3D model of the merchant vessel is shown in Fig. 7.11.

7.7.1 Diesel Engine Model

The dynamic Mean Value First Principle (MVFP) diesel model consists of several modules and is based on the 6-point Seiliger cycle. Firstly, the cylinder process is described. This principle is based on a 5 points Seiliger cycle, as described in (van Hees and van den Broek-de Bruijn 2018), but extended for a 6 points Seiliger cycle. An internal combustion model of Ges is connected to this process to correctly calculate the fuel consumption and the emissions of the diesel engine. The cooling system is not directly coupled to the diesel model and can run independently if the output of the cooling system is needed (Table 7.2).

Table 7.1 Main characteristics merchant vessel

Dimensions	Capacities	Propulsion system
Length O.A. 88,60 m	Hold capacities 5.250 m^3 (185.400 cuft)	Main Engine 1 × MAK, type 8 M 20 C, running on
Length B.P.P. 84,99 m	MDO/HFO 200 m^3	HFO fuel (IFO 380) or gasoil
Beam MLD. 12,66 m	Gas oil 28 m^3	Output 1.520 kW at 1000 rpm
Depth 7,00 m	Lub. oil Clean 6.7 + 1.9 m^3	Propeller 1 x CPP, 2.600 mm
Ballast draft 3,20 m	Dirty oil 4 m^3	Bow thruster FPP, 280 kW, electrically driven
Summerdraft 5.425 m	Sludge 4 m^3	
Deadweight 3.800 ton	Sewage 12 m^3	
Gross tonnage 2.545 ton	Potable water 28 m^3	
	Ballast water 1.375 m^3	
	Container cap. in hold 108 TEU	
	Container cap. ON DECK 68 TEU	
	Total number 176 TEU	

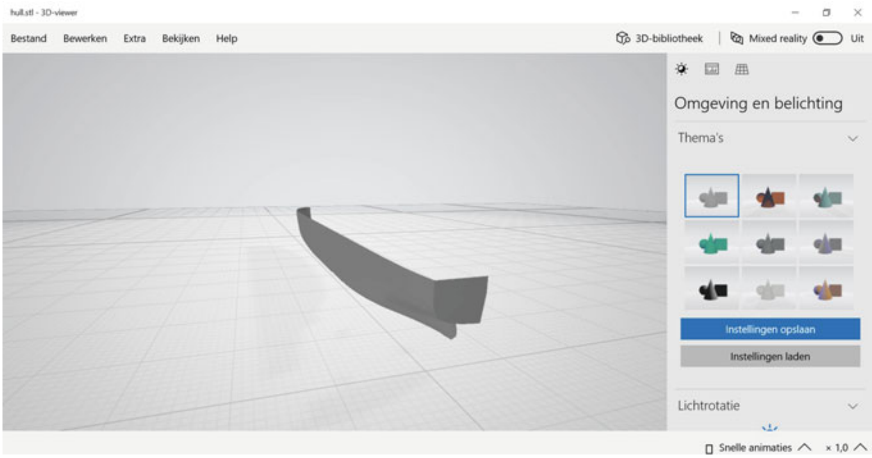

Fig. 7.11 Hull form model (half) of tested Merchant vessel

Mass moment of inertia for the engine is 50.7 kgm^2 and for the flywheel is 45 kgm2. The total inertia is 95.7 kgm2 and is incorporated into the dynamic diesel model.

Table 7.2 Main parameters diesel engine

Cylinder configuration	8 in-line
Bore	200 mm
Stroke	300 mm
Stroke/Bore-ratio	1.5
Swept volume	9.4 l/Cyc
Output cylinder	190 kW
BMEP	24.2 bar
Revolutions	1000 rpm
Output engine	1520 kW
Mean piston speed	10 m/s
Turbo charging single-pipe system	

7.7.2 Rudders

Two rudder designs are considered in the simulation: a high lift flap rudder and a full spade rudder see Figs. 7.12 and 7.13. In order to calculate the rudder, lift and drag force, as well as, the rudder torque as input for the ship manoeuvring simulation, and

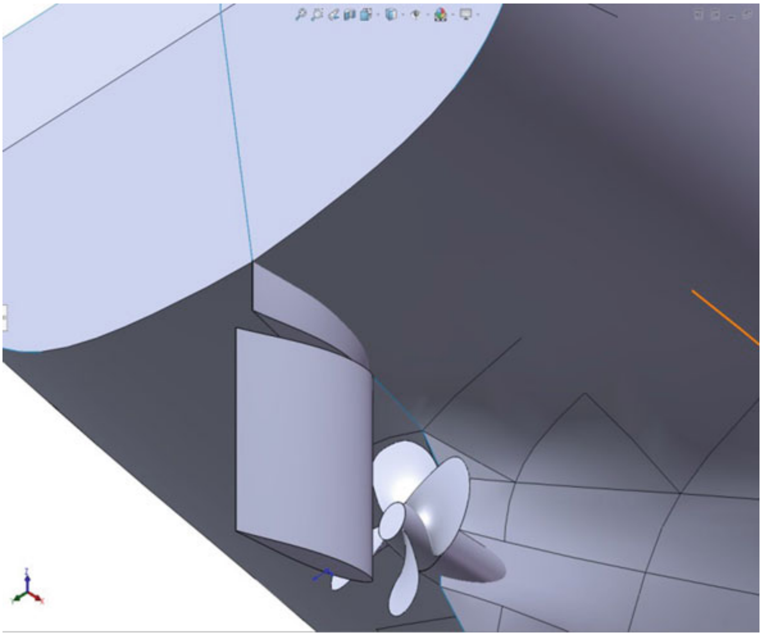

Fig. 7.12 Spade rudder

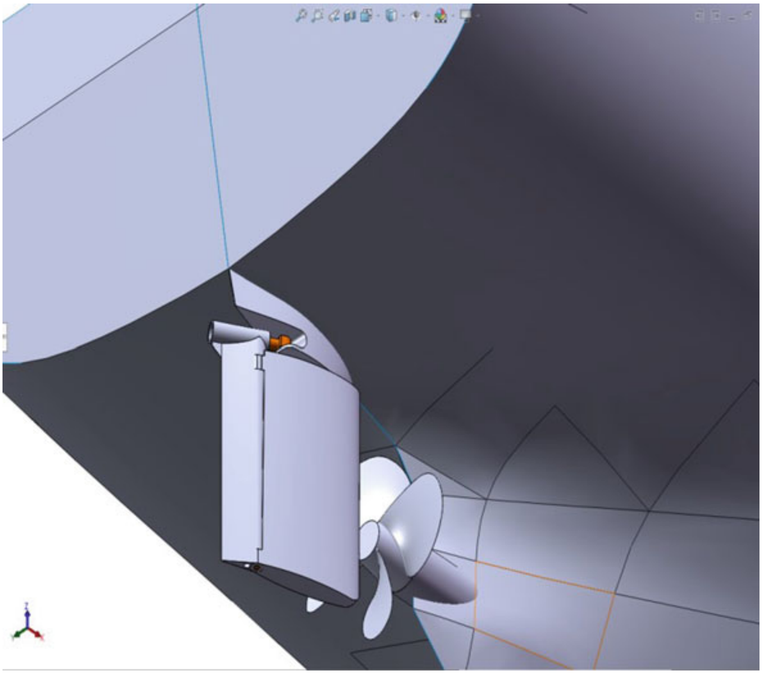

Fig. 7.13 Flap rudder

the dynamics of the steering gear, a parametric rudder force model was implemented. The model is based on a set of parameters derived from actual rudder geometry and the flow condition at the rudder position.

The parametric rudder force model, developed within the work package, is based on two sets of universal functions. These functions are assumed to be capable of describing the rudder force distribution over the rudder angle range from 0°–180° for a wide range of aspect ratios, profile shapes and Reynolds numbers. The first set of functions is used to describe the behaviour of the rudder lift, drag and torque in the linear range below the stall angle and the range around the stall angle and slightly beyond. The second set of functions is used to describe the behaviour in post stall or deep stall conditions. While the first set of functions is more sensitive to several parameters, the second set only depends on the aspect ratio and is assumed to be very robust towards changes of other parameters.

Data from wind tunnel tests carried out within the project, see Fig. 7.14, as well as from wind tunnel test data from the literature (CAESES 2020), see Fig. 7.15, gave a strong hint that the forces in the post stall regime of wing shaped bodies can be described by a set of simple trigonometric functions. The only parameters these functions depend on are the aspect ratio and the relative thickness ratio, which are responsible for the amplitude of the functions.

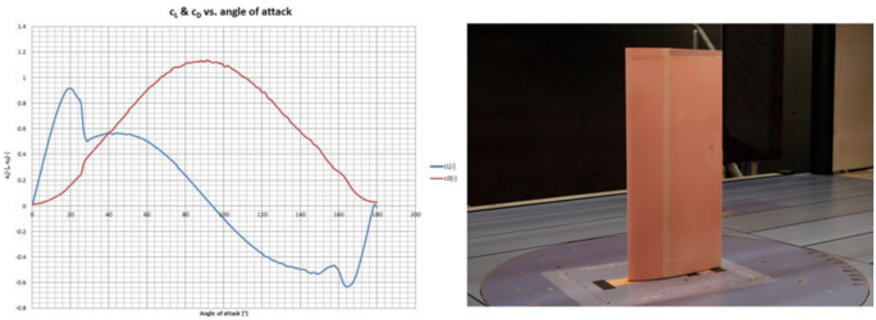

Fig. 7.14 Left: Lift & drag coefficients measured for a wing with aspect ratio two in the wind tunnel at Hamburg University of Technology, Right: Corresponding test model installed in the wind tunnel

7.7.3 Propeller Model

The remote components published on the cloud server are for now based on systematic Wageningen propeller series for open propellers and propellers in nozzles (G. Kuiper: The Wageningen propeller series):

- 1 (Fixed pitch open type propeller (B-Series))
- 2 (Fixed pitch propeller with 19A, 22 or 24 nozzle -> Kd 4–70)
- 3 (Fixed pitch propeller with type 37 nozzle -> Ka 4–70)
- 4 (Fixed pitch propeller with type 33 nozzle -> Kd 5–100)
- 5 (B-series in 4 quadrants)
- 6 (Ka 4–70 with nozzle 19A in 4 quadrants)
- 7 (Ka 4–70 with nozzle 37 in 4 quadrants)

The above series are available in the 'Vibrex' knowledge base from which two macros are published.

7.7.4 Ship Resistance

The resistance of a ship can be determined in several ways. A statistical approach is very quick but has low fidelity. A high fidelity solution is to run RANS computations. In this application case, use has been made of RANS computations to determine the ship resistance and hydrodynamic forces to derive a mathematical manoeuvring model.

In order to simplify the estimation of the hydrodynamic forces and moments acting on the hull by MARIN's RANS solver ReFreSCo, an automatic pipeline was developed. The process begins with two files; the first contains ship's general data (e.g. main particulars) and the second one defines the hull geometry. The output of

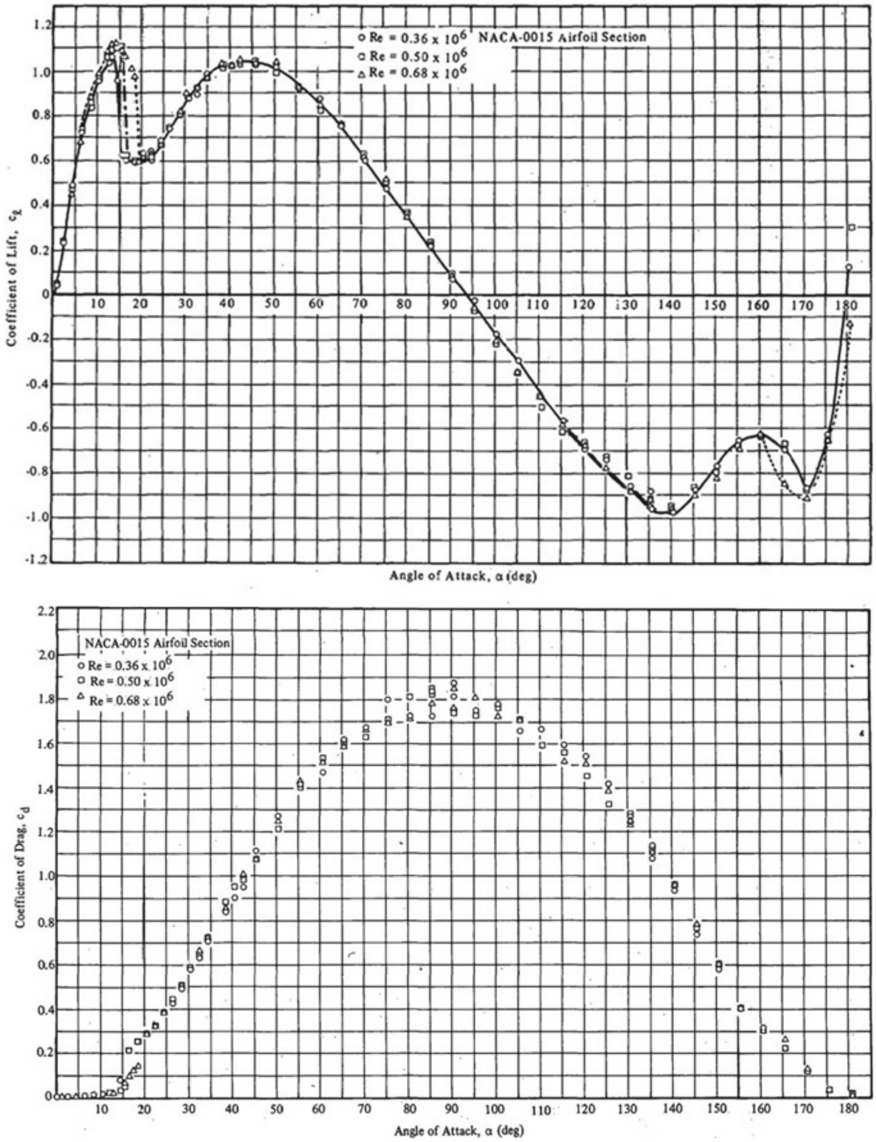

Fig. 7.15 WindLift (top) and drag (bottom) coefficients measured in a taken from reference (CAESES 2020)

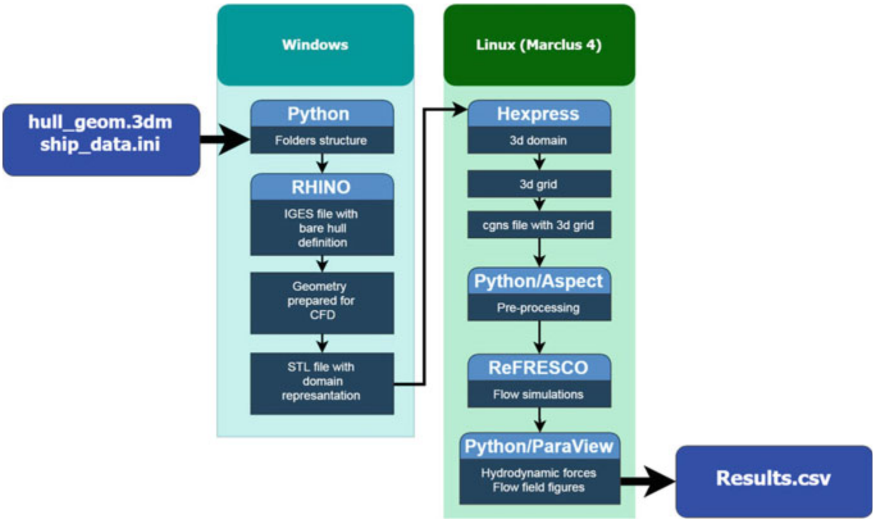

Fig. 7.16 Schematic view of the process of estimating hydrodynamic forces and moments

the process is CSV file ("coma separated values") with values of the hydrodynamic forces and moments acting on the hull in function of the drift angle and rotation rate. Additionally series of figures showing flow fields are generated.

The schematic view of the process is shown in Fig. 7.16.

Due to software limitations the process must be carried out in two operating systems. The first part of the pipeline, related with the geometry preparation, is carried out in Rhinoceros 5.0 which runs only under MS Windows. The numerical simulations (ReFRESCO) (including grid generation phase and post processing (ParaView)) must be done on the computational cluster, which is managed by Linux operating system.

7.7.5 VVF Model & Bridge Simulator

For the VVF-model in combination with the Bridge simulator a parametric approach was used in order to avoid delays in the interface over the internet. The Bridge simulator is completely real time in operation. In Fig. 7.17, the first approach for a VVF-model configuration is shown.

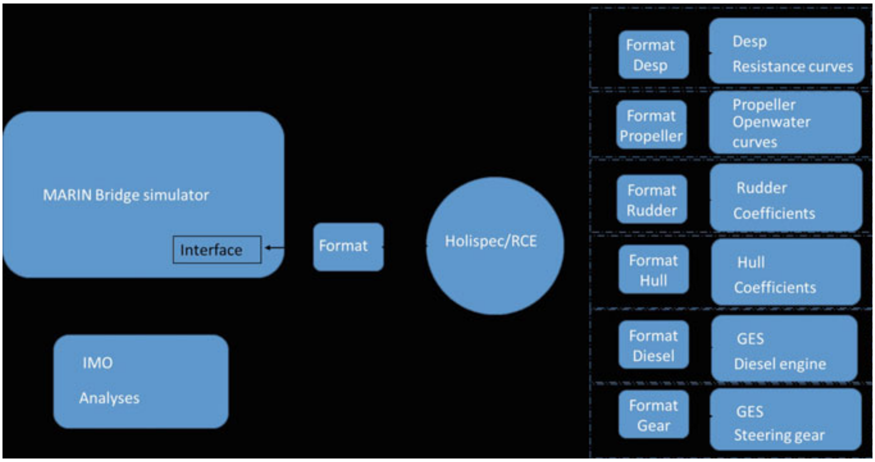

Fig. 7.17 Configuration parametric VFF model

7.7.6 Scenarios

Sixteen scenarios (see Table7.5) were developed to test eight different manoeuvres with a full spade rudder and a flap rudder. During one simulation day these sixteen scenarios were carried out. The background of the scenarios is to test and assess the rudder configurations in most of the normal manoeuvring situations (Table 7.3).

7.7.7 Results

The results of the simulations are presented in track and data plots. A track plot shows the position of the vessel every minute, see Fig. 7.18.

The data plot contains the information of each set of scenarios. The results are presented against the time (see Fig. 7.19).

- Speed through water (STW) [kn];
- Lateral speed [kn] (at centre);
- Rate of Turn [deg/minute];
- Rudder angle [degrees];
- Telegraph setting [%];
- Bow thruster force [%], if applied during the scenario.

In this way, the two configurations can be easily compared in a numerical way.

Table 7.3 Scenarios for real time simulations

Run nr	Rudder configuration	Manoeuvre
116	Full Spade Rudder	Unmooring
129	Flap Rudder	Unmooring
119	Full Spade Rudder	Turn on the spot
130	Flap Rudder	Turn on the spot
121	Full Spade Rudder	Turning circle
132	Flap Rudder	Turning circle
125	Full Spade Rudder	Sailing in cross wind 8 Bft
133	Flap Rudder	Sailing in cross wind 8 Bft
127	Full Spade Rudder	Testing course stability
134	Flap Rudder	Testing course stability
140	Full Spade Rudder	Steering with Thrust = 0
135	Flap Rudder	Steering with Thrust = 0
141	Full Spade Rudder	Controllability sailing astern
136	Flap Rudder	Controllability sailing astern
142	Full Spade Rudder	Turn into basin, moderate turning
143	Flap Rudder	Turn into basin, moderate turning

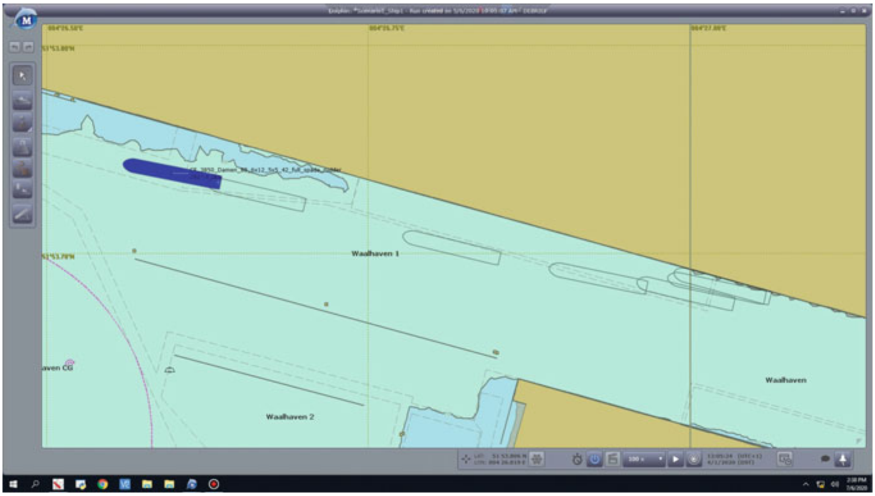

Fig. 7.18 Example of track plot

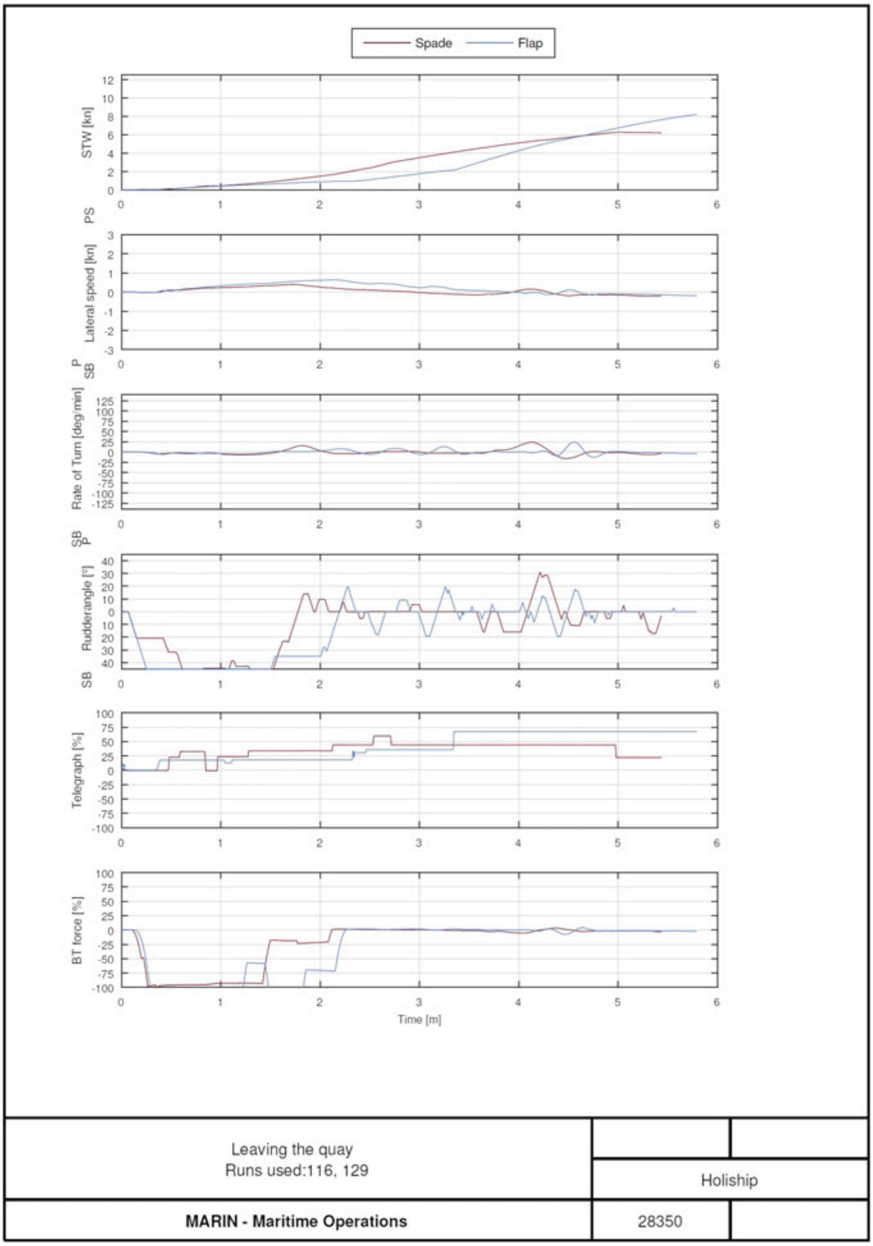

Fig. 7.19 Example of data plot

7.7.8 Results from the Demonstration

The Damen CF3850 merchant vessel is used as digital mock-up. Becasue a real-time approach in combination with the Bridge Simulator has too much time delay for a stable test circuit) a static approach is used. Tools were connected together on parametric base prior to the simulations.

During one simulation day sixteen runs were carried out. Eight different manoeuvres were tested with a full spade rudder and a flap rudder configuration. The results were assessed numerically as wel as by the captain conducting the tests. The following conclusions are drawn from the real-time manoeuvring simulations:

- In the applied simulator system (Dolphin Version 6.3.6) the different outputs of the tools and and sourses could be easily combined into a working simulation environment.
- The differences between the full spade rudder and a flap rudder configuration could be indicated quite well by the numerical analysis as well as by the captain conducting the tests.
- The vessel equipped with the full spade rudder performed unrealistically bad compared to the manoeuvring properties. Based on MARIN's database a better performance is expected for this type of merchant vessel. Especially the course unstable behaviour of the model with this rudder was remarkable. It is expected that the hull—propeller—rudder interaction, which was neglected, causes the poor manoeuvring performance.
- The results of the vessel equipped with the flap rudder configuration showed manoeuvring properties as could be expected from this type of merchant vessel. However, in reality the flap rudder would result in much better manoeuvring properties than the tested model.
- Although the difference between the two tested rudder configurations is shown quite well the absolute manoeuvring behaviour is not modelled correctly in absolute terms. This leads to the conclusion that combining the results of separate tools and sources, like a hull model from CFD and rudder data from third-party calculations, without a possibility for validating the results, may lead to unreliable behaviour of the integrated model.
- Care should be taken when combining tools from various suppliers, The integration of the tools requires expertise.

7.8 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.

A demonstrator case was developed, being a mock-up of a merchant vessel on a bridge simulator. In this demonstrator case, two different rudder designs were evaluated by an experienced captain. Besides standard IMO prescribed manoeuvres, also typical operations such as mooring and unmooring were simulated in typical weather conditions. The differences between the rudder configurations could be indicated quite well by both the numerical analysis and the captain conducting the tests.

Although the difference between the two tested rudder configurations is quite well shown, the absolute manoeuvring behaviour is not modelled satisfactorily in absolute terms. This leads to the conclusion that combining the results of separate tools and sources, like a hull model from a CFD code and rudder data from third-party software, without validating the intermediate results, may lead to unreliable perfomance of the integrated model. Care should be taken when combining tools from various suppliers, while the integration of the tools requires expertise. However, once validated and implemented by experts, the integrated setup of tools can be a very powerfull tool in the design process of ships.

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Chapter 8
Hydrodynamic Optimisation of a Containership and a Bulkcarrier for Life-Cycle Operation

George Zaraphonitis, Aggeliki Kytariolou, George Dafermos, Scott Gatchell, and Anders Östman

Abstract Efficient ship operation has always been a challenge of paramount importance to the ship owner, aiming to minimize operational expenditures and to maximize annual revenues. Nowadays, efficient ship operation is even more important due to the global warming phenomenon and the urgent need to reduce greenhouse gas emissions, next to the fuel cost. In the present chapter, we consider the possible retrofitting of two existing vessels, namely a bulk carrier and a container ship, on the basis of results of conducted hydrodynamic optimizations. For both vessels, bulbous bow and operational trim optimizations were carried out using advanced CFD tools. In addition, a weather routeing tool was developed and applied to the operation of both vessels, assuming realistic operational conditions and online weather data, while aiming at the reduction of fuel oil consumption.

Keywords Life-cycle cost · Optimization of operation · Trim optimization · Hullform optimization · Weather routeing · Ship routeing

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Abbreviations

CAESES®	Computer Aided Engineering System Empowering Simulation by FRIENDSHIP SYSTEMS AG, Germany
CFD	Computational Fluid Dynamics
ECAs	Emission Control Areas
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
FreSCo+	RANSE solver by HSVA and Technical University Hamburg
HSVA	Hamburg Ship Model Basin
IMO	International Maritime Organization
LOA	Length over all
LBP	Length between perpendiculars
MARPOL	International Convention for the Prevention of Pollution from Ships
MEPC	IMO's Marine Environment Protection Committee
NAPA	Naval Architecture Package for ship design by NAPA Oy, Finland
NEWDRIFT	3d potential flow, panel code for seakeeping analysis of ships and floating structures by NTUA
NTUA	National Technical University of Athens
RANSE	Reynolds-averaged Navier-Stokes equations
SEEMP	Ship Energy Efficiency Management Plan
SFOC	Specific Fuel Oil Consumption
ShipX	A comprehensive workbench by SINTEF Ocean, containing a variety of marine hydrodynamic analysis tools
SINTEF	SINTEF Ocean
TEU	Twenty Feet Equivalent Unit (container)

8.1 Introduction

Efficiency of ship operation is a challenge of comparable importance to ship design optimization, aiming to improve ship's performance, to reduce fuel cost and to ensure ship's safety and environmental protection, with the ship operating in a highly competitive market such as international shipping. While the latter was always a key priority for the ship operators, it can be argued that the importance of environmental protection was not realized for many years. A major step towards the protection against environmental pollution from shipping operation was the introduction of MARPOL (International Convention for the Prevention of Pollution from Ships) by IMO in 1973. Since then, many things have changed in maritime operations as the impact of climate change has been gradually recognized and is nowadays and universally acknowledged. Trying to respond to the increased societal concern, international or intergovernmental organizations, such as IMO or the European Union, national governments and regulators are setting into force specific regulations against pollution, setting hard constraints on polluting activities, or introducing incentives for greener operation and penalties to those not able or not interested to comply.

With global warming being the most important environmental concern, IMO issued a series of important regulations, aiming to reduce greenhouse gas emissions from ships. The introduced Energy Efficiency Design Index (EEDI) is applicable to all new ships and aims to reduce GHG emissions from shipping by design measures, i.e. by promoting the design and construction of more energy efficient ships. Ship Energy Efficiency Management Plan (SEEMP) on the other hand, which is mandatory both for new and existing ships "is an operational measure that establishes a mechanism to improve the energy efficiency of a ship in a cost-effective manner. The SEEMP also provides an approach for shipping companies to manage ship and fleet efficiency performance over time using, for example, the Energy Efficiency Operational Indicator (EEOI) as a monitoring tool". Both EEDI and SEEMP have been introduced by IMO resolution MEPC0.203(62), adopted in July 2011.[1]

With the freight rates persistently oscillating during the last 12 years around a small fraction of their 2007 and 2008 peak values[2] and with the fuel cost being the most important annual expenditure, reduction of fuel consumption would be of vital importance for ship operators, even without its paramount environmental impact and the need to comply with regulatory requirements. Considering the above, a study dealing with the operational optimisation of two widely used vessel types, namely a bulk carrier and a container ship was considered an essential Application Case of the HOLISHIP project. More specifically, the objectives of this Application Case and of the present book chapter were to investigate for two sample ships possible retrofitting solutions, including hullform modifications and/or the installation of energy saving systems and equipment, along with operational measures, such as trim optimization and route optimization, all aiming to reduce fuel oil consumption.

The sample ship characteristics, the optimization of ships' hull form and of their operation in calm water and under realistic environmental conditions, the tools that were developed or adjusted and the obtained results will be presented in the following sections.

8.2 The Sample Vessels

Two representative vessels, a 4235 TEU Cellular Container Ship operated by DANAOS and a Newcastlemax Bulk Carrier, operated by Star Bulk have been selected as the testbeds for the development and testing of the procedures and tools used in the HOLISHIP project for the optimisation of the operational performance of

[1]International Maritime Organisation (IMO), Energy Efficiency Measures, https://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Technical-and-Operational-Measures.aspx.

[2]See for example Baltic Exchange Dry Index, https://www.balticexchange.com.

typical merchant vessels. The main characteristics of the sample container ship are presented in Table 8.1. The ship is operating between East Mediterranean and USA via the Gibraltar straights, calling at the following ports: Ashdod, Haifa, Piraeus, Livorno, Genoa, Valencia, Halifax Nova Scotia, New York, Norfolk, Savannah, Valencia, Tarragona, Livorno and Ashdod.

The main characteristics of the sample Bulk Carrier are presented in Table 8.2. This ship is usually operating between South America and China: transit of Atlantic to Cape Town, transit of Indian Ocean, bunkering stop in Singapore (18 h) and transit through the Taiwan Strait to the gulf of Beihai in China. Alternative areas of operation of this ship are: North Australia to China and South America to Rotterdam.

Based on the 2d lines plan provided by the collaborating ship operators, 3d models of the hullform of each vessel were developed first in NAPA® and subsequently transferred to CAESES® (Figs. 8.1 and 8.2). In the case of the bulk carrier, a variant of its hullform has been created by adding a bulbous bow. Subsequently, the 'Free Form Deformation' tool provided by CAESES® to facilitate the variation of the bulbous bow form of the container ship and of the modified bulk carrier. To this end, a series of control points is added, located within a cube enclosing the area of the hull (here: bulbous bow), which is to be varied (Fig. 8.4). The control points located at the two aft layers and the two upper layers are kept at their original position, in order to ensure continuity of the surface, while some of the remaining control points are translated in space at selected directions resulting in a deformation of the

Table 8.1 Main characteristics of the container ship *ZIM LUANDA*

DWT (summer)	50,829
GT/NT	40,030/24450
L_{OA}	260.049 m
L_{BP}	244.80 m
Beam	32.25 m
Depth moulded	19.30 m
Draft (summer)	12.60 m
No. of holds/hatches	Seven (7)/Sixteen (16)
Nominal container capacity	4253 TEU
Reefer containers	400 UNITS
Homogeneous 14MT/TEU	2900 TEU
Main engine	HSD MAN B&W 8K90MC-C
MCR	49,680 BHP
Generators	4 X 1700 kW
Bow thruster	1 × 1600 kW
Speed	Abt 24.5 kn
Class	DNV GL

Table 8.2 Main characteristics of the bulk carrier *Star Marisa*

DWT (scantling)	208,000
GT/NT	106,900/66145
L_{OA}	299.88 m
L_{BP}	294.00 m
Beam	50.00 m
Depth moulded	25.00 m
Draft (D.L.W.L.)	16.10 m
Draft (Scantling)	18.50 m
No. of Holds	Nine (9)
Main Engine	MAN 6G70ME-C (Mark9.2) Tier II
SMCR	17,494 KW @ 78.7 RPM
Service Speed	Abt. 14.5 kn (CSR with 15% sea margin in design draft)
CLASS	BV

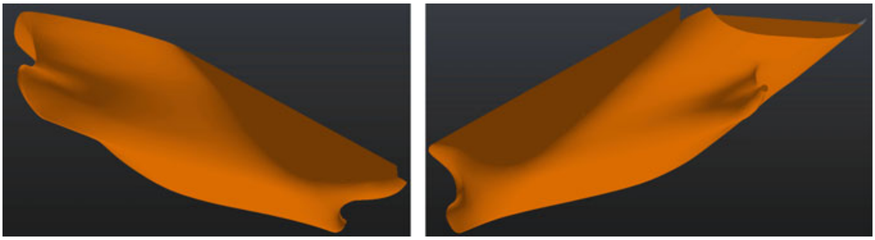

Fig. 8.1 3d model of the hullform of the container ship in NAPA®

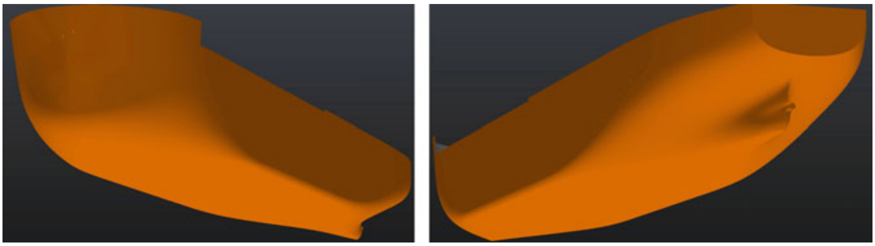

Fig. 8.2 3d model of the hullform of the bulk carrier in NAPA®

selected part of the hull. The translation of the control points is controlled by a set of variables. By assigning suitable values to these variables, the user can achieve the desired hullform deformation (Fig. 8.3).

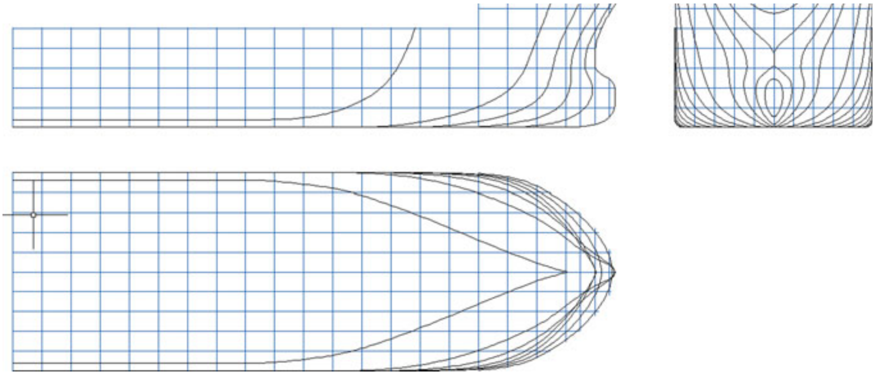

Fig. 8.3 Lines plan of modified bulk carrier bow

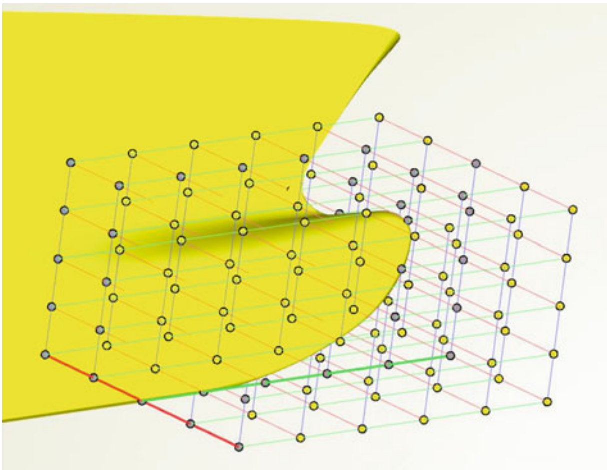

Fig. 8.4 Bow area of the container ship with the control points used for the bulb transformation

8.3 Hullform and Operational Optimization of a Container Ship

To support operational optimization and the possible retrofit process, HSVA performed a series of computations regarding the resistance and propulsion performance on a selection of hull form variations. These computations rely on the appropriate tool for the level of detail needed for the corresponding stage of development. At the initial stage, potential-based, panel code analysis tools were used. Such tools provide a fast, but moderately accurate overview of ship's performance. The information gained through these simple tools facilitates a narrowed selection of design characteristics for further optimization. At the later stages, more sophisticated and more time-consuming tools provide greater detail, and thereby distinguishing between subtle hull form changes, in order to reach the final design.

The ship under investigation is the container ship presented in Table 8.1.For this vessel, HSVA investigated the trim optimization, the bow shape optimization, and a combination thereof. The results were also used by other HOLISHIP partners for further investigation with regards to machinery retrofitting for reducing fuel oil consumption, and for the development and application of a weather routeing tool.

The first stage of the conducted investigation examined the (hydrodynamic) operational optimization of the container ship. No geometry changes were considered in this first stage and the original ship hull form was used. Instead, the investigation considered the simple change in loading, to produce a static trim, and the subsequent effect on the ship resistance and propulsion at a range of sailing speeds. In the second stage of the investigation, hull form variations were introduced. Initially, a search space consisting of 3 design parameters was applied. These design parameters correspond to the length of the bulbous bow, its width at the forward perpendicular and the height from baseline of its foremost point. Later, the search space was expanded to 5 design parameters adding the so-called upturn and fullness parameters. The upturn parameter can be used to modify the inclination of the upper part of the bulb's profile while with the fullness parameter the vertical centre of area of the bulb's transverse section can be shifted upwards or downwards. The hull form variations were limited to the bulbous bow. The operational conditions reflected the even keel loading condition at the design draft and the new (reduced) design speed of 18 knots. In the third stage, the combined effects of the first two stages were considered. The goal of each of the investigations was to determine the hull form and operating point for the lowest propulsion power requirement.

Before any computations could commence, the issue of some missing pieces needed to be resolved. The description of the hull form did not include a geometric description of the rudder, nor of the propeller. For the rudder, an approximation was created in CAESES®, based on 2-dimensional diagrams provided by the ship owner. A simple NACA profile was used in lieu of the actual rudder geometry. While this may have some effect on the absolute resistance and propulsion performance of the ship, the relative comparison between hull form variations was deemed adequate for the purpose of this investigation. A surrogate propeller was selected from the database of stock propellers available at HSVA for use in the investigation. As with the rudder, although an absolute powering performance is not reachable, the relative improvement between designs was also deemed adequate. At this point, a sufficient geometry description was reached, allowing the numerical analysis to begin in earnest.

The first step was to establish the computational domain. The free surface and the propeller region were of particular interest for the computations. The best practice guidelines at HSVA prescribed a finer mesh resolution in these regions to better capture flow details. The resulting meshes contained approximately 11.3 million hexahedral cells. The extent of the computational domain is presented in Fig. 8.5. As a basis for the subsequent optimization exercises, HSVA performed a series of calm water resistance and propulsion computations for the ZIM LUANDA container

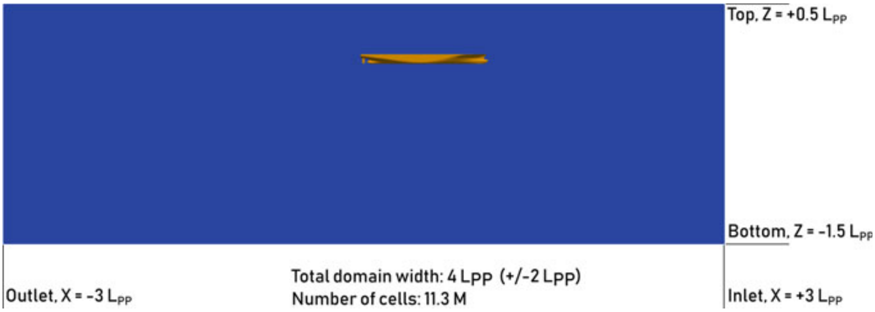

Fig. 8.5 Computational mesh for the case of the container ship

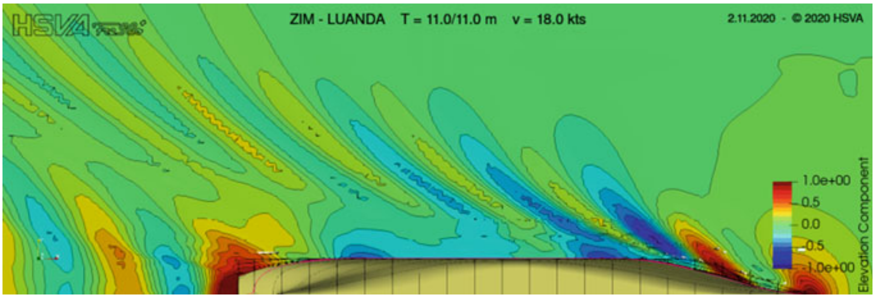

Fig. 8.6 Wave field, viewed from above for the original hullform at zero trim at 18 kn

ship. These computations cover a speed range from 12 to 24.5 knots for the ship at the even keel, designed loading condition of 11.0 m draft. Typical visualizations of the obtained results are shown in Figs. 8.6 and 8.7.

In an initial round of computations, the ship was computed over varying speeds: 18, 20, 22, 24 knots and varying hydrostatic trim conditions: 1 m by Stern, Even Keel, and 1 m by Bow. The results verified that the hydrostatic trim condition of 1 m by the bow is the best of the three conditions over all speeds computed. However, the optimal condition for each speed had not yet been determined. This merely indicated which side to explore in finer resolution. The second round of computations extended the trim to 2 m by the bow, as well as some intermediate steps. In general, a static trim of 1.5 m bow down gives the optimal power performance improvement between 2 and 3% over the speed range and draft, as shown in Fig. 8.8.

The next stage of the study was the bulbous bow optimization. The software platform CAESES® provided the means to modify the bulb geometry by way of the Free Form Deformation Tool. For this study, a series of calculations with ν-Shallo, the HSVA's in-house panel code for wave resistance was carried out, using equidistant spacing of the five design parameters (namely the bulbous length, width, height, upturn and fullness). The obtained results were used as the basis for the creation of a Response Surface Model (see Marzi et al. 2018), enabling the fast evaluation of

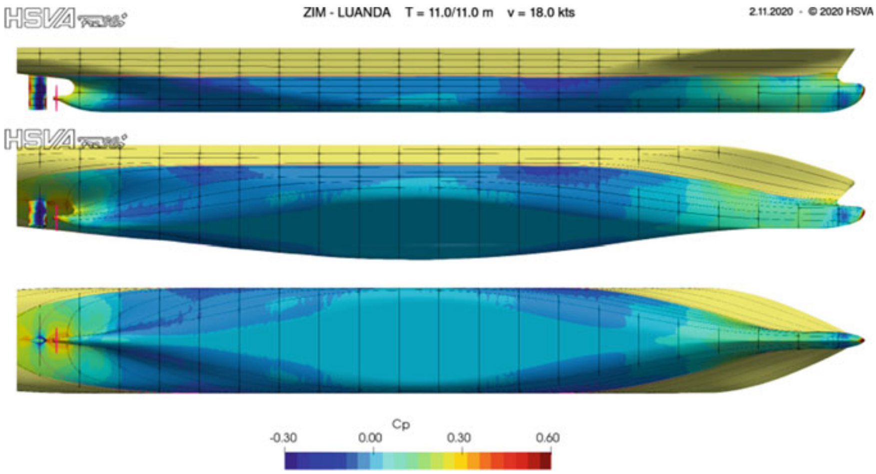

Fig. 8.7 Pressure distribution (Cp) on hull for different view angles, original hullform at zero trim at 18 kn

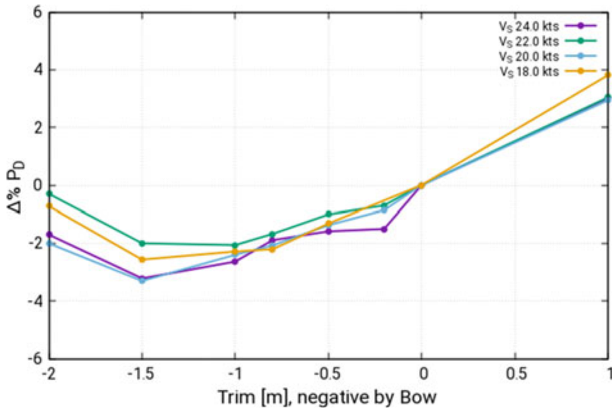

Fig. 8.8 Trim optimisation results for the original hull form of the container ship at 11.0 m draught and a speed range from 18 to 24 kn (negative trim corresponds to bow down)

alternative hullforms replacing computationally demanding CFD calculations. Then, a formal optimization of the bulbous bow was carried out using a Tangent Search optimization algorithm along with the Response Surface Model instead of CFD calculations. The verification of the performance of the optimum hull was carried out using HSVA's in-house tools, i.e. the panel code ν-Shallo and the RANSE code FreSCo^{+} (Gatchell et al. 2000; Hafermann 2007). A comparison of the performance of the original (baseline) hullform and the optimized one is presented in Fig. 8.9 and Table 8.3. As can be observed from Table 8.3, in comparison with the baseline the total resistance of the optimized design is reduced by 4.8% according to the ν-Shallo

Fig. 8.9 Comparison of wave profile around the baseline and the optimized bulbous bow

Table 8.3 Comparison of resistance and propulsion power for the baseline and the optimized bulbous bow at zero trim

	R_t (potential flow code) [kN]	R_t (viscous flow code) [kN]	P_D [kW]
Baseline	742.59	804.1	10294
'Best'	706.7 (−4.8%)	780.6 (−2.9%)	9982 (−3.0%)

Table 8.4 Comparison of propulsion power for the baseline and the optimized bulbous bow at zero and optimum trim

	P_D at Even Keel [kW]	Optimum Trim (negative bow down)	P_D at Optimum Trim [kW]
Baseline	10294	−1.5 m	10002 (−2.8%)
'Best'	9982 (-3.0%)	−1.0 m	9867 (−4.1%)

results and by 2.9% according to the results of the RANSE viscous calculations with FreSCo+. The propulsion power, calculated with FreSCo$^+$ and QCM (the propeller Vortex Lattice Method QCM developed at HSVA) is reduced by 3% in comparison with the baseline. Calculations with the optimized design at the optimum trim (1.0 m bow down) resulted in a propulsion power of 9867 kW, i.e. a total reduction of 4.1% in comparison with the baseline (Table 8.4).

8.4 Hullform and Operational Optimization of a Bulk Carrier

The optimisations studies on the Newcastlemax Bulk Carrier consisted of the optimisation of the bulbous bow fitted to the modified bulk carrier's foreship, along with a trim optimisation of the original vessel without bulbous bow. Both studies were performed at the design speed of 14.5 kn. The vessel resistance was computed using the FINE^{TM}/Marine CFD solver (Deng et al. 2005, 2015). The CFD simulation was set up to account for the effect of the propulsion force on the dynamic trim of the vessel. This was done by applying a body force model, setting thrust force equal to the computed resistance at the position of the propeller, acting in the direction of the propeller axis. The propeller force was therefore accounted in the computation of the hydrodynamic force balance of the vessel. The vessel resistance was computed assuming a smooth hull surface, while the additional resistance component due to hull roughness was added in a subsequent post processing step, in a similar procedure as applied to model test data obtained from physical experimental towing tests. The resistance from the CFD simulation is used as input to the ShipX Speed and Power module. ShipX, developed by SINTEF Ocean, is a comprehensive workbench containing a variety of marine hydrodynamic analysis tools, such as speed prognosis, stations keeping, sea keeping analysis, etc. The ShipX Speed and Power module computes the required shaft power necessary to maintain a given speed. In addition to the computed resistance from the CFD simulations, the module also takes the propulsion efficiency into account. The computed nominal wake at the location of the propeller plane is extracted from the CFD simulations and used as input to the ShipX module when the propulsion efficiency is evaluated.

The size of the computational domain is based on the length overall of the ship (L_{OA}). The upstream inlet boundary is located $1.5L_{OA}$ in front of the vessel, the downstream outlet boundary is located $3L_{OA}$ behind it, while the far field side is located $2L_{OA}$ from the centreline. The bottom boundary is located $1.5L_{OA}$ below the undisturbed water surface and the top boundary is located $0.6L_{OA}$ above the water surface. By applying a symmetry boundary condition at the centreline, the computational domain is reduced to only include the port side of the vessel. The computational mesh was generated using the HEXPRESS mesh generator, which is part of the FINE™/Marine CFD package. The total number of grid cells was about 4.5 M. The computational domain and mesh at outer boundaries are visualised in Fig. 8.10. The turbulence model used in the RANS simulations was the k-ω SST model. The free surface interface was captured using the VOF technique.

The Sobol sensitivity analysis method, as implemented in the CAESES® optimisation software, was used to sweep the parameter space to identify combinations of design parameters that result in a low value of required shaft power. To find the local minimums, refined optimisation must be conducted in the vicinity of the location of the local minimums. The global minimum can thereafter be found as the minimum of the local minimums.

A set of simulations was conducted for the original vessel without bulbous bow, with variation of trim angle while keeping the displacement constant. The trim angle ranges from -2 to $+2°$ where a positive angle means a bow down trim. The required power as a function of trim angle is presented in Fig. 8.11. The lowest required power was equal to 12390 kW, corresponding to a trim angle of 0.25°. The even keel trim angle resulted in a required power of 12523 kW. Thus, by trimming the vessel 0.25° bow down, the required power is reduced by 1%.

A modified version of the bulk carrier was designed by adding a bulbous bow. The shape of the bulb was parametrized in CAESES®, using the Free Form Deformation tool. Shape parameters describing the length (L_{bulb}), thickness (T_{bulb}), vertical extent

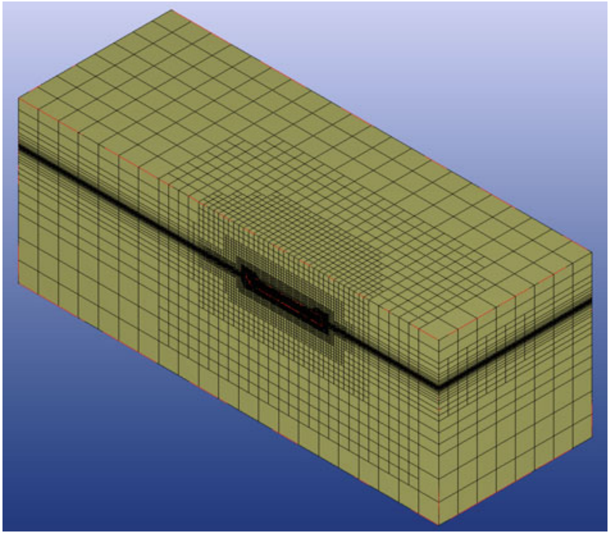

Fig. 8.10 Computational mesh for the case of the bulk carrier (4.5 Mio cells)

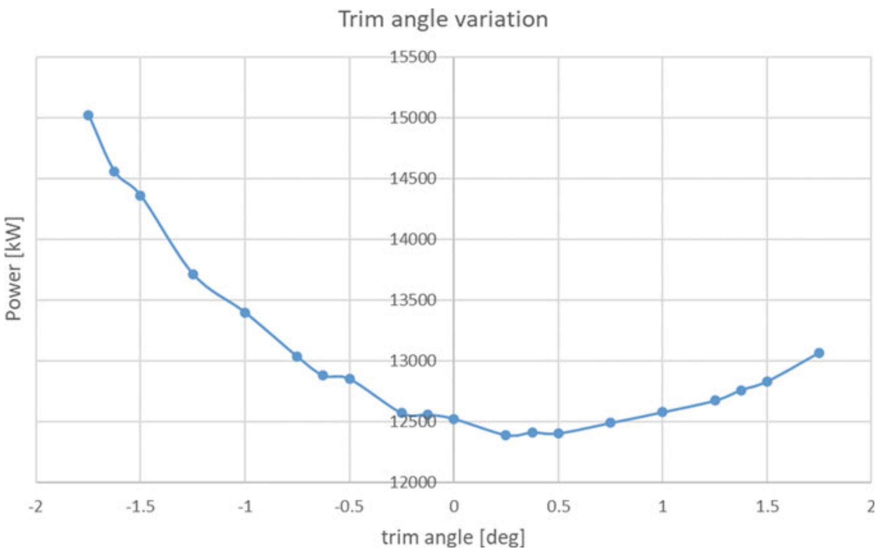

Fig. 8.11 Required shaft power as a function of trim angle for the original bulk carrier (positive trim: bow down)

Table 8.5 Lowest computed required power and bulb shape parameters for each tested trim angle

Trim angle	L_{bulb}	T_{bulb}	VE_{bulb}	VP_{bulb}	P [kW]
0° (even keel)	−0.125	0.44375	0.9875	0.328125	12412
0.125°	−0.75	0.5375	1.175	−0.21875	12414
0.25°	2.5	0.475	0.95	0.5625	12427

(VE_{bulb}) and vertical position (VP_{bulb}) of the bulb were defined and used to create bulb shape variations. A set of 35 bulb variations were defined using the Sobol sampling method.

The displacement at even keel loading condition was set to be the same as for the original vessel design without bulbous bow. The computed power varies from 12412 kW to 12574 kW. The vessel with the bulb that requires the lowest power is about 1% better in terms of power consumption than the original vessel without bulb at even keel loading condition (computed to 12523 kW). However, the best bulb found does still require marginally more power than the vessel without bulb at optimum trim loading condition (computed to 12390 kW at 0.25° trim angle). The reason for the reduced propulsion power of the trimmed vessel could be the reduced submergence at the aft, and therefore reduced wetted transom area, which results in a reduction of pressure/wave resistance contribution from the aft ship.

To further investigate this, a set of simulations with forward still water trim angle was conducted. Simulations were performed for 0.125 and 0.25° forward trim. For each of the forward trim angles, a Sobol sequence was defined with 20 variations of the bulb design variables. The result for the best bulb in each set of simulations is presented in Table 8.5. The minimum required power is still found for the even keel condition, although the simulations at 0.125° forward trim resulted in practically the same required power, with only 2 kW difference. It is possible that, although the resistance component from the aft ship is reduced by trimming forward, the increased submergence of the bulb makes the bulb less effective and the total resistance is increased. It is also possible that by expanding the set of simulations with forward trim angle, an improved bulbous bow design, with further reduced shaft power can be found.

The wave pattern of the original vessel without a bulbous bow is compared at 0.25° forward trim against the even keel (0°) loading condition (Fig. 8.12). As may be observed in this figure, the elevation of the transom stern wave crest height is reduced in the simulation with the forward trim. Also, the wave trough at the aft shoulder is reduced. At the same time, due to the increased submergence of the bow, an increased wave trough is observed at the forward shoulder. But, overall, the resistance computations show that the benefit from the improved aft ship wave pattern outweighs the worsening of the wave pattern at the forward shoulder of the ship. In Fig. 8.13, the wave pattern generated around the ship equipped with the best bulbous bow found at even keel loading condition is compared against the wave pattern generated by the original vessel without bulb. The bulb generates a more

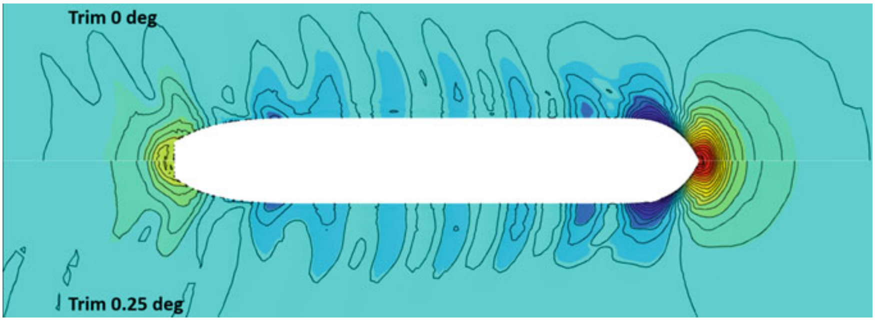

Fig. 8.12 Free surface wave pattern. Comparison of even keel loading condition (above) against 0.25° forward trim loading condition (below)

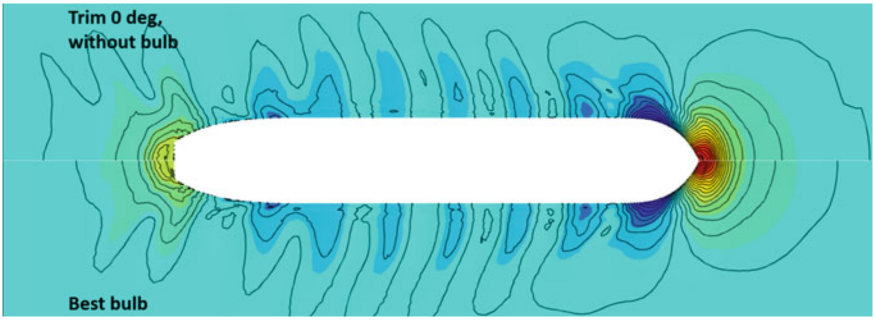

Fig. 8.13 Free surface wave pattern. Comparison of base case without bulb (above) against best bulb found for even keel loading condition (below)

favourable forward shoulder wave with reduced wave trough. Also, as expected since both simulations are performed at even keel loading condition, the aft ship wave pattern is very similar.

8.5 Weather Routeing

8.5.1 Development of a Ship Routeing Tool

In the framework of the HOLISHIP project a new ship weather routeing tool was developed and used for the operational optimization of the sample vessels, the container ship and the bulk carrier. The ship-routeing tool was developed in Matlab®, making use of the numerous functions and toolboxes available.

Matlab® combines a desktop environment tuned for iterative analysis and design processes with a powerful programming language. Users are provided with a variety of toolboxes, which are professionally developed and rigorously tested. The mapping toolbox in particular, that is widely used for the development of the ship-routeing tool, provides algorithms and functions for analysing geographic data and creating map displays in Matlab®. Users can import vector and raster data from a wide range of file formats and web map servers. Vector and raster data can even be displayed together as needed.

The geographic data is in vector format and is referred to as a vector map. This format consists of specific points, along with some indication as to how they should or should not be connected to each other. In the mapping toolbox, vector data consists of sequentially ordered pairs of latitude and longitude coordinates. A map projection displays the surface of a sphere (or spheroid) in a two-dimensional plane. There are many different ways to project a map, but in all cases, various types of distortions are introduced. Maps oriented for sea navigation commonly use Mercator projection which is adequately efficient as long as the route of interest is located at a safe distance from poles, where distortion is high. For regions near poles, it is more suitable to revert to conic or azimuthal projection. The ship-routeing map can be enriched by adding relevant raster data and 3d displays can be created. Such kind of data may correspond to surface (land) elevation and bathymetry layers. The simplest way to display raster data is to assign colours to matrix elements according to their data values and plot them in two dimensions.

After setting up the map environment, the next step was to develop an algorithm in Matlab®, which would be used to plan alternative ship routes and display them on the map. A route is defined by its starting and end points along with a number of n intermediate waypoints. These points can be given directly by the user either by clicking on the map or by typing their exact coordinates. Moreover, these points can also be read from an external file. This group of points create $n + 1$ legs, each one of which can be handled and analysed separately. For instance, for each point along the route it is possible to calculate water depth, or its distance from the nearest coast, or to check whether it lies within specific areas (for example within an Emission Control Area (ECA), or a possibly dangerous or non-permitted area). Apart from being defined by the user, the coordinates of n intermediate waypoints can be also selected randomly, or by an optimization algorithm so that it is possible to generate and analyse automatically a large number of routes, connecting the same starting and end points at almost zero computing time. The user can specify a series of constrains, such as minimum distance from coast, minimum depth along the route, time spent or distance travelled within Emission Control Areas, avoidance of non-permitted areas etc. Any route that doesn't comply with the given constrains is considered unfeasible and is neglected from the process, whereas feasible routes are stored for further analysis.

Weather forecast data along any route can be readily imported by a variety of sources, enabling the user to perform seakeeping analysis along the suggested routes. To this end, detailed seakeeping calculations for the vessel in question at various loading conditions, speeds of advance and for a range of incident waves are carried out beforehand and the results are stored in a database to be used during the ship route optimization. By doing so, the evaluation of the performance of a ship along a route can be considerably faster, while at the same time the ship routeing tool is completely de-coupled from the software tools that maybe used for the seakeeping calculations and it is therefore possible to use seakeeping results from any available source.

Reliable weather predictions, as possible for the whole duration of the crossing, are essential in order to be able to evaluate and compare the performance of a ship along alternative routes. The routeing tool can access such data from various weather prediction providers, including Copernicus Marine Environment Monitoring Service (https://marine.copernicus.eu), providing a 7-days forecast, or the weather forecast platform SKIRON, developed and maintained by the University of Athens, School of Physics (https://forecast.uoa.gr/) providing a 7-days forecast horizon. Forecast data from Copernicus are available at a spatial resolution of 0.083° × 0.083° and temporal resolution of 3 h for waves, spatial resolution of 0.025° × 0.025° and temporal resolution of 24 h for currents and spatial resolution of 0.025° × 0.025° and temporal resolution of 6 h for wind predictions. Forecast data from SKIRON are available only for waves, at a spatial resolution of 0.5° × 0.5° world-wide, while a much finer resolution of 0.05° × 0.05° is used within the Mediterranean. All data are in GRIB[3] format and a suitable code in Matlab® has been prepared to read all the components that are needed for the analysis. From the various types of data included in the weather predictions, the most important ones for the routeing tool are the wave height, mean period and direction. Relevant data regarding sea currents predictions are obtained from Copernicus Marine Environment Monitoring Service.

Integration of the ship-routeing tool with optimization algorithms available in Matlab® enables the user to optimize the ship route according to appropriate optimization criteria, each time selected by the user. In addition, relevant constraints on the ship motions and accelerations along the route can be introduced, aiming to ensure safety of operation and acceptable comfort standards for the crew.

8.5.2 *Container Ship Weather Routing Optimization*

The 4235 TEU container ship operated by DANAOS has been extensively used as a testbed for the development of the routeing tool, namely to test its potential for the operational optimization of the ship and the minimization of the annual fuel consumption. The ship is serving a route starting from the Ashdod and Haifa ports in Israel, then sailing via Piraeus, Livorno, Genoa and Valencia in the Mediterranean and through the Strait of Gibraltar, it crosses the Atlantic heading Halifax in Nova Scotia, Canada and from there proceeding to New York, Norfolk and Savannah. From there it returns to Valencia, Tarragona, Livorno and finally to Ashdod. Apart from its typical route, the ship has been tested in many other areas of operation, using available weather predictions, as well as recorded weather data in order to

[3]GRIB files are a special binary format, commonly used in meteorology to store historical and forecast weather data.

test and validate the potential of the routeing tool. The objective function used in most of these studies was the minimization of the fuel consumption, while a set of constraints on the ship motions and accelerations along the route have been applied. For the evaluation of the fuel consumption a series of software tools have been used for the calculation of calm water resistance, the added resistance in waves, the wind resistance and the modelling of the propeller and main engine.

For the calm water resistance, calculations were carried out by HSVA, using the CFD code FreSCo+ (Hafermann 2007). FreSCo^{+} is a RANSE (Reynolds-Averaged Navier-Stokes Equations) solver jointly developed by HSVA and Technical University Hamburg since 2005, based on a finite volume method and is capable of handling fully unstructured polyhedral meshes. For the added resistance in waves as well as for the evaluation of the ship motions in waves, the NEWDRIFT+ code is used. NEWDRIFT + is a 3d panel code based on Green Function's method, developed by NTUA, which can be employed for the evaluation of motions, wave loads and mean second-order forces on ships and floating structures subject to incident waves in the frequency domain (Papanikolaou, 1985, Papanikolaou and Zaraphonitis, 1987, Papanikolaou and Schellin, 1992). The original version of NEWDRIFT calculates the second-order drift forces of a ship or a floating object at zero forward speed based on direct integration over the wetted surface (near field method). However, for ships with forward speed a variation of the far field method is developed and used in NEWDRIFT+ for the calculation of added resistance (Liu et al. 2011). In addition, a simplified formula proposed by Liu and Papanikolaou (2015) for the calculation of added resistance of ships in waves can also be used. A comparison of numerical predictions with experimental measurements for two well-known and extensively studied vessels, i.e. the KVLCC2 ship and the S175 container ship is illustrated in Figs. 8.14 and 8.15 extracted from Liu and Papanikolaou (2015).

Using NEWDRIFT+, extensive calculations have been carried out for a series of loading conditions, ship speeds, headings and wave lengths assuming regular

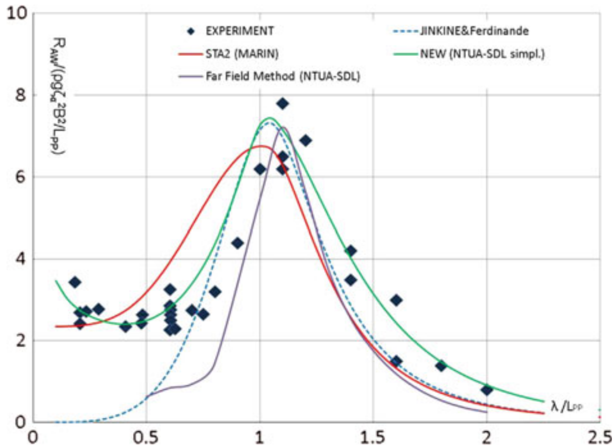

Fig. 8.14 Added resistance of KVLCC2 ship in head waves at Fn = 0.142

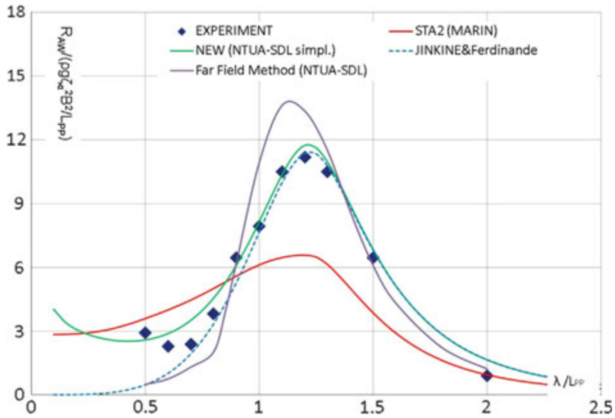

Fig. 8.15 Added resistance of S175 container ship in head waves at Fn = 0.275

waves. Based on the collected results, the ship responses for a series of sea states characterized by JONSWAP wave spectra with significant wave height from 0 to 10 m, peak period from 4 to 15 s and wave headings from 0° (following seas) to 180° (head waves) have been evaluated and stored in a database to be used by the routeing tool. Wind resistance is calculated using Blendermann's coefficients (Blendermann 1994).

Using the results obtained by the above methods, the routeing tool can evaluate the ship's total resistance at any point of its route, based on the weather predictions at the specific point and time and for the assumed ship speed and heading. Then, the required propulsion power can be readily calculated, based on the available propeller curves. The specific fuel oil consumption (SFOC) is then calculated, based on data provided by the engine manufacturer.

To demonstrate the potential of the weather routeing tool, results from the optimization of a crossing of the Atlantic Ocean with the vessel assumed at its design draught will be presented in the following. The vessel exits the Mediterranean from the Strait of Gibraltar, heading towards Halifax, Nova Scotia. The crossing is assumed to start on 06/01/2018 and the ship should arrive at its destination within 144 h. The minimum[4] distance of the voyage is 2373.5 nm and with the specified crossing duration can be travelled at an average speed of 16.7kn. The route optimization is based on weather forecasts provided by Copernicus Marine Environment Monitoring Service and is carried out via the genetic algorithm solver, available in Matlab's® optimization toolbox, using a population size of 200 and 100 generations. Mutation and crossover functions are used to provide genetic diversity, to enable the genetic algorithm to search a broader space and to ensure that feasible parents give rise to feasible children, where feasibility is with respect to bounds. The objective of the optimization was the minimization of fuel consumption, subject to the following set of constraints:

[4]The distance corresponding to the great circle between the departure and arrival points.

- Travel time no more than 144 h
- Significant vertical acceleration at the bridge of the ship:
  - between 0.30 g and 0.45 g for not more than 12 h
  - between 0.45 g and 0.60 g for not more than 10 h
- Significant vertical acceleration at the bow of the ship:
  - between 0.70 g and 0.80 g for not more than 12 h
  - between 0.80 g and 0.90 g for not more than 10 h
- Significant roll angle:
  - from 8 to 10° for not more than 6 h
  - from 10 to 14° for not more than 2 h

Thirteen optimization variables were used, consisting of the coordinates (longitude and latitude) of four intermediate waypoints and the speed of the vessel along each one of the 5 voyage legs. The optimization was carried out for 100 generations, resulting in 20,000 voyage alternatives, 668 of which were feasible. The evolution of the fuel oil consumption is illustrated in Fig. 8.16. As can be observed from this figure, the members of the initial generations are characterized by extremely high FOC, while improved results are obtained gradually, and finally a large number of voyages are identified with a FOC below 240 t.

The key point in order to reduce the FOC is to navigate the vessel in a way that avoids the most severe wave conditions during the crossing. This is evident from the following figures (Figs. 8.17, 8.18 and 8.19) where the fuel oil consumption is plotted against the total number of hours during the crossing for which the vessel responses are kept within the specified limits (i.e. significant vertical acceleration at the bridge and at the ship bow less than 0.30 g and 0.70 g respectively and significant roll angle less than 8°).

The route minimizing FOC, while fulfilling the specified constraints was found in the 100th generation. The route length is equal to 2390.6 nm and the calculated FOC is equal to 237.83 tons. The FOC along the optimal route is 5 tons less (2% reduction) than the FOC calculated for the vessel sailing along the great circle (i.e.

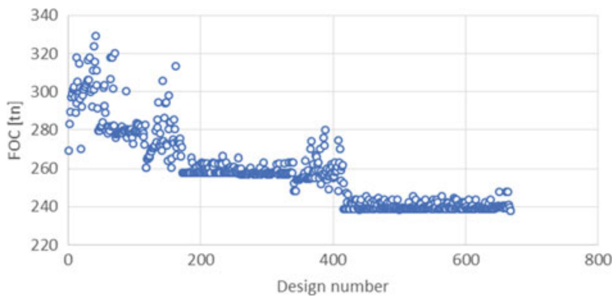

Fig. 8.16 Evolution of fuel oil consumption (only feasible voyages shown)

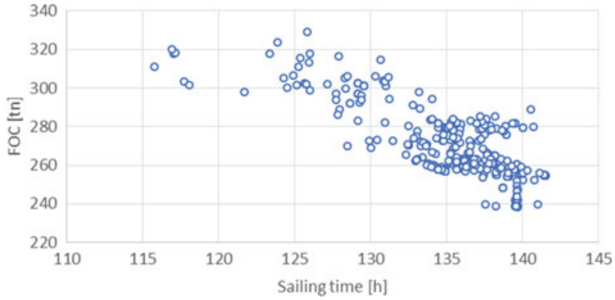

Fig. 8.17 Aggregate time during sailing with significant vertical bridge acceleration not greater than 0.30 g

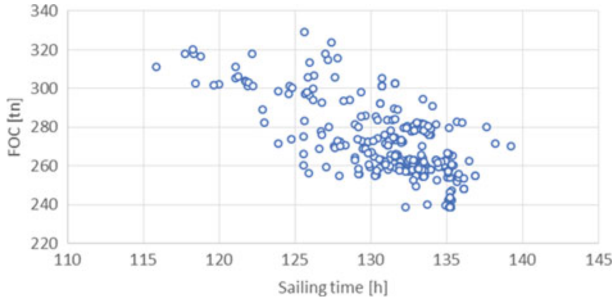

Fig. 8.18 Aggregate time during sailing with significant vertical bow acceleration not greater than 0.70 g

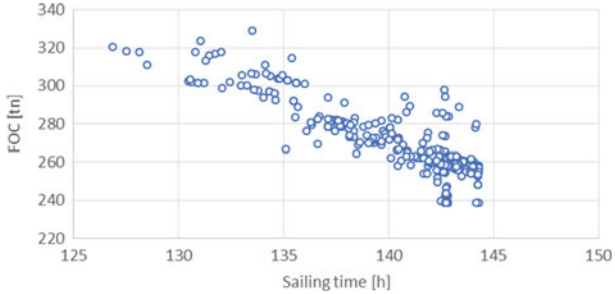

Fig. 8.19 Aggregate time during sailing with significant roll angle not greater than 8°

along the route minimizing the distance between the departure and destination points, also known as the orthodrome). The distance along the great circle is 2373.5 nm, i.e. 17.1 nm less than that of the optimal route. In addition, the FOC along the optimal route is 5.9 tons less (2.4% reduction) than the FOC calculated for the vessel following the rhumb line (i.e. along the route with constant heading between the departure and destination points, also known as the loxodrome, shown as a straight line in a Mercator projection). The distance along the rhumb line is 2399.1 nm, i.e. 8.5 nm more than that of the optimal route and 25.6 nm more than the great circle. The reduction in FOC obtained by the route optimization is relatively small, it should be noted however, that the above mentioned FOC along the great circle and the rhumb line have been obtained by a systematic speed optimization along each route using the same weather routeing tool. These optimizations were carried out in order to bring the ship responses along these routes within the specified constraints, while the achieved fuel oil consumption was just a side effect. Without the speed optimization, sailing along the great circle or the rhumb line (for example with constant speed) resulted in significant violation of the specified seakeeping constraints.

The trajectory of the optimal route with a step of 24 h (the time of departure appearing top left) plotted against the prevailing significant wave height prediction at each instant is presented in Fig. 8.20. At the bottom-right plot of Fig. 8.20 the optimal route (green line) is compared with the great circle and the rhumb line, (appearing as a circular ark and a straight line in a Mercator projection respectively, both in red colour).

8.6 Conclusions

The outcome of the work that was carried out on the operational optimization and hull form retrofitting of two widely used vessel types, namely a bulk carrier and a container ship was presented. For both vessels, trim optimization was carried out using advanced CFD tools, while the required propulsion power reduction by systematic bulbous bow optimization was also investigated. In addition, a ship routeing tool was developed and applied to both vessels's operation using realistic operational conditions and online weather data, aiming to reduce fuel oil consumption, while keeping set margins for travel time and seakeeping criteria.

For both vessels, trim optimization studies indicated that it is possible to reduce calm water resistance and required propulsion power by a bow down trim angle. For the original hull form of the bulk carrier (the hull without the bulbous bow), the optimum trim angle at design speed (14.5 kn) minimizing the calm water propulsion power is equal to 0.25°. At this trim angle, the calm water propulsion power is reduced by approximately 1% in comparison with the power required at level trim. The corresponding optimum trim angle for the container ship is found in the range between 0.23° to 0.35°, depending on the ship speed. The propulsion power reduction ranges between 2 and 3%, depending on speed.

Fitting of a bulbous bow on the bulk carrier can reduce the propulsion power by approximately 1%, both at level trim, and with a bow down trim between 0.125° and 0.25°. For container ship at the specified speed of 18 kn, a reduction of propulsion power by a bulbous bow optimization in the order of 3% was obtained with the vessel at zero trim and up to 4% with a bow down trim angle of 0.23° (1 m trim by the bow). The positive impact of bow down trim on the resistance and propulsion might be attributed to the reduction of the immersed area of the transom.

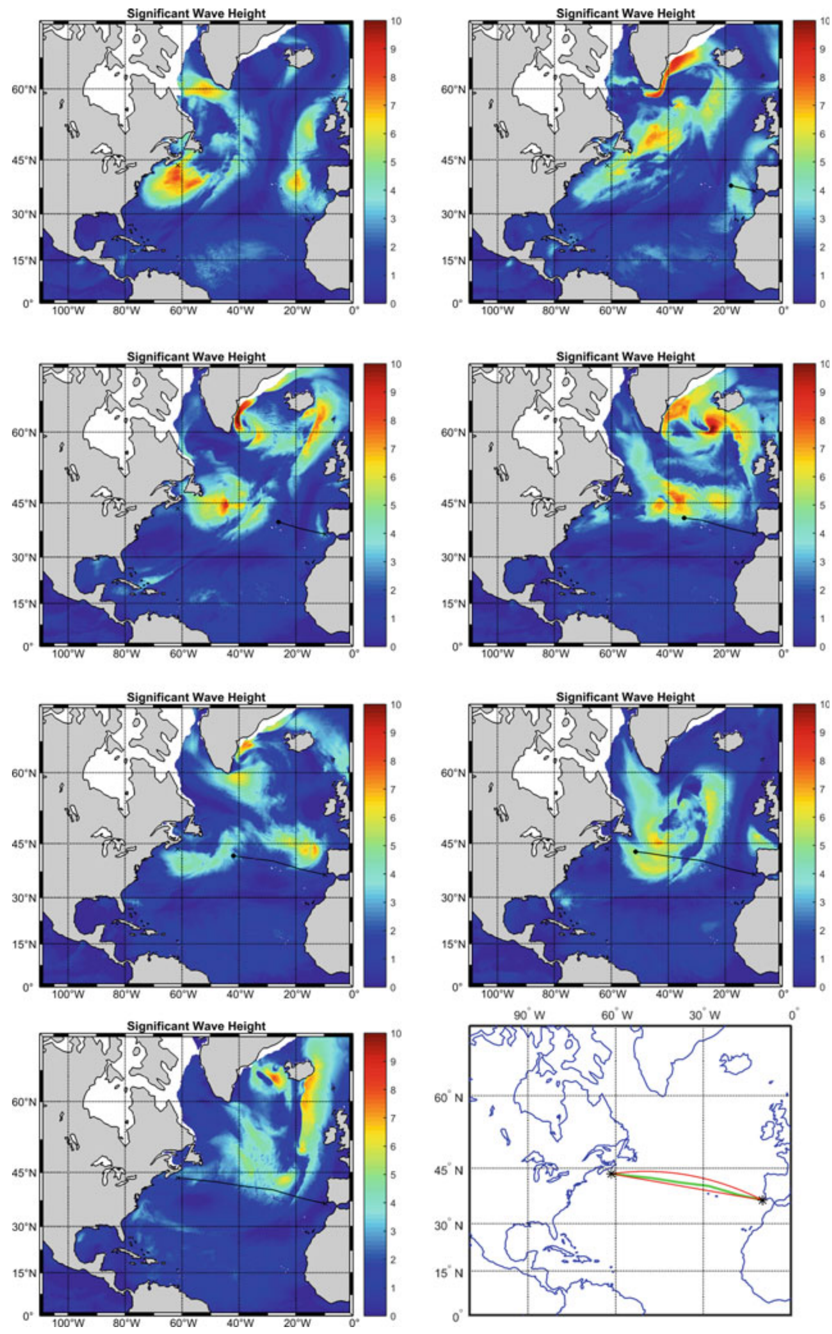

Fig. 8.20 Distance travelled per day against the significant wave height and comparison of optimal route (green) with great circle and rhumb line (both in red)

Given that the original hull forms of both vessels have been already extensively optimized by the shipbuilders, the obtained improvements may be considered quite satisfactory, particularly for the container ship.

Weather routeing optimization studies for both vessels resulted in a reduction of the fuel consumption in the order of 2% in comparison with the fuel consumption obtained when sailing along the great circle (despite the increase of the route length and the average speed) and in the order of 2.4% in comparison with the fuel consumption obtained when sailing along the rhumb line (i.e. along the route with constant heading between the departure and destination points, shown as a straight line in a Mercator projection). It should be noted however, that the fuel oil consumption along the great circle and the rhumb line which are compared with that along the optimum route have been both obtained by a systematic speed optimization along each route using the same weather routeing tool. These optimizations were carried out in order to keep ship responses along these routes within the specified constraints, while the achieved fuel oil consumption was just a side effect. Without the speed optimization, sailing along the great circle or the rhumb line (for example with constant speed) resulted in significant violation of the specified seakeeping constraints. The obtained results indicated that even if the fuel oil savings are not quite high, the obtained reduction of the vessel's responses (in this particular case the vertical acceleration at the bridge and at the bow and the roll angle) may be particularly significant, improving the quality of the crossing and enhancing the safety of the ship and cargo (e.g. minimization of the risk of lost deck containers). It should be also noted that the studied ships are quite large in absolute size and it may be expected that similar studies on smaller vessels on the same route would result in more striking impact.

Based on the obtained results, it may be concluded that optimization methods, when properly applied can be valuable tools both for the hull retrofitting and for the improvement of ship operation. Cumulative savings obtained by the combined effect of carefully optimized hullform retrofitting and operational optimization can become quite substantial, resulting in significant reduction of fuel consumption and greenhouse gas emissions along with significantly improved ship responses in the waves.

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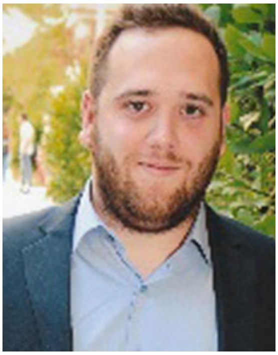

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Chapter 9
Model-Based Systems Engineering for the Design and Operational Assessment of Marine Energy Systems and Retrofitting Solutions

Chara Georgopoulou, Lefteris Koukoulopoulos, and George Dimopoulos

Abstract Nowadays, a variety of technical solutions to improve energy efficiency and reduce emissions is available to the shipping industry, offering a wide range of possible solutions to ship builders and operators. However, the selection of the best performing option is subject to the individual specifications of the vessel, its trade route, lifetime expectancy and many other factors. Furthermore, the decision-making process usually accounts for multiple objectives, such as energy efficiency, environmental impact, reliability and safety, which in various cases may be conflicting. This chapter demonstrates how Model Based Systems Engineering methods and associated tools can support the assessment and quantification of ship machinery system performance at concept design and in retrofit applications, aiding decision makers. Two typical application cases of the HOLISHIP project are presented: the energy efficiency and reliability assessment of a hybrid Offshore Supply Vessel; and the retrofitting of a bulk carrier with a fuel recovery from a sludge unit.

Keywords Risk-based design · Energy efficiency · Reliability · Model-based systems engineering · Marine hybrid systems · Retrofit assessment · System optimisation

Abbreviations

DP2	Dynamic positioning mode, harsh weather
MBSE	Model-Based Systems Engineering
FRU	Fuel from sludge Recovery Unit

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A. Papanikolaou (ed.), *A Holistic Approach to Ship Design*,
https://doi.org/10.1007/978-3-030-71091-0_9

FOC	Fuel Oil Consumption
KPI	Key Performance Indicators (KPIs)
OSV	Offshore Service Vessel
PMS	Power Management Strategy

9.1 Introduction

The selection of the best performing ship machinery system among a set of alternative options and technologies is a complex problem that requires systems engineering knowledge and tools. Model-based systems engineering (MBSE) tools can help to deal with the inherent complexity of ship systems and analyse a variety of technical solutions, while assessing multiple objectives and constraints, such as the design of systems for optimal operational performance and maximum reliability. Furthermore, the use of MBSE tools is not restricted to the concept design stage, where the optimal selection of ship machinery takes place, but also expands over the whole vessel's lifetime to monitor performance and assess retrofit options.

As an example, at concept design stage, model-based systems engineering tools can help determine the best performing machinery system configuration that ensures energy efficiency and reliability of service over a wide spectrum of operational modes. At the retrofitting stage, the inclusion of new technologies can be analysed with the use of computer models and the potential benefits can be quantified to support decision making. The EC funded project HOLISHIP (HOLISHIP 2016–2020) aims at demonstrating and integrating advanced methods and tools for the holistic optimization of ship design and life-cycle operation. The use of MBSE tools in Holiship is a key part of the project and provides the necessary assessment capabilities for the integration of the machinery system into the holistic ship design process (Papanikolaou 2010).

This chapter is dedicated to the application of developed advanced modelling and simulation methods, (Papanikolaou 2019), to two examples of ship machinery assessment at concept and retrofit stages, respectively:

a. Energy efficiency and reliability performance assessment of an Offshore Supply Vessel (OSV) machinery system with and without batteries. This case is part of HOLISHIP WP9 – Application Case 1, OSV Case 2, and is extensively described in Chap. 3 of this book. This paradigm demonstrates how systems engineering tools can help assess multiple objectives during the concept design stage and identify hybrid technology benefits over a range of operational scenarios.
b. Retrofit solution performance assessment for a bulk carrier. This case is part of HOLISHIP WP14 – Application Case 6. In this example, modelling tools quantify the anticipated performance and life cycle costs for a novel retrofit system that recovers fuel from a sludge unit.

DNV GL COSSMOS is an innovative computer platform developed by DNV GL for the modelling, simulation and optimization of integrated ship machinery systems, introducing formally systems engineering in shipping (Dimopoulos 2009; Dimopoulos et al. 2014). COSSMOS stands for Complex Ship Machinery Systems Modelling and Simulation and is based on an in-house library of generic reconfigurable component models of marine machinery systems, providing thus the opportunity to develop different configurations including baseline and/or innovative technologies. The COSSMOS library has been extensively used for a wide variety of highly complex ship applications, including the assessment of different Liquefied Natural Gas (LNG) carrier energy system configurations, the analysis of real-time performance of marine hybrid systems, the evaluation of waste heat recovery technologies at part-load conditions, etc.

The following sections are dedicated to the presentation of the two HOLISHIP Application Cases, demonstrating the potential benefits of MBSE approaches in systems understanding and analysis.

9.2 Risk-Based Assessment of an OSV Hybrid Machinery System

9.2.1 Objective and Scope

A key step in the design of hybrid machinery systems is the evaluation of the hybrid system performance at design and operating conditions. Hybrid systems and batteries bring significant benefits when used for receiving peak demands, allowing the rest of the power converters to operate at constant loading (Stefanatos et al. 2012, 2015). This capability has positive impact on both reliability and energy efficiency (Manno et al. 2015). The benefits from the hybrid system in terms of energy efficiency and reliability can be quantified and assessed, in order to support decision making towards the final configuration and operational strategy setup of the vessel. These results provide essential feedback to risk assessment methods and tools, as not only qualitative information is provided, but also quantitative understanding on the integrated system behaviour.

This section presents the results of risk-based performance analysis of a hybrid machinery system for the concept design of an OSV. The study is part of the HOLISHIP project Application Case 1 (WP9), Phase 2, (De Jong et al. 2018). The objective is to analyse the hybrid system's performance over a set of prospective operational modes and demonstrate savings and reliability benefits. For this purpose, DNV GL COSSMOS was used to:

- Assess the performance of the OSV concept design at a range of operating modes with and without battery and quantify the hybrid system gains.
- Account for reliability and demonstrate the benefits from hybridization, via the quantification of hot reserve capacity of the baseline and hybrid systems.
- Assess transients: Evaluate the OSV performance at demanding conditions like dynamic positioning with harsh weather (DP2) at transient conditions. A pseudo-transient profile is considered for this purpose.

9.2.2 Technical and Operational Characteristics

The case of interest is an OSV vessel, powered by four Bergen C25:33 L6 Diesel engines of 1990 kW at 900 rpm. The concept vessel is propelled by two main azimuth thrusters of 2470 kW (750–1800 rpm), two tunnel thrusters of 1150 kW (980–1190 rpm) and a forward thruster of 2000 kW at 1800 rpm. Table 9.1 shows a typical annual operational envelope of the vessel.

9.2.3 Baseline System Modelling

The baseline system model in DNV GL COSSMOS is shown in Fig. 9.1. The following Power Management Strategy (PMS) elements are implemented:

- Switchboard status can be “connected” or “disconnected”.
- Forward thruster load can be shared at variant rates between switchboards.
- Equal load sharing is assumed for operating engines at one switchboard.
- 90% maximum engine load for power dispatch between engines is used.

9.2.4 Baseline System Performance and Reliability Assessment

The baseline OSV fuel consumption performance is estimated at 4269.7 tons per year subject to the mission envelope of Table 9.1. Apart from fuel consumption, the hot reserve capacity per operation mode is calculated, as shown in Table 9.2. The hot reserve capacity is determined as the difference between the maximum continuous rating (MCR) of the engines in operation minus the power output. In case of engine failure, the remaining engines’ hot reserve is expected to supply power to cover the additional demand. A color code is used to indicate whether the hot reserve is enough to cover the demand dispatched at the engines that went off the grid due to the failure event:

Table 9.1 Operational profile of the OSV

Type	Relative time spent [%]	Hotel 1 + 2 [kW]	HC[a] 1 + 2 [kW]	2 × Main azimuth thrusters [kW]		2 × Tunnel thrusters [kW]		Forward thruster [kW]
Harbour	20	300	0	0	0	0	0	0
Transit 11 knots	10	500	0	1121	1121	0	0	0
Transit 13 knots	10	500	0	1400	1400	0	0	0
Standby (wind = 5 m/s, current = 1 m/s)	20	500	0	442	438	186	183	272
Standby (wind = 12.5 m/s, current = 3 m/s)	10	500	0	567	541	406	396	1034
DP2 (wind = 5 m/s, current = 1 m/s)	20	500	500	442	438	186	183	272
DP2 (wind = 12.5 m/s, current = 2 m/s)	10	500	500	567	541	406	396	1034
Full power to main thrusters (not part of OP)	0	500	0	2470	2470	0	0	0
DP2 Failure mode with max crane load	0	500	1000	798	0	1097	0	966

[a]Crane load

– Red indicates failure to supply the additional demand;
– Yellow indicates that the additional demand is partly covered; and
– Green indicates that the demand is fully covered, even after failure.

Furthermore, the baseline system performance is analysed over a pseudo-transient operational profile at DP2 mode conditions (wind = 5 m/s, current = 1 m/s) involving also failure events in engine operation. Two cases are simulated and assessed in terms of energy efficiency and reliability: (a) three engines in operation; and (b) four engines in operation; both with potential loss of one engine. A repetitive transient

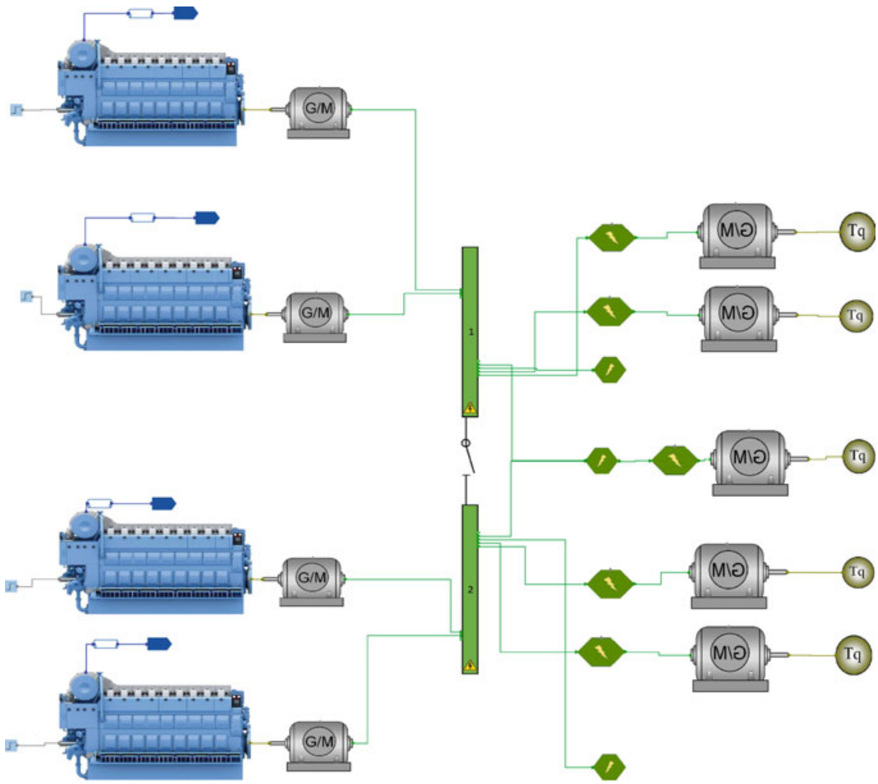

Fig. 9.1 Baseline OSV machinery system in DNV GL COSSMOS

profile around the mean expected DP2 demand of 2521 kW is considered, with a perturbation of ±600 kW being caused every 7 s by fluctuations in wind and current strength. The power production against the demand is shown in Fig. 9.2 over a time period of 1000 s.

In case of three engines in operation, the maximum power production is 3543 kW, at an engine loading of 62%. The mean engine load is 50% and the fuel consumption is 0.563 tons per hour, i.e. close to the baseline of 0.561 tons per hour without transients. In case of one engine loss, the rest two engines will operate at 92%, whereas if two engines are lost, the system will fail to cover the demand. In case of four engines in operation, the maximum engine load is 46% and the fuel consumption is 0.604 tons per hour, i.e. 8% higher than the baseline without transients. If one engine is lost out of grid, the rest three engines will cover the demand running at 62% load, whereas if two engines are lost or (a switchboard), the rest will run at 92% and the system will manage to supply power (Table 9.3).

Table 9.2 Assessment of hot reserve capacity for baseline system without batteries

	Normal operation results			case of 1 engine loss		case of 2 engines or 1 SWB loss	
Modes	Total engines in operation	Mean load per operating engine [%]	Total production [kW]	Hot reserve in [kW]	Demand that must be covered by hot reserve [kW]	Hot reserve [kW]	Demand that must be covered by hot reserve [kW]
1 day at harbour	1	17%	320	0	320	0	320
1 day at transit 11kn	2	81%	3106	368	1552	0	3105
1 day at transit 13kn	3	65%	3735	1351	1245	675	2489
1 day at standby (wind 5 m/s, current 1 m/s)	3	40%	2328	2288	776	1144	1552
1 day at standby (wind 12.5 m/s, current 3 m/s)	4	51%	3951	2797	988	1865	1975
1 day at DP2 (wind 5 m/s, current 1 m/s)	3	50%	2856	1936	952	968	1904
1 day at DP2 wind (12.5 m/s, current 3 m/s)	4	58%	4478	2402	1119	1601	2239
1 day at full power	4	80%	6126	1165	1531	777	3062
1 day at harbour	1	17%	320	0	320	0	320
1 day at transit 11kn	2	81%	3106	368	1552	0	3105

This example indicates that, at the expense of + 8% fuel consumption, a reliable operational strategy over a wide range of possible failure events is possible. The trade-off between energy efficiency and reliability is very often found in similar engineering problems (see Fig. 9.3), and MBSE tools allow the quantification of the performance at variant operating scenarios. In addition, design decisions on the engine sizing may have to consider transient conditions per mode, and possibly higher engine nominal power. Furthermore, hybridization and battery size selection to ensure system reliability is another possible option that can be tested through MBSE. The operation of the baseline system without batteries is characterized by high engine load cycling -to cover the demand peaks- affecting the maintainability of the engines. The use of batteries would instead bring significant benefits in engine cycling reduction.

9.2.5 Hybrid System Modelling and Simulation

The hybrid system model for the OSV is shown in Fig. 9.4. The system is the same as the baseline one, with the addition of batteries at a capacity of 1920MWh, capable to

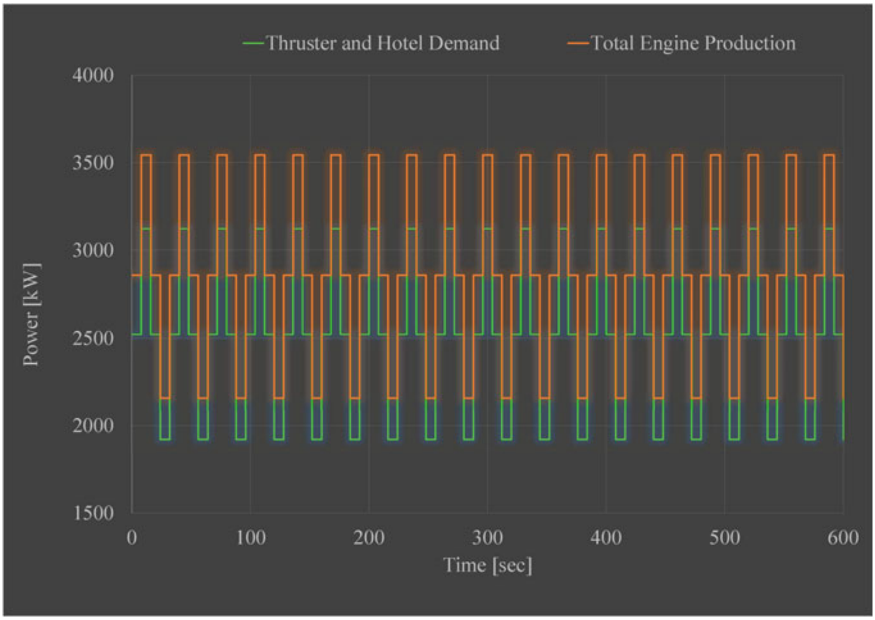

Fig. 9.2 Case of 3 engines in operation: Demand profile and engine production of the baseline system at transient conditions

Table 9.3 Assessment of hot reserve capacity for baseline system without batteries at DP2 transient operation (wind = 5 m/s, current = 1 m/s)

	Normal operation results			Case of 1 engine loss		Case of 2 engines or 1 SWB lossWmmm	
Total engines in operation	Mean load per operating engine (%)	Max load per operation engine (%)	Fuel consumption [tons per hour]	Hot reserve at worst condition (max load) [kW]	Demand that must be covered by hot reserve at worst condition (max load) [kW]	Hot reserve in worst condition (max load) [kW]	Demand that must be covered by hot reserve at worst condition (max load) [kW]
3	50	62	0.561	*1477*	*1181*	**739**	**2362**
4	37	46	0.604	*3098*	*887*	*2065*	*1775*

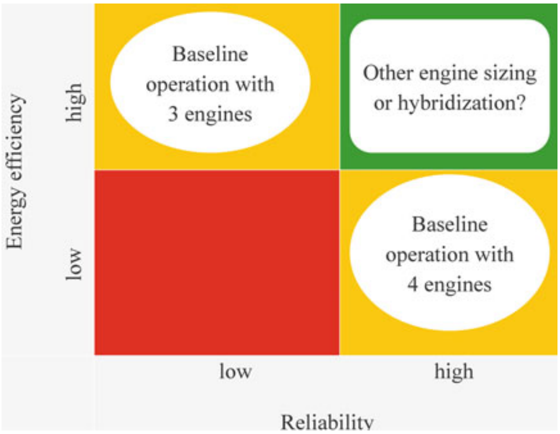

Fig. 9.3 Qualitative graphical representation of the results of the analysis of DP2 transient operation (wind = 5 m/s, current = 1 m/s), for efficiency and reliability

deliver the nominal engine throughput for 1 h. The following options of the battery management system were considered:

1. Peak shaving: Engines operation at constant load and supply of peak demands from the battery system. When the demand is lower than the average engine production plus losses, the free part of the engine load is used to charge the batteries. This mode of operation can be adjusted to reproduce operating modes where the engines are optimally loaded – close to their loading point for maximum efficiency.
2. ON/OFF: Use of the battery and shut off an engine. This mode of operation is used to avoid engine operation at low load/low efficiency. The battery supplies a threshold of the demand, so that an engine is kept off the grid. When the battery is discharged, the load of the remaining engine(s) increases to supply the demand and charge the battery. The energy efficiency benefits come from the optimal engine loading and the avoidance of running the engines at low loads, where fuel consumption is high. The cycling of the battery, on the other hand, increases.
3. Load shift: Shift part of the demand to the battery, instead of having the engines supplying this demand and charge the battery at optimal engine loading during other operating modes. The use of this mode depends on the timing of the system mission envelope and the design characteristics of the energy storage system.
4. Spinning reserve: Keep the battery at idle mode and use it as hot or spinning reserve, in case of failure.

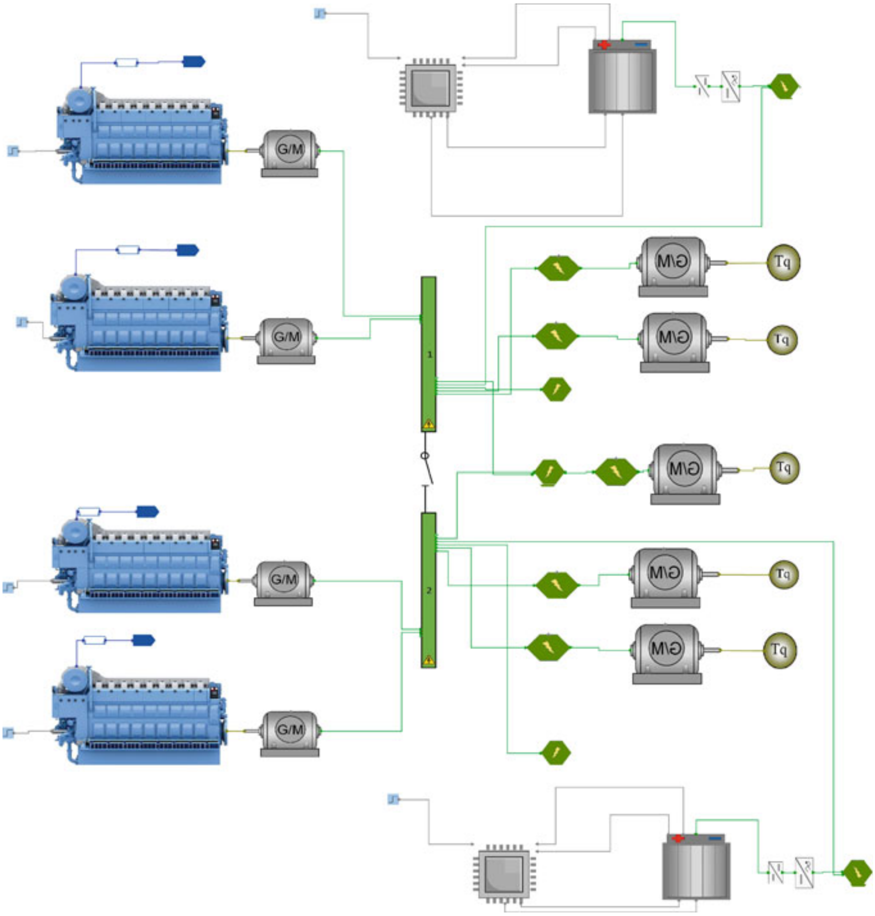

Fig. 9.4 Hybrid OSV machinery system (with batteries) modelled in DNV GL COSSMOS

9.2.6 Hybrid System Performance and Reliability Assessment

The hybrid performance at transient and failure events is assessed. The results are shown in Table 9.4 (use of battery as spinning reserve) and Table 9.5 (use of battery at ON/OFF mode). The annual vessel fuel consumption with batteries is estimated to vary between 4077.5 tons (battery ON/OFF at harbour) and 4113.3 tons (battery at spinning reserve mode), which, compared to the baseline, yields an energy efficiency improvement of between 2 and 8% per mode (where the battery is used as spinning reserve) and 3.7–4.5% in total. The use of the battery at ON/OFF mode at harbour brings an efficiency improvement of 26%, accounting for less 35 tons of fuel per year. This benefit comes with the drawback of increased battery cycling that affects maintenance negatively.

Table 9.4 Hybrid system performance at the prospective OSV operating modes. Battery is used for spinning reserve only

Operating mode	Engine loading [%]				Fuel [tons per day]	Fuel [tons per annum]	Improvement against baseline [%]
Harbour	0	0	0	17	1.94	133.91	0
Transit 11 knots	0	81	0	81	13.90	479.49	0
Transit 13 knots	0	65	65	65	16.91	583.27	0
Standby (wind = 5 m/s, current = 1 m/s)	0	60	0	60	10.59	730.86	8
Standby (wind = 12.5 m/s, current = 3 m/s)	0	68	68	68	17.77	613.18	4
DP2 (wind = 5 m/s, current = 1 m/s)	74	0	74	0	12.78	881.95	5
DP2 (wind = 12.5 m/s, current = 2 m/s)	0	78	78	78	20.02	690.60	2
Full power to main thrusters (not part of OP)	80	80	80	80	27.42	0	0
Transit with battery charging at nominal C-Rate 1920 kW from 20 to 80%	75	75	75	75	Fuel tons per charging: 0.22		

Table 9.5 Hybrid system performance at the prospective OSV operating modes. Battery is used at ON/OFF state

Operating mode	Engine loading [%]				Fuel [tons per day]	Fuel [tons per annum]	Improvement against baseline [%]
Harbour	0	0	0	77	1.42	98.14	26
Transit 11 knots	0	81	0	81	14.11	486.74	Not observed
Transit 13 knots	0	65	65	65	17.06	588.41	Not observed

In terms of hot reserve capacity (Table 9.6), some modes are shown in yellow, meaning that normal operation is not enough to cover demand in case of 2 engines failure loss. However, if these modes are operated at a more conventional manner,

Table 9.6 Hybrid system hot reserve capacity: 1920 kWh battery pack

	Normal operation results			Case of 1 engine loss		Case of 2 engines or 1 SWB loss	
Modes	Total engines in operation	Mean load per operating engine [%]	Total production [kW]	Hot reserve in [kW]	Demand that must be covered by hot reserve [kW]	Hot reserve [kW]	Demand that must be covered by hot reserve [kW]
1 day at harbour	1	17	326	*1920*	*326*	Not applied	
1 day at transit 11kn	2	81	3110	*2285*	*1555*	**1920**	**3110**
1 day at transit 13kn	3	65	3744	*3264*	*1248*	*2592*	*2496*
1 day at standby wind = 5 m/s, current = 1 m/s	2	60	2304	*2688*	*1152*	**1920**	**2304**
1 day at standby wind = 12.5 m/s, current = 2 m/s	3	68	3917	*3149*	*1306*	**2534**	**2611**
1 day at DP2 wind = 5 m/s, current = 1 m/s	2	0	2842	*2419*	*1421*	**1920**	**2842**
1 day at DP2 wind = 12.5 m/s, current = 2 m/s	3	78%	4493	*2765*	*1498*	**2342**	**2995**
1 day at Full power	4	80%	6144	*3072*	*1536*	**2688**	**3072**

i.e. with more engines in operation, the risk from loss of 2 engines is mitigated at the expense of extra fuel burnt.

This aggregated level of assessment allows only a bulk demonstration of the benefits of the hybrid system. In order to monitor the actual benefits, the simulations need to evaluate the savings from using the hybrid system at peak shaving mode in transient conditions.

9.2.7 Failure Event Analysis at DP2 Mode on a Transient Profile

The failure event of one engine loss at transient operation in DP2 mode (wind = 5 m/s, current = 1 m/s) is studied. The transient profile is the same as the one analysed for the baseline case. At normal operation, two engines supply the demand at 74% load, and the battery covers peak demands at a mean state of charge of 80% (so both spinning reserve and peak shaving condition). The engine load is constant due to battery operation and the repetitive character of the demand profile. The failure event occurs after 1 h of operation at normal conditions. One engine is assumed lost out of the grid and the system demand is covered by the other engine in operation and the batteries. After 1.3 h with the battery receiving the demand transients and the load shift from the failed engine, the battery system is at a minimum state of charge of 20%. The resulting autonomy is estimated therefore at 1.3 h. Batteries of higher capacity would result in higher autonomy at the expense of capital and maintenance expenses (this technoeconomic study can be performed at concept design stage using MBSE tools). As this transient profile is repetitive, the effect of state-of-charge reduction due to demand fluctuations is not shown here—though it can be captured by DNV GL COSSMOS.

The fuel consumption at normal operation (prior to failure) is 0.532 tons per hour. After the failure -due to the load shift to the battery- the fuel consumption drops to 0.432 tons per hour. The fuel burden to charge the battery from 20 to 80% during transit at 13knots is also estimated. These results provide valuable input both for design reliability assessment, as well as for cost-benefit analysis regarding the battery size.

In total, the battery system provides enough spinning reserve capacity to operate with less engines in DP2 compared to baseline, keeping the engine load constant with less cycling. In the failure event of two engines loss, the battery capacity and the remaining engine hot reserve is not enough to supply demand. In this case, normal operation with three engines at 50% load and peak shaving with battery could ensure enough spinning reserve to mitigate a two-engines failure event (Table 9.7), at the expense of extra fuel. Equivalent to this case, the baseline system could operate with 4 engines at 0.604 tons per hour fuel demand. Compared to the baseline system of four engines in operation, the hybrid system yields an efficiency increase of 7%.

Table 9.7 Assessment of hot reserve capacity for hybrid system at DP2 transient operation (wind = 5 m/s, current = 1 m/s)

Normal operation results			Case of 1 engine loss			Case of 2 engines or 1 SWB loss		
Total engines in operation	Load per operating engine (%)[a]	Fuel consumption [tons per hour]	Hot reserve at worst condition (max load) [kW]		Demand[b] that must be covered by hot reserve at worst condition (max load) [kW]	Hot reserve at worst condition (max load) [kW]		Demand[b] that must be covered by hot reserve at worst condition (max load) [kW]
			Engine	Battery		Engine	Battery	
2	74	0.532	499	1920	1421	0	1920	2842
3	50	0.561	1920	1920	960	960	1920	1920

[a]Constant engine loading
[b]Including losses

9.2.8 Conclusions on Risk-Based Assessment of an OSV Hybrid Machinery System

This section presented parts of a HOLISHIP application study dealing with the model-based analysis of an OSV machinery system, with and without batteries, focusing on energy efficiency and reliability. MBSE methods and tools provided quantification and understanding of the benefits from machinery hybridization with respect to energy efficiency and reliability. Design and operation conditions, as well as transient modes were analysed to conclude on the overall performance of the complex hybrid ship machinery system against its baseline counterpart without batteries. Different operating strategies were evaluated, namely peak shaving, ON/OFF, load shift and idling. The integral performance of the hybrid OSV machinery system was estimated, as shown in Table 9.8.

9.3 Model-Based Technoeconomic Assessment of a Bulk Carrier Retrofit

9.3.1 Objective and Scope

This section demonstrates the use of MBSE techniques in the holistic performance assessment and improvement of ship machinery retrofits. Retrofits aim at improving the vessels' energy efficiency and environmental performance subject to economic, safety, reliability, lifecycle and operational aspects. MBSE techniques allow the quantification of performance benefits in case of ship machinery retrofits, thereby giving valuable information to decision makers to choose the best fitting of machinery equipment alternatives to their vessels.

The present case study vessel is a Newcastlemax Bulk Carrier that operates between South America to China and North Australia to China. The study refers to the performance of a machinery retrofit technology, namely a fuel sludge recovery system (FRU). This study is part of HOLISHIP Application Case 6 (WP14).

A digital twin of the vessel's machinery and the FRU is built in DNV GL COSSMOS to act as a digital replica of the actual ship machinery, allowing the quantification of performance metrics and the analysis of alternative options of machinery systems. Both systems, namely the baseline machinery and the retrofitted system with FRU, are analysed through simulations for the entire mission profile of the vessel subject to realistic operating conditions. The results are analysed over ship's lifetime and the benefits from the retrofit solution are quantified and discussed. Background data referring to the vessel's ship machinery system and to the ship's trade patterns were provided by the collaborative HOLISHIP partner Star Bulk Carriers Corp.

Table 9.8 Hybrid system performance summary against baseline

	Performance at risk level 1 (no failure events considered)			Performance at risk level 2 (failure of 1 engine and cycling effects considered)			Performance at risk level 3 (failure of 2 engines and cycling effects considered)		
Operating mode	Fuel [tons per annum]	Improvement from baseline [%]	Engines and ESS use for the hybrid system	Fuel [tons per annum]	Improvement from baseline [%]	Engines and ESS use for the hybrid system	Fuel [tons per annum]	Improvement from baseline [%]	Engines and ESS use for the hybrid system
Harbour	133.9	0	Spinning reserve	134	0% fuel saving	Harbour	133.9	0%	Spinning reserve
	98	26	ON/OFF						
Transit 11 knots	480	0	Spinning reserve	480	0% fuel saving Autonomy for 2 h and 38mins	Spinning rezserve	498	Conservative operation with 3 engines Autonomy for 43 min	Spinning reserve
Transit 13 knots	583	0	Spinning reserve	583	0% fuel saving Autonomy for 57 min	Spinning reserve	583	Conservative operation with 3 engines Autonomy for 57 min	Spinning reserve
Standby (wind = 5 m/s, current = 1 m/s)	731	8	Spinning reserve & spinning reserve by 80%	731	8% fuel saving Autonomy for more than 1 h	Spinning reserve & Peak shaving	796	Conservative operation with 3 engines Autonomy for 33 min	Spinning reserve & Peak shaving

(continued)

Table 9.8 (continued)

	Performance at risk level 1 (no failure events considered)			Performance at risk level 2 (failure of 1 engine and cycling effects considered)			Performance at risk level 3 (failure of 2 engines and cycling effects considered)		
Operating mode	Fuel [tons per annum]	Improvement from baseline [%]	Engines and ESS use for the hybrid system	Fuel [tons per annum]	Improvement from baseline [%]	Engines and ESS use for the hybrid system	Fuel [tons per annum]	Improvement from baseline [%]	Engines and ESS use for the hybrid system
Standby (wind = 12.5 m/s, current = 3 m/s)	613	4	Spinning reserve & spinning reserve by 80%	613	4% fuel saving Autonomy for 1 h	Spinning reserve & Peak shaving	638	Conservative operation with 4 engines Autonomy for 31 min	Spinning reserve & Peak shaving
DP2 (wind = 5 m/s, current = 1 m/s)	882	5	2 engines running Peak shaving & spinning reserve by 80%	882	5%fuel saving Autonomy for 1 h and 55mins	Spinning reserve & Peak shaving	930	Conservative operation with 3 engines Autonomy for 39 min	Spinning reserve & Peak shaving
DP2 (wind = 12.5 m/s, current = 2 m/s)	691	2	Peak shaving& spinning reserve by 80%	691	2%fuel saving Autonomy for 1 h and 31mins	Spinning reserve & Peak shaving	708	Conservative operation with 4 engines Autonomy for 36 min	Spinning reserve & Peak shaving

Table 9.9 Typical ranges of operational features for the retrofit technology

Metric	Value
Nominal feed capacity [l/h]	500
Power consumption max [kW]	6
Steam consumption max [kg/h]	60
Demulsifier consumption [l/24 h]	5

The vessel machinery system includes one 2-stroke marine Diesel engine of 17,494kW MCR (max continuous rating) at 78RPM, three 4-stroke Diesel generator sets of 970 kW at 900RPM, a min engine economizer of 650 kg/h nominal steam production capacity (7 bar) and an auxiliary boiler of 2,500 kg/h nominal steam production capacity.

The retrofit FRU technology is a waste fuel minimisation system that continuously recovers fuel from the waste fuel oil that is collected by the machinery spaces of Diesel engine installations on-board ships. Input to the system are waste fuel oil from service tank drains, leakages, filters, purifiers, etc. The system recovers the wasted fuel and the separated water is led to the bilge system. Such systems separate the waste fuel oil in three phases: (a) fuel oil of low water content (less than 5%); (b) water of low oil content (less than or equal to 1000 ppm oil); and (c) super-dry solids for disposal. The system uses saturated steam to heat up the waste fuel oil inflow. A demulsifier is used to dilute the sludge and support the separation process. For the operational characteristics of the FRU, typical values publicly available from manufacturers are considered, as shown in Table 9.9.

A set of Key Performance Indicators (KPIs) is determined for energy efficiency, environmental performance, space footprint and lifecycle costs, as shown in Table 9.10. In terms of safety and reliability, it is assumed that the systems assessed have approval by Administration for onboard installation and use. The next paragraphs of this section are dedicated to the presentation of the retrofit technology, the baseline vessel performance analysis, and the techno-economic assessment of the retrofitted machinery system.

9.3.2 FRU System Modelling

To model the FRU, the technology governing mechanisms are recognized and associated with the modelling objective and KPIs, as shown in Table 9.11.

The FRU model captures the part-load performance of the system as shown in the following equations. The fuel oil consumption (FOC) per day [kg/day] can be estimated by:

$$FOC_{day} = FOC_{day}^{ME} + FOC_{day}^{AE} + FOC_{day}^{AB} \tag{9.1}$$

Table 9.10 Key performance indicators

Ship energy efficiency	Fuel recovery rate per mode of operation and year
	Fuel consumption improvement per mode and year
	Parasitic consumptions (energy and consumables)
Environmental performance	Emissions reduction per mode and year
	Sludge production per year
Space footprint	System dimensions against available space capacity in the machinery room
Cost	Capital cost
	Operational cost in terms of consumables. The parasitic fuel consumption from system operation is accounted in the energy efficiency KPIs
	Maintenance costs are assumed to be 5% of capital cost. This is just an estimate; if actual figures are available, the results can be re-evaluated
	System Net Present Value, subject to fuel price developments, current vessel age and expected lifetime

where ME is the main engine, AE are the auxiliary engines, AB is the auxiliary boiler. All the consumptions are calculated from the ship machinery model. The oil separator losses per day OSL_{day} [kg/day] are assumed as percentage of the fuel consumption:

$$OSL_{day} = 1.5\% FOC_{day} \tag{9.2}$$

The fuel recovery rate per day FR_{day} [kg/day] can be estimated by:

$$FR_{day} = 99.15\% OSL_{day} \tag{9.3}$$

The bunker water content in fuel are estimated at 0.3496%, based on past bunker data analysis; the cyclone losses are estimated at the order of 0.5% leading to a recovery rate assumed of 99.1504%. The power demand is estimated as function of partial loads [kW]:

$$P = P_{max}\left(\frac{OSL}{OSL_{max}}\right)^{0.3} \tag{9.4}$$

The exponent is assumed to be 0.3, because parasitic electric loads may not solely depend on feed flowrate, but also other sub-processes that require a bulk power demand to be operated. The demulsifier's consumption is estimated as function of partial loads [l/day]:

Table 9.11 Retrofit study KPIs and modelling specifications

KPI category	KPI	Governing mechanism	Modelling approach
Energy efficiency	Fuel recovery rate	Separation efficiency at different inflow rates	The model captures part-load performance of the system, assuming a fixed recovery rate and a variant inflow rate as function of fuel consumption
	Fuel consumption reduction	Recovered fuel is fed back to the fuel tank, reducing annual consumption	The model calculates annual fuel consumption with and without the retrofit technology
	Parasitic consumptions	The retrofit technology requires electricity, steam supply and demulsifier dose	The model captures part-load requirements of the system, assuming a fixed consumption rate per inflow rate
Environmental performance	Emissions reduction per year	Emissions reduction due to reduced fuel consumption	Emission factors are used to convert annual fuel consumption for baseline and retrofitted vessel
Space footprint	Space capacity	Manufacturer dimension data and the vessels' baseline machinery room arrangement are used to assess the machinery room space availability, for fitting in the module	
Costs	Capital costs	No cost data available for the system. Correlation to existing separation systems based on capacity are assumed; yet associated with high uncertainty	
	Operational savings	Savings from system use are calculated, based on fuel consumption reduction and fuel price assumptions	
	Operational costs	No cost data available for the system consumables. Costs from system use are calculated, based on demulsifier consumption and assuming a price range of 25 to 100USD/lt; yet associated with high uncertainty on this price range	
	Maintenance	No cost data available for the system. Correlation to CAPEX as percentage and assuming maintenance every 9 months	
	NPV	Net Present Value (NPV) calculation assuming ranges of above costs and savings, and a discount rate of 10%	

(continued)

Table 9.11 (continued)

KPI category	KPI	Governing mechanism	Modelling approach
	Fuel price	Average fuel price from 2018 to 2019 year end is used (2020 prices are excluded due to pandemic impact): 425USD/t for heavy fuel oil (HFO) and 582USD/t for Marine Diesel Oil (MDO). A fuel price development scenario is also assumed (DNV GL 2020)	

$$D = D_{max} \frac{OSL}{OSL_{max}} \tag{9.5}$$

A linear analogy between demulsifier's consumption and feed flowrate is assumed. The steam demand is assumed as z function of partial loads [kg/day]

$$ST = ST_{max} \left(\frac{OSL}{OSL_{max}} \right)^{0.8} \tag{9.6}$$

The exponent is herein assumed to be 0.8, because we assume an analogy between the heat exchanger steam demand and the incoming flowrate. In the above algorithms, P_{max} is an assumed maximum power production of 6 kW, D_{max} is the maximum demulsifier dosing, ST_{max} is a maximum steam demand and OSL_{max} is a nominal feed capacity. Prior to developing the system model, a study was conducted on the basis of past bunkering records of the bulk carrier over one year of operation (2017–2018). Data analysis aimed at determining solids' composition and sludge production amounts. The data analysis results were then used to derive the rates presented in the above algorithms (e.g. sludge production ratio, etc.). Furthermore, for estimating emissions, the emission factors of the IMO 3rd GHG study 2014 (IMO 2014) are used. Following a lifecycle approach, we use conversion factors to account for the equivalent impact of other greenhouse pollutants like CH_4 and N_2O.

9.3.3 Ship Machinery System Modelling

Figures 9.5 and 9.6 present the digital twins of the baseline vessel and the retrofitted case, respectively. The machinery models capture the part-load performance of the engines, economizer and auxiliary boiler. The engine model uses lookup tables for fuel consumption at various loads. Economizer steam production is calculated based on economizer design data for heat transport and considering the exhaust gas temper-

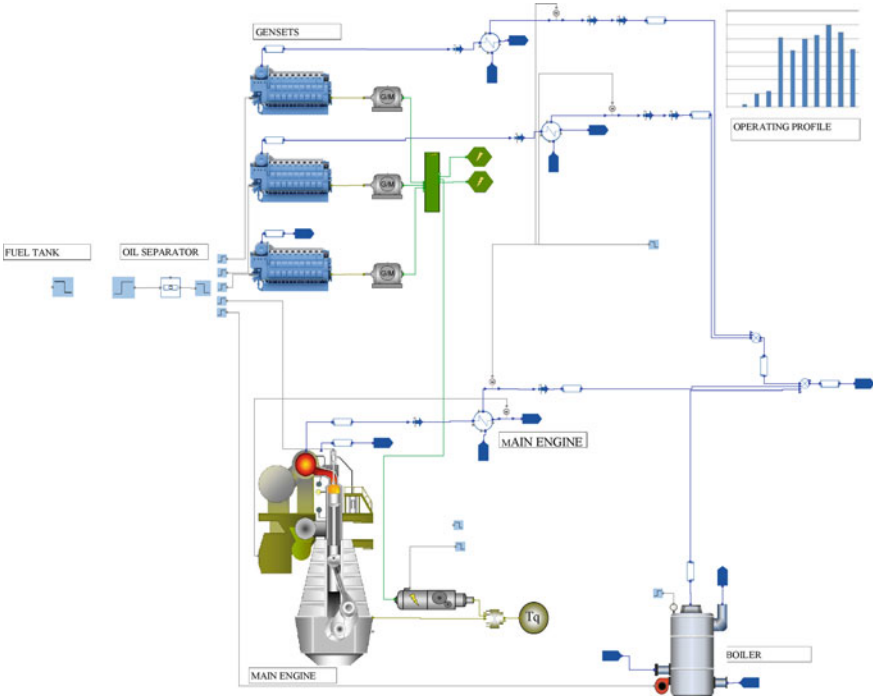

Fig. 9.5 DNV GL COSSMOS ship machinery system model without FRU: Baseline

ature and flow variation in partial loads. Auxiliary boiler consumptions are calculated as functions of boiler part-load efficiency. The models are calibrated and validated against actual information on the baseline performance of the vessel at sea trials.

9.3.4 Techno-Economic Assessment

Data on vessel's speed and operating mode are analyzed, to derive an annual mission profile, as shown in Fig. 9.7. A comparison of the propulsion power during sea trials and operation, at a certain range of vessel speeds, was done. The vessel spent 72 days in 2018 sailing at an average speed of 12.5 knots, representing most of the vessel's sailing time and meaning that the power calculations for 12.5 knots are most accurate, when compared with those for 12 and 13 knots. For these speeds, minor deviation between sea trials and operation power is observed and, thus, the power curve of sea trails can be used for propulsion power demand estimation per speed.

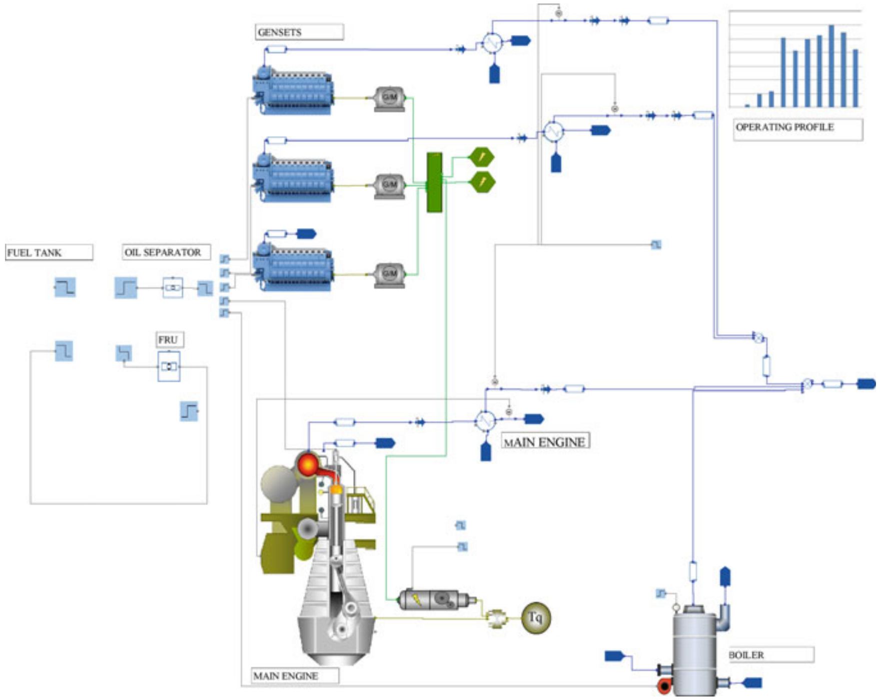

Fig. 9.6 DNV GL COSSMOS ship machinery system model with FRU: Retrofit

Using the system models with and without the retrofit technology, the annual fuel oil consumption (FOC) is calculated for both cases. Figure 9.8 shows the distribution of FOC per operating mode and speed over the year at relative values: fuel per mode as percentage of annual FOC. The absolute consumption values are not presented, for sake of confidentiality. Comparing the annual total consumptions with and without the retrofit technology, a gain of 1.4% with the FRU is estimated. Equivalent gains in terms of CO2 emissions are calculated. It is noted that the parasitic loads for FRU operations are already accounted for in the study.

Figure 9.9 shows the model results for the estimated FRU power and steam consumptions per mode. The energy consumption of the FRU per year is estimated at 15.2MWh, which is 0.24% of the annual onboard electricity production (6,355MWh). The average steam demand is estimated at 3.5 kg/h, accounting for only 0.15% of mean onboard steam demand. The maximum demulsifier consumption is 5lt/day, which for 360 days operation accounts for an upper bound of 1530lt/year. Using the expression adopted for part-load performance, the annual consumption of demulsifier is estimated in the order of 50 lt per year.Wmm.

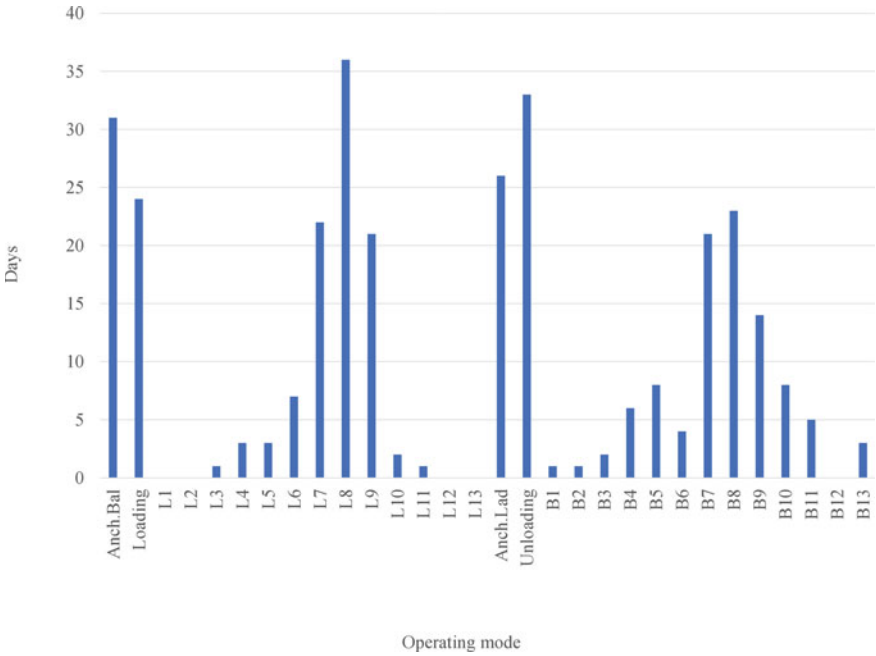

Fig. 9.7 Annual operating profile per mode: Days per mode

Based on the model results on the potential annual fuel savings and system consumptions, the breakeven FRU capital cost is estimated in the order of 320 kUSD assuming a discount rate of 8%, a fuel price of 425USD/ton (average 2018–2019 IFO380 price), a demulsifier price of 50USD/lt, a 5% maintenance cost over CAPEX, and a life expectancy of 21 years for the vessel. Yet, this value is subject to the assumptions made for fuel and demulsifier costs, as well as the modelling of the FRU recovery efficiency at partial loads. If more detailed information about the FRU technology performance is provided, then the models can be recalibrated and used to update the results of the technoeconomic analysis.

The cost calculations are repeated for a hypothetical fuel price development scenario with the following characteristics:

a. The low fuel prices due to COVID19 implications are reduced for a period of 2 years, getting the price back to average 461USD/ton in 2022.
b. A price fluctuation every 5 years is also assumed.

Under these conditions, the breakeven FRU price is estimated at 300 kUSD. If detailed data on system part-load performance and consumptions are provided, these values will change.

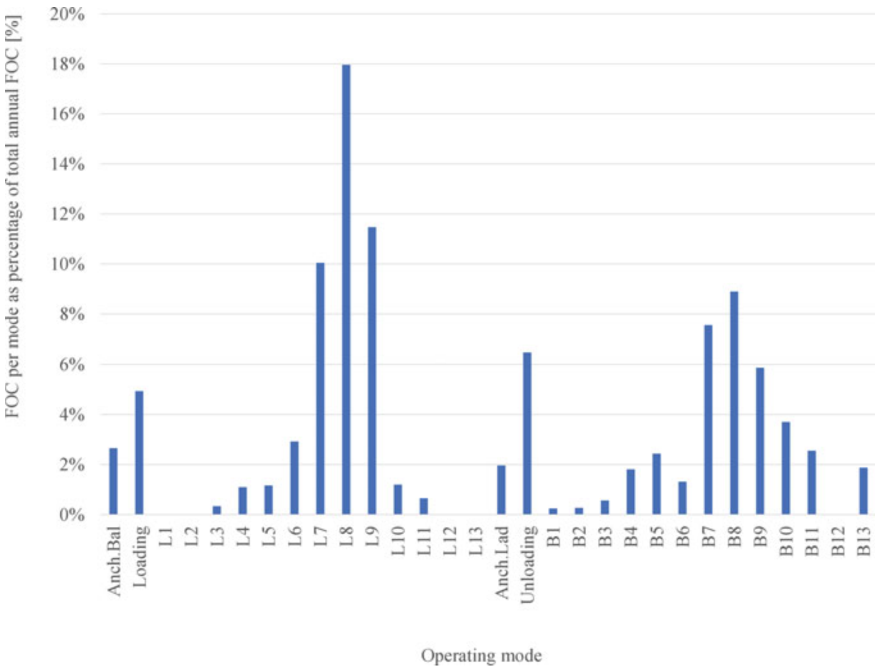

Fig. 9.8 Baseline system: Fuel consumption per mode as percentage of total annual consumption

9.3.5 Conclusions on Model-Based Technoeconomic Assessment of a Bulk Carrier Retrofit

MBSE methods were used to analyse the baseline performance of a Newcastlemax bulk carrier over a year and to estimate the potential fuel and emission reduction benefits by retrofitting with a fuel recovery from sludge unit (FRU). The performance improvement was estimated at 1.4% subject to modelling assumptions related to the technology part-load performance. The breakeven capital cost of the technology was estimated for zero net present value of the investment, accounting for assumptions on fuel and chemical consumption prices. The study demonstrated how advanced engineering tools can structurally assess various aspects related to the adoption of a novel technology onboard an existing vessel, providing quantitative results and thus important support for decision making.

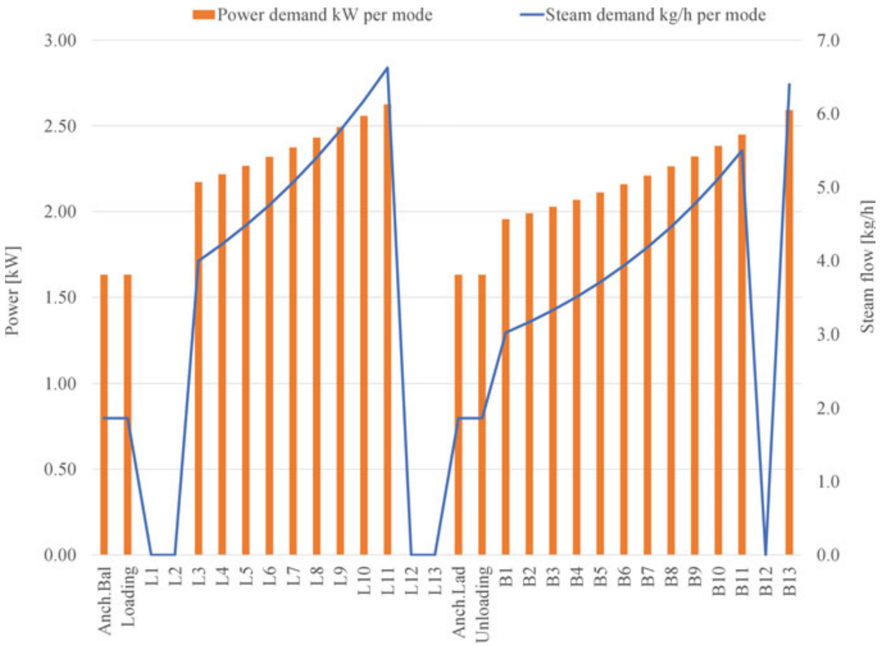

Fig. 9.9 Retrofit system: Estimated FRU power and steam flow demand per operating mode and speed

Acknowledgments The authors would like to acknowledge the contribution of Mr. Alexis Papadatos, Star Bulk Carriers Corp., and Dr. Sverre Torben, Martijn Peter De Jongh, Lars Husdal, Michel Rejani Miyazaki, Bjørnar Vik and Paulo Macedo, Kongsberg Marine, for their contribution and support in conducting the presented work. The authors would like also to acknowledge the contribution of Mr. Jason Stefanatos for his knowledge and expert advice on hybrid systems.

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Chapter 10
Gravity Base Foundation Concept for a Platform in Icy Shallow Waters

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Abstract The currently available foundation options capable of handling both ice and wave loads on offshore structures are very few. In most cases, even the few available design options create high wave and/or ice loads, of which they must be able to withstand. In addition, the construction and installation procedures of these foundations are challenging to undertake due to often high environmental loads, short weather windows, and limited accessibility. This Application Case within WP15 of the HOLISHIP project refers to the conceptual design of an offshore foundation concept to manage both wave and ice loads in shallow waters with soft bottom seabed. Specifically, this chapter outlines the concept design, the structural analysis, and early project cost estimates of the construction, transportation and on-site installation. The

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A. Papanikolaou (ed.), *A Holistic Approach to Ship Design*,
https://doi.org/10.1007/978-3-030-71091-0_10

adopted approach is holistic by looking into all main issues of the platform design, of construction installation and life-cycle cost. The application area selected for this study is the Northeast Caspian Sea. However, the concept is also well suited for other regions of the world with similar conditions. The concept can be used in hydrocarbon field development, bridge piers, oil piers (offshore loading facilities), wind turbine foundations, channel markers, lighthouse foundations, dolphins and harbour berth wall structures. In the concept development work, basic structural assessment and cost estimation tools and models have been developed. They have been integrated into the HOLISHIP concept design platform based on CAESES® enabling the iterative or optimisation designs in future feasibility studies.

Keywords Gravity base foundation · Caspian Sea · Offshore platform · Transportation and installation · Shallow water · Wind energy · Arctic oil and gas · Soil model · Soil-structure-interaction · Finite Element Method · Structural analysis · Ice load · Soft soil

Abbreviations

AC	Application Case
BH	Backhoe dredger
CMT	Center of Maritime Technologies gGmbH
GBF	Gravity base foundation
HOLISHIP	HOLIstic optimisation of SHIP design and operation for lifecycle
MOGA	Multi-Objective Genetic Algorithm
R&I	Soil **r**eplacement and caisson **i**nfilling
SSI	Soil-structure-interaction
T&I	Transportation and installation
WP	Work Package as defined in the HOLISHIP Project

10.1 Introduction

10.1.1 Background

High competition among players in the hydrocarbon industry has increased the demand for cost effective solutions in hydrocarbon fields development especially in the shallow waters of the Arctic and sub-Arctic cold climate regions.

Similar competition exists in the offshore wind energy industry. This is driving investors to look for cost-efficient solutions for offshore wind power development. According to the New York Energy Policy Institute, as cited in Brown et al. (2015), offshore wind turbine foundations account for roughly 50% of the total cost for offshore windfarm development. Hence, a cost-efficient foundation will outperform its rivals in a competition for funding, and ultimately deliver a high return on investment.

A cost-efficient or cost-effective foundation, in the context of this report, is one that is cheaper, quicker to construct and install, environmentally friendlier and yet safe to operate.

An offshore platform is made up of a topside and a foundation, also known as substructure herein. Generally, the topsides of oil platforms are the steel structures that hold the spaces for crew quarters, production facilities and/or drilling rigs. The foundation, on the other hand, provides the base for the topside at a height safely above the sea level. In some cases, oil platform foundations also house oil and gas drilling and/or extraction equipment. The foundation and topside are usually constructed individually and joined together afterwards at an offshore or inshore location.

Elomatic Oy, a Finnish engineering company and the leader of this work package (WP) of the HOLISHIP project (2016–2020), has developed a novel gravity base foundation (GBF) concept for the ice infested shallow waters of cold climate regions. The concept's structural performance, including the development of simulation tools, was performed by *S.M.I.L.E.-FEM gGmbH*, a German Engineering Company. The turnkey cost estimation, including the development of tools, was performed by the German engineering *Center of Maritime Technologies (CMT) gGmbH*. The turnkey cost estimates also include the transportation and installation (T&I) of the foundation.

As shown in Fig. 10.1, the basic idea behind the foundation concept is utilising the technology of ice-resistant steel foundations with gravel infill to produce a GBF. That is, after prefabricated thin walled circular steel shells are installed at site, they are filled with gravel to avoid stability issues, namely overturning and sliding. The structure's overturning or slipping resistance can be improved by adding a ring footing to give anchorage. For high ice loads, the steel shells may require stiffening.

The technology of ice-resistant steel foundations has been in existence for more than a century and has been applied in the construction of bridge piers, oil piers (offshore loading facilities), channel markers, lighthouse foundations, wind turbine foundations (See Fig. 10.2), and harbours (dolphins and berth wall structures) in cold climate regions.

Section 10.2 of the present report provides a deeper explanation of the concept. This solution is cost-efficient and provides the owner with the possibility of expanding an oil drilling and exploitation platform into a production complex (see Fig. 10.3) that can be easily decommissioned and/or moved to another site. It is environmentally friendlier and a very good alternative to the use of artificial islands usually encountered in icy shallow waters; typical examples are the artificial islands of the Kashagan Offshore Oil Field in the Northeast Caspian Sea (see Fig. 10.4).

Fig. 10.1 Model testing of Elomatic's Multi-Caisson Structure Module

Fig. 10.2 An ice-resistant steel wind turbine foundation with gravel infill in icy waters in the Gulf of Bothnia (Hyötytuuli 2020)

Fig. 10.3 Illustration of a production complex built around Elomatic's Multi-Caisson Structure Modules

Fig. 10.4 Some artificial Islands in the Kashagan Field (Greenberg 2012)

10.1.2 Gravity Base Offshore Foundations

A GBF, as the name suggests, is a foundation concept that can resist stability losses (overturning and sliding) and local loads by relying on its own mass.

GBFs can be manufactured from just concrete, steel, or a blend of steel and concrete. Over the years, worldwide, different companies have developed different GBF solutions for different water depths, seabed conditions, and environmental loads. Generally, GBFs are the preferred solutions for shallow waters, even up to 60 m water depth, because they are usually economical and safe (Ulrich-Evers and Hoog 2015; Attari et al. 2016). The foundation provides the basis for facilities and operations, like hydrocarbon development drilling and production, fitting of wind turbines, heliport, crew accommodations, etc.

10.1.3 Objectives

Figure 10.5 shows the design process of this application case in the HOLISHIP Project. Some tasks results are to be delivered as part of the Deliverable D15.2.

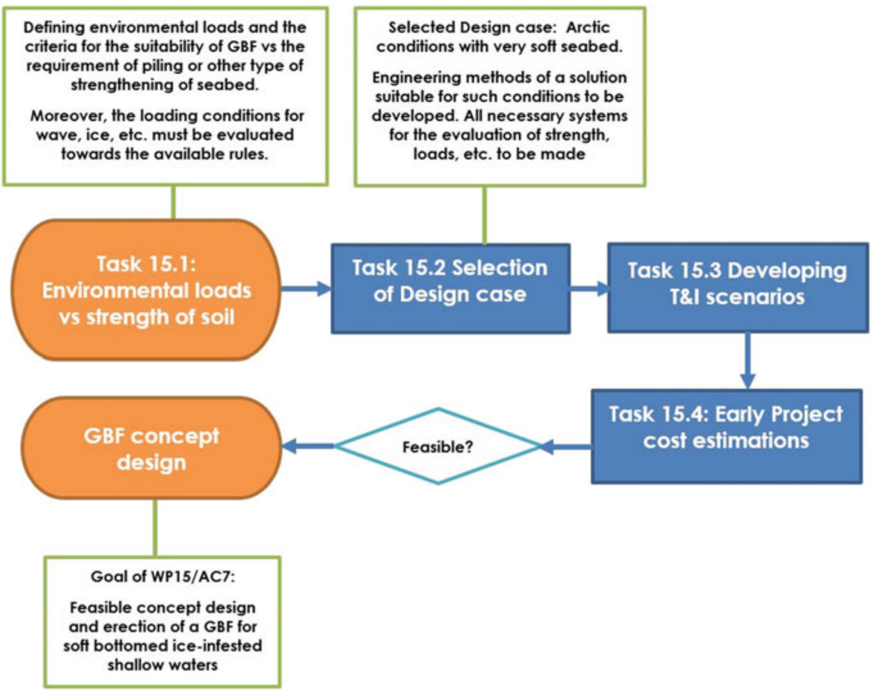


Fig. 10.5 Illustration of the design process of WP15/AC7

Work Package 15 (WP15), as defined in the HOLISHIP Project, is a task about an Offshore Foundation Design. The Offshore Foundation Design task, also referred to as Application Case 7 (AC7), and WP15 are used interchangeably in this report, and they practically mean the same.

The *first objective* of the study is to make a concept design, including its structural analysis, of an offshore foundation, for hydrocarbon field development, for *shallow ice infested waters with soft bottom seabed*. As the name suggests, soft bottom, is the type of seabed that has mostly fine-grained sediments, mud and sand.

The shallow waters of the Northern Caspian Sea are an important area for hydrocarbon development, and have, therefore, been chosen as an application area for the concept. The proposed foundation concept for oil drilling and production in the area must be a cost-efficient alternative to the artificial islands that are currently being used (see Fig. 10.3). The concept should also be able to be *applied in other potential areas of hydrocarbon development, such as the shallow waters* of the Russian and Canadian Arctic regions.

In addition to the foundation design, owners or clients usually request support information (consultancy) about the means of T&I of the foundation, as well as its maintenance. The remoteness of the potential areas, like the Northern Caspian Sea and the Russian Arctic Coasts, means weak industrial infrastructure. Also, offshore construction equipment there is limited, or is non-existent, or has major capacity limitations. It is important to also consider that such areas pose a challenge of seasonal construction limitations. They may have just 3 months weather window for foundation erection. Hence, the *second objective* of the presented study is to develop the accompanying T&I scenarios for the concept, while the T&I solutions should be easy and feasible. This will extend the foundation's concept selling point beyond the concept design.

The *third objective* is to undertake early cost estimations for the foundation and the associated T&I in the Life-Cycle approach of the HOLISHIP project. This will help to minimize the risk of hidden costs and to make judgements on the financial feasibility of the project at an early stage.

In the end, this study should contribute to the overall goal of the HOLISHIP Project by developing tools, mainly for structural assessment and project cost estimation, to assist in future technical and economic feasibility studies of the GBF concept. These tools should be integrated into the HOLISHIP concept design platform based on CAESES® for easy iterative optimisation design.

The goal of the HOLISHIP project is to "*develop innovative, holistic ship design optimisation methods, in which all main design functional requirements, constraints and performance indicators are considered. This includes development of software tools for multi-objective and multi-disciplinary holistic system optimisation and integration to design ships and offshore structures for life-cycle operation*".

For the optimization work, the main selected objectives, in this study, are:

- Total project cost
- Total project duration

- Maximum deformation. Deformation, in this case, refers to the sinking of the foundation (that is, the settlement of the soil underneath the foundation) caused by the various loads.

For example, if *Total project cost* is the optimisation objective, the user inputs the *Total project cost* value in CAESES®. CAESES® will then run a series of iterations and return the caisson geometry and lightweight as well as the soil replacement that delivers the user's cost input. Another way is the user selects the *Total project cost* as the main objective within the optimization engine. CAESES® will then run a series of iterations and return the caisson geometry and lightweight as well as the soil replacement with the *Minimum total project cost*.

Structural assessment (or deformation assessment) can, afterwards, be performed on the resulting caisson (or GBF), if desired or automatically. The results of the structural assessment are the maximum deformation as well as the radius or width of the replacement area. For this assessment, CAESES® works with ANSYS Mechanical to return the maximum deformations.

For the total project cost and duration optimisation, CAESES® works with the Caisson Geometry Check Excel Tool and the Turnkey Cost Estimation Excel Tool. These Excel tools have been created as part of WP15 and have been described in Sects. 10.4.2 and 10.5.2. The results of the optimisation, in this case, are only the caisson geometry and lightweight as well as the soil replacement.

At the time of writing this chapter, additional work was being done on the optimization process. Hence, additional objectives will be defined in the upcoming Deliverable 15.2. In addition, refinement of the optimization process will be made.

10.2 Modular Offshore Foundation Concept

This Sect. 10.2 presents an innovative GBF concept proposal for a drilling and production platform in the Northeast Caspian Sea as an alternative to artificial islands. The concept is also suitable for other purposes, like the foundation of a heliport, of crew accommodation, of wind turbine, etc.

It is worth noting that artificial islands are more expensive and slower to construct and less friendly to the marine environment. Construction of an artificial island involves huge dredging operations and the use of huge quantities of rock materials; hence, posing potentially huge decommissioning challenges.

The concept proposal, from this study, however, is cheaper, less harmful to the marine environment, and yet safe to operate. It provides the owner with the possibility of expanding an oil drilling or extraction platform into a production complex (as illustrated in Fig. 10.4), easy decommissioning and/or moving the foundation to another site.

10.2.1 Functional Requirements

The concept has been developed for

- Shallow water
- Icy condition
- Soft soil

10.2.2 Basic Structure

The support structure for the offshore platform in the present concept consists of a stiffened steel shell without any bottom and cover structure. The concept is illustrated in Figs. 10.1, 10.3 and 10.6. The circular steel shell is filled with granular material, normally gravel. The filling gives stability to the steel shell under environmental loads against buckling and sliding by adding weight and friction force. The soil (seabed) supports the shell, the infill and topsides. The loads against the seabed are both gravitational and environmental.

In most cases the vertical load due to the topsides is necessary to put on the infill, either totally or in combination with the steel structure. To do that it may be practical to cast cover of concrete or to use beams to transfer the load.

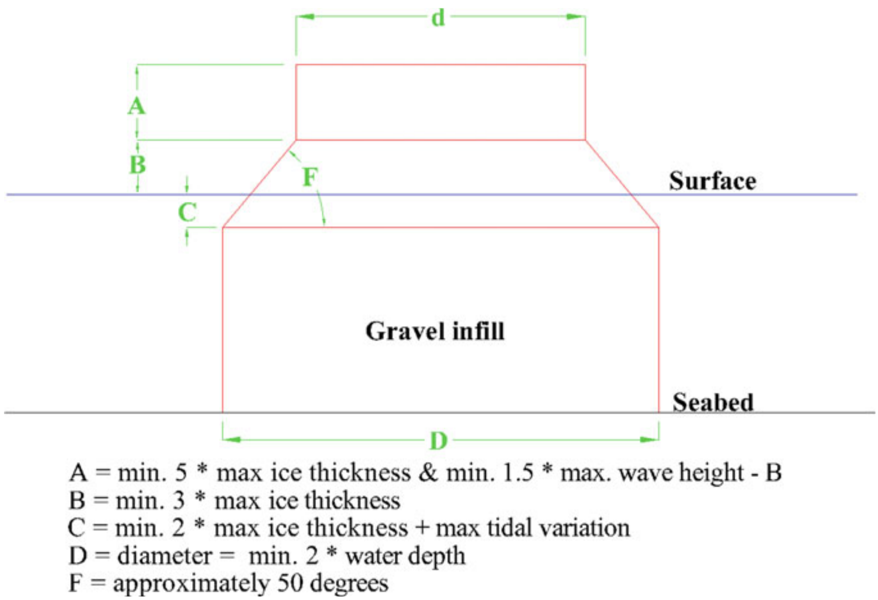


Fig. 10.6 Parametrized form of the caisson of the GBF platform

For applications where a considerable large area of platform topsides is required, several support structures in a cluster may be installed.

The topsides may be installed either by using a heavy lift crane vessel or by using the skidding-method from a barge. For clustered support structures also a *float-over technique* may be applied.

10.2.3 Basic Dimensions

Based on Elomatic's experience and expertise, the initial model, as shown in Fig. 10.6, is created in a parametrized form to understand the dependence of various dimensions on each other. The height of the lower cylindrical shell depends on the water depth. For icy conditions there may be at the surface level an inclined (conical) section to facilitate the ice breaking and thus to decrease the horizontal loads due to the pressure caused by the moving ice. Its' height depends on the foreseeable fluctuations of the surface of the water and/or maximum tidal variation. The height of the upper cylindrical section depends on the height of the foreseeable waves and ice mounds. Based on the site conditions selected for this application case, the resulting caisson dimensions are given in Fig. 10.7.

The caisson is stiffened with bulb flats every 600 mm in vertical direction and small and large T-profiles in circumferential direction, five in total, see Fig. 10.8.

As already explained, the caisson geometrical dimensions are dependent on the site conditions (as a minimum requirement), the foundation's purpose as well as the optimisation objectives.

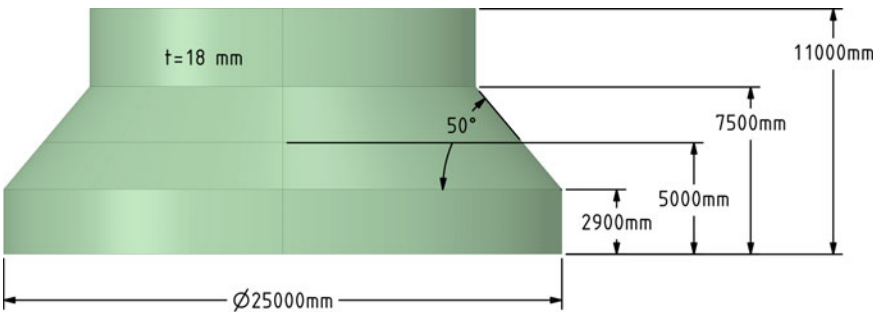


Fig. 10.7 Dimensions of the GBF in the specific application case

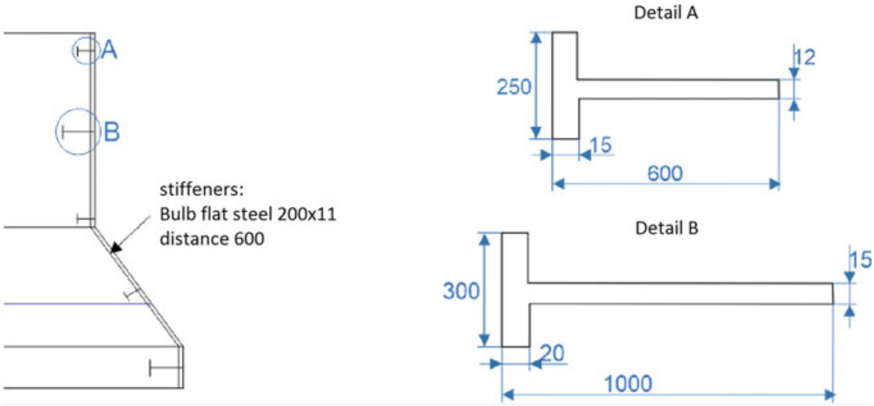


Fig. 10.8 Drawing of the steel caisson structure

10.2.4 Design Loads

For demonstration of the employed analysis method and in order to verify its feasibility, a case study is conducted. The following loads are defined on defining the input side:

The self-weight of the structure is implemented by applying gravitational forces to the employed finite element model (FEM).

It is assumed that about 1/100 of the volume of the superstructure is made of steel, which results in a vertical force due to the *weight of the superstructure of 12.24 MN.*

Live load is supposed to cause a vertical force of 9.81 MN. Live load, in the context of this study, refers to all non-permanent (usually of short duration) or moving loads. "Live load" in Civil Engineering is synonymous to "deadweight" in Naval Architecture.

The generated buoyancy force of the submersed structure is calculated using the Archimedean principle (Meyer-Bohe 2017). The volume of the submersed structure is 2315.4 m^3, which results (with a density of water of 1025 kg/m^3) in an *upward vertical force of 23.28 MN*.

Wind load is calculated separately for the topside, cylindrical part, and conical part of the foundation according to the American Petroleum Institute (2000), with an assumed wind speed of 50 m/s and air density of 1.515 kg/m^3. This leads to *horizontal forces of 2.55 MN (topside), 0.32 MN (cylindrical part), and 0.11 MN (conical part).*

Current velocity is assumed to be 1 m/s which according to the American Petroleum Institute (2000) leads to a *drag force of 0.15 MN*.

Wave loads are estimated for a slightly different platform using ANSYS AQWA panel code software. This calculation is documented in Kimmling (2017). The result of this calculation is a *horizontal force due to wave load of 8.48 MN*.

The maximum ice action on a sloping structure caused by level ice is a function of several different parameters. Theoretical models developed to calculate level ice actions on sloping structures can provide reasonably accurate estimates of ice action. A number of methods to determine ice actions on sloping structures have been developed. The Ralston's formula used here is based on the theory of plasticity (Det Norske Veritas AS 2014; International Organization for Standardization 2010) and comprises one part expressing the breaking force due to bending of the ice and a second part expressing the ride-up force. *Level ice thickness is assumed to be 1 m* (without snow cover). This results in *a horizontal force of 7.17 MN* and a *vertical force of 2.91 MN*.

10.2.5 Application Area

Northeast Caspian Sea is selected for the application area that is rich in hydrocarbons. The water depth in most parts of the area is below 5 m.

Because of the continental climate, the winter season is cold. During most part of winter, the area is covered by ice. Salinity of the water is close to zero, mainly due to the Volga river. As a result, the sea's ice strength is similar to that of a lake.

The ice thickness may reach up to 0.6 m. This means that service vessels in the area need to be ice-classed and may need assistance by icebreakers.

10.2.6 Material Properties

The properties of the soil (seabed) can vary in very wide range. There are soil types which are very soft, and they do not provide a good base for this type of design. On the other hand, there exists hard types of soil, like rock and almost unlimited number of types in between.

If the soft layer is relatively thin it may be removed and replaced by a suitable material, for instance gravel. At least a thin infill layer is recommended to ensure that the base for the stiffened steel structure is even and horizontal.

It is important to perform a solid survey at the exact location of the platform installation site, because the properties of the soil may vary much depending on the location and time period.

For this application case, Table 10.1 and Fig. 10.9 summarize the selected soil and steel properties used.

Table 10.1 Material properties

	Soil layer			Infill and soil replacement	Steel
	1	2	4		
Density ρ [g/cm³]	2.63	2.63	2.66	2.3	7.85
E-modulus E [MPa]	1.20	10.9	36.6	1836	200,000
Poisson's ratio ν [−]	0.26	0.26	0.30	0.35	0.3
Frictional angle ϕ [°]	0	32.7	34.4	42	–
Cohesion c [MPa]	0	11.0	8.0	0	–

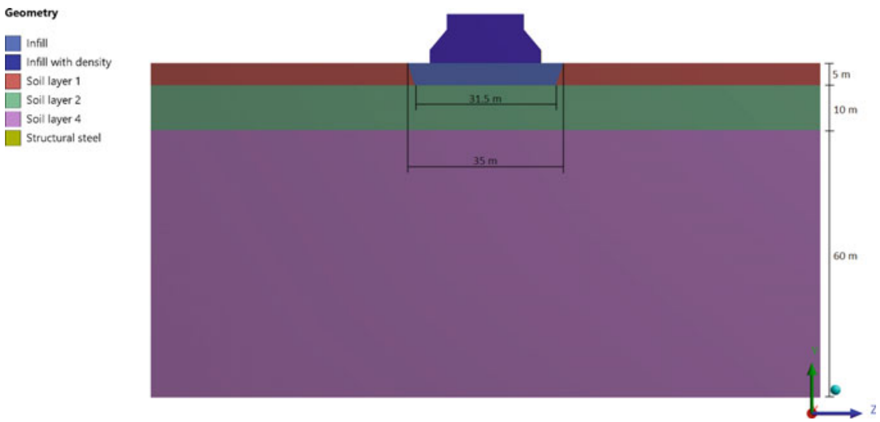


Fig. 10.9 Height of soil layers and soil replacement

10.3 Structural Assessment

This Sect. 10.3 presents the overview of the structural analysis of the concept described in Sect. 10.2.

10.3.1 Steel Shell Structural Assessment

A quasi 2D-model is used to study the influence of the stiffeners. Only the circumferential stiffeners are considered (T-profiles) due to the fact that the stiffeners are mostly subjected to vertical loads so that the vertical ribs have hardly any influence on the power transmission of the infill on the steel structure.

Only one stiffener is considered to simplify the FEM-model. Another simplification consists of the conservative assumption that only the small stiffeners are used.

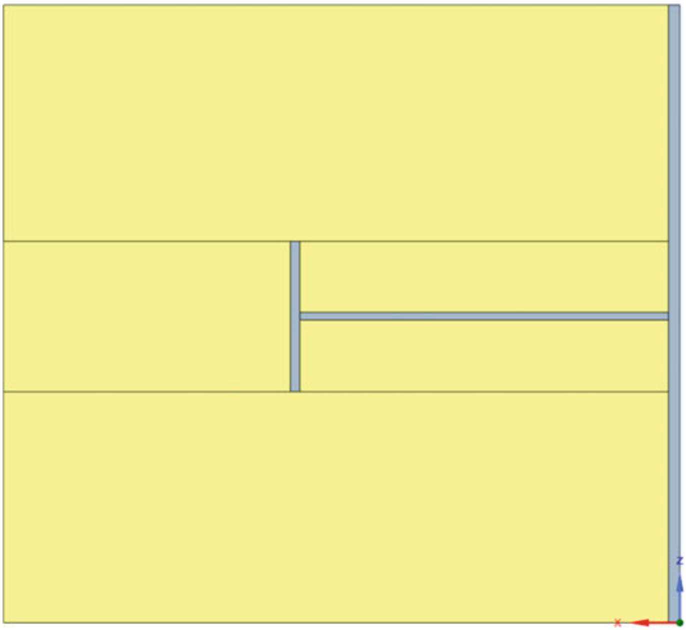


Fig. 10.10 Geometry of the quasi 2D-model for the stiffener-soil-interaction

The complete model represents a rectangle with a size of 980 mm × 1055 mm and a depth of 18 mm, whereby it is only a quasi-2D model due to its depth. It is modelled as a cuboid, since it can be assumed that the diameter of 25 m of the caisson has only a very small influence on the effect and accordingly the curvature of the housing can be neglected. The dimensions of the stiffeners are according to detail A in Fig. 10.8. The stiffener is attached to the steel caisson which is 18 mm thick. The remaining free area of the rectangle is filled and represents the infill. The model is shown in Fig. 10.10.

The steel housing and the adjacent profile have a linear elastic material behaviour and are made of steel. The required values are shown in Table 10.1. A linear elastic material is used to describe the behaviour of the infill, as no plasticity takes place under the applied load. The infill material shown in Table 10.1 is used.

The contact between infill and steel is conservatively assumed to be frictionless to allow the infill to slide along the steel caisson. A displacement of 0 mm is applied to the three outer rims of the infill.

The load on the steel stiffener depends on the displacement of the infill which is calculated analytically according to DIN 4019:2015–05 (2015).

$$S = \frac{\pi}{2} \cdot (1 - v^2) \cdot \sigma_z \cdot \frac{r}{E} \qquad (10.1)$$

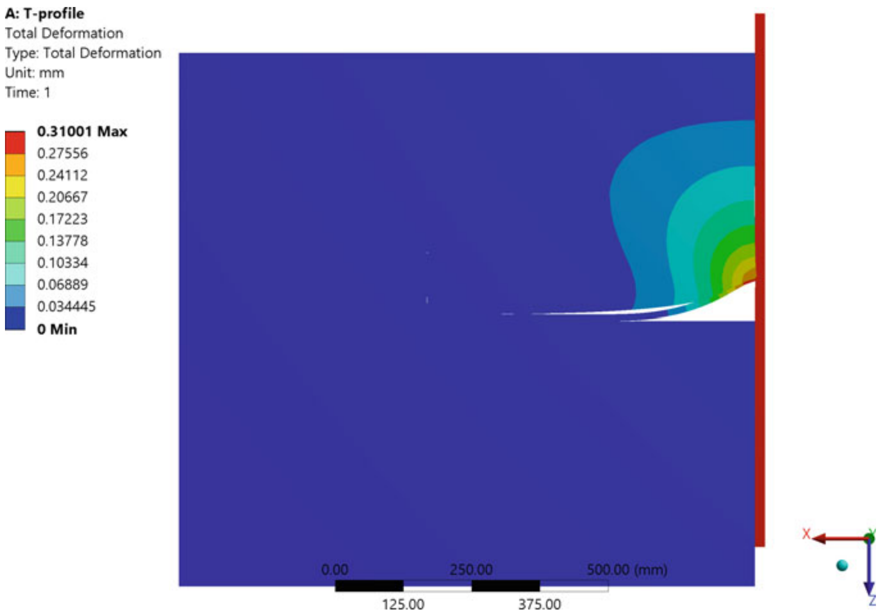


Fig. 10.11 Displaced quasi-2D model (scaled by 230)

The initial stress due to settlement σ_z is calculated using the upper infill diameter of 17,244 mm and the vertical force induced by the topside and live load of 22.4 MN. This leads to a settlement of 0.31 mm. This displacement is applied to the steel caisson in the FE-model. Figure 10.11 shows the displaced T-profile with surrounding infill. The displacements lead to a maximum equivalent von Mises stress inside the T-profile of 97 MPa, see Fig. 10.12. This is below the yield strength of structural steel.

10.3.2 Soil-Structure-Interaction

Different soil modelling technics have been evaluated and are documented in Kimmling (2017). The technic chosen here is to model the soil as a solid half model to obtain realistic deformation behaviour.

The representation of the soil by a linear elastic material model inside ANSYS static analysis allows a good first assessment of the settlement of the foundation. A half model is used to use symmetry and reduce the number of elements and therefore calculation time. The width and depth of the half model is 5 times the lower diameter of the foundation (see Fig. 10.13) to ensure that the boundary conditions do not influence the deformation behaviour underneath the foundation.

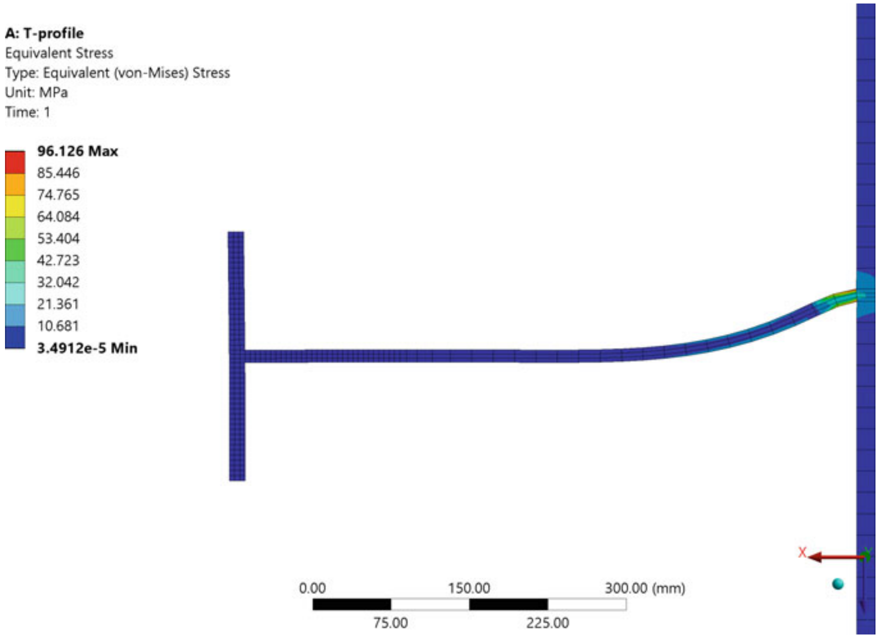


Fig. 10.12 Equivalent von Mises stress in the T-profile

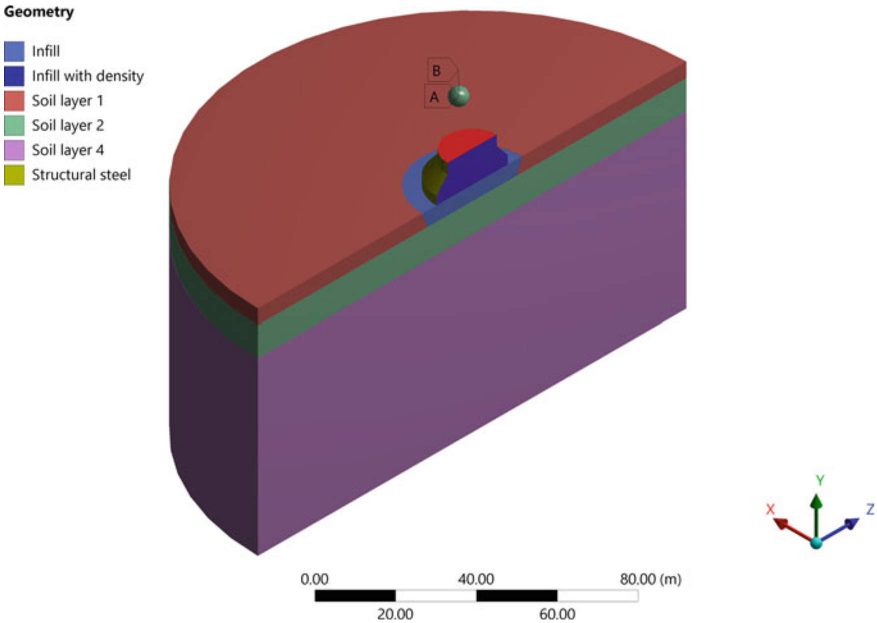


Fig. 10.13 ANSYS Half model of the soil, caisson and infill

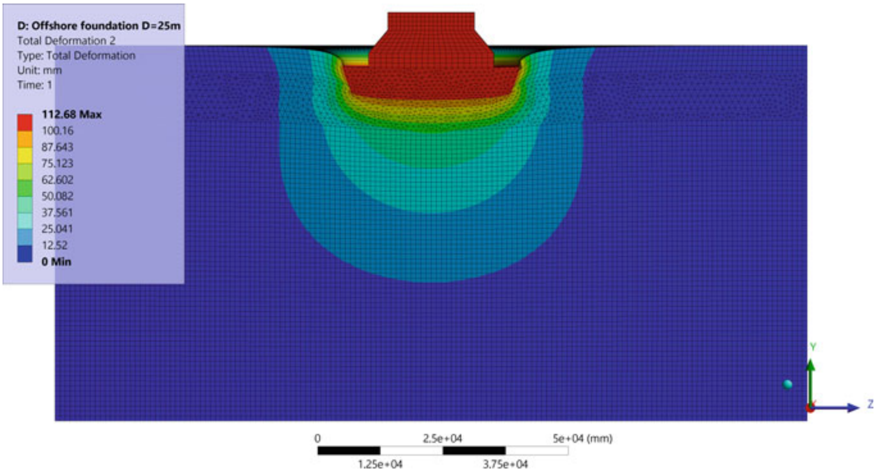


Fig. 10.14 Deformation of the foundation and the soil under vertical load

The displacement of the symmetry area is fixed in global x-direction. A fixed support is applied to the bottom and the outer shell of the soil half model. The soil is connected to the gravel with bonded contacts and whilst the caisson to gravel is with frictionless contacts. To analyse the influences of vertical and horizontal forces, three load steps have been implemented, the first one including the vertical forces, the second one including all forces but ice load, the third one including all forces but wave load. The steel caisson is modelled without stiffeners, as they have been analysed earlier.

Figures 10.14 and 10.15 show the deformation in load case 1 (all vertical loads: gravity and buoyancy) and load case 2 (all loads but ice loads). These two are the worst-case load cases including horizontal load. A scale factor of 40 is used. The maximum total deformation is 141 mm, about 28 mm are due to the additional horizontal force and the resulting tilting of the foundation.

The resulting displacements in our example calculation are too high and shall be limited to a certain value. This is an application case for the parameterization tool CAESES®, which will be shown in Sect. 10.5.

Figures 10.16 and 10.17 show the equivalent elastic strain inside the soil for load case 1 and 2. The strain mostly occurs inside soil layer 1 and 2, the soil replacement and the infill mostly remain their shape. This shows that the infill properties affect the displacement only slightly and most of the displacement is due to the very soft properties of soil layers 1 and 2. The height of the soil replacement does not affect the displacement found in the analysis, but by increasing the width of the replacement area, the deformation due to gravity could be reduced.

The equivalent von Mises stress inside the steel caisson under vertical and horizontal load is shown in Fig. 10.18. The maximum of 44 MPa is due to a numerical peak stress at one element. The overall maximum inside the steel caisson is 32 MPa, which is lower than the stress inside the T-profiles estimated in Sect. 10.3.1.

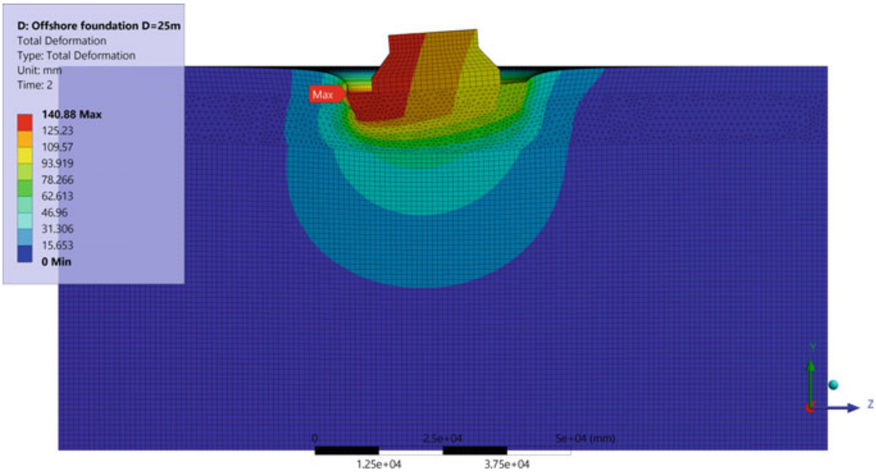


Fig. 10.15 Deformation of the foundation and the soil under vertical and horizontal load excluding ice load

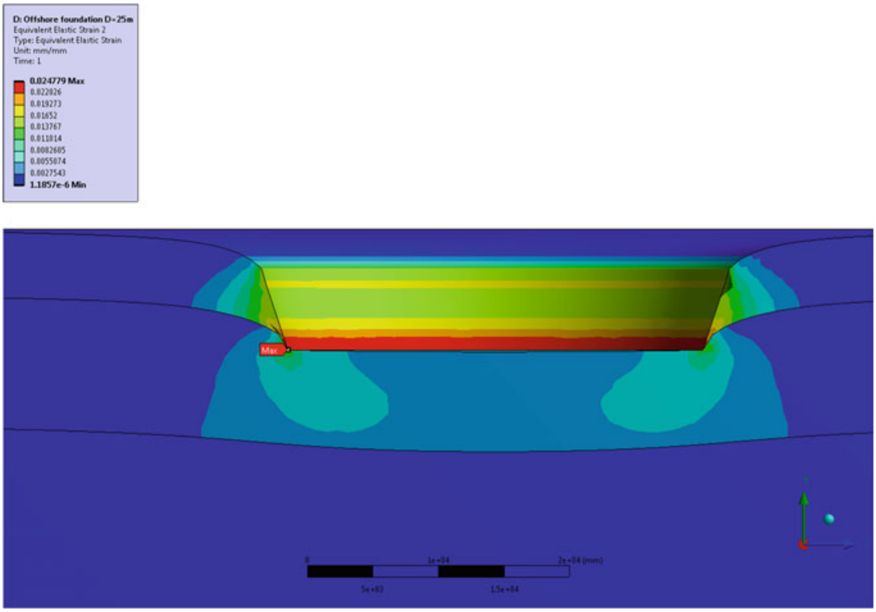


Fig. 10.16 Equivalent elastic strain inside the soil under vertical load

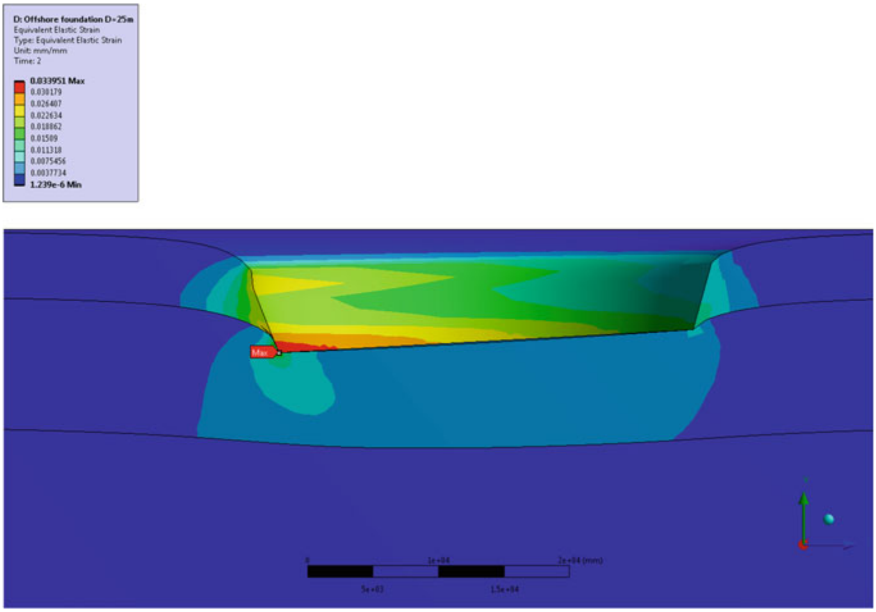


Fig. 10.17 Equivalent elastic strain inside the soil under vertical and horizontal load excluding ice load

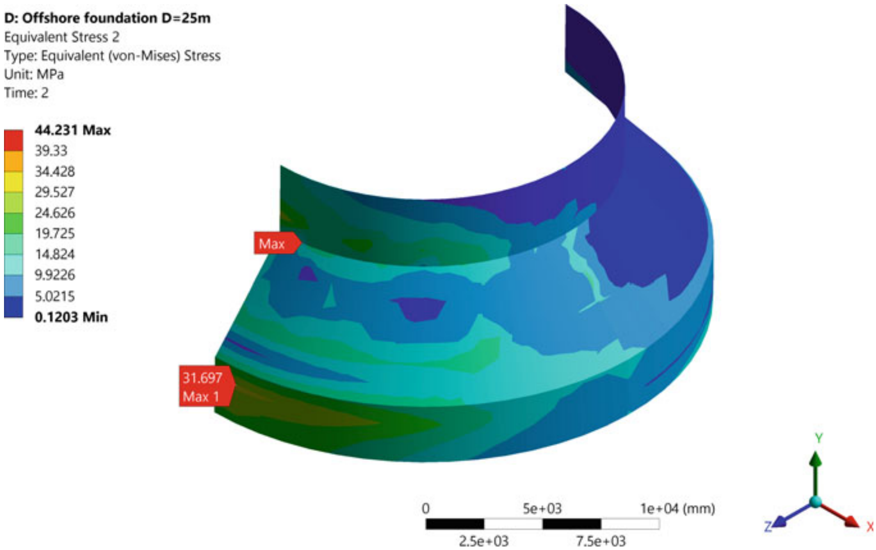


Fig. 10.18 Equivalent von Mises stress inside the steel caisson under vertical and horizontal loads

10.3.3 *Structural and Geotechnical Uncertainties*

Some soil types show a non-linear material behaviour, which can be represented by the Drucker-Prager material model. However, this material model shows bad convergence behaviour inside ANSYS static structural analysis due to highly deformed elements, see Fig. 10.19. The solver aborts the solution of the model with the Drucker-Prager material model. Therefore, the Drucker-Prager model can only be used to represent the beginning of the plasticizing process at the edges, but not the entire process of plasticizing the soil under the foundation. Before the rest of the soil can plasticize, the solver terminates and thus does not show the whole simulation. The ANSYS Static Structural analysis uses the Lagrangean approach for the description of continuous motion in a 3D discretization space. To solve dynamic problems the FEM uses the explicit or implicit scheme for first or second order integration according to Galerkin. One result of the analysis therefore is that programs like ANSYS LS-DYNA should be more suitable for such calculations. It might also be beneficial to consider a software such as Plaxis that is designed particularly for geotechnical analysis.

This simple linear model used here could be compared to a more complex and realistic non-linear model and the comparison could be used to estimate the values of deformation and stress with more accuracy. The simple linear model requiring less computational effort could then be used to estimate the behaviour, in reality, by using a suitable factor for stresses and deformation.

10.4 Concept Cost Assessment

This Sect. 10.4 presents the overview of the early turnkey cost estimates of the GBF concept described in Sect. 10.2.

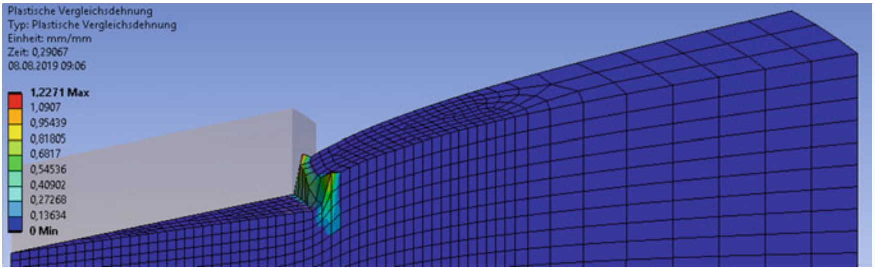


Fig. 10.19 Highly distorted elements due to high plasticizing at the interfering region of the foundation and the soil

10.4.1 Construction Workflow

Figure 10.20 demonstrates in a simplified manner the construction work phases of the drilling and production platform. It starts by dredging of soft bottom with a suitable dredger, an example being a *backhoe dredger* (BHD). The dredged soil is then replaced with good quality gravel. The soil replacement in this application case is 3,650 m^3 or 8,380 tons. The replacement and levelling are done with the same BHD. As this phase is nearing completion, the caisson, which has been manufactured in a nearby yard, is being transported to the site. The distance between the staging port and the offshore site has been assumed, for the purposes of this work, to be 150 NM.

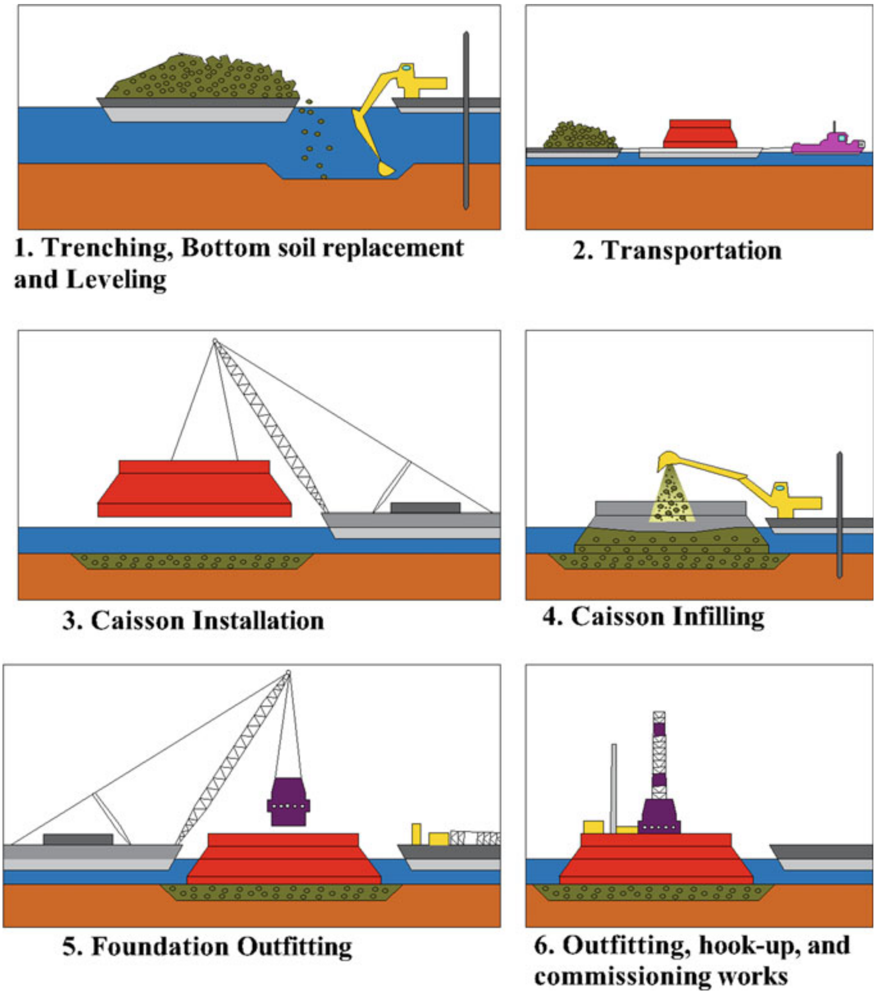


Fig. 10.20 Illustration of the construction work phases of the drilling and production GBF platform

In addition to the BHD, the dredging operation may require up to nine deck barges and six tugs for transportation of gravels and dredged muck. It may require about one month to complete, the whole dredging and replacement phase, at the site. The caisson transportation can be done with a cargo barge, or floating units like Marine Salvage Airbags. Five different transportation and installations (T&I) scenarios have been developed and documented in Anku-Vinyoh (2018); namely:

1. Caisson T&I by Marine Salvage Airbags
2. Transport by barge and installation by two crane vessels
3. Transport by barge and installation by one sheerleg
4. Caisson T&I by one heavy lift self-propelled crane barge
5. Caisson T&I by one heavy-lifting project cargo ship

The next phase involves the in-situ caisson installation and the subsequent infilling with gravel. The installation operation may be done as a float-over when the caisson transportation is by means of floating units. When the transportation is done by a cargo barge, then the installation requires a 500-ton lifting capacity crane vessel. The same BHD, barges and tugs from the soil replacement operation may be used for the caisson infilling and erosion protection works. This whole phase may take about 3 weeks at the site to conclude.

The last phase is the outfitting works, including lifting in-place facilities for the drilling and production, bringing consumables, hook-up and commissioning works. This phase falls outside the scope of this work and, hence, has not been included in the cost estimation study. Experts, however, suggest that it may only take about 6 weeks at the site to finish this phase.

Hence, the whole construction work of the GBF can be completed in less than 3 months in the open water season of the Northeast Caspian Sea. Depending on the five caisson T&I scenarios mentioned above, the turnkey cost may be between 8.2 and 10.7 million euros. Section 10.4.2 gives a brief insight into the estimation of cost and duration of the T&I process. Section 10.4.3 presents the turnkey cost breakdown of the GBF.

For the purpose of the cost estimation study, the caisson is to be transported in one piece. Transportation in pieces with an offshore site assembly is too costly and hence, not considered as a scenario in the cost calculations.

10.4.2 Cost Estimation Tool

In the design process the designer needs as early as possible a feedback of what the cost will be for the manufacturing, transportation, and installation. In the frame of the HOLISHIP project an Excel-based tool was developed to estimate the total cost, the duration, and feasibility of the operations for the T&I of the GBF with respect to weather conditions, draft and size of the GBF. The tool also gives the breakdown of the cost in terms of the GBF's caisson manufacturing, soil replacement operations, caisson T&I, caisson filling operations, and deployment of resources.

The tool has been integrated into Friendship System's CAESES® Platform of HOLISHIP. The user can adapt and configure the Excel spreadsheets for his/her own uses. Section 10.5 explains the tool integration in the CAESES® Platform.

The first tab of the tool is the "*Cockpit*" which contains the basic input parameters and the output results (see Fig. 10.21).

The green area represents the input and the blue area the results. When integrated into the CAESES® platform, the inputs to the tool come directly from the CAESES® platform and the output will be transferred back to the platform. However, the tool can also be used as a standalone tool where the inputs are entered directly by the user.

Besides the cockpit tab, further Excel tabs in the tool are used to structure the configuration and calculation of the cost, time, and feasibility.

Most algorithms developed for the operational module are described in Sect. 10.4.1 and in Anku-Vinyoh (2018); their integration is shown in Fig. 10.22. The different colours represent the different construction work phases for soil replacement, T&I, and filling the caisson.

The tool accounts for material costs, production costs of the structure itself, costs of design and project management, contingency costs, and cost of deployment and operation of the resources. The different scenarios use different resources and the specific data is provided through an integrated resources table. The effects of weather are also empirically accounted for.

The vessel day-rates, material costs, cost factors for design, project management, and contingency are based on experts' experience. These are default values (see Tables 10.2 and 10.3) in the tool and can be changed by the user based on his/her experience.

Input Parameters

Except for the water depth, wave height, distance to installation and engineering days that come from the user, all the other the inputs come from the results/output

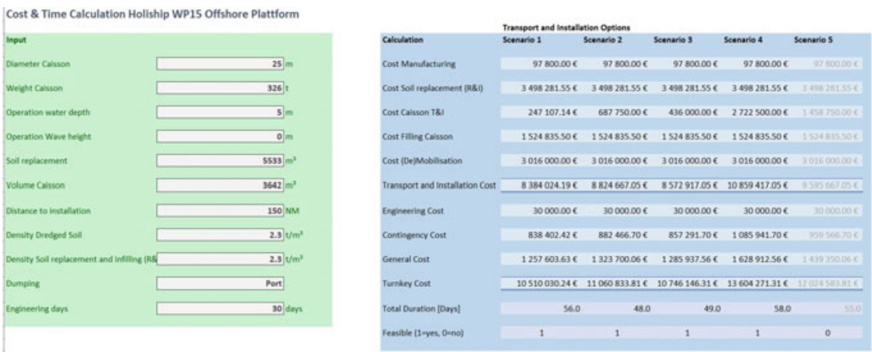


Fig. 10.21 Cockpit of the Turnkey Cost Estimation Tool

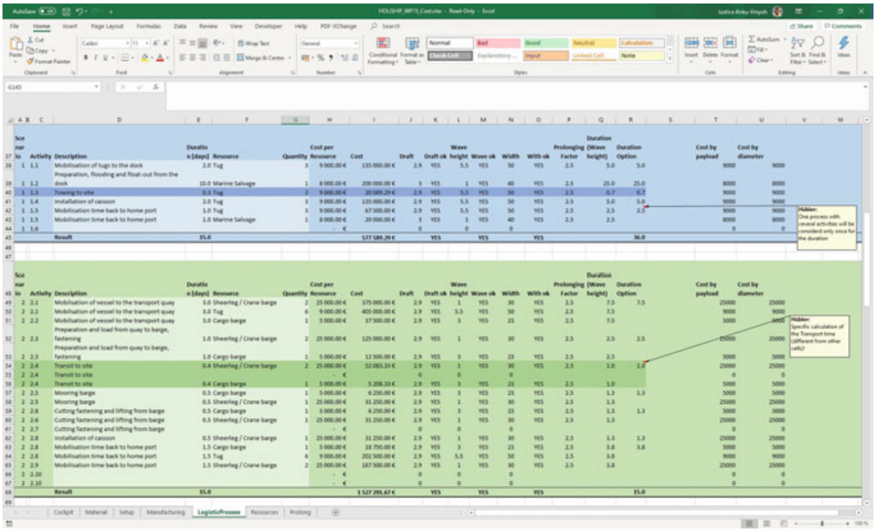


Fig. 10.22 Excel Sheet with Transport and Installation processes

Table 10.2 Some default vessel capacities, operational limitations, and day-rates

Resource	Payload [t]	Transport speed [knots]	Min Water depth [m]	Max Wave height [m]	Cost per day [€/day]	Diameter limit [m]
Marine salvage	3 000	5	3	1	8 000	40
Project cargo ship	2 000	20	10.5	2	60 000	32
Cargo barge	500	5	2.9	3	5 000	23
Cargo barge	1 500	5	2.9	3	9 000	30
Cargo barge	2 500	5	3.7	3	14 000	35
Tug	2 500	7	2.9	5.5	9 000	-
Sheerleg/Crane barge	500	5	2.9	2	25 000	30
Sheerleg/Crane barge	2 500	5	3.7	1	70 000	35
Sheerleg/Crane barge	4 000	5	4	1	90 000	40
SP Crane barge/Sheerleg	2 000	5	3.7	2	90 000	30
Cargo barge/Tug 1	2 500	5	3.7	3	23 000	28
Tug towing	2 500	5	2.9	5.5	9 000	–
Dredger	5 000	6	1.5	10	50 000	–

Table 10.3 Some default material, fabrication, and project cost factors

	Value or factor	Unit	Comment
Steel	250	€/ton	
Steel works (fabrication)	50	€/ton	
Gravel	50	€/ton	
Engineering cost	1000	€/day	
Contingency costs	10	%	% of total cost of manufacturing and erection
General costs	15	%	% of total cost of manufacturing and erection

of the Structural Assessment Tool. Brief description of the inputs and their role in the calculations are:

- **Diameter Caisson**—will influence the selection of the resources considering the limits of the transport resource.
- **Weight Caisson**—limits the selection of the resources due to payload or lifting capacities.
- **Operation water depth**—check the feasibility of the resource to operate in shallow water.
- **Operation wave height**—considers the weather conditions in the installation area.
- **Soil replacement**—needed to calculate the number and volume of transportation, dredging and filling facilities of the soil disk
- **Volume Caisson**—used to calculate the number and volume of transport and lifting capacities for the filling material.
- **Distance to installation**—for the calculation of the transit time between harbour and installation area.
- **Density Soil, Filling material**—to calculate the weight of the soil and filling material considering the payload of the transport facilities.
- **Dumping**—considering the destination of dumping location of the soil.
- **Engineering days**—for the calculation of the effort to plan, design and do the project management.

Output

There are three categories of output from the tool: Cost, Time, and Feasibility.

The *feasibility* indicates that a scenario will work. An algorithm in the tool checks whether the T&I resources as well as the soil replacement and caisson infilling (R&I) resources are operating within their physical limits in the operational simulation. The feasibility of the scenarios with respect to restrictions like wave height, water depth, payload, etc. are assessed. A scenario could operate (that is, adjudged feasible) if the given limits are not exceeded.

The difference between all five scenarios is the mode of T&I of the caisson only (see Table 10.4). However, they all use the same resources (logistics) for the R&I operations.

The *duration* indicates the total time required to perform the whole GBF construction as described in Sect. 10.4.1.

Finally, the *total cost* of the GBF is calculated based on:

- **Cost of (de)mobilisation** contains the effort to bring the required resources like barges, crane vessels, dredger, etc. to the installation location or staging port and back to their home ports after finishing their assigned tasks.
- **Cost of manufacturing** considers the fabrication (welding, steel assembly, etc.) of the caisson onshore.
- **Cost of soil replacement** considers the effort and time including renting resources to replace the soil disk with gravel. It also contains the transport of the soil to dumping location. The soil replacement cost is divided into dredging (trenching) and trench filling costs.
- **Cost of caisson T&I** considers the effort and time for transport of the caisson to the installation place as well as the installation.
- **Cost of filling the caisson** with rocks or gravel including the material cost. The cost also includes the transport effort from port to the offshore location.
- **Engineering cost** reflects the effort for design, engineering, project management, etc.
- **Contingency cost** makes allowance for uncertainties during the transport and installation.
- **General cost** contains insurance, financing, port, and staging, etc.

Table 10.4 Comparison of the five scenarios

	Comparison	
	Difference	Similarity
Scenario 1	Caisson T&I by Marine Salvage Airbags	All other operations like caisson manufacturing and R&I including the de-/mobilisation of the resources (logistics) for the R&I are the same for all scenarios
Scenario 2	Caisson transport by barge and installation by two crane vessels	
Scenario 3	Caisson transport by barge and installation by one sheerleg	
Scenario 4	Caisson T&I by one heavy lift self-propelled crane barge	
Scenario 5	Caisson T&I by one heavy-lifting project cargo ship	

10.4.3 Concept Costs and Uncertainties

The offshore installation of a GBF is a complex process with a lot of uncertainties. In the beginning of the tool development, a simplification of the logistic concept and algorithm was made. During the project, it was discovered that it needs more constraints and parameters to get more accurate results. For example, considering weather conditions, number of resources, interdependencies of processes, etc. lead to much more complexity in the logistic simulation and the cost estimation.

In Figs. 10.23 and 10.24, cost breakdown of the results given in the cockpit are shown. The graph shows that both the soil replacement operations (dredging and de-/mobilisation) and caisson infilling are the most cost-intensive operations. On the other hand, engineering and manufacturing do have a very low relative cost.

Soil replacement and caisson filling operations are done with the same resources in a very similar way. The use of resources in those operations is very intensive as it needs the work in parallel of many vehicles and machinery, and it grows with the size of the structure and the distance to the staging port.

Engineering and production costs are diluting with the comparatively high costs of the project, which are basically due to the time and quantity of resources in operation.

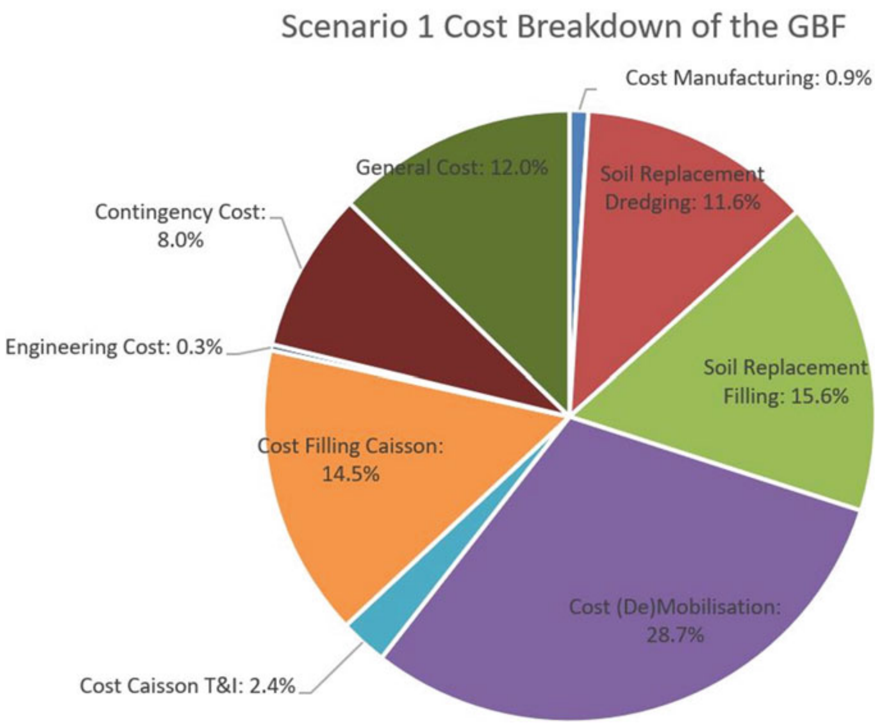


Fig. 10.23 Turnkey cost breakdown for the GBF according to Scenario 1

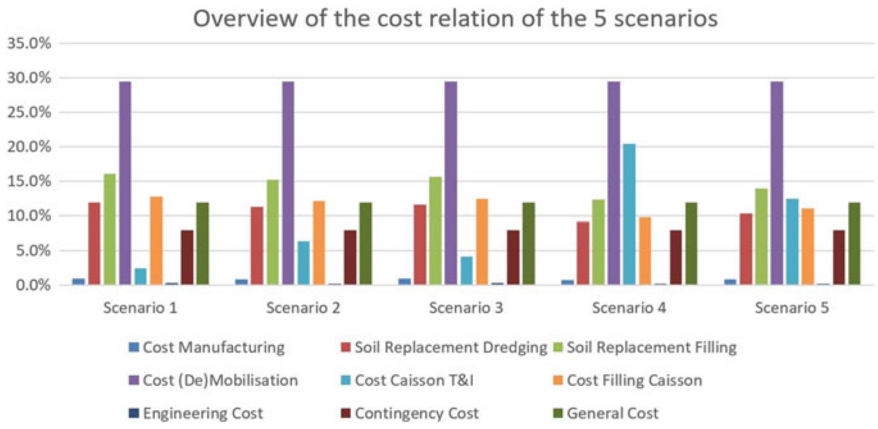


Fig. 10.24 Comparison of the cost breakdown for the five T&I scenarios

In terms of production costs, this type of structure is a very simple steel body with a basic local stiffener network inside, so the production costs are coming from the raw material and the simple welding operations which make it comparatively economic.

As a very last step, the resulting cost was compared in the manner shown in Fig. 10.24 and the results were validated by experts. Furthermore, it is important to note that this proportional graph varies between the five different T&I scenarios (see Table 10.4), as well as projects with smaller structures or shorter distances to the staging port, where the costs of the soil replacement and caisson filling operations will be reduced.

It is also important to note that the difference between all five scenarios is the mode of T&I of the caisson only (see Table 10.4). All other operations like caisson manufacturing and R&I including the de-/mobilisation of the resources (logistics) for the R&I are the same for all scenarios.

10.5 Optimization Platform

10.5.1 CAESES® Platform

CAESES® stands for “CAE System Empowering Simulation” and its ultimate goal is to design optimally flow-exposed products. For simulation purposes, it serves to create robust geometry variations of the baseline definition dictated by the user.

In addition, CAESES® comes with integrated strategies for parameter studies and shape optimization. Together with the geometry modelling, the user can investigate large sets of design candidates in a massively reduced time frame.

CAESES® can also be used in combination with external optimization tools, such as Dakota, OptiSLang, Optimus, ModeFrontier etc. In these situations, CAESES® runs in the background as efficient and robust geometry engine and process manager.

10.5.2 Tool Integration

CAESES® is used to integrate each separate tool with the help of the CAESES® *Software Connector ACT app*. Here, CAESES® acts as a platform that combines and creates the connection between each tool and gathers/processes the obtained data.

As shown in Figs. 10.25 and 10.26, the workflow for the user/designer and the tools can be described as follows.

In CAESES®, the user first submits the necessary inputs for the Caisson Geometry Check Excel Tool (see Fig. 10.28). This tool has been created to check the validity of both the user's inputs and the resultant caisson geometry according to the conditions in Fig. 10.6. In addition, this tool computes the caisson lightweight as well as the mass and volume of the R&I. These results are subsequently used as inputs for the Turnkey Cost Estimation Excel Tool (see Fig. 10.21).

Having received the evaluation for the validity of the input parameters, CAESES® either uses the submitted value or modifies it with respect to the violated constraints.

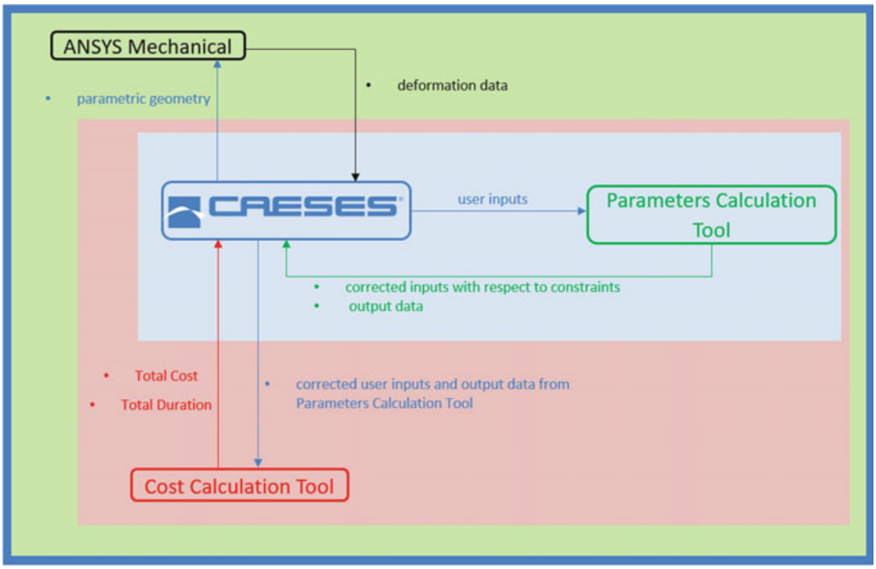


Fig. 10.25 Workflow of CAESES® platform, FEM analysis and Cost assessment tool for GBF concept design

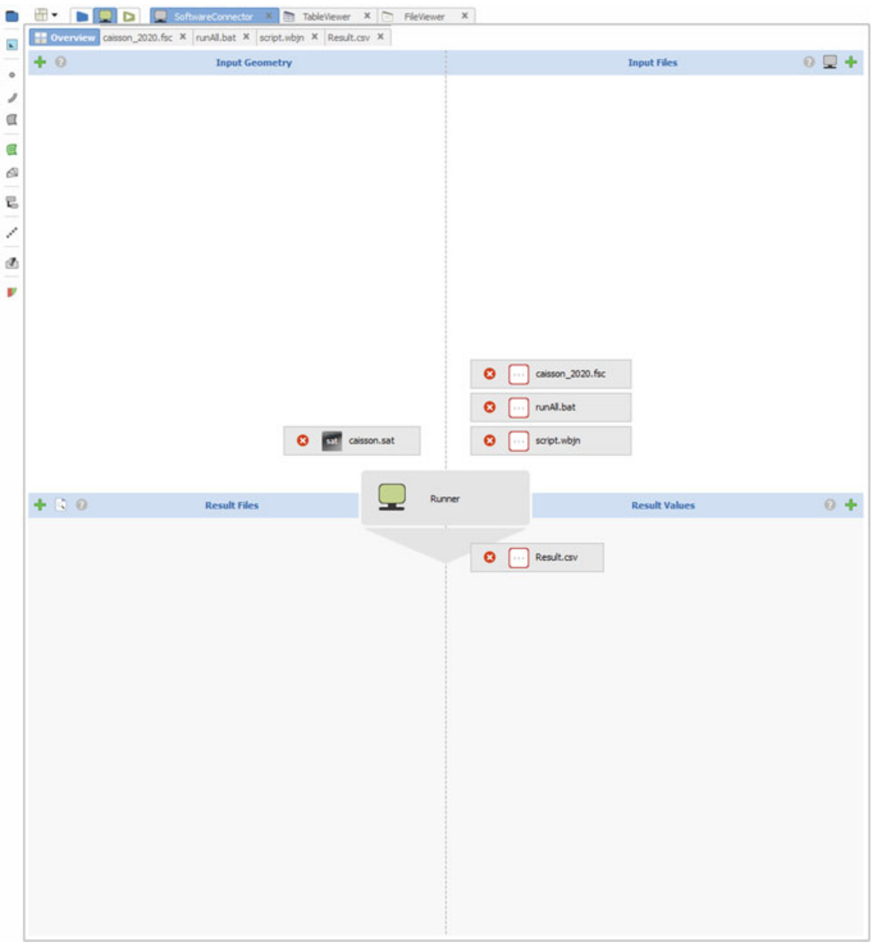


Fig. 10.26 Software connection setup in the platform for the FEM Tool

eg:
if (lower bound > × 1).
× 1 = lower bound.
if (×1 > upper bound).
× 1 = upper bound.

Afterwards, the validated input parameters are used to create the 3D model with geometry of the caisson automatically.

Having created the geometry, some inputs and outputs of the Caisson Geometry Check Excel Tool are subsequently used as inputs for the Turnkey Cost Estimation Excel Tool. The user is expected to submit the remaining inputs requested for the Turnkey Cost Estimation Excel Tool. After CAESES® has initialized the Turnkey

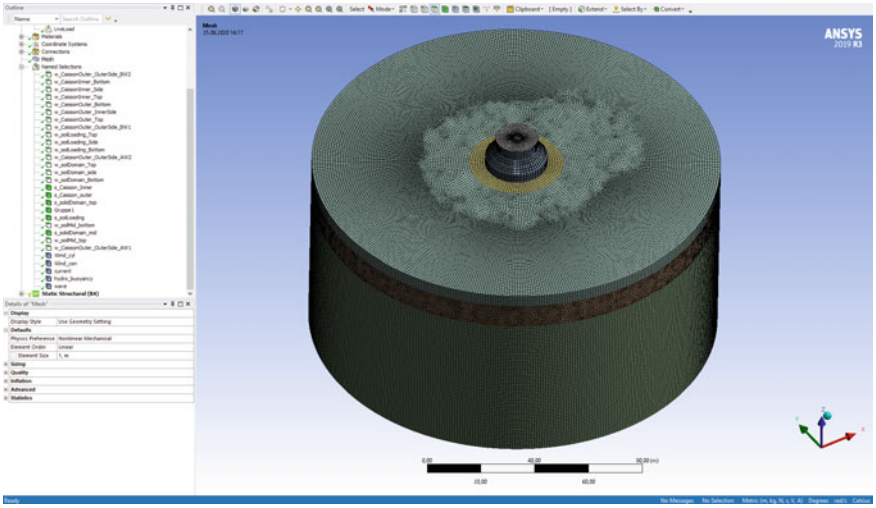


Fig. 10.27 Definition of the geometry in FEM solver with data provided by CAESES® (Caisson and Soil disc)

Cost Estimation Excel Tool with these inputs, it retrieves the result data among which is the feasibility of the scenarios, total costs, and total duration.

The final stage of the workflow is the FEM analysis. In this study, ANSYS Mechanical was selected as the solver. Having passed through feasibility and validity checks in the previous calculations, CAESES® sends the geometry data, named selections assigned to geometrical patches, some output data from the previous calculations that will serve to define the physical model to ANSYS Mechanical. For this purpose, a new tool, CAESES® Software Connector ACT app, has been developed to make the ANSYS Mechanical run in batch mode and has to be installed in ANSYS Workbench (see Fig. 10.29). Then the remaining setup has been performed within CAESES® (see Fig. 10.26) that enables the FEM Model to be updated, meshed and solved automatically (see Fig. 10.27).

The results from the FEM analysis concerning deformation, strain, etc. will be delivered to the CAESES® platform. The platform will prepare and present all results as tables or diagrams (see Figs. 10.30 and 10.31). Now the user can assess his design in respect of the structural analysis, the soil replacement as well as regarding cost, duration, and T&I feasibility.

10.5.3 Optimization Process

Having performed the Software Connection, the user is able to start the optimization process.

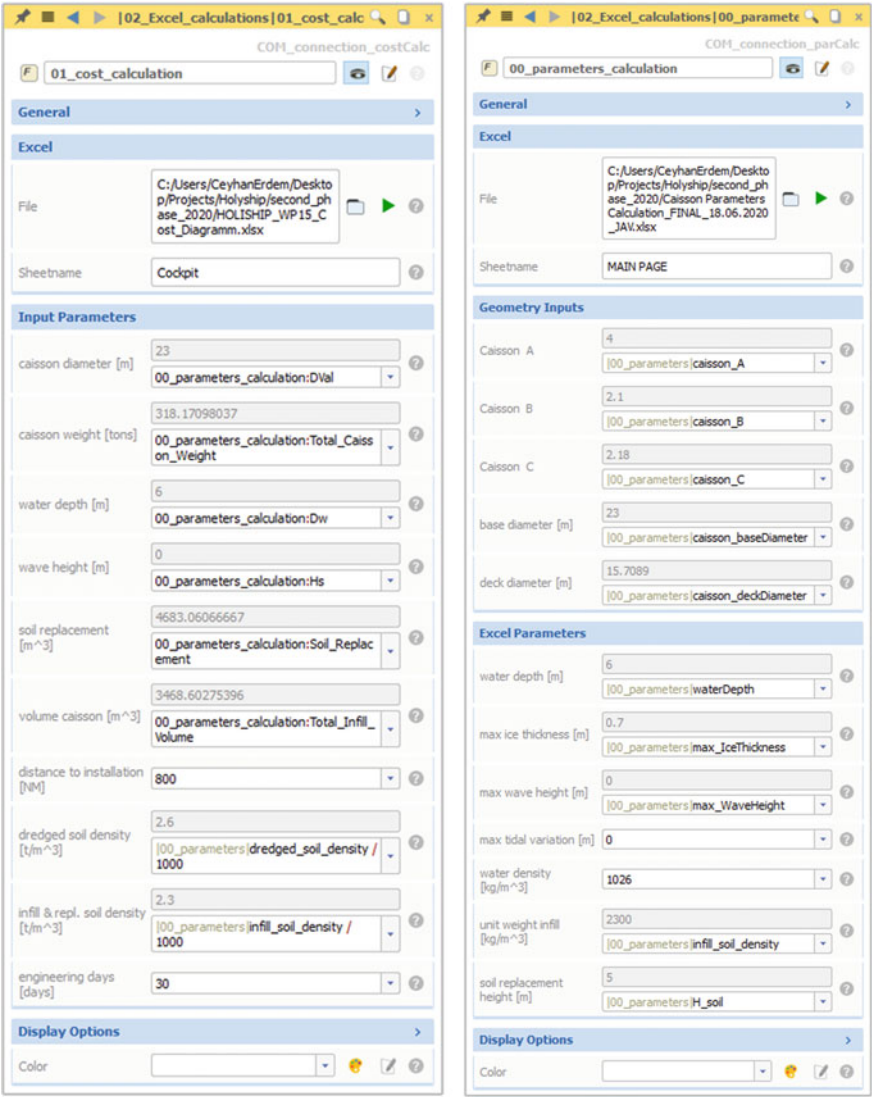


Fig. 10.28 Definition of the Excel Control Menus within the CAESES® platform

For the optimization, two objectives from the Turnkey Cost Estimation Excel Tool and three objectives for the FEM analysis have been selected (see Fig. 10.32). These objectives are:

- Total project cost
- Total project duration
- Max deformation due to only gravitational load (t1)

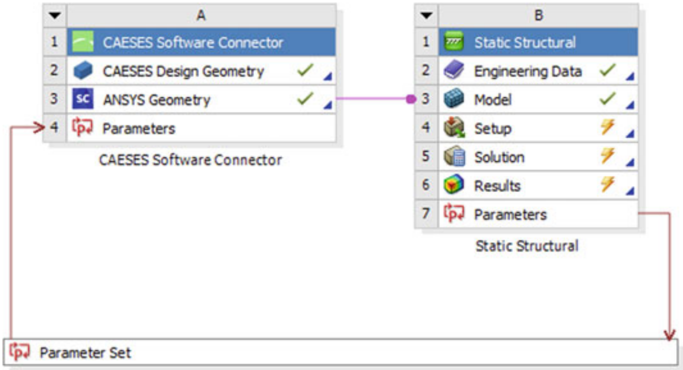
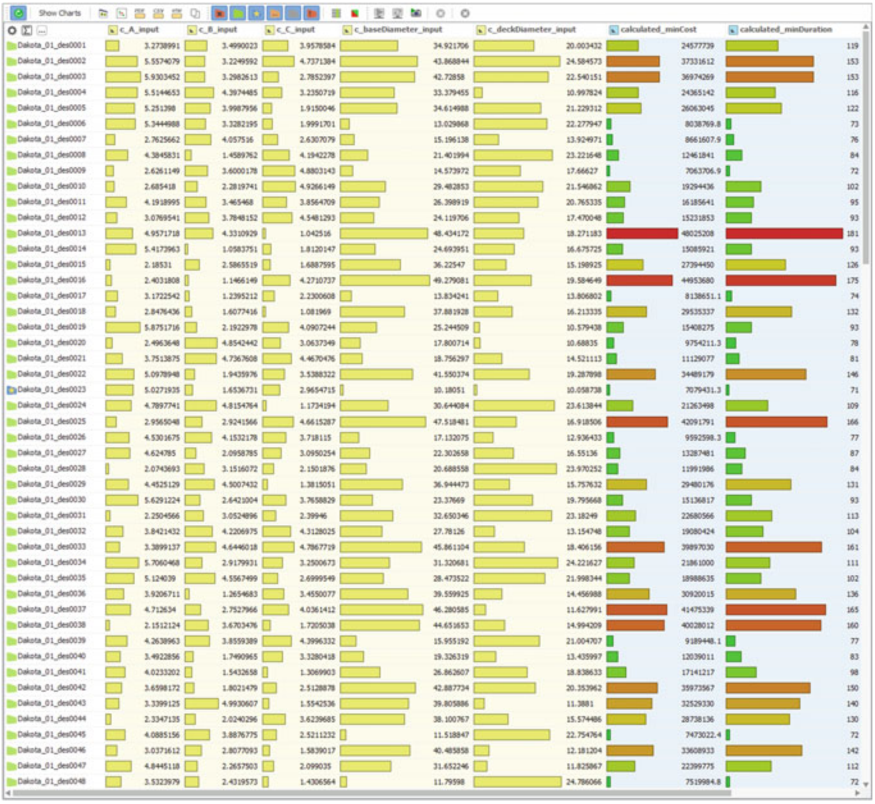


Fig. 10.29 Definition of CAESES® Software Connector ACT app in ANSYS Workbench



	c_A_input	c_B_input	c_C_input	c_baseDiameter_input	c_deckDiameter_input	calculated_minCost	calculated_minDuration
Dakota_01_des0001	3.2738991	3.4990023	3.9578584	34.921706	20.003432	24577739	119
Dakota_01_des0002	5.5574079	3.2249592	4.7371384	43.868844	24.584573	37331612	153
Dakota_01_des0003	5.9303452	3.2982613	2.7852397	42.72858	22.540151	36974269	153
Dakota_01_des0004	5.5144653	4.3974485	3.2350719	33.379455	10.997824	24365142	116
Dakota_01_des0005	5.251398	3.9987956	1.9150046	34.614988	21.229312	26063045	122
Dakota_01_des0006	5.3444988	3.3282195	1.9991701	13.029868	22.277947	8038769.8	73
Dakota_01_des0007	2.7625662	4.057516	2.6307079	15.196138	13.924971	8661607.9	76
Dakota_01_des0008	4.3845831	1.4589762	4.1942278	21.401994	23.221648	12461841	84
Dakota_01_des0009	2.6261149	3.6000178	4.8803143	14.573972	17.66627	7063706.9	72
Dakota_01_des0010	2.685418	2.2819741	4.9266149	29.482853	21.546862	19294436	102
Dakota_01_des0011	4.1918995	3.465468	3.8564709	26.398919	20.765335	16185641	95
Dakota_01_des0012	3.0769541	3.7848152	4.5481293	24.119706	17.470048	15231853	93
Dakota_01_des0013	4.9571718	4.3310929	1.042516	48.434172	18.271183	48025208	181
Dakota_01_des0014	5.4173963	1.0583751	1.8120147	24.693951	16.675725	15085921	93
Dakota_01_des0015	2.18531	2.5865519	1.6887595	36.22547	15.198925	27394450	126
Dakota_01_des0016	2.4031808	1.1466149	4.2710737	49.279081	19.584649	44953680	175
Dakota_01_des0017	3.1722542	1.2395212	2.2300608	13.834241	13.806802	8138651.1	74
Dakota_01_des0018	2.8476436	1.6077416	1.081969	37.881928	16.213335	29535337	132
Dakota_01_des0019	5.8751716	2.1922978	4.0907244	25.244509	10.579438	15408275	93
Dakota_01_des0020	2.4963648	4.8542442	3.0637349	17.800714	10.68835	9754211.3	78
Dakota_01_des0021	3.7513875	4.7367608	4.4670476	18.756297	14.521113	11129077	81
Dakota_01_des0022	5.0978948	1.9435976	3.5388322	41.550374	19.287898	34489179	146
Dakota_01_des0023	5.0271935	1.6536731	2.9654715	10.18051	10.058738	7079431.3	71
Dakota_01_des0024	4.7897741	4.8154764	1.1734194	30.644084	23.613844	21263498	109
Dakota_01_des0025	2.9565048	2.9241566	4.6615287	47.518481	16.918506	42091791	166
Dakota_01_des0026	4.5301675	4.1532178	3.718115	17.132075	12.936433	9592598.3	77
Dakota_01_des0027	4.624785	2.0958785	3.0950254	22.302658	16.55136	13287481	87
Dakota_01_des0028	2.0743693	3.1516072	2.1501876	20.688558	23.970252	11991986	84
Dakota_01_des0029	4.4525129	4.5007432	1.3815051	36.944473	15.757632	29480176	131
Dakota_01_des0030	5.6291224	2.6421004	3.7658829	23.37669	19.795668	15136817	93
Dakota_01_des0031	2.2504566	3.0524896	2.39946	32.650346	23.18249	22680566	113
Dakota_01_des0032	3.8421432	4.2206975	4.3128025	27.78126	13.154748	19080424	104
Dakota_01_des0033	3.3899137	4.6446018	4.7867719	45.861104	18.406156	39897030	161
Dakota_01_des0034	5.7060468	2.9179931	3.2500673	31.320681	24.221627	21861000	111
Dakota_01_des0035	5.124039	4.5567499	2.6999549	28.473522	21.998344	18988635	102
Dakota_01_des0036	3.9206711	1.2654683	3.4550077	39.559925	14.456988	30920015	136
Dakota_01_des0037	4.712634	2.7527966	4.0361412	46.280585	11.627991	41475339	165
Dakota_01_des0038	2.1512124	3.6703476	1.7205038	44.651653	14.994209	40028012	160
Dakota_01_des0039	4.2638963	3.8559389	4.3996332	15.955192	21.004707	9189448.1	77
Dakota_01_des0040	3.4922856	1.7490965	3.3280418	19.326319	13.435997	12039011	83
Dakota_01_des0041	4.0233202	1.5432658	1.3069903	26.862607	18.838633	17141217	98
Dakota_01_des0042	3.6598172	1.8021479	2.5128878	42.887734	20.353962	35973567	150
Dakota_01_des0043	3.3399125	4.9930607	1.5542536	39.805886	11.3881	32529330	140
Dakota_01_des0044	2.3347135	2.0240296	3.6239685	38.100767	15.574486	28738136	130
Dakota_01_des0045	4.0885156	3.8876775	2.5211232	11.518847	22.754764	7473022.4	72
Dakota_01_des0046	3.0371612	2.8077093	1.5839017	40.485858	12.181204	33608933	142
Dakota_01_des0047	4.8445118	2.2657503	2.099035	31.652246	11.825867	22399775	112
Dakota_01_des0048	3.5323979	2.4319573	1.4306564	11.79598	24.786066	7519984.8	72

Fig. 10.30 Definition of the design variation within the optimization process

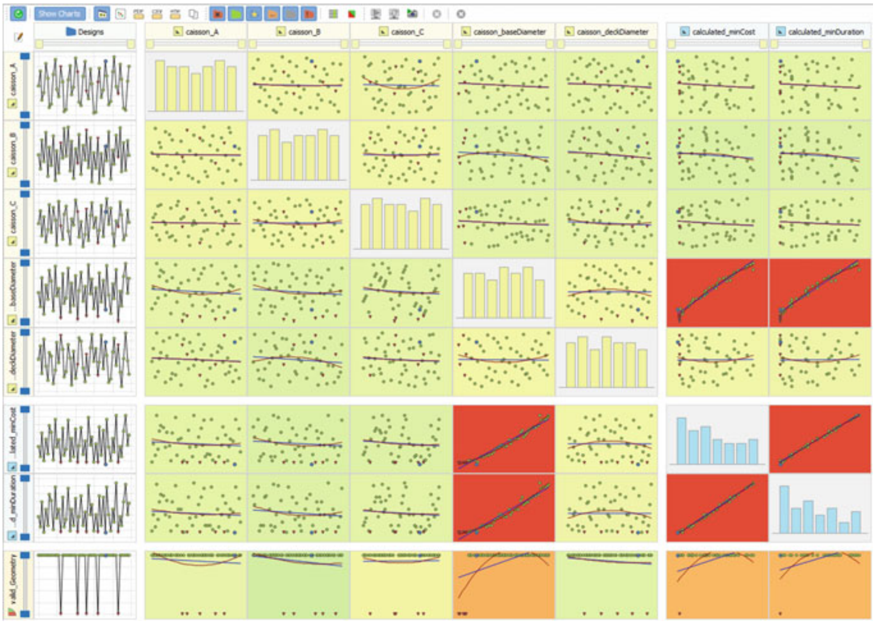


Fig. 10.31 Definition of the parameter and objective function variation within the optimization process

- Max deformation due to all but ice loads (t2)
- Max deformation due to all but wave loads (t3)

As a method, Dakota Global Optimization on Response Surface has been selected. In this method, a Multi-Objective Genetic Algorithm (MOGA) is conducted on a response surface that is created iteratively. The best designs of each MOGA run get evaluated and are added to the response surface. This update and improves the response surface model in each iteration. With this approach, the method tries to reduce the number of expensive evaluations such as FEM or CFD runs.

At the time of putting together this chapter, additional work was being done on the optimization process. Hence, additional objectives will be defined in the upcoming Deliverable 15.2. In addition, refinement of the optimization process will be made, and the results will be documented.

10.6 Conclusion

In this section a summary of the results of the present application case, lessons learnt, and recommendations for future work are outlined.

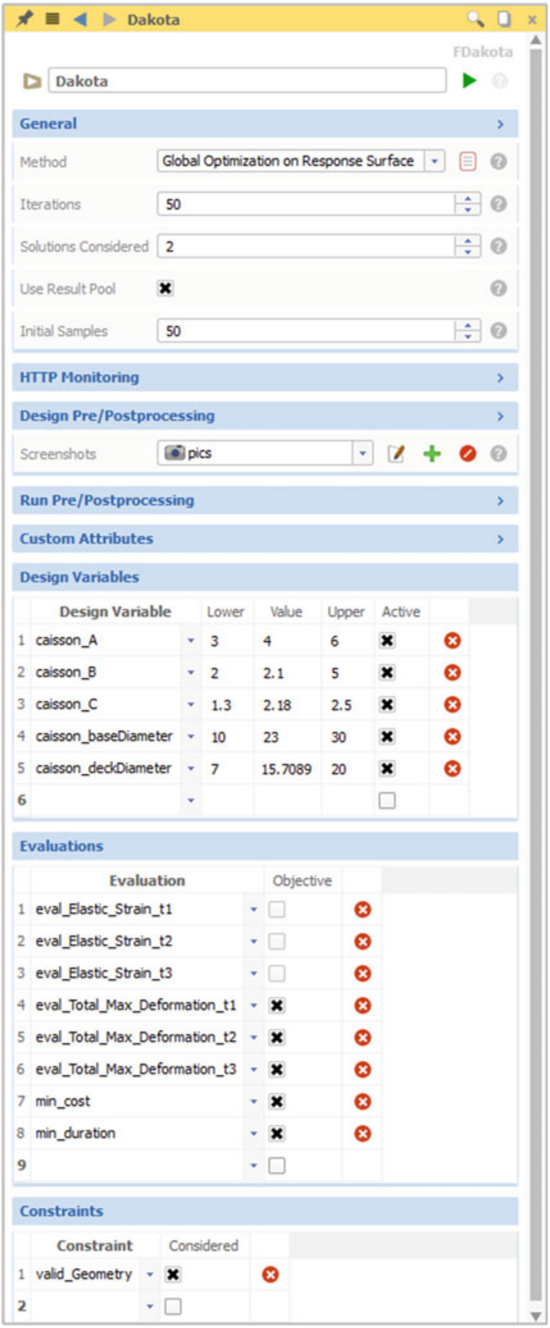


Fig. 10.32 Definition of the optimization setup in CAESES®

10.6.1 Concept Design

Figure 10.33 shows the concept proposal for a drilling and production platform foundation for the Northeast Caspian Sea. This area is rich in hydrocarbons and has lots of ongoing field developments. The concept introduces an innovative foundation base solution for off/inshore platforms for operation in icy and shallow waters that may dramatically result in low-cost projects with a high return on investment.

Compared to alternative artificial islands, studies suggest that the ice-resistant steel shell GBF concept is a very cost-efficient solution. It can be installed in a single open water season. Experts agree that drilling could easily start within a year of investment decision.

The owner or operator can expand the platform into a production complex. It allows for easy decommissioning and/or moving the foundation to a new location. The concept's construction does not require unique equipment; standard offshore construction equipment found in almost all remote regions can be used.

The concept is suitable for water depths from 3–20 m and a range of bottom conditions. An alternative solution to soil replacement in a soft bottom condition is

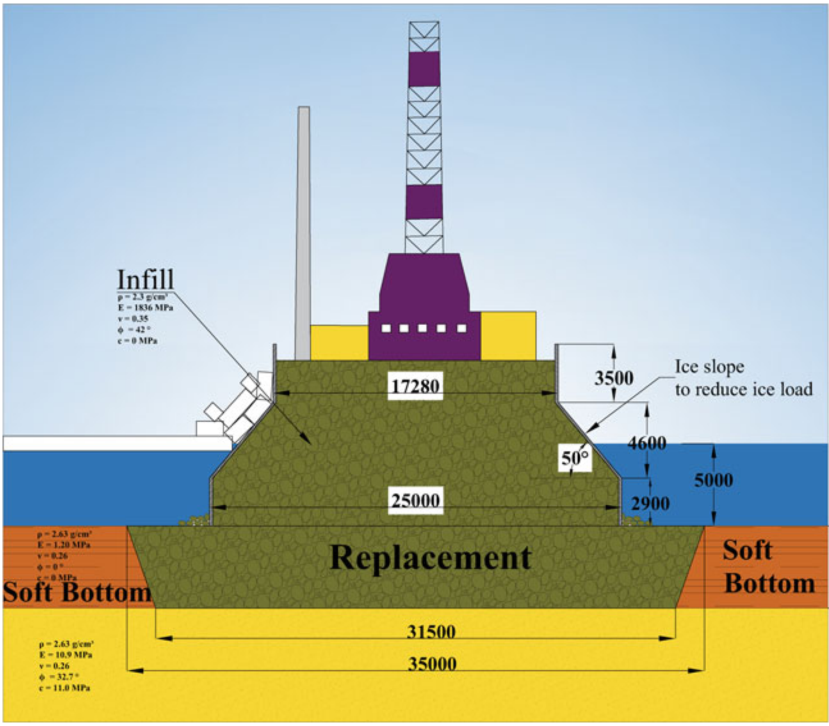


Fig. 10.33 Concept proposal for a Northeast Caspian Sea drilling and production platform. All geometrical dimensions in millimetres

to use capped piles to carry the vertical loads. However, experts agree that in most cases, soil replacement may be the least costly choice. This can be a recommendation for further studies where a comparative cost study is done on soil replacement and the use of capped piles.

It is, therefore, important to perform model tests, computations, and geotechnical surveys of the exact spot of the would-be platform, to validate the concept's structural performance. This will further provide assurance to potential clients about the concept's feasibility.

Assessment tools have been developed as part of WP15 of HOLISHIP to assist designers in future feasibility studies (both technical and economic). All these tools have been integrated into the HOLISHIP concept design platform based on *Friendship Systems*' CAESES® Platform for easy optimisation or iterative design. Apart from hydrocarbon field development, the concept can be used for bridge piers, oil piers (offshore loading terminals), lighthouse foundations, wind turbine foundations, channel markers, dolphins and harbour berth wall structures in cold climate regions.

10.6.2 Structural Assessment

The static structural analysis of the steel caisson shows that the T-profiles are sufficiently dimensioned. In case of the soil-structure-interaction, the settlement due to the gravity of the filled caisson reads 113 mm. The additional displacement of the filled caisson due to environmental horizontal loads reads 28 mm. A linear elastic soil model is used, which is suitable for sandy soils. However, in case of clayey soils a non-linear soil model such as the Drucker-Prager model is preferable. ANSYS Static structural has been discovered to be not the ideal tool to integrate non-linear soil behaviour, as the static mesh definition leads to highly distorted elements. Modelling non-linear soil with these elements would require revised contacts, refined mesh, and additional calculation time. Future work could therefore include the testing and implementing of different software such as ABAQUS or ANSYS LS-DYNA where a changing mesh could be used. It might also be beneficial to consider a software such as Plaxis that is designed particularly for geotechnical analysis.

This simple linear model used here could be compared to a more complex and realistic non-linear model and the comparison could be used to estimate the values of deformation and stress with more accuracy. The simple linear model requiring less computational effort could then be used to estimate the behaviour, in reality, by using a suitable factor for stresses and deformation.

Behaviour of gravity based offshore structure in soft soil depends strongly on the properties of soil and loads. The structure analysed in this study works in soft soil, but still requires the soil to have some strength or rigidity in order to support the structure. The needed soil properties depend on the size of the structure, weight of the structure and used loads. Therefore, it is important to know the properties of the soil and ice conditions where the structure is to be installed as closely as possible.

This gives the opportunity to estimate the size of structure and feasibility of the concept for the desired location.

10.6.3 Cost Estimation

Many variables need to be considered when modelling real-life complex scenarios where different resources, human teams, geography, and weather conditions might introduce unknown factors. At some point, it is necessary to make assumptions and simplifications which still make a good enough tool for initial estimation and optimization. This means that the results are to be strictly taken as estimates and will need a subsequent case-by-case refined calculation.

In this application case, assuming the distance from the staging port to the installation site is 150 NM, the turnkey cost of the GBF may be between 8.2–10.7 million euros. The whole construction time may be less than 3 months. These results must, however, be seen in relation to the constraints, e.g. distance to installation location, weather conditions, etc.

The Turnkey Cost Estimation Tool provides a light algorithm that can be easily implemented in an optimization tool. A simulation of logistics could be used for an investigation in detail, but it will take more time for computation and will not have the fast response that was anticipated in this study. Input and output as well as calculation method are presented consistently so that they are not only ready for machine use but also human understanding.

Finally, the tool is based on a given structure type and building method presented in Sect. 10.4.1 with given operational profile and limited to a given range. This range is determined by the capacity of the resources and the magnitude and complexity of the operations. That means the tool might need a redesign for structures exceeding the capacity of the given resources, structures of different nature or foundation system, operations carried in deep water or with an added logistic complexity like offshore conditions, and any other immaterial variable which can heavily affect an optimal work and logistic organization like specific administrative or regulatory issues as well as lack of inshore infrastructure.

There is still room for further developments of the cost estimation tool. In the future, more available options and different scenarios could be added to account for different types of structures. At the same time, the given scenarios could be updated after lessons learned once the results are compared to a real-life project. Probably then, the area to do the optimization would be in the logistic concept method. On the other hand, improvement of the specific capacity and performance data of the resources, more different available resources in certain categories, as well as a resource-specific prolonging factor, would provide a more accurate and optimized result.

10.6.4 Optimisation Platform

The workflow for the tool integration controlled by CAESES® using different software like ANSYS Mechanical and Excel tools can be regarded as a suitable configuration where several tools are integrated and can be visualized interactively.

With the recent modifications, instead of two separate platforms, now the user is only expected to control the whole setup through CAESES®. The ANSYS Workbench platform and hence ANSYS Mechanical are now working in batch mode being controlled by CAESES®.

The optimization objectives can be changed easily with respect to user needs and hence provide the desired data output with less user effort.

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Chapter 11
RoPax Design Revisited—Evolution or Revolution?

Cantekin Tuzcu, Cameron Dinsdale, Jack Hawkins, George Zaraphonitis, and Fotis Papadopoulos

Abstract The design development of a RoPAX vessel is very complex, in fact one can argue that stricter regulatory requirements and multitude of operational flexibility required by the owner and operator makes it one of the most challenging vessel types to bring any real improvement. Although the know-how and experience of the design team is vitally important, an optimising platform such as that offered by HOLISHIP can help develop design solutions much more tailored to the needs and challenges the prospective owner and the marketplace brings about. This application case demonstrates how a RoPAX design can be optimised by using the HOLISHIP platform. A number of critical ship design development tools and methods, particularly parametric modelling tools and their use in design optimisation, are presented and discussed. Although the focus of the optimisation problem and the complexity may vary the processed employed here demonstrates the capabilities and potential of the HOLISHIP platform. This chapter also offers an insight to the predicament of weather to follow traditional designs to meet owners' specifications or make a special effort to accomplish something new, go beyond the norm.

Keywords Ship design · Concept design · Contract design · Structural design · Design optimisation · Machinery optimisation · Parametric design · Parametric modelling · Surrogate models · Optimisation

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A. Papanikolaou (ed.), *A Holistic Approach to Ship Design*,
https://doi.org/10.1007/978-3-030-71091-0_11

Abbreviations

BV	Bureau Veritas
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAESES	Computer Aided Engineering System Empowering Simulation
CASD	Computer Aided Ship Design
CAPEX	CapitalExpenditure
CFD	Computational FluidDynamics
CPP	Controllable Pitch Propeller
cST	CentiStokes: unit of kinematic viscosity = 1 mm^2/s
DF	Dual Fuel (engine)
DG	Diesel Generator
DoE	Design of Experiment
DWT	Deadweight
EU	European Union
EC	European Commission
EEDI	Energy Efficiency Design Index
IMO	International Maritime Organisation
HFO	Heavy Fuel Oil
H_2	Hydrogen
KPI	Key Performance Indicator
LFO	Light Fuel Oil
LNG	Liquid Natural Gas
LSMDO	Low Sulphur Marine Diesel Oil
MARPOL	Marine Pollution
MCR	Maximum Continues Rating
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
ME	Main Engine
NAPA	Naval Architecture Package of Napa Oy
NiAlBr	Nickel-Aluminium Bronze (Propeller material)
NPV	Net Present Value
NM	Nautical Mile
OPEX	Operational Expenditure
PAX	Passenger Number
PMS	Power Management System
PTO	Power Take Off
R&D	Research and Development
RFR	Required Freight Rate
RNPV	Required Net Present Value
ROI	Return On Investment
RoPAX	Ro-Ro Passenger Ferry
SEECAT	Ship Energy Efficiency Calculation and Analysis Tool

SOBOL Sobol Sampling Method
SOLAS Safety of Life at Sea

11.1 Introduction

The development of parametric models for the hull form and of the internal layout for a series of ship types along with the appropriate assessment tools and their interconnection with optimisation algorithms has been presented and discussed in the preceding chapters of this and the first volume of this book (Papanikolaou (ed) 2019). The present chapter focuses on RoPAX design development as one of the major Application Cases of the HOLISHIP project.

In order to demonstrate how a design can be developed with integrated design optimisation platforms, which are mature to a level that can be presented as an investment ready solution, the selection of the RoPAX ship type for an Application Case is not a trivial decision. Considering the significance of the RoPAX ships in the European transportation industry, in terms of mobility of people and goods, it is important to allow their designs to mature and potentially evolve alongside a contemporary set of socio-political, financial and environmental requirements in the European Union.

In the context of this application chapter the notion of "mature designs" does not only apply to efficiency improvements of existing vessels in terms of accommodation spaces, propulsion machinery, fuel efficiency, cost-effective operation, safety and environmental performance, etc. It primarily applies to designs that can accommodate state-of-the-art technology (e.g. gas burning propulsion engines as opposed to diesel engines) and at the same time are sufficiently future-proofed, i.e. capable of being upgraded and to remain in operational condition beyond the standard 25 years lifecycle. From this point of view the HOLISHIP methodology and design platform presents a unique opportunity to set the pace for technological evolution in the RoPAX sector of the marine transportation industry.

The objective of this chapter is to demonstrate how one can use the HOLISHIP methodology and design platform(s) in the development of two RoPAX designs with the same design specification (route, passenger number, lane metres, speed, etc.). The first design, named "Alpha" will be elaborated to basic/contract design stage and will be based on technology and arrangements similar to contemporary ships operating in European waters today. The second design, named "Bravo" will be an advanced concept of "Alpha" and will be enhanced with cutting-edge machinery and propulsion technology to demonstrate the capability of the platform to efficiently adapt significant design changes. This scope is set primarily in response to advanced future requirements and to pave the way for the shipping industry to seek more fit-for-purpose and environmentally friendly solutions. Needless to say, that both designs will conform to regulatory standards in terms of safety (SOLAS) and environmental performance (MARPOL) from the outset.

This design development has been conducted by a team of HOLISHIP participants[1] and their contributions, who were tasked with this application case; their contributions have been vital because methods and tools developed in other parts of the project had to be tested and validated in this application case for large RoPAX vessels. Therefore, the design team refers not only to the authors of this chapter but to all partners who contributed to it.

11.2 Design Specifications

The design team has been given a set of design specifications by TRITEC, who has transferred their RoPAX building and operational know-how as part of their parent ship management company, Northern Marine Group, setting the requirements and the materials to be used in the design of the Alpha and Bravo designs. The design specifications for this application case have been compiled in a way that gives opportunity for the designers to choose and explore advantages of the optimisation platform and of the tools that are integrated into it. In other words, if the design specifications are written in a very detailed way, as it is often the case in the contract stage, this could lead to a design being selected from a small part of the huge design space and the outcome will have been optimal of only that subset as prescribed by the owner or operator. This means that it will be missing the rational exploration of the entire design space and the identification of a series of "optimal" or "near-optimal" design solutions, according to a suitable set of design criteria.

To this end, the guidance principles of the design specifications are outlined as follows:

- Minimising the fuel consumption while maintaining stability according to in force regulations and maximising payload capacity,
- Increased connectivity between public service spaces,
- Readiness for alternative future fuel use and storage,
- Minimising the emissions and environmental footprint; and
- Operational simplicity and standardisation, the highest degree of safety, easy maintenance, and maximum overall economy.

The design of the ship should be based on the requirements of this specification for its operation in European waters. The selected operational route of the vessel is between the ports of Ancona, Italy and Patras, Greece as this route is a well-established trade route within EU waters. Although a stopover is possible (e.g. the port of Igumenitsa, NW Greece, or the port of Bari, Italy), this application case refers to a direct sailing as shown in Fig. 11.1, which is typically a whole year-round operation. On this route, the designs should achieve a service speed of 24 knots with

[1]TRITEC, NTUA, FSS, HSVA, BV, ALPHA, HSB, ULG, BALANCED, CNR, EPSILON.

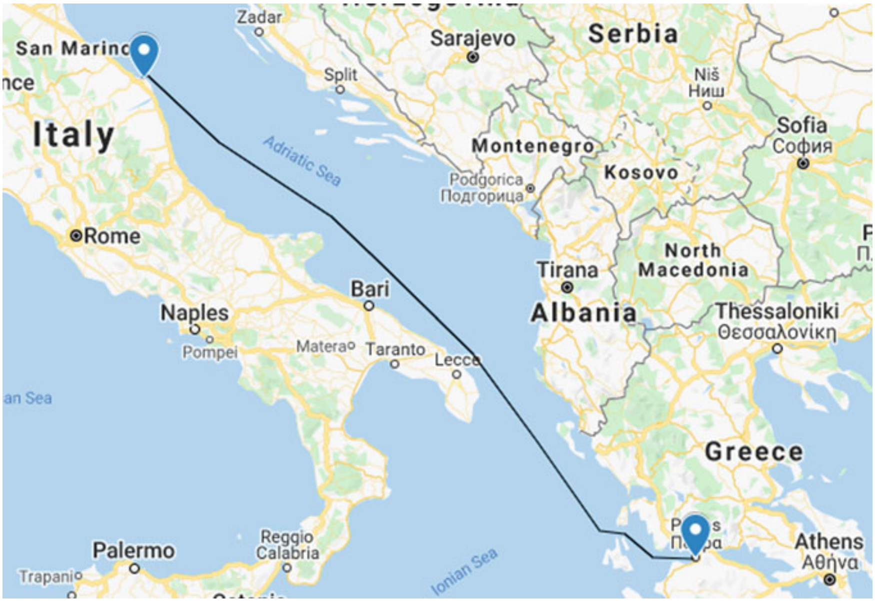

Fig. 11.1 Selected route between ports of Ancona, Italy to Patras, Greece; total distance about 515 NM

the vessel at design draught, even keel and in deep water, with 15% sea margin and with the main engines operating in the region of 85% MCR. With such a speed, the 515 NM one-way crossing would take approximately 22 h.

Although there are many more design specifications for the design team to make a focused start, a number of other key design specifications are presented in Table 11.1, in a comparative manner.

The service speed of the vessel on design draught, even keel, in deep water, Beaufort 2, is specified to be 24 knots with 15% sea margin and the main engines at 85% MCR.

The designs are to be developed as compliant with all Regulations laid down by the Authorities and IMO for international and unrestricted operation in EU waters. These are including, but not limited to, the most up to date (as of year 2020) applicable provisions of SOLAS, MARPOL, ILLC, EC Directives (IMO 2005, 2017a, b, 2020; EC 2003) and all other codes and resolutions, as applicable to RoPAX vessels. The designs must be detailed and constructed in accordance with Class rules (BV 2020a, b). There should be no need to apply for any exception or exemption.

Although it is not that critical to or the purpose of this Application Case, nonetheless an initial donor/baseline design and its GA has been included as part of the design specifications. The indicative GA provides a typology for the design development as well a guidance to the design team for the style of RoPAX preferred by the prospective owner. It can be noted from the donor/baseline vessel GA, as given in Fig. 11.2, that the key futures are the presence of a centre casing on the RoRo deck,

Table 11.1 Key design specifications: comparison between Alpha and Bravo design

	Design alpha	Design bravo
General arrangement	The accommodation block will be arranged for 65 crew and 880 passengers	At least 10% increase of passengers should be pursued
Main engine	Main propulsions engine information Number of units, type and power output should be suitable to the operational profile of the vessel Cont. Service rating: 85% of MCR (approx.) Cooling: fresh water Fuel HFO, 380 cST/50 °C	Diesel-electric propulsion Fuel: gas (LNG, H_2, etc.)
Propulsion	The vessel will be provided with adequate number of cp type propellers, each with four blades of nickel- aluminium bronze (nialbr) Type: CPP with skewed blades Number of blades: 4 Diameter: abt. 5.0 m Rotation: inward turning Material (hub and blades): NiAlBr Hub: 100% MCR on reverse thrust Hubcap: integrated design with rudder bulb	Podded propulsion Green fuel: gas (LNG, H_2, etc.)
Auxiliary power	No units: 3 Rating: 2 × 1760 kW approx. At max 1000 rpm 1 × 1320 kW Current: 50 Hz, 3-phase at 440 V Type: turbocharged, 4 stroke in-line marine diesel Rpm: 1000 RPM (max.) Cooling: water, built on pumps Fuel type: HFO or MGO/gasoil Starting: compressed air Sets are to be arranged for parallel operation	Suitable selection of generator sets to be made to support the diesel electric propulsion installation Green fuel: gas (LNG, H_2, etc.)

a long lower hold below the main deck, a car deck at higher deck level and a stern loading and unloading facility. These are the key desired features by the prospective owners and operators. Furthermore, some of the initial approximate dimensions and capacities are given to the design team; these are summarised in Table 11.2.

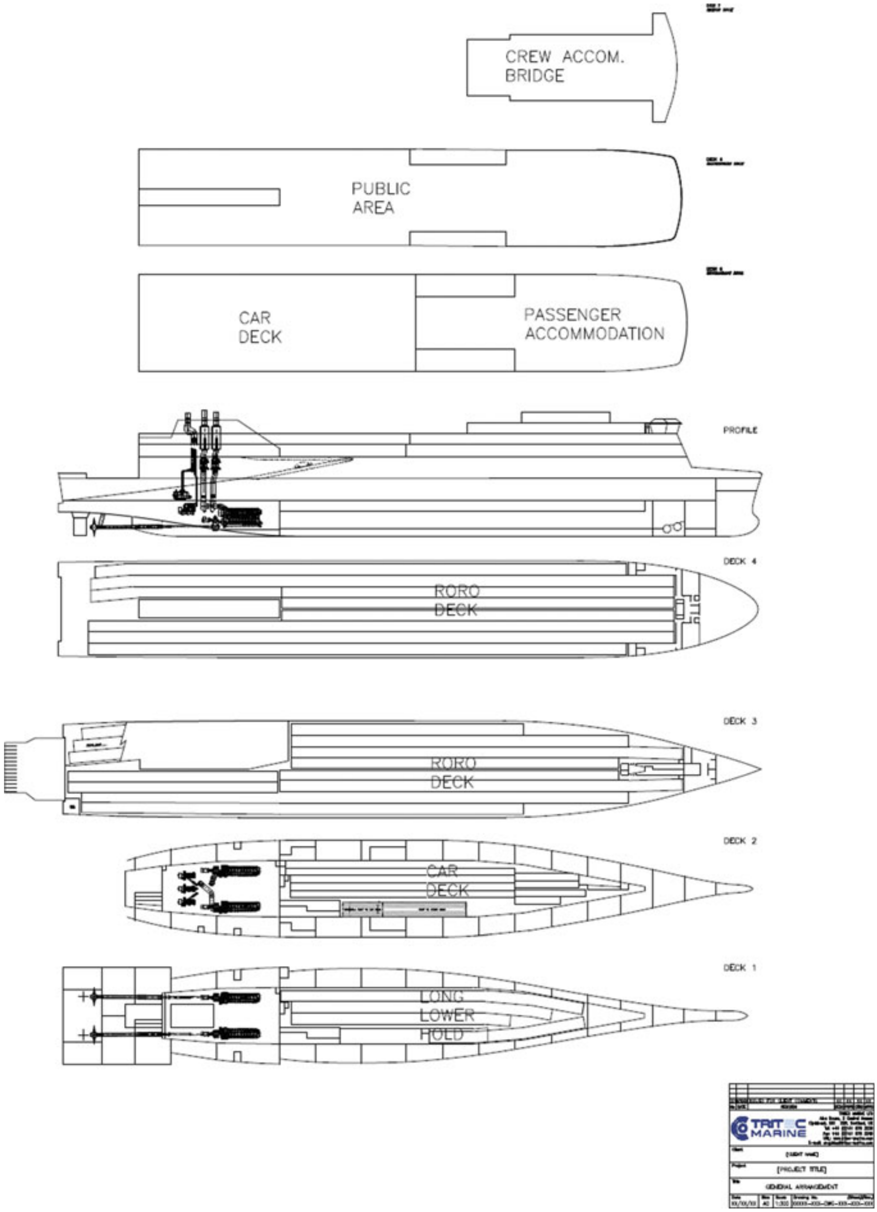

Fig. 11.2 Initial indicative GA issued to the design team

Table 11.2 Approximate principal dimensions

	Intial value
Length overall	187.m
LBP	177 m
Beam mLd	26 m
Depth to main deck	9 m
Draught (scantling)	7 m
Draught (design)	6 m
Deadweight (design)	6,000 mt

11.3 Optimisation Platform Synthesis

The present RoPAX design Application Case has effectively employed two platforms that are linked together for the optimisation runs. Optimization algorithms and tools for the systematic exploration of the design space available in CAESES® platform (Harries and Abt 2018) have been used for the optimization of the RoPAX vessel. This is the main platform that initiates and controls the optimisation runs and gather the evaluation results. On the other hand, a parametric model for the fully automated design of a ship's internal layout (including both the watertight subdivision and a coarse arrangement of the upper decks) has been created in the NAPA® platform, based on a series of macros, developed by using NAPA Basic, i.e. a programming language embedded in NAPA®. The two platforms are linked through the hull geometry definition and they are sharing the key control parameters. This allowed the design team to also employ other tools and calculation methods, as required for the design evaluation; they were integrated into the platform, as needed. A bespoke and expandable optimisation synthesis has been developed and extensively used; the design variants are generated for the exploration of the design space and they are sent to other software platforms for detailed evaluations, as and when required. This is illustrated in Fig. 11.3, the green coloured link shows continuous link, blue coloured shows a link used, when needed, such in the case of development of response surfaces or for a single selected design evaluation.

External software tools are integrated into the parametric design and optimization platform, mainly CAESES®, and for the assessment of each alternative design, the following tools are needed:

- Potential flow or viscous flow solvers for the calculation of calm water resistance and required propulsion power of alternative hull forms.
- Potential flow solvers for the calculation of seakeeping performance and added resistance in waves.
- NAPA macros for the evaluation of compliance with intact and damage stability requirements outlined by IMO instruments (IMO 2008, 2020).
- Link to NAPA Steel® for the elaboration of the structural design.

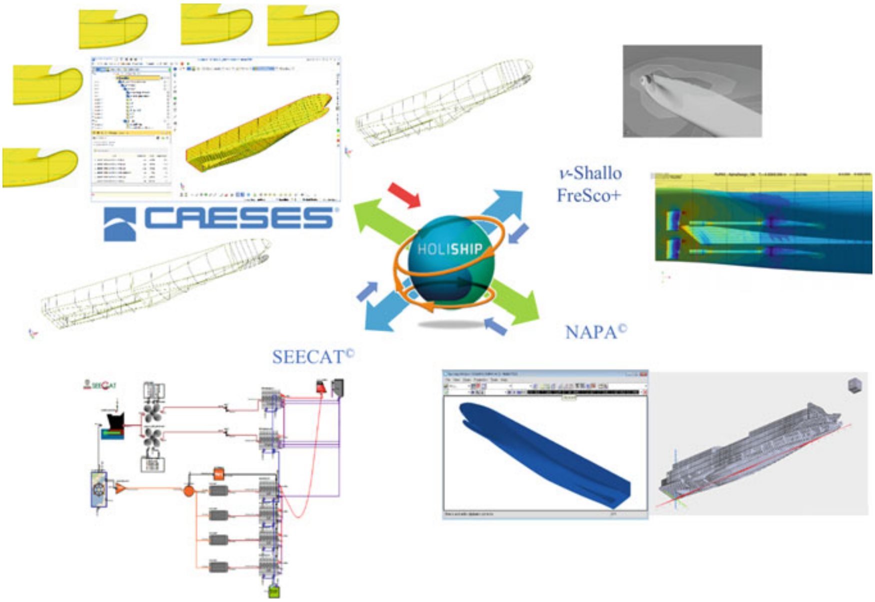

Fig. 11.3 Application Case RoPAX: optimisation platform synthesis

- NAPA macros for the elaboration of a variety of calculations (light ship and DWT calculations, formulation of loading conditions, calculation of EEDI, assessment of selected KPIs including a series of economic indices such as NPV, RFR, payback period etc.).

Since several of the above calculations require significant computer resources, their use during a design space exploration or during an optimization study, involving the evaluation of several hundreds of design alternatives is quite problematic. 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 practically instantly. However, this is with the exception of the NAPA macros as they were streamlined to run directly for each design variant, including the calculations performed under NAPA Steel® module in this application case.

The performance assessment and optimisation of the machinery systems were carried out by SEECAT® of Bureau Veritas (Marty 2014). Although, SEECAT® has been integrated into the CAESES® platform, as shown in Marzi et al. (2018), due to the limited time available the machinery system simulations are carried out only for the final selected designs of Alpha and Bravo.

11.4 Optimization Process for the Alpha Design

As the RoPAX vessels are significantly influenced by their internal space utilisation for maximisation of their carrying capacity namely, RoRo decks and passenger spaces, the balance between internal subdivision, loaded VCG and available margins in terms of compliance with the applicable stability and subdivision regulations do play a significant role. This is also the main reason why a naval architectural software package, such as NAPA®, has been extensively used together with the main optimisation driver platform CAESES®. Therefore, this combined with the design specifications given to the design team led to a design process, where a given hull form and GA available as a starting point were optimised for finding the best designs. The process implemented in this Application Case can be illustrated in Fig. 11.4.

Although the optimisation process adopted in this application case is not exactly a parallel processing of data, the use of surrogate models, in the form of response surfaces, makes it possible to evaluate the generated design variants of the hull first, whilst the internal subdivision was evaluated by NAPA, typically for damage stability compliance; this kind of focused optimisation process are well developed and documented, see, Zaraphonitis et al. (2012).

To this end the optimisation process for the Alpha design starts from the given donor vessel, in way of reflecting owners' operational preferences, and guided by the design specifications to come up with an optimised RoPAX design that can also be regarded as a typical RoPAX vessel with respect to its' internal layout. Once the internal layout topology is determined suitable for the size of the vessel, the optimisation process can be set up by streamlining the process of assessing key objectives and constraints. This is done by determining the key variables and parameters known to influence the design exploration in the design solution space. Then the response surfaces are created primarily by using SOBOL sampling method (Sobol 1976) for structural weight, ship resistance to be used for the initial testing of the platform. Verification and test runs have shown that NAPA Steel® macros can be streamlined to a direct calculation of each design variant, thus only the generated response surfaces for ship resistance have been adopted for the optimisation runs.

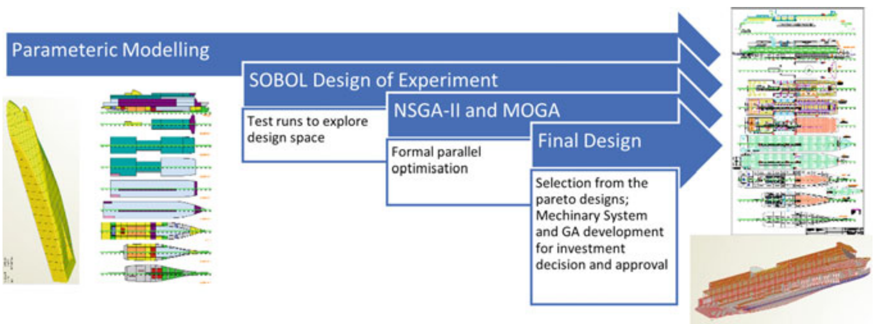

Fig. 11.4 RoPAX optimisation process

Upon completion of the design space exploration through genetic algorithms, the selection and promotion of a favourable design from the Pareto fronts is straightforward. It is up to the designer to evolve the design to a level of maturity that matters in the "contract/ready for approval" stage. Some details are always left to be dealt with at the detailed design stage; however, the platform tested here can handle a lot more details if deemed necessary. The only real limits are the computational time available and of course the hardware and software capacity and associated cost implications.

We will go through the main elements of the optimisation process in a manner that also shows the process flow in the following subchapters.

11.4.1 Determination of Design Objectives and Constraints

In order to demonstrate the capability of the HOLISHIP platform in developing two RoPAX designs based on the same design specifications with only prescribed differences, an obvious choice for design objective is the economic value of the designs. Intuitively, the first optimisation criterion is the maximisation of the design's Net Present Value (NPV) for a selected operational profile.

The second objective was selected, amongst the many other arguably important objectives, as the fuel consumption for a roundtrip. The NPV is inherently related to the fuel consumption; at the same token, one can argue that many optimisation criteria can be translated to NPV. As the selected route runs with a tight round the clock schedule, a direct measure of the running/operational cost saving is a good measure for design variants, therefore the selected second objective is the minimisation of fuel consumption.

The first volume of this book (Papanikolaou (ed) 2019) explains the employed economic models in a much greater depth. However, in the context of this application case the evolution of the actual value of these economic indicators are of secondary importance from the point of view of showing the platforms capabilities. As long as the relative values of economical KPIs, as CAPEX, OPEX and NPV, are captured correctly, the selection of the best performing designs will not be compromised.

A number of other key constraints are included in the optimisation platform, typically to ascertain feasibility of each design variant produced. The key constraints, namely those that are explicitly required by the specifications and by the applicable rules and regulations in the optimisation search are presented in Table 11.3.

11.4.2 Selection of Variables and Parameters

Developed parametric models allow the control the hull and internal layout with a set of 28 parameters in total; however, for the herein conducted global optimisation only the main design variables were used in optimisation within the limits shown in Table 11.4.

Table 11.3 Key constrains used for search optimisation and in DoE

Number of passengers	≥880	Lane length	≥1,950 m
Passenger cabins	>300	Payload	≥3,500 t
Intact stability compliance margin	Differential $KG_{Intact} \geq 0.05$ m		
Damage stability compliance margins	$A - R \geq 0.01$; $A_{d,\,p,\,1} - 0.9R \geq 0.01$; Differential $KG_{R8.1,\,R8.2\text{–}3} \geq 0.05$ m; Differential $KG_{WOD} \geq 0.05$ m		
Attained EEDI	Differential $EEDI_{phase2} - EEDI \geq 0.2$ g/tm		

Table 11.4 Design variables and limits

	Lower limit	Upper limit
Length BP	170 m	210 m
Beam	26 m	28.5 m
Depth to Deck 3	9.0 m	9.4 m
Block coefficient	0.58	0.62

For the calculation of the annual income and expenditure, an operational scenario has been specified as presented in Table 11.5—Operational parameters, according to which the annual operation is divided into three periods, namely a low, a medium and a high season. For each season, different percentile occupancies and freight rates are assumed following RoPAX practice in the area of operation. It is also possible to specify different numbers of round trips per week, or different operating speed for each operating period.

11.4.3 Parametric Modelling of Hull Form

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 design team partners. A typical example of a hull form created by the above parametric model is presented in Fig. 11.5. The size and the hull form details of each design are controlled by a series of design variables, enabling the user to specify among others:

- the ship's main particulars; LBP, beam, design draught, depth,
- the length of entrance and run,
- the block coefficient (CB) and the midship section coefficient (CM) at design draught and the corresponding Longitudinal Centre of Buoyancy (LCB),
- the size and shape of the bulbous bow (length, height, thickness, inclination),

Table 11.5 Operational parameters

	Low season	Medium season	High season
Duration (weeks)	46	2	2
Passenger occupancy in enclosed spaces	0.50	0.80	0.95
Passenger occupancy on open decks	0.30	0.80	0.95
Private cars occupancy	0.50	0.80	0.95
Trailers occupancy	0.80	0.80	0.95
Private car freight (USD)	99.0	109.8	121.5
Trailer freight (USD)	510.3	631.8	754.2
Passenger fare (outside cabin, USD)	154.8	188.1	221.4
Passenger fare (berthed, inside cabin, USD)	143.1	164.7	198.9
Passenger fare (economy class lounges, USD)	90.0	100.8	112.5
Passenger fare (business class airliner-style seats, USD)	99.0	109.8	121.5
Passenger fare (open deck, USD)	88.2	91.8	103.5
Avg. income per passenger for on-board services (USD)	25.0	25.0	25.0

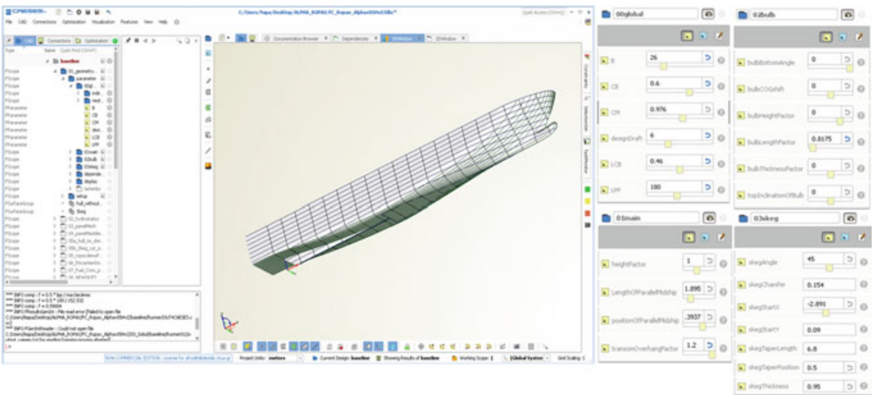

Fig. 11.5 A typical parametric model for the hull form in CAESES®. The control windows used for the hull form variation are shown on the right view

- the details of the transom and duck tail (height, longitudinal extent, inclination),
- the details of the skeg (longitudinal extent, thickness, inclination angle).

The developed parametric model can be used for the elaboration of hull forms in a wide range of dimensions. In the presented application case work, it has been used without any problems for hull forms with length between perpendiculars from 155 to 215 m, beam from 24.6 m to 30.6 m, block coefficient from 0.56 to 0.62 and LCB from 44 to 48% of LBP.

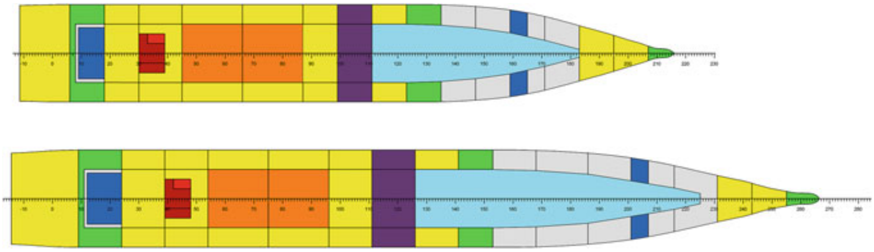

Fig. 11.6 Effect of the length variation of the ship on the watertight subdivision. Top layout for LBP = 170 m, bottom layout for LBP = 210 m

The generated hull form serves as input to a series of software tools, which have been integrated within CAESES® and are used for the assessment of each design alternative. The design team has used a special scripting in CAESES® to reproduce the surface definition in NAPA® platform as a direct input, so that NAPA scripts can create the parametric internal layout model and parametric structural design for the given hull form.

11.4.4 Parametric Modelling of Internal Layout

A parametric model sufficiently detailed and able to produce the watertight subdivision, a coarse arrangement of the upper decks and RoRo spaces, and associated arrangements was setup in NAPA®. This is done automatically based on a series of macros, developed using NAPA Basic, i.e. a programming language embedded in NAPA®. The parametric model has been rigorously tested and can be used for the design of large RoPAX vessels, ranging from 160 to 220 min length between perpendiculars, well beyond the variation range consider in this application case.

The parametric model of the internal layout starts with the evaluation of the appropriate number (depending on the ship's LBP) and longitudinal position of the main transverse bulkheads. The starting point of this algorithm is a pre-defined subdivision of a baseline RoPAX design developed from the donor vessel layout, which was given with the design specifications early on. The embedded topology is also able to respond to an increase in length while keeping control of compartments and fire zones length and vertical continuity; see Fig. 11.6 for an example comparison. This initial subdivision adapts to the length of the design in question by lengthening or shortening selected watertight compartments by adding or subtracting one web frame space to each of them whilst obeying certain constraints such as requirements of MFZ limits and minimum acceptable engine compartment length.

The accommodation decks are divided into three or four main vertical zones, depending on the vessel's length, while noting the maximum length should not exceed 48m according to SOLAS, IMO (2020). One main fire bulkhead is always aligned with the watertight bulkhead between the two engine rooms. One fire zone is positioned aft of the aforementioned fire bulkhead and the remaining two or three are located forward of it.

Designs created by the parametric model are all configured to have eight decks. However, the model can accommodate changes easily depending on the designer's preferences. Deck 1 coincides with the tank top, while deck 3 is the subdivision deck, which is also the main RoRo deck. With the exception of Deck 1, all decks are created as horizontal planes, with the corresponding deck heights specified by the designer and are direct input variables. Deck 1 on the other hand is created by three stepwise horizontal planes, located aft, forward and in way of the two main engine rooms. Two lower hold levels for private cars or trailers are fitted on Deck 1 and Deck 2, forward of the main engine rooms and within the longitudinal bulkheads (typically situated within the B/5 side penetration limit line). Two more trailer decks are fitted on Deck 3 and Deck 4. Decks 5, 6 and 7 are intended mainly for passenger and crew accommodation. Depending on the designer's selection, it is possible to use one or two fire zones at the forward end of Deck 5 for the carriage of private cars.

The lower holds are accessed from Deck 3 via fixed ramps with ramp covers. The wing compartments surrounding the lower holds are mainly void spaces, while some of them are used for the installation of auxiliary machinery (e.g. sewage treatment plants), or various tanks (fresh water, heeling or ballast tanks). Forward of the lower holds, three or more watertight compartments are created, where auxiliary machinery spaces (e.g. bow thruster room) or ballast tanks are installed.

Decks 3 and 4 are the two main ro-ro decks for trailers. Access from the shore to deck 3 is provided via two stern ramps for vehicles and one ramp on the starboard side for the embarkation and disembarkation of the passengers. A central casing is arranged to provide access to lower decks, as well as for the fitting of ventilation and exhaust ducts. The central casing is positioned either symmetrically or on the one side of the centre plane, based on the beam of the ship in order to maximize trailer lanes number. Vehicles access Deck 4 from Deck 3 via an internal ramp, which the parametric model can treat either as fixed or hoistable. The spaces aft and forward of the garage space on Deck 4, are reserved for the anchoring, mooring and towing equipment of the ship.

Passengers entering the ship on Deck 3 may access the accommodation decks via an escalator enclosed in a side casing on the starboard side of the vessel leading to Deck 5. The aft two main fire zones on Deck 5 are used for the passengers' accommodation and they are occupied by public spaces, including the reception, lounges, a restaurant, shops. The open decks at each side of the second zone (measured from the stern), intended for the installation of lifesaving appliances. Another open deck area is also provided at the aft end of Deck 5. The remaining one or two main fire zones at the forward part of Deck 5 can be used either as an additional garage space for the transportation of private cars, or as a passengers' accommodation space (usually as public spaces and/or Pullman seats areas) as explained previously. Deck 6 houses the passenger cabins and a Pullman seat lounge (if not fitted on Deck 5). The crew spaces and the wheelhouse are placed on Deck 7. Finally, the aft part of Deck 7

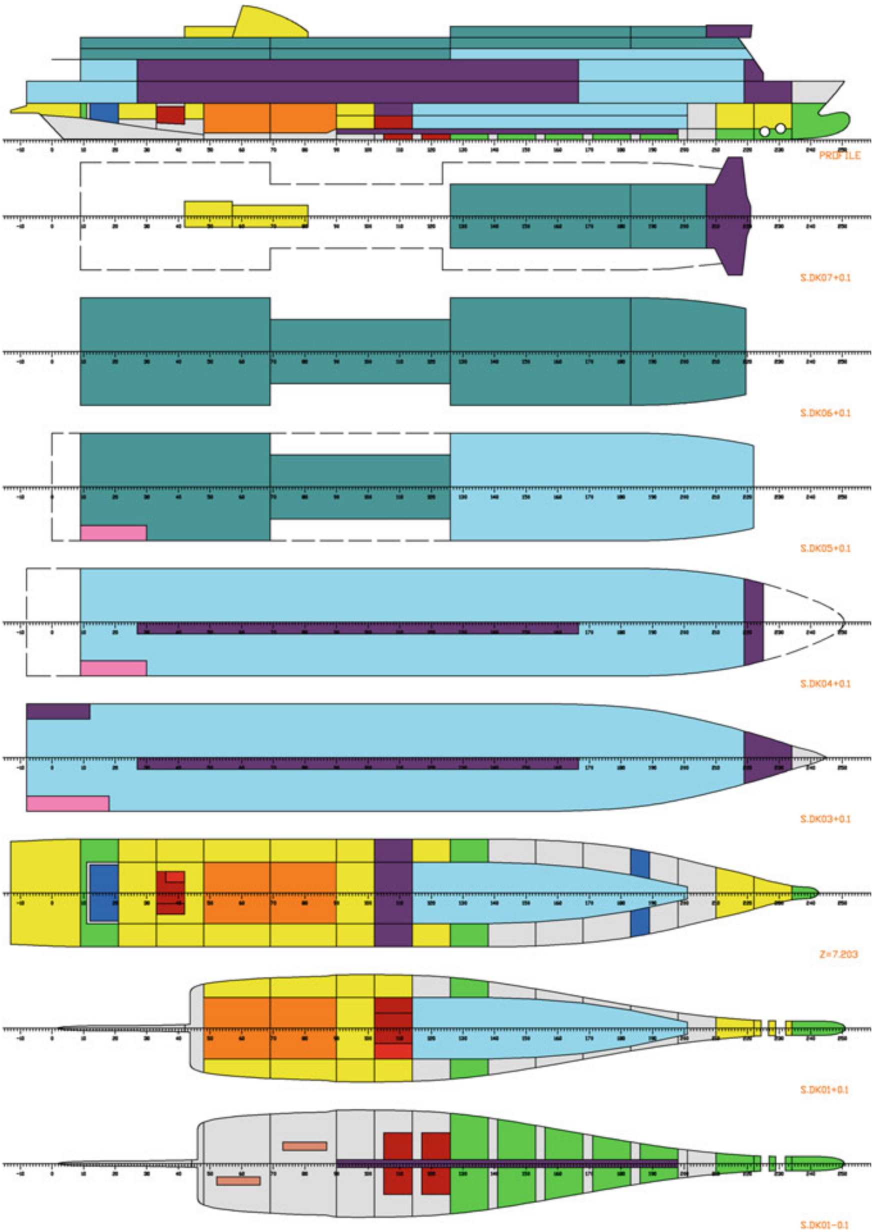

Fig. 11.7 Typical internal layout arrangement produced by the parametric model

serves as a large sun deck for passengers. A typical arrangement of a large RoPAX ship, elaborated by the parametric model is illustrated in Fig. 11.7.

In order to verify the feasibility of each particular design alternative, a series of checks and constraints have been implemented. For example, the vertical position of Deck 1 should comply with SOLAS Part B, Regulation 9 requirements for the double bottom height (IMO 2020). Further details on compartmentation and internal subdivision checks are given in Chap. 7 of this book. However, it should be noted that some of the parametric modelling options are not used in this application case and are left at their default values to prevent incompliance with the Stockholm Agreement requirements (IMO 1995). These requirements are specific to RoPAX vessels and are also part for the respective European Directive (EC 2003). To this end, the longitudinal bulkheads are kept at inside the B/5 penetration limit line, which is measured from the side shell throughout the length of the vessel.

The other design variables mainly controlling local variations were varied to conduct checks during the test runs. For example, the LCB/LBP ratio is a hull form control parameter; however; the best value of 0.46 for keeping the trim at an acceptable level has been determined by conducted hydrodynamic studies and therefore this value is kept constant. If desired, final adjustments can be carried out at the detailed design stage. Another example is the use of the garage deck space on Deck 5, for the control of the layout topology. As explained previously, the available options for the garage space, which is located in the forward part of the Deck 5, are: (a) cars only (the default option), (b) passenger space only, and (c) mixed use. The NAPA macros are built to create a layout topology enabling the necessary changes according to the preferences of the end user.

11.4.5 Parametric Structural Design

Developing a model for the accurate calculation of the steel weight for a single vessel design is an expensive process due to the amount of data to be calculated at a high degree of accuracy; the entire vessel is built on a grillage type structure, but the requirements of the grillage structure vary throughout the vessel depending on the location and the purpose of the structure. This is further complicated with any changes in the main parameters of the vessel as the scantlings of the grillage structure may need to change accordingly.

A balance is required to successfully and efficiently automate the scantling calculations without an exhaustive and iterative process that produces sufficient detail to capture changes in the parameters at an acceptable degree of accuracy. In order to develop a parametric steel model for the present RoPAX, as envisaged in the HOLISHIP project, the NAPA Steel® module was used, while the hull model is prepared and distributed through CAESES® and then transferred to NAPA®.

With the help of NAPA Steel® scripting implemented to this application case, the plate and primary structure are modelled parametrically and are automatically updated for any geometric variations. The same cannot be said with the secondary stiffening, although stiffeners can be created in NAPA Steel, it does not automatically update with geometric variations. Therefore, the cross-sectional area of the secondary

Table 11.6 Example equivalent keel plate thickness

Keel plate	Thickness
Plate net thickness (mm)	12.32
Corrosion margin addition (mm)	1.5
Plate gross thickness (mm)	13.82
Plate CSA (mm^2)	8292
Stiff CSA (mm^2)	2066
Total Area (mm^2)	10,358
Equivalent plate thickness	17.26

stiffeners was added to the plates to achieve an ‘equivalent’ plate thickness with respect to its weight. It should be noted that, for clarity, this is acceptable to achieve the equivalent weight per unit length (and therefore ship’s total steelweight) but it does not have equivalent strength characteristics and would not be an appropriate method for strength assessment. The primary reason to use equivalent plate thickness is strictly for the purpose of obtaining the steel weight and its distribution accurately, as necessary for initial design stages. This is what matters the most at this pre-contract or contract ready design stages, the detailed design will then be adding these secondary stiffener elements only for the optimum design selected. The following Table 11.6 shows an example calculation of ‘equivalent’ keel plate thickness.

The structural scantling, in the first place, has been developed using BV Rules for Ships (BV 2020b). The scantlings of the plate and stiffening were calculated for the following range of vessel parameters; lengths of 150 m, 170 m, 190 m, 210 m and breadths of 26 m, 28 m, 30 m for the specific application case. The areas of plate and stiffening were calculated for the following areas: keel, bottom, inner bottom, side shell, inner side, floors, vehicle deck, car deck, accommodation deck and superstructure side shell.

All objects were created parametrically, often using NAPA’s structural library as a starting point, so that when the geometry or input parameters e.g. frame spacing were changed, the structural arrangement would update in parallel. Once all structure was created, the objects were added to a steel model and assigned an object type according to the structural type and location. An example structural model with shell plating and internal structural elements only can be seen in Figs. 11.8 and 11.9.

The object types were based on the locations of the structure in question, and whether the structure was a deck, web, bulkhead, etc. A limited number of object types were selected to streamline the process, as defining separate structure types for every different element onboard would add a complexity to the model that would not give much benefit in return. The plate thicknesses calculated previously were applied to each object type, which then enabled a steel weight to be calculated accurately.

The other advantage of parametric structural design is that every design variant has an internal geometrical output showing its structural design. The output of each design can be imported into CAESES® for visual and perhaps virtual demonstration of the design variants, see example results imported in CAESES® Figs. 11.10 and 11.11.

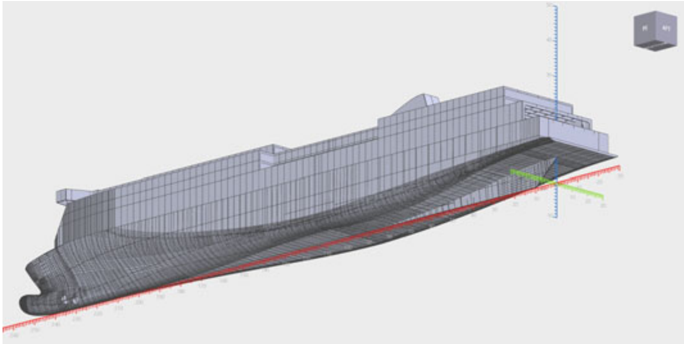

Fig. 11.8 Typical structural design with shell platting

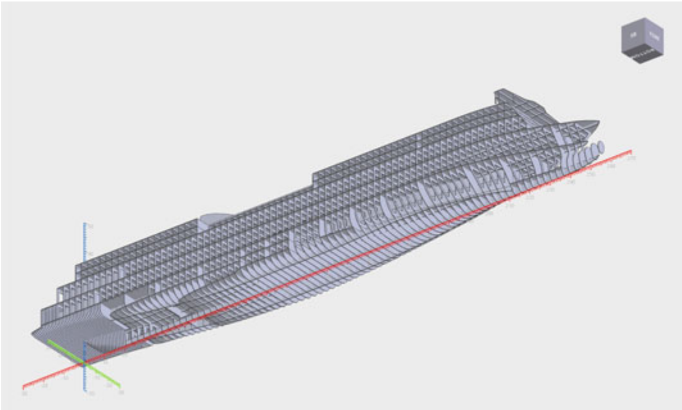

Fig. 11.9 Typical structural design shell plates are hidden, showing internal elements

11.4.6 Resistance, Powering and Machinery Selection

The evaluation of the calm water resistance and subsequently of the required propulsion power are carried out with the help of surrogate models. To this end, systematic calculations were carried out by using the ν-Shallo panel code software tool of HSVA (Gatchell et al. 2000), both at 21 knots and 27 knots as an extreme case, 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) sampling, varying selected design variables within a specified range of variation. Selected cases have been tested using the RANS FreSCo+ tool of HSVA (Hafermann 2007), 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

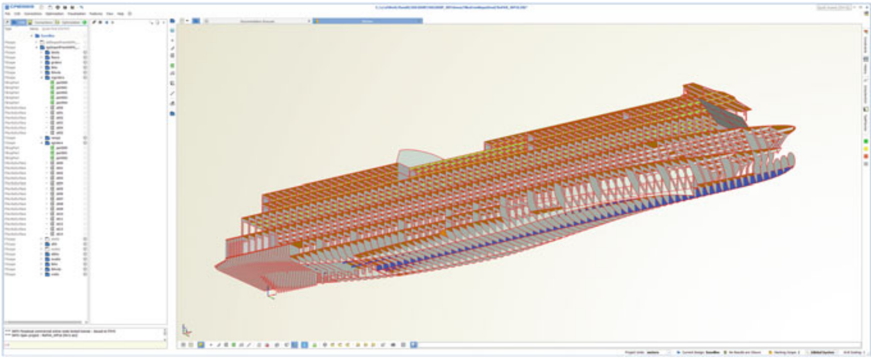

Fig. 11.10 A typical structural model import in CAESES®, hull shell is hidden, showing internals

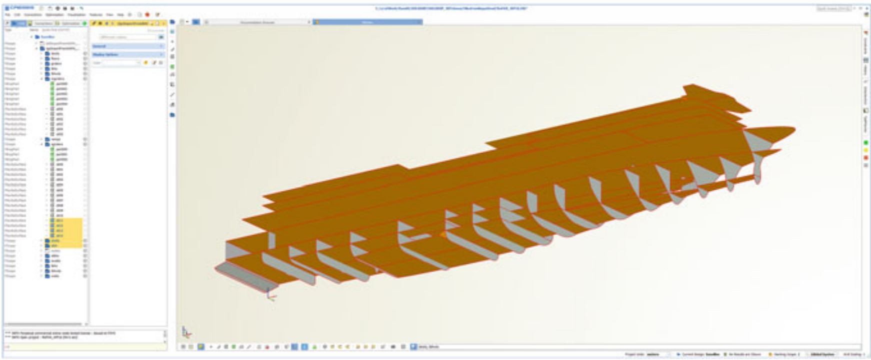

Fig. 11.11 A typical structural model import in CAESES®, showing only main WT bulkheads and decks

these response surfaces using the CFD code with respective results of direct calculation by the ν-Shallo code are illustrated in Fig. 11.12 and in Fig. 11.13, for 21 knots and 27 knots, respectively. 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 ±1% in all cases. In addition, the results from the systematic resistance calculations have been used in the HOLISHIP project to develop a modified version of Hollenbach's method (Hollenbach 1998) for the estimation of the calm water resistance of twin-screw, single-skeg RoPAX vessels. Results obtained with this method have been also used for the development of another surrogate model that was used for the calculation of the calm water resistance during the global optimization (concept design) carried out in this application case.

Surrogate models were also used for the prediction of added resistance in waves. In this case, systematic calculations were carried out by using NEWDRIFT+ (Liu et al. 2017) for a JONSWAP spectrum with significant wave height, $H_s = 3$ m

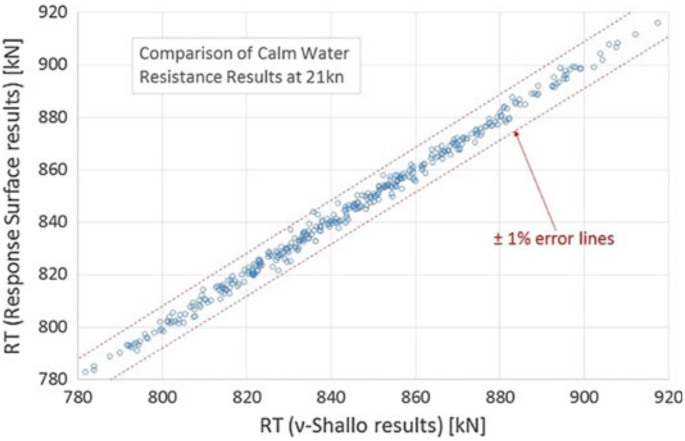

Fig. 11.12 Comparison of calm water resistance predictions by ν-Shallo at 21 knots

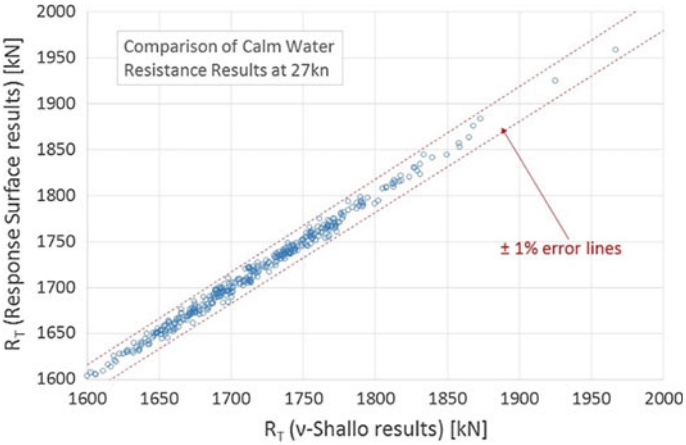

Fig. 11.13 Comparison of calm water resistance predictions ν-Shallo at 27 knots

and peak wave period, $T_P = 7$ s in 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®. A comparison of the estimations obtained by the response surface and those obtained by direct NEWDRIFT+ calculations is presented in Fig. 11.14. As may be observed from this figure, the estimations obtained by the response surface are in a very good correlation with those by the direct use of the code, with their difference being less than ±2.5% in almost all cases. A similar conclusion was derived from the comparison of the results obtained by a linear regression. An alternative, more traditional way of accounting

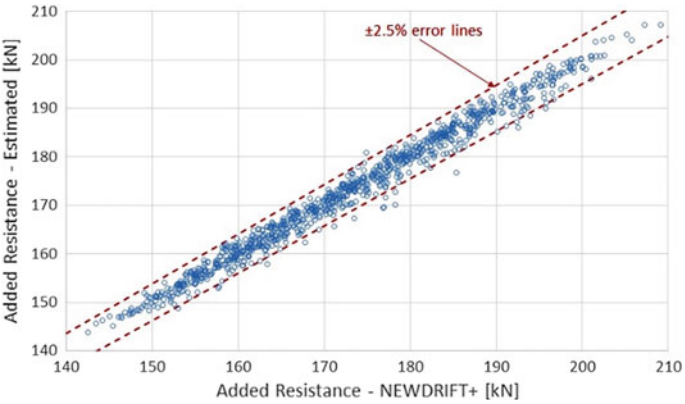

Fig. 11.14 Comparison of added wave resistance in head seas at 27 knots calculated by NEWDRIFT+ and estimated by a response surface

for the impact of added resistance and/or hull fouling on the total resistance is to add a user-defined sea margin on top of the calculated calm water resistance and propulsion power.

Once an estimation of the required propulsion power is available, with 90% maximum loading limit consideration a preliminary main engine selection was made from a list of dual-fuel, four-stroke diesel engines; such list of engines has been implemented within the NAPA parametric model. However, it became apparent during initial exploration of the design space that for keeping the desired main deck height below 9.5 m due to port compatibility and also for keeping the VCG down, the number of engines able to fit inside the machinery space of the Alpha designs was reduced down to the Wärtsilä V46DF series. The evaluation alternative machinery system configurations, such as the use of engines with different number of cylinders: 12, 14 or 16 were also considered in order to explore the potential use of shaft generators. These alternatives were modelled and evaluated using the SEECAT® simulation platform of Bureau Veritas. In addition to the main engine variants, different sizing was considered for each shaft generator from 1000 to 2250 kW, considering a step of 250 kW in between the variants. Finally, the gensets were considered to be of type Himsen H25/33. The vessel was assumed to accommodate up to 4 gensets with minimum 6 and up to 9 cylinders. The design space for machinery optimization is summarized in Table 11.7 and the model used in SEECAT® for Alpha designs can be seen in Fig. 11.15.

As the ship is designed with one engine per shaft line and possibly one PTO, the maximum number of engines was implemented in the model. Each of the variants, as well as the PTO, can take zero (0) value and therefore be equivalent to a design without PTO or with fewer gensets. The main engines (Wärtsilä V46DF) drive CPP propellers in a combinator curve mode. KPIs such as total fuel oil consumption and emissions (CO_2, NOx, SOx) are returned over the operational profile for each of the simulated combinations.

Table 11.7 Limits of design space for the machinery optimisation of the Alpha design

	Number	Min size [kW]	Max size [kW]	Step [kW]
Main Engine	1 per shaft line	13,740	18,320	2290
Shaft generator	Ø or 1 per shaft line	1000	2250	250
Auxiliary engine	2, 3 or 4	1500	2250	250

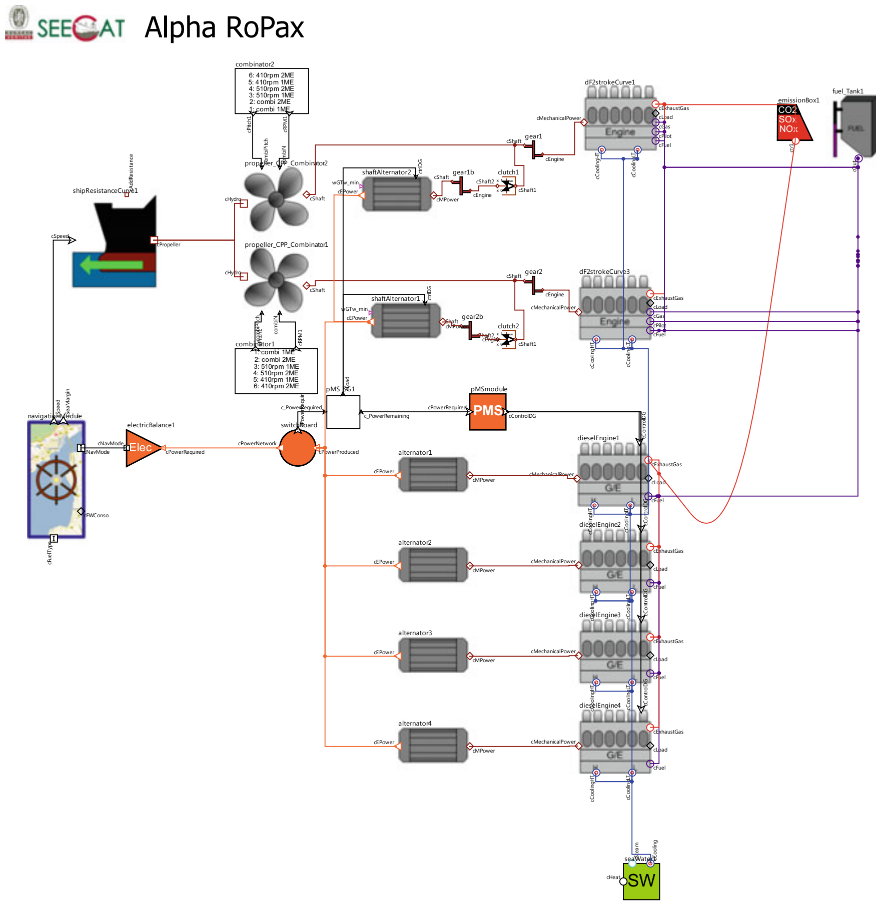

Fig. 11.15 SEECAT model used for the machinery system optimisation of the Alpha design

Additionally, weights and volumes of the engines and PTOs were estimated based on maker's data sheets. For compensation, costs were estimated based on average costs per kW: DF main engine 290 €/kW, DF gensets 470 €/kW and 625 €/kW for the shaft generators.

11.5 Optimisation Results

The economic potential of each design variant is assessed as part of the first design objective, namely of the maximisation of NPV. In order to achieve that, the building cost is subdivided into steel, outfitting and accommodation, machinery and non-weight costs. The first three components are estimated using empirical coefficients (USD per ton), while the non-weight cost is considered to be a fraction of the rest. Then, a margin is added to the building cost in order to obtain the CAPEX. For the calculation of the annual income and expenditure, an operational scenario has been specified as presented in Table 11.5—Operational parameters, according to which the annual operation is divided into three periods, namely a low, a medium and a high season. For each season, different percentile occupancies and freight rates are assumed. It is also possible to specify different numbers of round trips per week, or different operating speed for each operating period. Regarding the assumed occupancies, it is recognised that the demand for transport work in a shipping line is not unlimited. Therefore, when examining alternatives having different transport capacities, it is important to ensure that larger ships do not unrealistically benefit from economies of scale. In other words, the market demand for capacity will not grow with the extra capacity in offer; this is particularly true for the selected route which is a well-established market already. In the developed parametric model, this is achieved by assuming that the provided percentile occupancies correspond to given "baseline" capacities for each ticket category, and by providing the possibility to reduce these occupancies as the actual capacities are substantially increased in comparison with the specified baseline values. In the results presented herein, three capacity utilisation alternatives have been examined in line with the aforementioned assertion; these are presented graphically in Fig. 11.16.

Before the optimisation runs, 450 SOBOL DoE runs were conducted to explore the design solution space; of the 450 DoEs, 201 designs were feasible, and 249 designs were infeasible. As the platform produced results successfully, the formal optimisation runs were carried out in parallel. The genetic algorithm NSGA II (Non-dominated Sorting GA II) and MOGA by the *Dakota* toolbox were utilised as both toolkits are available within CAESES®. All the results including the initial DoE results were collated for the subsequent analysis. In total, 3207 design variants were produced; of that 1478 designs were feasible, and 1729 designs were marked as infeasible. The graphical representation of the results is given from Figs. 11.17, 11.18, 11.19, 11.20, 11.21, 11.22, 11.23, 11.24, 11.25, 11.26, 11.27 and 11.28; feasible designs are plotted in blue and infeasible designs are plotted in orange.

The alternative effective capacity calculations clearly affected the main objective's outcome as seen in Fig. 11.17, while noting that the design team proceeded with the NPV3 option. The following results will be presented based on this selection. It is worth noting, however, that for both NPV2 and NPV3, the values reach a pick for a length around 190 m. As it is seen in Fig. 11.17 for NPV, where the capacity utilisation is unaltered for size changes, there is an almost linear dependence of transport capacity and lightship weight on L_{BP} that is also observed in Figs. 11.20 and 11.21.

Design variants with a beam of 27 m or above can accommodate one more trailer lane on the main and upper deck in the region of the ramp connecting the two decks and as a result, there are two separate groups of points appearing in Figs. 11.18 and 11.19.

The subdivision A-Index margin has a strong dependence on beam, as expected. As it can be observed from Fig. 11.22 that the probabilistic damage stability A-Index margin is the clear governing criterion for the designs marked as infeasible. As the index requirements (R index) increases with the vessel length, the margin of compliance clearly decreases. The deterministic minor damage regulations of SOLAS compliance are positively influenced by beam, as shown in Fig. 11.23. A

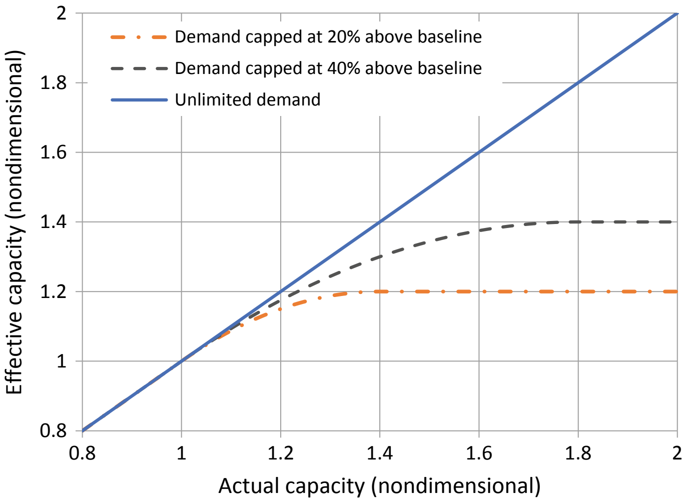

Fig. 11.16 Effective capacity calculation for increasing ship's size

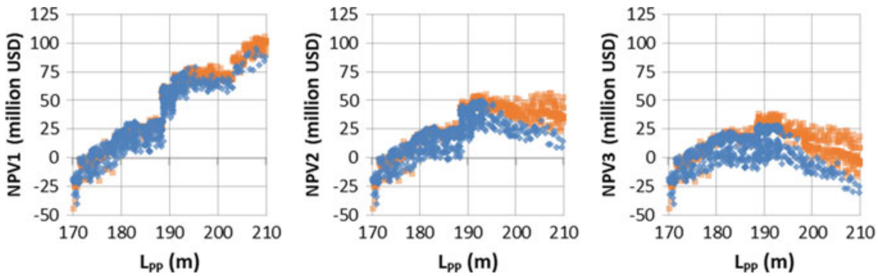

Fig. 11.17 NPVs per Effective capacity calculation. NPV1 denotes values calculated with unlimited demand adjustment; NPV2 denotes values calculated with demand capped at 40%; NPV3 denotes values calculated with demand capped at 20%

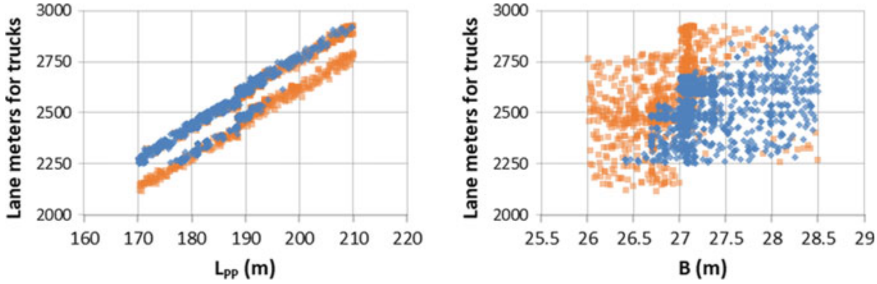

Fig. 11.18 Lane meters for trucks versus LBP and Beam

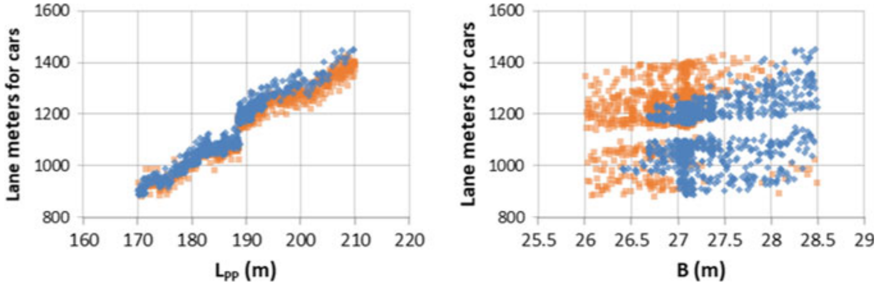

Fig. 11.19 Lane meters for cars versus LBP and Beam

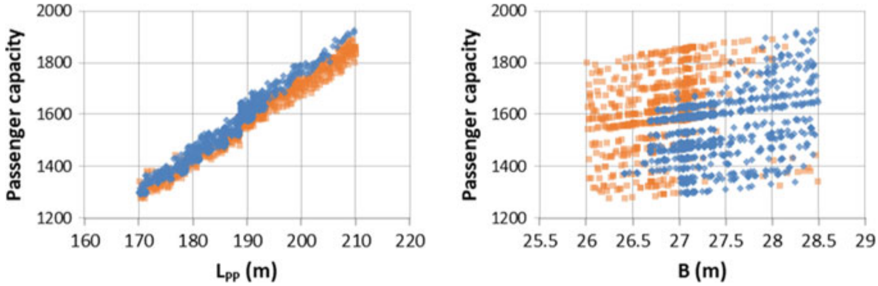

Fig. 11.20 Passenger capacity versus LBP and Beam

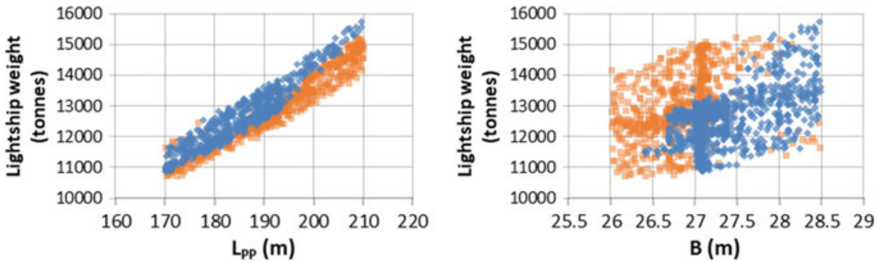

Fig. 11.21 Lightship weight versus LBP and Beam

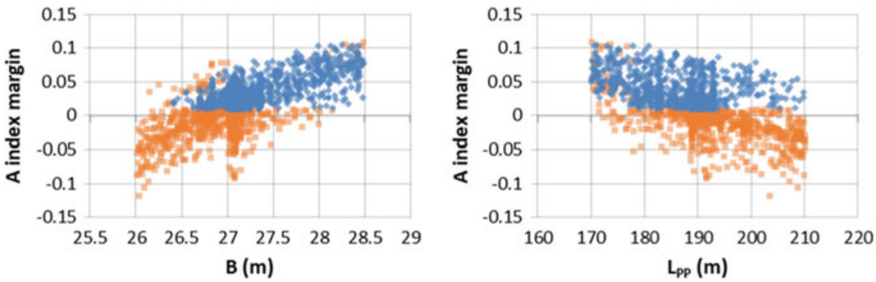

Fig. 11.22 A-Index margin versus LBP and Beam

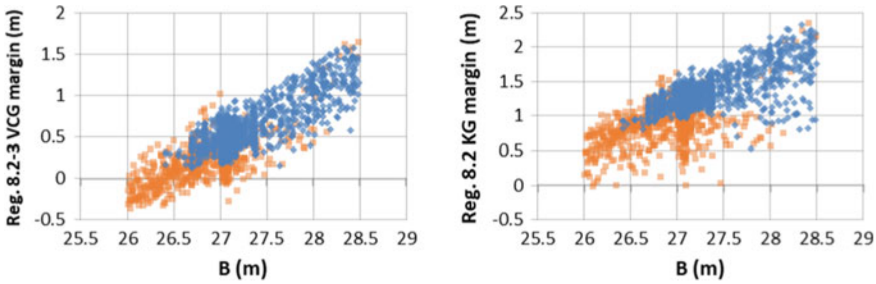

Fig. 11.23 SOLAS Reg.8.2–3 VCG margin and Reg.8.2 VCG margin versus Beam

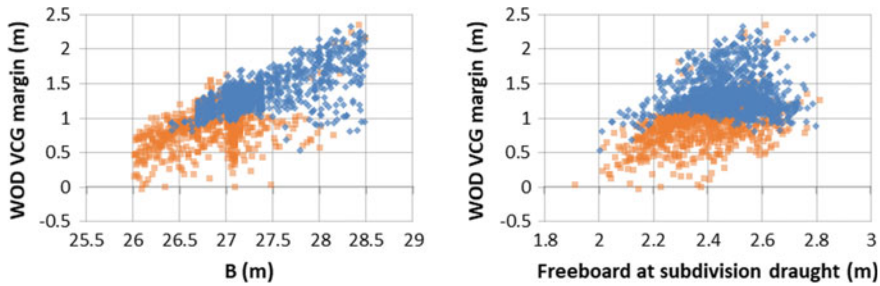

Fig. 11.24 Stockholm Agreement Regs. (WOD) VCG margin versus Beam and Freeboard at subdivision draught

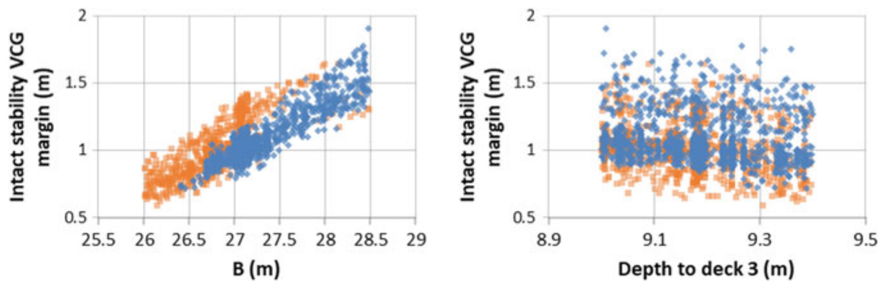

Fig. 11.25 Intact Stability VCG margin versus Beam and Depth to Deck 3

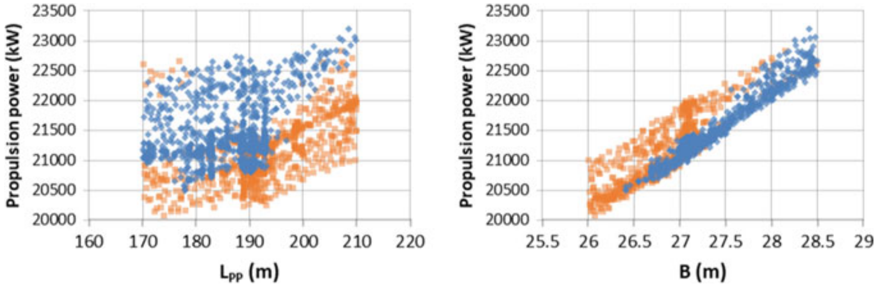

Fig. 11.26 Propulsion power versus LBP and Beam

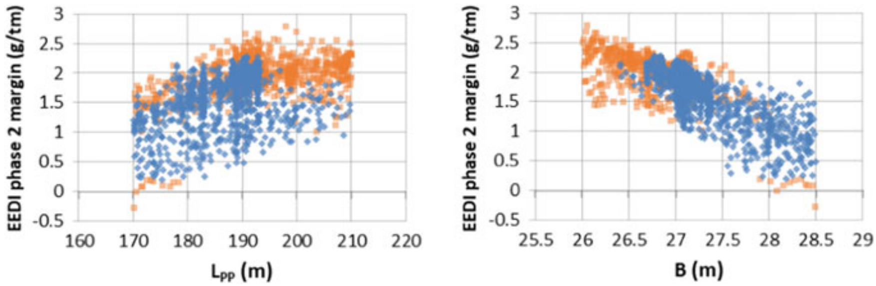

Fig. 11.27 EEDI, phase 2 margin versus LBP and Beam

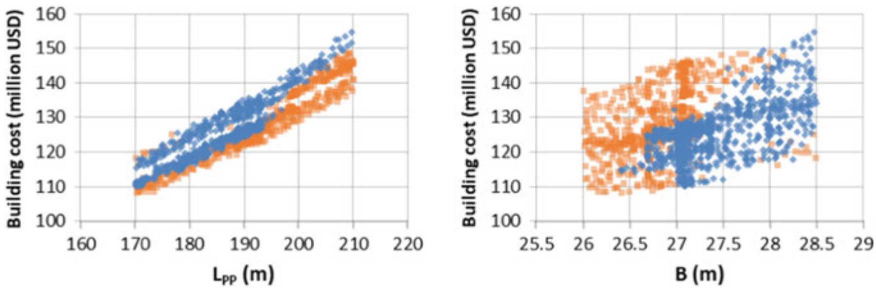

Fig. 11.28 Building cost versus LBP and Beam

scatter diagram of the stability margin according to the Stockholm Agreement versus intact freeboard at subdivision draft is illustrated in Fig. 11.24. Having a large intact freeboard to start with results in smaller volume of water likely to be accumulated on the subdivision deck, therefore a higher freeboard (up to a certain point) should be beneficial.

As expected, the intact stability margin decreases with the increase of Depth to Deck 3, because of the higher centre of gravity, also increases, with a higher correlation, by beam, (Fig. 11.25). A small increase of propulsion power with LBP is shown in Fig. 11.26, obviously because of the corresponding decrease of the Froude number. The dependence of propulsion power on beam on the other hand is much stronger.

The EEDI margin is higher for vessels with smaller propulsion power (Fig. 11.27). However, since most of these vessels have a smaller beam, they fail to comply with stability requirements and therefore they are marked as infeasible. Nevertheless, a significant number of feasible designs have been identified, even with a smaller EEDI margin. A linear dependence of Building Cost on L_{BP} is observed in Fig. 11.28.

11.6 Final Review of the Results for Selection of the Main Dimensions

After going through the optimisation results as demonstrated in the previous section, the NPV and A-Index margins come up as the most critical selection criteria. Furthermore, the second selected optimisation objective, namely Fuel Consumption, became redundant as the machinery selection option was somewhat limited in the global optimisation (due to machinery size/ space limitation); thus, the design team focused on the optimisation of the propulsion power as a substitute to carry out the machinery selection optimisation in the final design. Therefore, looking at the NPV, the A-Index Margin and the Propulsion Power evaluation results, only a smaller group of designs formed the Pareto fronts of favourable design, as plotted with red in Fig. 11.29.

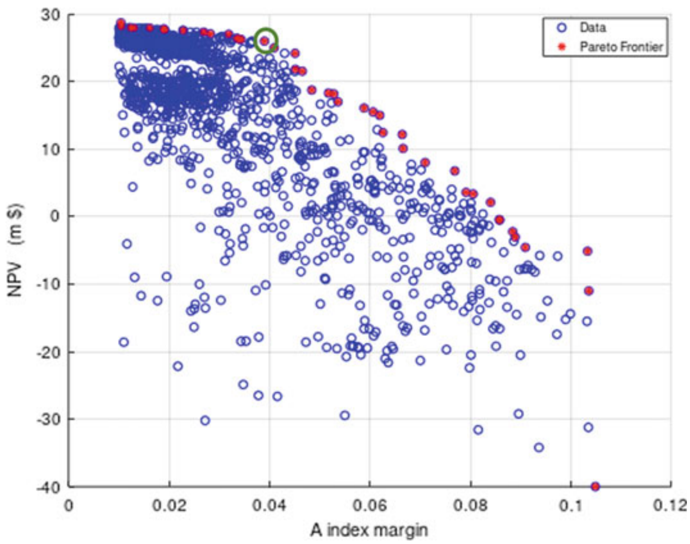

Fig. 11.29 Pareto Frontiers on NPV versus A-Index

Table 11.8 Optimal Alpha design particulars

L_{PP}	193.0 m	Prop. power (calm sea, clean hull, design speed)	21,330 kW
L_{OA}	214.3 m	Installed main engines	2 × Wärtsilä 12V46DF
	27.2 m	Main engine MCR	2 × 13,740 kW
D	9.2 m	Nominal main engine SFOC (at service speed with 15% sea margin)	176.1 g/kWh
C_B	0.62	Auxiliary engines MCR with system optimisation, *with PTO*	3 × 1750 kW (2 × 1500 kW)
Design draught	6.33 m	GM at design departure	3.62 m
Maximum draught	6.62 m	Required subdivision index	0.8554
Design DWT	8103 t	Attained subdivision index	0.8971
Maximum DWT	9402 t	Required EEDI (phase 2)	22.12 g/tm
Lightship weight	13,130 t	Attained EEDI	20.10 g/tm
Passengers	880	Building cost	128.7 million USD
Lane meters for trucks	2677	NPV (for ideal (NPV1)/for intermediate (NPV2)/for conservative (NPV3) scenario)	74.05 / 48.84 / 24.86 million USD
Lane meters for private cars	1270	PBP (for ideal (NPV1)/for intermediate (NPV2)/for conservative (NPV3) scenario)	10.16 / 11.59 / 13.38 years

Obviously, it is not desirable to select lower NPV values, so the team focused on the Pareto designs with NPV higher than 20 m$. It must be noted that absolute value of NPV obtained here are indicative and by no means reflect true market value, however they were sufficiently accurate for design ranking and selection. When further consideration is given to both shortest payback period and highest A index margin, the design marked with green circle is finally selected as the Alpha design, as shown in Fig. 11.29. The details of the Alpha Design are given in Table 11.8. The Figs. 11.30 and 11.31 show the Alpha design against the other design alternatives in the scatter diagrams.

As the final step in Alpha Design development, a machinery optimisation has been carried out using the SEECAT® software model shown in Fig. 11.15. The different combinations of arrangements in the machinery design space led to a total of 1365 simulations. In the Fig. 11.32, the maximum load experienced by any of the engines in the 1365 simulations is reported.

As described in Sect. 11.4.6 of this chapter, values above 0.9 were rejected as they are not fulfilling the vessel's requirements. The threshold is presented in the figure with a red dashed line. Some comments on the outcome of this study are given next.

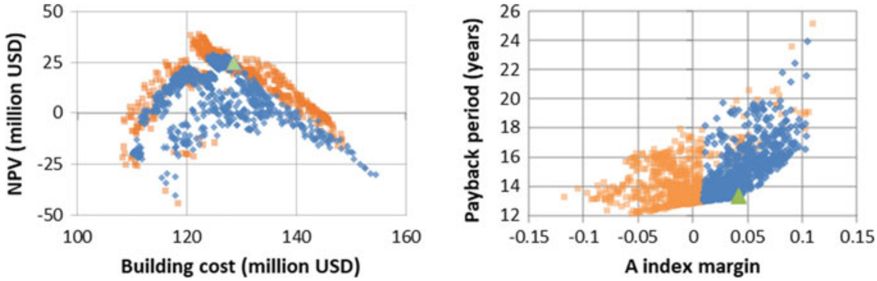

Fig. 11.30 Selected Alpha design (marked green): NPV versus Building Cost and payback period versus A index margin comparative diagrams

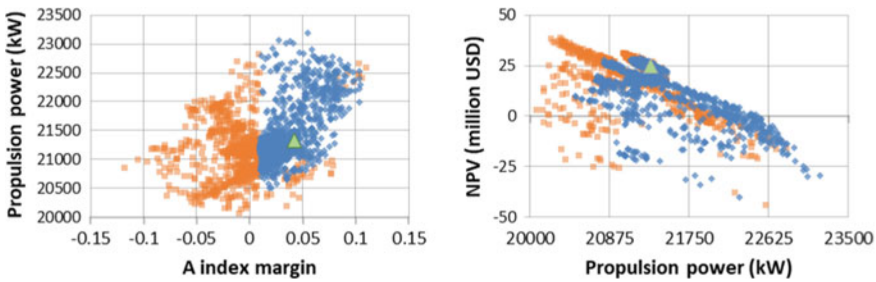

Fig. 11.31 Selected Alpha design (marked green), Propulsion power versus A-index margin and NPV versus propulsion power comparative diagrams

First, it can be noted that due to the discrete nature of the values chosen from the machinery maker's catalogues, the fuel oil consumption evolves in a stepped fashion. If one considers a design with 4 gensets of 2000 kW each and if the operations never require more than 3 simultaneously running gensets, then it this arrangement has a similar performance with a design with 3 × 2000 kW and higher CAPEX cost. Secondly, a design without PTO is the least expensive of all designs. However, if one wants to optimize the fuel oil consumption, the design with PTO becomes an interesting alternative though it comes at a higher CAPEX, as seen in Fig. 11.33. In such circumstances, the designer should be in a position to select the best configuration regarding costs using a Return On Investment (ROI) calculation. For that, the fuel oil consumption should be converted into OPEX. Additional costs such as maintenance should also be considered. In the SEECAT® model, it is assumed that LSMDO is only used for harbour and port manoeuvring operations. As the objective is to optimise at first the LFO consumption for one round trip and then the Low Sulphur Marine Diesel Oil LSMDO consumption, this leads to the following designs presented in Table 11.9.

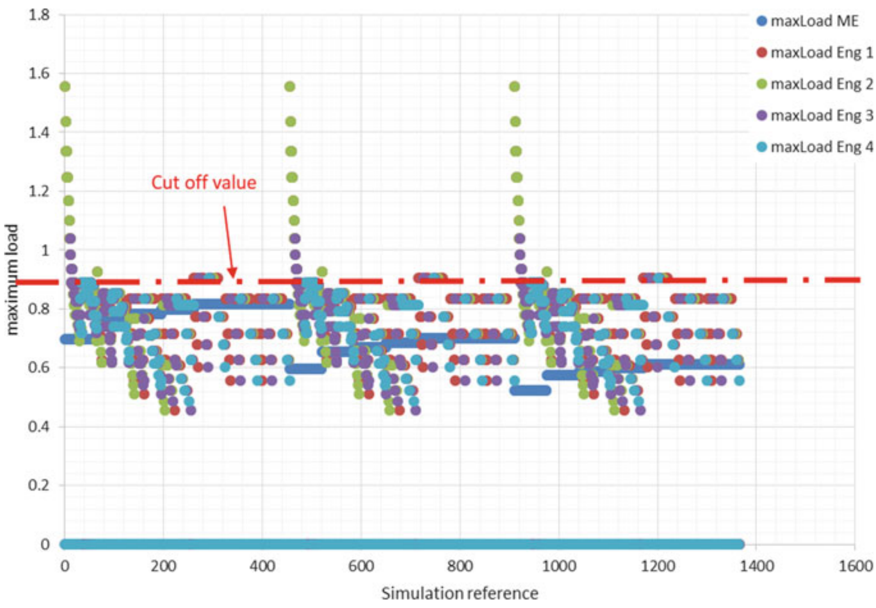

Fig. 11.32 Maximum loads of the different engines for each simulation run

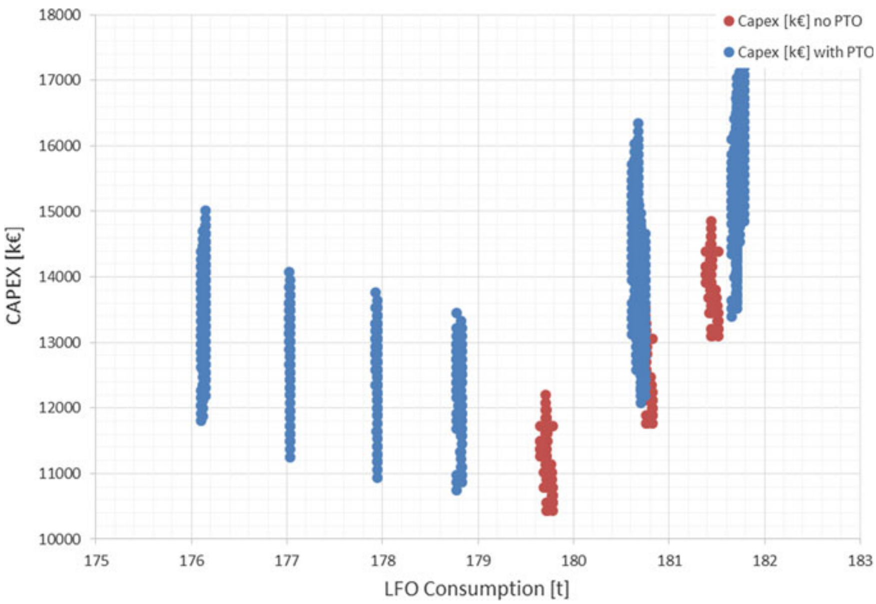

Fig. 11.33 Estimated CAPEX cost versus LFO consumption

Table 11.9 Optimal values for Alpha design with fuel oil consumption as KPI

PTO each [kW]	Main Engine (Wärtsilä - 12V46DF)	Gensets (Himsen -H25/33)	LFO [t] per round trip	LSMDO [t] per round trip	LFO relative decrease	CAPEX relative increase
0.0	2 × 13,740 kW	3 × 1750 kW	179.7	7.5	0%	−7%
0.0	2 × 13,740 kW	4 × 1750 kW	179.7	7.5	–	–
1750	2 × 13,740 kW	2 × 1500 kW	176.1	7.62	−2%	4.8%

It should be noted that the two designs without PTO are identical except that the second one has an additional genset. The 4 gensets are never running at the same time in operations, however this configuration increases the redundancy and reduces the running hours of each genset and hence maintenance. This is usually the chosen sizing for such a vessel. It appears that the design with PTO allows to reduce the percentage of fuel consumed by 2%, while representing 4.8% of the increase in capital.

The optimal design has been further detailed in order to present the GA suitably detailed, so that prospective owner and then Flag-state/Class approval can be obtained. The GA for Alpha Design is presented in Fig. 11.34, with necessary details. There is always some opportunity to further modify the design layout in order to bring in prospective owner preferences without jeopardising the optimal design. For example, allocation of spaces in the upper decks can easily be done, as well as compartment boundaries below the subdivision deck can be further adjusted by altering the transversal bulkhead locations with smaller increment in order to increase the A-Index margins.

11.7 Concept Design Development of Bravo Design

In order to fulfil requirements outlined in the design specifications for the Bravo design, which are outlined in Table 11.1, the design team would have probably gone through the same process, as followed for the Alpha design. However, with the RoPAX optimisation platform already setup, savings of time and effort are evident. Even more importantly, in order to have a direct comparison basis, the outcome of the Alpha design optimisation has been taken as the basis for the Bravo Design. Relatively small straightforward changes are implemented to create alternative layout topologies for accommodating the change of machinery systems for LNG as fuel conversion and Pod propulsion in NAPA®. The model is reconfigured to deliver various options such as those shown in Figs. 11.35 and 11.36.

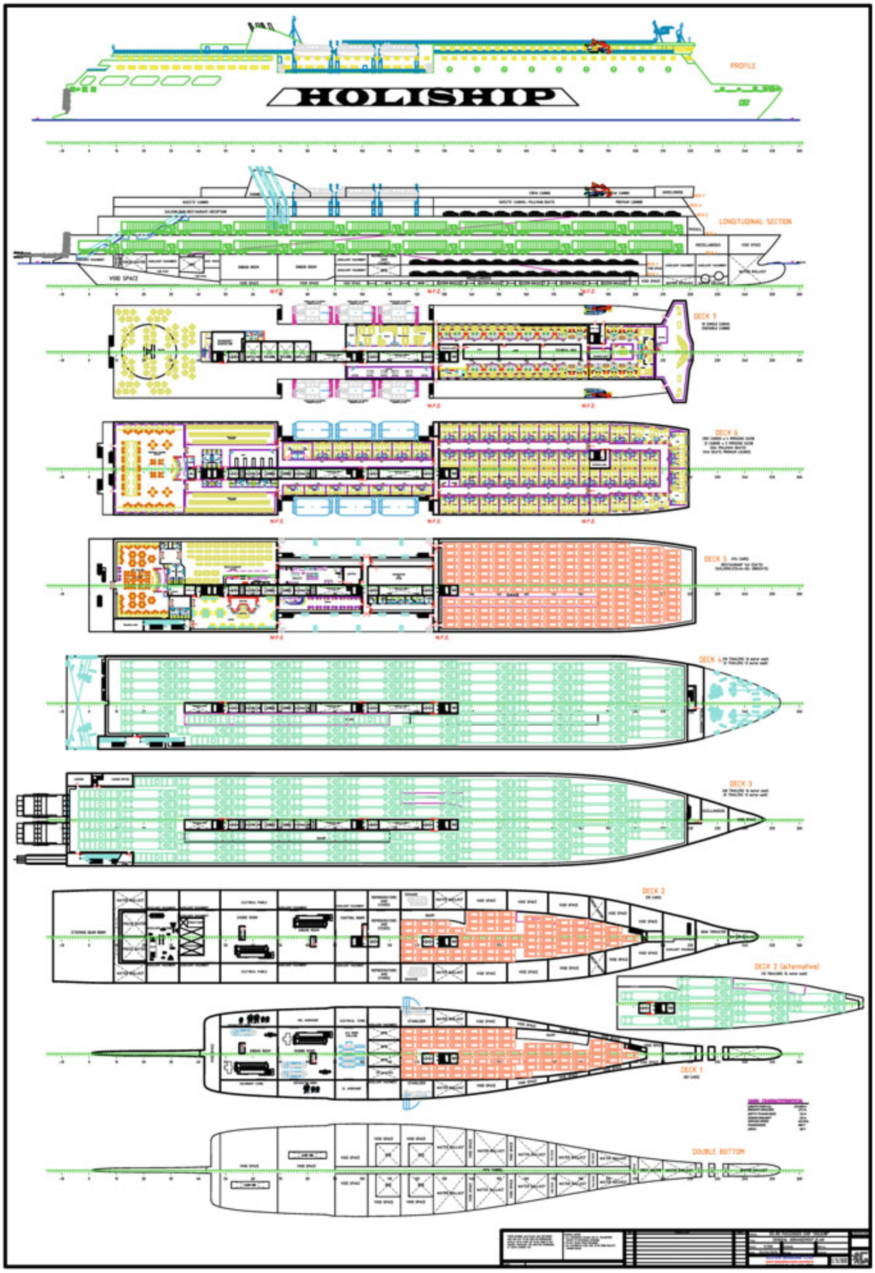

Fig. 11.34 General Arrangement of Alpha Design

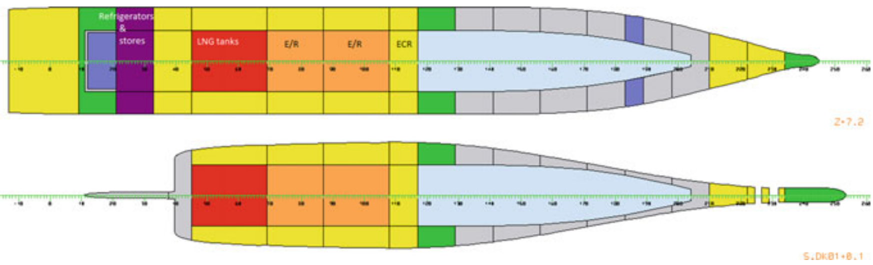

Fig. 11.35 Bravo designs, internal layout option 1, LNG tanks (in red) aft of engine rooms

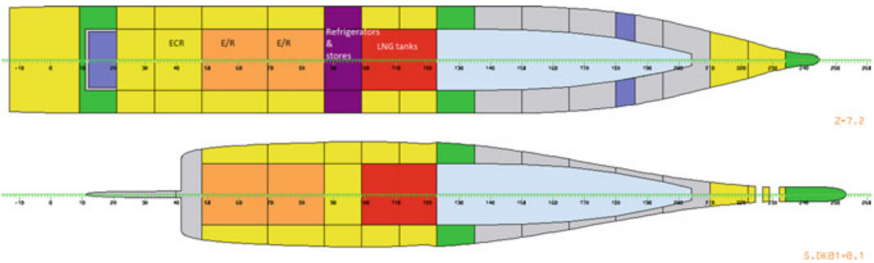

Fig. 11.36 Bravo designs, internal layout option 2, LNG tanks (in red) forward of engine rooms

11.8 Design Objectives for Bravo Design and Design Development Process

The main objective of the Bravo design development is to advance the Alpha design at concept level for the next generation of fuels and propulsion, whilst also to explore ways to achieve higher passenger capacity at least by 10%.

The transition to next generation greener fuel options whilst keeping the use of conventional but cleaner fuel for regulatory compliance mandates that the Bravo concept must have duel fuel functionality. Therefore, both form of fuel, low sulphur marine diesel oil (LSMDO) and liquified natural gas (LNG) must be provisioned.

The Bravo design was considered to have identical hull shape and hence resistance as the Alpha design. The main difference is that the Bravo design uses LNG as main source of energy.

Based on the specified operational profile, the estimated power demands and the fuel gas consumption of the selected generating sets, the expected LNG consumption per round trip is approximately 160 tonnes or 360 m^3. Due to the increased volume requirements of LNG in comparison with fuel oil for a given power output and the stringent regulations set by MSC.391(95) (IMO 2016) with regard to its storage onboard, the sailing-range requirements have been herein relaxed, to only once round trip, in comparison to the Alpha design, aiming to minimise the loss of lane meters from the lower holds. Thus, two identical tanks with a net total capacity of 450 m^3

have been selected for the Bravo design, which is sufficient for one round trip with an additional 25% safety margin. Of course, some fuel oil tank capacity has been retained and it is possible to switch to fuel oil operation if required. There are several suppliers offering LNG Fuel storage and supply solutions as a pack. The design team considered that a compartment space of 24 frame long would be sufficient to house one of these solutions; the bravo design alternatives presented in Figs. 11.35 and 11.36 show dedicated LNG tank spaces in red colour.

The propulsion for the Bravo concept is performed through 3 pods instead of the 2 CPP propellers like for the alpha design. It was also prescribed by the design specification that the Pods are powered by a suitable diesel electric system for the required speed. The selection of the pods has been done with the input provided by Kongsberg. The system selected Kongsberg, *Elegance Pulling Pod 1570-O/S and Drives*, see Fig. 11.37. All necessary data has been provided by Kongsberg to the design team for optimisation evaluations such as space allocation, weight, resistance, machinery system evaluations etc.

For the machinery optimisation for the Bravo design, additional assumptions were made to account for the different energy requirements during the summer and the winter operations.

Indeed, as described in Table 11.5, compared to the high season, only half of the number of passenger travel during the low season. However, with only 2 weeks duration, the high season is very short in comparison to the total 50 weeks of operations per year. Besides, the need for propulsion might be smaller in the summer due to more favourable sea conditions. The design space boundaries used for the optimisation are summarised in Table 11.10.

The engine reference is Wärtsilä V46DF, the same as the Alpha design, but the number of cylinders were considered from 6 to 16. Figure 11.38 presents the SEECAT model setup for the Bravo design.

Assumption was made that the three pods provide a similar thrust to the vessel. Due to the difference in wake fraction, this results in different operating points for

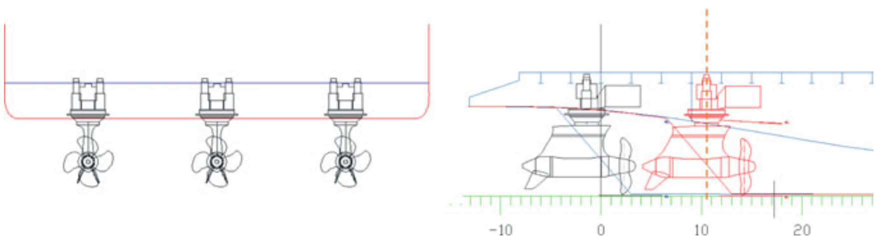

Fig. 11.37 Illustration of PODs in section and plan views

Table 11.10 Machinery design space of the machinery optimisation of the bravo design

	Number	Min size [KW]	Max size [KW]
WÄRTSILÄ V46DF	2, 3 or 4	6870	18,320

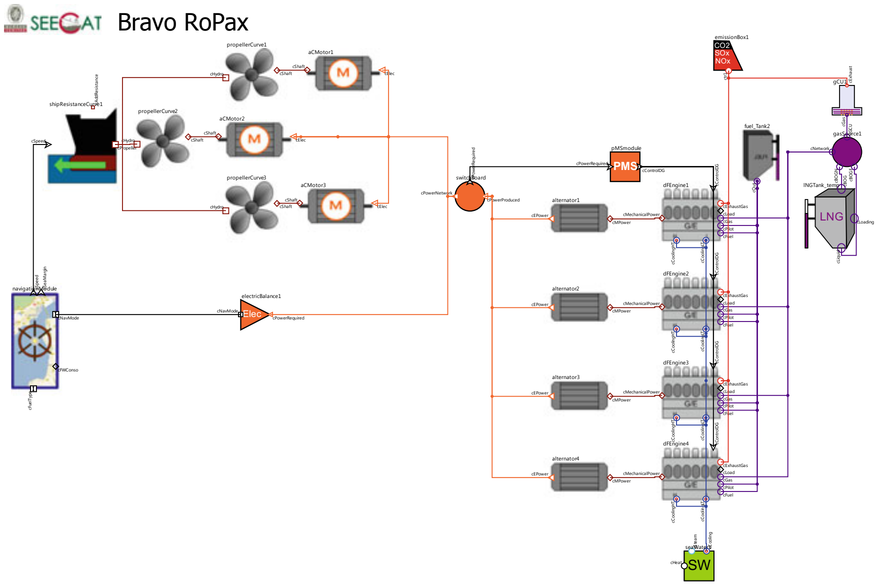

Fig. 11.38 SEECAT model used for the machinery system optimisation of the bravo design

the central and for the wing pods. Regarding the LNG powering, the assumption was made that the vessel always uses LNG as primary source of energy and that the vessel never uses the composite boiler to manage the Boil Off Gas.

Even if, by nature of the engine size, the solutions are discrete, a Pareto front can be identified in Fig. 11.39. The optimum design appears to be a trade-off between the CAPEX and fuel consumption; it therefore depends on the importance that the designer/owner will give to the different KPIs. Table 11.11 shows the two different configurations selected. The first one considered the CAPEX as the primary KPI to optimise, the second one the fuel oil consumption. It should be noted that no availability (redundancy) criteria (spare engine) were accounted for in selection of the two engine alternatives. The chosen designs only cover the needs for the vessel to perform its normal operation. As the dual-fuel engines use pilot fuel to start the combustion process, a small capacity of marine fuel oil is required. Therefore, the LFO consumption is included, and the amount needed is determined as a function of the engine load as outlined on the maker’s datasheet.

Figure 11.39 shows the investigated alternative engine configurations, with the min. CAPEX configuration as KPI marked with a green circle and the min. Fuel Consumption configuration as KPI with a red circle.

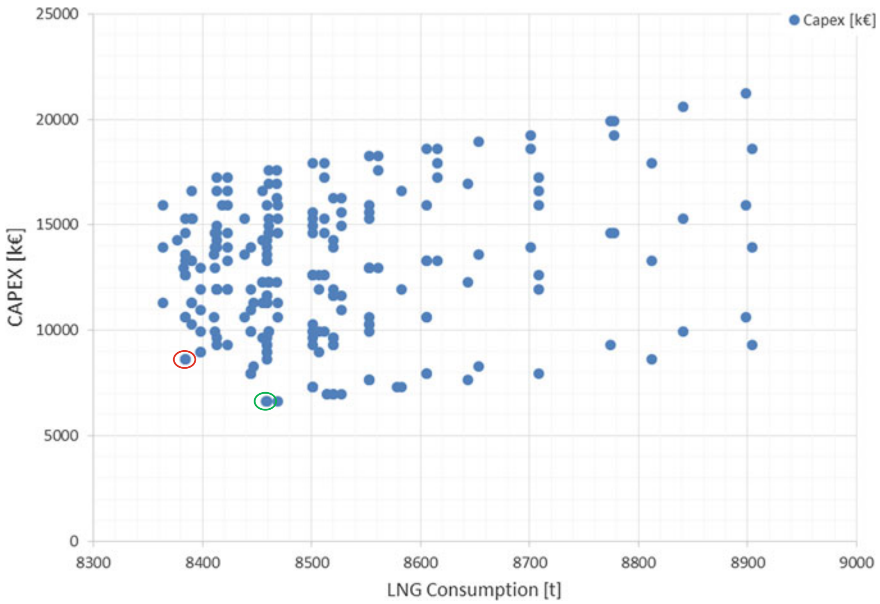

Fig. 11.39 CAPEX versus half year LNG consumption for the different engine configurations. Selected configuration based on CAPEX, circled in green, Selected configuration based on Fuel Consumption, circled in red

Table 11.11 Optimal values for the bravo design machinery for different KPI

Main KPI	Engine configuration	LNG consumption	LFO Consumption	CAPEX
CAPEX	2 × 6L46DF, 8L46DF	8458.8 t (per-6 month) [112.78 t (per round-trip)]	86.1 t (per-6 month) [1.15 t (per round-trip)]	6641 k€
CONSUMPTION	6L46DF, 8L46DF, 12V46DF	8384.4 t (per-6 month) [111.79 t (per round-trip)]	78.7 t (per-6 month) [1.05 t (per round-trip)]	8633 k€

The design team developed the layout shown in Fig. 11.40 as the final subdivision of spaces below the subdivsion deck. The rooms housing POD driver units are allocated as shown; aft pod room is positioned centrally aft of frame 6, and fwd PODs are located inside the forward POD room, which runs from frame 6 to frame 21. A FW tank is located between the POD units.

Finally, based on the optimisation work carried out on the arrangement of the public spaces, the design team has further refined the accommodation block to achieve the additional passenger capacity. The deck 7 has internal space has been increased to full beam. The forward fire zone, forward frame 171 is allocated for crew cabins

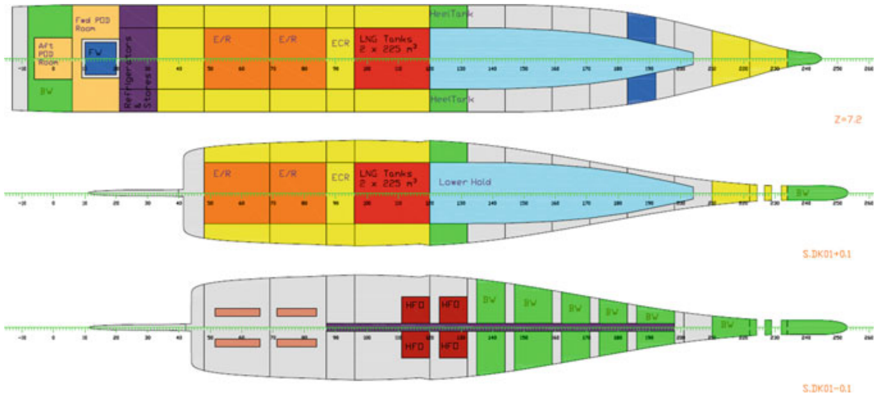

Fig. 11.40 The selected bravo design internal layout

only and the wheelhouse is then moved up to the newly introduced deck 8. This made it possible to allocate an additional pullman lounge with 62 seats and introduction of additional public spaces with 108 seats. The additional seating provided all on deck 7 and totals 170 additional capacity. This is almost 20% increase, and above the prescribed minimum increase of 10% for the Bravo concept. As the helicopter landing areas is moved forward, it is also possible to extend summertime capacity with additional seating arrangement on deck 7 as additional 15 seats or repurpose the new public space on deck 7 as pullman or airliner seats with up to 25 additional capacity. However, additional increase in passenger capacity will result in an increase in Required Index which will reduce A–Index margin.

The final GA for the Bravo design is given in Fig. 11.41, and Table 11.12 shows the comparison between the Alpha and Bravo designs developed in this application case.

11.9 Discussion on the ROPAX Application Case

11.9.1 Value Created for Capturing Designer's and Owners' Preferences

The framework presented here showed the use of an optimisation platform capable of bringing together many evaluation tools and methods for arriving at a design that does not rely solely on the experience and know-how of the design team. Making it possible to explore many design solutions that might otherwise not explored. As long as designers and owners' preferences can be quantified rationally through a method or tool, they can be integrated. Even quantitative preferences and opinions can be processed to include them in a design evaluation process as it has been demonstrated

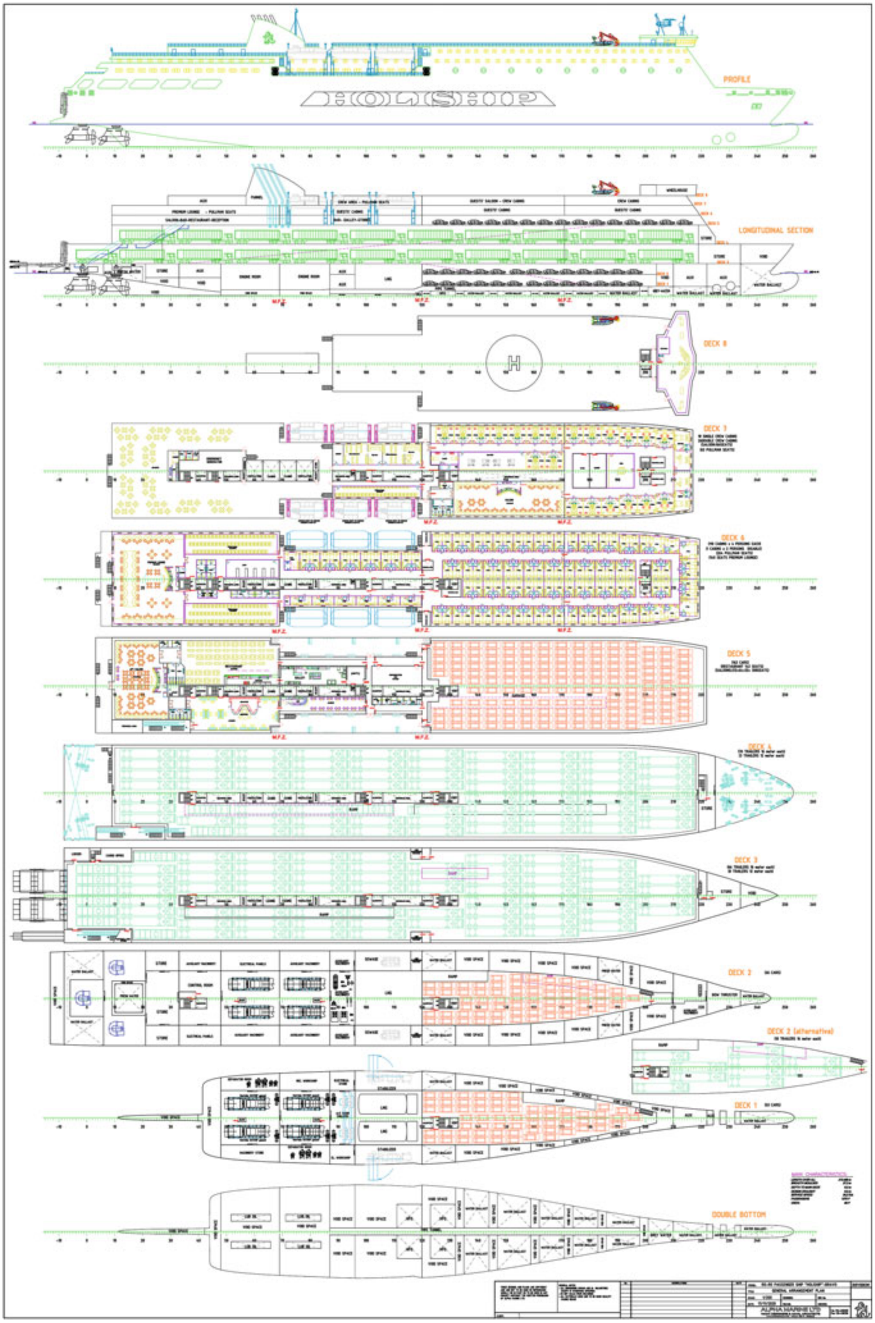

Fig. 11.41 General arrangement of bravo design

Table 11.12 Alpha versus bravo designs

	Alpha	Bravo
L_{PP}	193.0 m	193.0 m
L_{OA}	214.3 m	214.3 m
B	27.2 m	27.2 m
D	9.2 m	9.2 m
Design speed	24 kn	24 kn
C_B	0.62	0.62
Design draught	6.33 m	6.29 m
Maximum draught	6.62 m	6.47 m
Design DWT	8103 t	7341 t
Maximum DWT	9402 t	8191 t
Lightship weight	13,130 t	13,702 t
Passengers, crew	880, 65	1050 (+25), 65
Lane meters for trucks	2677	2645
Lane meters for private cars	1270	1298
Brake power (calm sea, clean hull, design speed)	21,950 kW	21,950 kW
Installed main engines	2 × Wärtsilä 12V46DF	6L46DF, 8L46DF, 12V46DF
Main engine MCR	2 × 13,740 kW	1 × 6870 kW + 1 × 9160 kW 1 × 13,740 kW
Optimised fuel consumption per round-trip (at service speed with 15% sea margin)	179.7 t (LFO), 7.5 t (LSMDO), or with PTO; 176.1 t (LFO), 7.62 t (LSMDO)	112.8 t (LNG) 1.15 t (LFO), or 111.8 t (LNG) 1.05 t (LFO)
Auxiliary engines MCR	3 × 1980 kW	–
GM at design departure	3.62 m	2.90 m
Required subdivision index	0.8232	0.8495
Attained subdivision index	0.8971	0.8669

before e.g. Olcer et al. (2006). What are these design preferences and how they can be incorporated? If one looks at the design development as a cluster of trades-offs to be made between various aspects of the ship as a business case, these influential factors are shown in Fig. 11.42 (HOLISHIP 2016), and each would have a degree of variation from designer to designer as well and owner to owner. Such as a company promoting use of greener fuel sources and environmentally friendly operation will have more emphasis on making trade-off decision with that in mind. A company with zero-tolerance attitude towards safety record will bring in safety features over and above the regulatory requirements as their own normative constraints. Therefore, it is important that an optimisation platform must allow making these trade-offs. For example, over 100 variables and thousands of designs were evaluated, within the setup of the optimisation platform, for each design variant of Alpha and Bravo. Obviously,

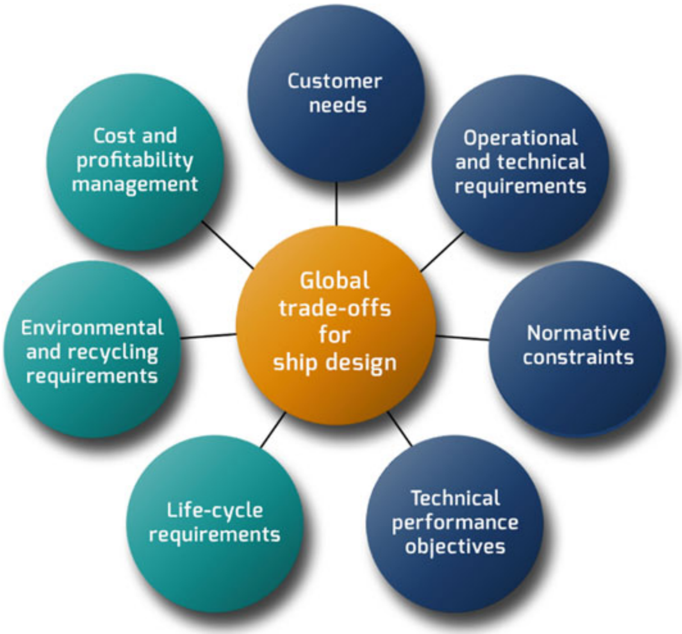

Fig. 11.42 Ship design as global trade-offs (HOLISHIP 2016)

many of these parameters are included to test the platform and inter-connectively of the assessment tools and methods, nonetheless it demonstrates the tremendous capacity to include many things the designer and operator wish to address.

These are particularly important in accounting for in design optimisation of a RoPAX vessel which is a ship type not only rigorously regulated but also one of the very competitive and demanding trade runners.

11.9.2 Design Evolution or Revolution?

For any engineering design development undertaking, the end product must be commercially viable, able to deliver required functionality and maintain its operability for the desired duration of its life-cycle; which includes its environmentally friendly decommissioning in the end. For the RoPAX ships, international safety regulations for people onboard and emission quality for environment impact greatly affect their design. The shipping industry has been slowly, but surely steadily, developing in this direction in parallel to the volatile financial makeup of the investors who are looking at the marine assets as an investment with a predetermined life-cycle for return on their investment. This is forcing the traditional shipping culture to open its doors to new ideas to maximise their competitiveness in the market. The change sometimes happens gradually as is the case with the development of the Alpha Design, where an owner would keep their fleet operation the same with minor, at times incremental, improvements. This is where the design evolution takes place. The present Alpha Design has been developed by using all the cutting-edge methods and assessment tools integrated under the HOLISHIP platform. On the other hand, with some extra work the *evolution can become a revolution* to bring about a real change, such that the same hull envelope can hold a next generation design operable with the new dual-fuel technology, next generation propulsors and achieve this without compromising any payload capacity, in fact achieving an increase. We have demonstrated that this can be achieved with the "Bravo Design". This was just one application of the HOLISHIP methodology to RoPAX vessels showing the potential for many more revolutions in the design of many ship types.

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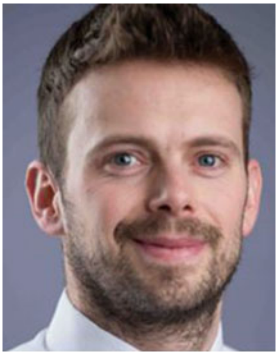

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Chapter 12
Design of a Double Ended Ferry

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Abstract One of the 9 application cases of HOLISHIP is the design of a double-ended ferry. The double-ended ferry was seen ideal for the case study because it has clearly defined constrains and objectives, while it attracts the significant interest by customers of the designer, ELOMATIC Ltd. The General Arrangement (GA) of a double-ended ferry is mainly built around the need to carry a certain number of cars. Double-ended ferries have strict schedules which can only be achieved by hydrodynamically optimized hull design, trim, efficient propulsion system and low lightweight. The present chapter "Double-Ended Ferry" focuses on the synthesis of software tools forming the Intelligent GA s/w platform (IGA) that is used in the double-ended ferry case study. Software tools forming the Intelligent GA

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A. Papanikolaou (ed.), *A Holistic Approach to Ship Design*,
https://doi.org/10.1007/978-3-030-71091-0_12

are CAESES (hull design), Cadmatic (structure and outfitting), NAPA (stability), HSVA's Fresco+ (resistance and propulsion), HSVA's ν-shallo (wave resistance), BV's Mars2000 (midship analysis) and BV's SEECAT (energy simulations). The Intelligent GA utilizes parallel multi-disciplinary design and analysis, which is made possible by use of surrogate models, as they have been introduced in the HOLISHIP project. The chapter elaborates on the links between CAESES, Cadmatic and other tools, namely how the general arrangement data are transferred between CAESES and Cadmatic during the design process. It explains what parameters were optimised, and what were the constraints in the optimisation process. It also describes the link between Cadmatic and BV's structural design tool Mars 2000. Resistance and propulsion optimisation is also elaborated. The stability section explains the link to NAPA ad what intact and damage stability rules are applied for the double-ended ferry, which is classified as "D" class according to NON-SOLAS rules. Of key interest for a zero or reduced emissions double-ended ferry is the optimal dimensioning of the batteries' capacity. The chapter explains how the batteries were dimensioned and compares the fully electric vessel against a hybrid version where the batteries are the main source for propulsion and diesel engines/generators are the auxiliary source of energy. The final general arrangement/design of the double-ended ferry is the synthesis of all naval architectural disciplines and is presented at the end of the chapter. Constraints, rules, the functionality of the general arrangement, and the optimal solutions proposed by the Intelligent GA platform decide on the final form of the general arrangement. The exploration of design alternatives, both mathematically and by visual testing/verification, is the basic idea behind the Intelligent GA concept that is fully complying with the basic concept of HOLISHIP. It was concluded that Intelligent GA can be used as an efficient decision-making tool and a tool for the rapid design space exploration. Intelligent GA is not meant to replace designers, as the final verification of the GA quality stays for the naval architects.

Keyword Intelligent general arrangement · Double-Ended Ferry · Electric propulsion · Optimisation platform · Net present value · Capital expenditure · Operational expenditure · Batteries technology · Batteries state of charge

Abbreviations

2D	Two-dimensional
3D	Three-dimensional
BV	Bureau Veritas
CAESES	Computer Aided Engineering System Empowering
CADMATIC	Computer Aided Design software
CAPEX	Capital Expenditure
CFD	Computational Fluid Dynamics
CNR	National Research Council of Italy
GA	General Arrangement

HILLTOP	High level topology
HOLISHIP	Holistic optimisation of Ship
HSVA	Hamburg Ship Model Basin
IMO	International Maritime Organisation
INM	Institute of Marine Engineering
LIWL	Lower Ice Water Line
NAPA	Naval Architectural Package
NPV	Net Present Value
NSGA	Non dominated Sorting Genetic Algorithm
OPEX	Operational Expenditure
PAX	Passengers number
POD	Pitch propeller mounted on a steerable gondola
RANS	Reynold Averaged Navier-Stokes
ROPAX	Ro-Ro Passenger Ship
RSM	Response Surface Model
SEECAT	Ship Energy Efficiency Calculation and Analysis Tool
SOC	State of Charge
SOLAS	Safety of Life at Sea
UIWL	Upper Ice Water Line
XML	eXtensible Markup Language

12.1 Double Ended Ferry Case Study

One of the 9 application cases of HOLISHIP is the design of a double-ended ferry. The double-ended ferry was seen ideal for the case study because it has clearly defined constrains and objectives, while it attracts the significant interest by customers of the designer, ELOMATIC Ltd. The General Arrangement (GA) of a double-ended ferry is mainly built around the need to carry a certain number of cars. Double-ended ferries have strict schedules which can only be achieved by hydrodynamically optimized hull design, trim, efficient propulsion system and low lightweight (Fig. 12.1).

12.1.1 Mission and Operational Requirements of the Double-Ended Ferry

The double-ended ferry is supposed to operate in the Finnish archipelago, sailing between Galtby and Houtskari islands (see Fig. 12.2). The ferry shall utilize a new zero emission propulsion system, namely it should be a fully electric, battery driven vessel. It should be an ice strengthened vessel, having the ice class 1A according to Finnish-Swedish ice rules. The classification society of the ferry is the Finnish Traficom, which will classify the ship according to Non-SOLAS rules.

Fig. 12.1 Double-ended ferry created in HOLISHIP project

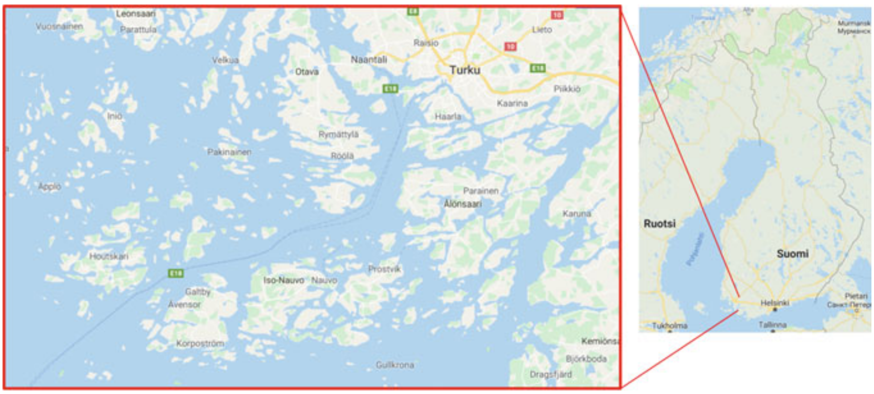


Fig. 12.2 Double-ended ferry route in the Finnish archipelago (Google 2020)

The double-ended ferry is dimensioned to carry at least 150 cars and 400 passengers. The length of the round trip is 10 nautical miles, and the ship operates from 5 am to 11:30 pm every day. Its half trip (5 nm) takes approx. half an hour and the ship is at port for about 10 min. The harbour time is used to load and unload cars and trucks, and to recharge the batteries, because of the minimisation of their size.

The assumed 10 min time in the port is based on observations of real double-ended ferries loading and unloading. An empirical formula was constructed, which considers 2 min of fixed time for each port operation, and 8 min for cars and trucks to be loaded or unloaded.

Defined load cases of the double-ended ferry are presented in Table 12.1. The ship is fully loaded between 7 and 8 am and 4–5 pm, which are starts and ends of working days. During these times, the vessel is either loading at ports, or unloading. In other words, loading and unloading are not happening simultaneously at the same port.

Table 12.1 Loading cases (in % of maximum capacity)

	Outbound (%)	Return (%)	Round trips
Load case 1	100	10	3
Load case 2	20	50	6
Load case 3	10	25	6

Otherwise, the double-ended ferry is estimated to be half loaded during the rest of day, and in mornings and nights only loaded between 10 and 25%. The estimated numbers of cars travelling daily onboard is 480.

Total round trip takes 1 h 15 min, which allows the double-ended ferry to do 15 round trips for 18.5 h daily operation time.

12.1.2 Initial Sizing

The initial sizing of the double-ended ferry is shown in Table 12.2. Initial main dimensions were based on reference of 118 vessels, of which only 10 operate in international routes and are subject to SOLAS regulations. Based on this analysis, several regression analyses were drawn, which formed the basis for the initial sizing of the double-ended ferry.

The initial length of the ship was calculated using a standard car length and its longitudinal parking distance to another car as a parameter (5 m in total). Utilizing a rough 2D GA of the car deck, and using seven lanes as a starting point, a 121 m—long vessel was derived.

The lane number of the double-ended ferry was defined to be seven or eight lanes. Originally there was the alternative of a six lanes variant, but it was noticed that the length of the vessel would then be over 130 m in order to fit 150 cars. According to Non-SOLAS rules for RoPax, vessels over 130 m in length, need to have a helicopter landing area, so for that reason the length was limited to 129.9 m.

The minimum breadth for the vessel was calculated with the following dimensions:

Table 12.2 Initial sizing of the ferry

	Initial	Range
CARS	150	150+
PAX	400	400
LANES	7	6 – 8
L [m]	121	Max. 129.9
B [m]	19.2	16.7–22
T [m]	2.5	No limit
D [m]	4.2	Freeboard
DWT [t]	400	400+

- Side shell including the supporting structure 400 mm
- Walkway 600 mm
- Disabled walkway 900 mm
- Car lane 1900 mm

With these dimensions, the 7-lanes variant should have a minimum breadth of

$$B_{7^{th}lane} = 0.4 + 0.6 + 7 * 1.9 + 6 * 0.6 + 0.9 + 0.4 = 19.2\,\text{m} \tag{12.1}$$

In the same manner, the 8-lanes variant should have a minimum breadth of 21.7 m. Initial draft, depth and deadweight were interpolated from reference vessels.

12.1.3 Fully Electric or Hybrid Ferry

The double-ended ferry shall be either a fully electric battery driven vessel or a battery—diesel generator set hybrid vessel. Batteries are always the main source of energy, but the size of the vessel and the resistance/propulsion requirement in winter may require additional energy from diesel generator sets. The recharging capacity of the land infrastructure is another important decision aspect, when deciding on the battery size and use of the propulsion system.

A comparison between the fully electric ferry and hybrid ferry options is detailed in Sect. 12.3.8.

12.1.4 Double-Ended Ferry Case Study Tools

Methodologies and tools developed during the HOLISHIP project and explained in the HOLISHIP Book Volume I (Papanikolaou 2019) were tested and used in the double-ended ferry case study. Employed Tools were CAESES® (hull design and optimization platform), Cadmatic (hull structure), NAPA (stability), BV SEECAT (ship's energy and fuel consumption prediction), HSVA FreSco+ (CFD) and ν-Shallo (CFD). The synthesis of these tools form the Intelligent GA (see Figs. 12.3 and 12.4), the basic concept idea of which is presented HOLISHIP Book Volume I (Yrjänäinen et al. 2019).

In Harries et al. (2019) additional examples and preliminary results of this double ended ferry application case are presented.

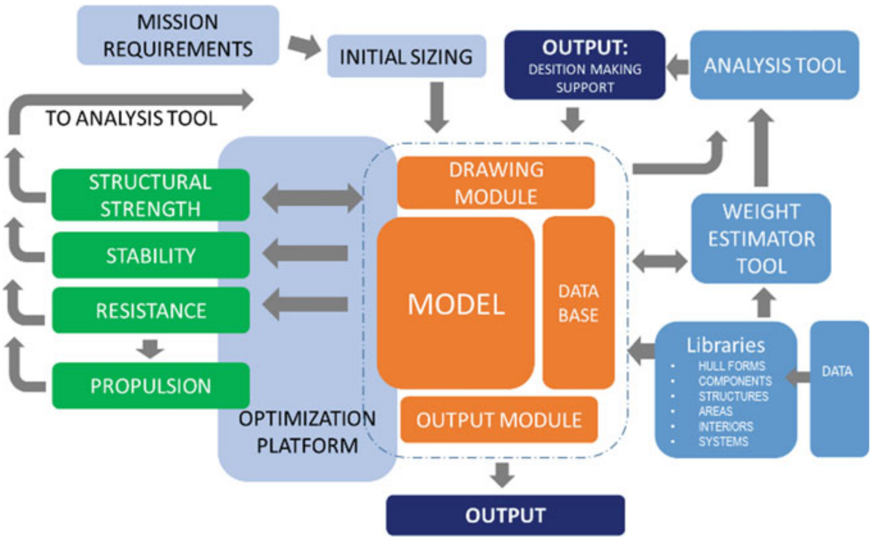


Fig. 12.3 Intelligent GA

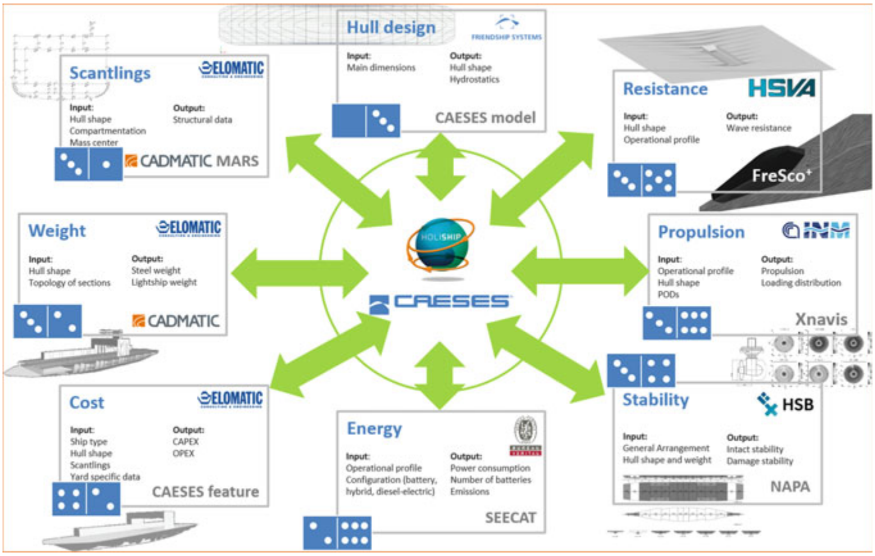


Fig. 12.4 Design synthesis in double-ended ferry project (Harries and Abt 2019)

12.2 Intelligent GA Platform Used to Generate the Initial GA of the Double-Ended Ferry

This section explains the procedure of how the initial GA is formed, and how it is optimized later. As a starting point, CAESES is used to generate the hull form and Cadmatic for the hull structure including the 2D GA. This section explains how these two tools are connected to allow for an automated optimization procedure.

12.2.1 Caeses Model

The general arrangement starts with an initial hull design developed in CAESES. At this early stage, already a fully parametric model is implemented to allow automated variant generation and shape variation throughout the process. The main design variables used are the maximum breadth, length overall, length of the forebody (which in return defines the length of the parallel midship) and depth. In addition, the deadrise and bilge radius are introduced to allow further variations in shape when optimizing for minimal resistance and propulsion. Aside from these design variables, a number of parameters has also been included which allow to easily adjust the initial design in a manual process. In this manner, should the need arise at a certain stage, it can be ensured that the design matches the given constraints and complies with given design considerations.

The initial hull shape of the double-ended ferry model generated by CAESES is shown in Fig. 12.5. The sectional area curve is shown, as well as a schematic representation of the two sets of thrusters on either end of the vessel.

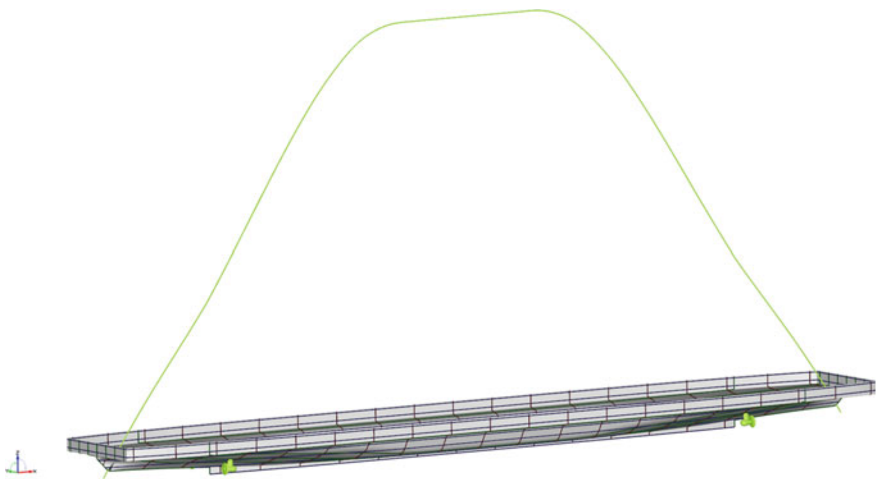


Fig. 12.5 Initial CAESES double-ended ferry model

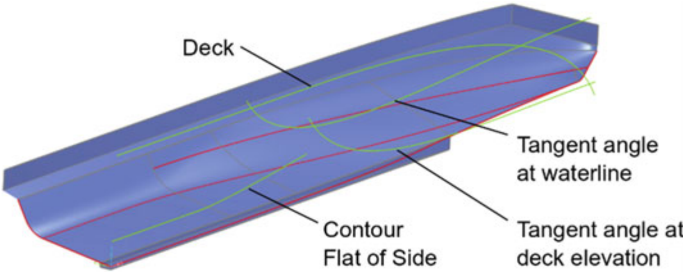


Fig. 12.6 Basic network of curves in CAESES defining the hull shape (due to symmetry to both the x–z plane and the y–z plane only a quarter of the hull needs to be defined)

Most of the individual surface patches of the hull form are ruled (in many cases even developable) surfaces, simply defined by two rail curves. The majority of the wetted (and hence, hydrodynamically relevant) area is generated via CAESES Meta Surfaces (see Harries et al. 2015) for a detailed explanation of the concept). A grid of (parameterized) curves is used as an input for the parametric section definitions giving detailed control over the shape characteristics, such as the longitudinal distribution of flare angles, the contour of the center-plane curve, the outline of the bottom flat, deck shapes, etc. (see Fig. 12.6).

While some of these characteristic curves (depicted in red), e.g. the main frame, center-plane curve or waterline, are defined in 3D, they can also be given in 2D in a user-defined plane (i.e. the center plane). Curve Engines, a CAESES specific entity type, are then used to extract the relevant measures from these input curves and provide the values to the parametric definitions of the sections. As a result, the exact shape of a section at any longitudinal position along the hull is given and MetaSurfaces can be extruded along the length of the hull to represent the shape.

12.2.2 Cadmatic as a Design Tool in Double-Ended Ferry

Cadmatic Marine is an intelligent 3D design, engineering and information management software system for all kinds of ships and offshore structures. It consists of three modules, which are: Cadmatic Hilltop, Hull and Outfitting.

Cadmatic Hilltop comes from words “High level topology”, which means that designers can create and manage parameters in Hilltop. These parameters are basically reference surfaces such as bulkhead and deck positions and angles. Designers can use formulas to define positions, for example bulkhead location can be defined with respect to another bulkhead. In addition, a bulkhead or deck position can be derived from the required area or volume, such as PAX area size or freshwater tank volume.

Cadmatic Hull is meant for generating the structural design of the hull and superstructure. It can either utilize reference surfaces (bulkheads and decks) created in

Hilltop to generate actual construction parts with stiffeners, materials and thicknesses. Another powerful option is to generate 3D model from 2D lines as shown in Fig. 12.7.

The generation of a 3D structural model from a 2D lines model is done through Cadmatic Hull's bulkhead tool, which allows the creation of perpendicular plates and bulkheads in series, and convert drawn lines to plates. This method is fast and straightforward, but does not allow the utilization of parametric design through Cadmatic Hilltop.

Cadmatic Outfitting is a modelling tool for outfitting items such as engines, batteries, staircases, doors, tanks, pumps, HVAC and piping, etc. Together with the Hull module, Cadmatic Outfitting can also be used when generating 2D general arrangements.

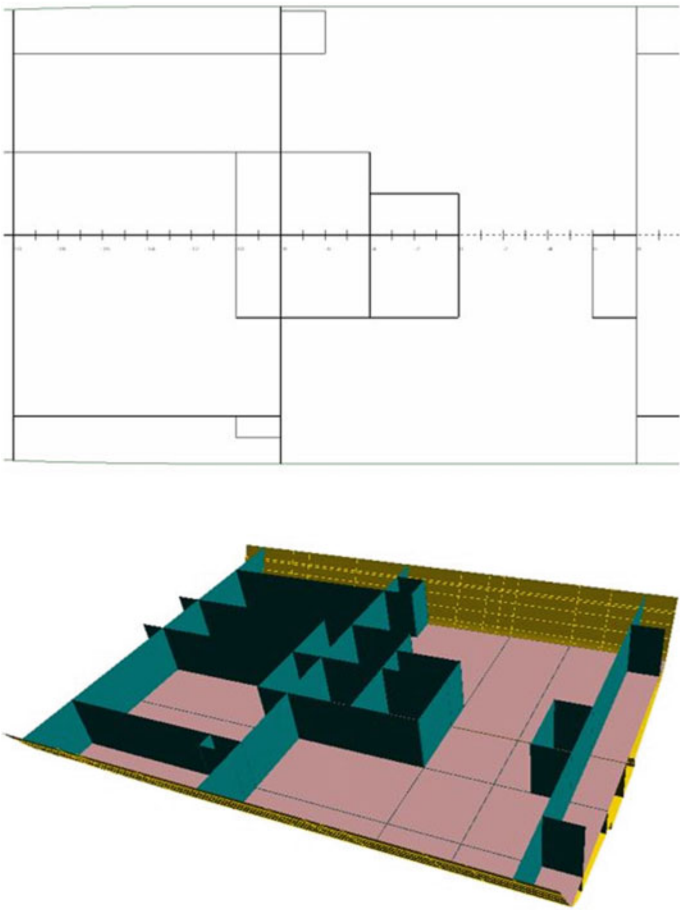


Fig. 12.7 Bulkhead tool of Cadmatic Hull. 2D lines arrangement and the automatically generated 3D model

12.2.3 Caeses—Cadmatic Link

Figure 12.8 shows in a high level sketch how CAESES and Cadmatic communicate/are kinked during the design process. The hull shape from CAESES is sent to Cadmatic, where the design of the GA can begin. Parameters such as deck, main fire bulkhead and other major bulkhead (tanks and pillar bulkheads mainly) positions are created in a table format in Cadmatic Hilltop. These parameters are sent to CAESES via an xml file for further optimization.

Parameters are used to create reference surfaces in Hilltop, which are then used in Cadmatic Hull to generate actual construction elements. The steel weight of plates and stiffeners is sent to CAESES in xml format. The steel weight together with the machinery, outfitting and interior weights form the lightweight of the ship; together with the assumed deadweight hey lead to ship's displacement.

Outfitting and interior weights can be estimated based on areas and coefficients, which again are based on reference vessels and the type of area (machinery, PAX area, mooring deck, etc.). For innovative designs, it would be handy to get main component weights and centers of mass directly from 3D model. Therefore, it was considered that Cadmatic Outfitting, using existing component libraries, could quickly provide an initial but more accurate estimate for weight of the outfitting items in the 3D model.

A future development vision is to have a 3D volume/room definition possibility in Cadmatic's Hilltop module. This allows more efficient estimation of interior weights based on types and areas; and enables deadweight estimation when volumes and weights of tanks can be extracted from Hilltop.

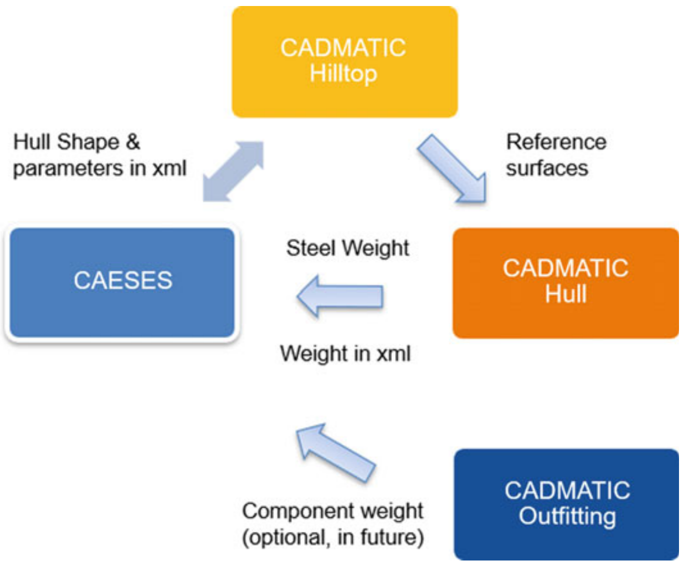


Fig. 12.8 Optimization link between CAESES and Cadmatic

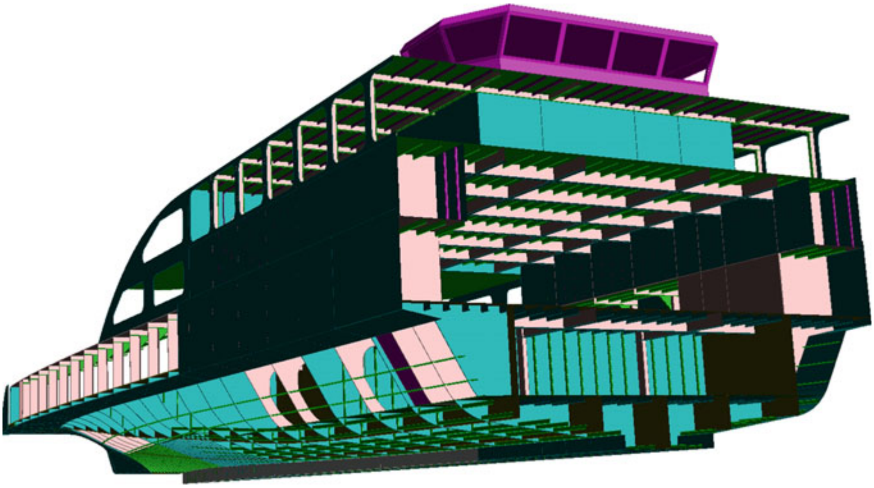


Fig. 12.9 Main structure of the double-ended ferry visualized in Cadmatic

After a double ended ferry project has been created by the designer, the hull imported from CAESES to Cadmatic, reference plans created in Hilltop, and construction plates and stiffeners modelled in Hull (see Fig. 12.9), the first GA can be generated and is ready for inspection. Next steps are the optimization phases. CAESES starts to optimize the hull form for resistance/powering and to modify parameters of Cadmatic Hilltop. Cadmatic replaces the existing hull form by a new one, and updates the structural geometry based on new parameters. Resulting steel weight and center of mass are sent back to CAESES. For the details on data transfer see Harries and Abt (2019).

12.3 Intelligent GA Platform Used to Optimise the Double-Ended Ferry

The HOLISHIP double-ended ferry was optimized by utilizing tools and procedures forming the intelligent GA. This section goes through the undertaken multi-disciplinary optimization procedures, which were carried out in parallel using the *surrogate modelling* concept of HOLISHIP. First, the hull form optimization by use of CAESES is discussed, followed by the structural design optimization by use of Cadmatic, BV's Mars 2000 and CAESES, the hydrodynamic analysis by use of various CFD tools of HSVA and INSEAN, the stability analysis by use of NAPA, and finally a ship systems and energy source comparative study by use of SEECAT of BV.

12.3.1 Optimisation in Caeses

The purpose of using the CAESES model was to make it as robust as possible for the optimization. In Sect. 12.2.1, it is explained how the initial CAESES model was built, and what were the parameters used in the optimization process.

The setup CAESES model for the present double-ended ferry design consists of a series of algorithms and procedures, which are used in the calculation process. The purpose of the optimization procedure was to optimize Net Present Value (NPV), which tells whether the investment is profitable. Main factors for the NPV calculation are the payload capacity (cars, trucks and passengers) on the income side, capital cost CAPEX (steel structure prize, the cost of machinery, navigational equipment and outfitting) and operational costs OPEX (electricity cost/fuel consumption, crew wages etc.). By maximizing the payload, and by minimizing CAPEX and OPEX, the NPV could be maximized.

The NPV is calculated in the double-ended ferry project as follows:

$$NPV = \sum_{t=1}^{n} \frac{Income_t - OPEX_t}{\left(1+\frac{i}{100}\right)^t} - CAPEX + \frac{0.05}{\left(1+\frac{i}{100}\right)^{25}} CAPEX \tag{12.2}$$

where $Income_t$ is cash inflow (payload) and $OPEX_t$ is operational expenditures during a single period t. Discount rate i was 6%, which describes the return that could be earned in alternative investments. The last part of the equation describes the resale price of the ferry after 25 years period.

In order to estimate CAPEX, the steel weight was obtained from Cadmatic, which is called in batch mode by CAESES. The unit steel price was assumed 7500 €/t, which comprises the unit steel price, and the cost to build the ship from the steel, i.e. manufacturing cost including welding and painting. The Cadmatic steel weight was estimated 940 t, thus resulting to 7 M€.

The cost of the batteries was estimated to be 4 M€. Machinery cost excluding batteries was 4.2 M€, which was based on required engine power 1400 kW and unit cost 3000 €/kW. Interior, navigational equipment and outfitting costs were estimated to be 3.5 M€. Therefore, the obtained total CAPEX was 18.7 M€.

The OPEX depends on engine power demand, electricity costs for the batteries' charging (+fuel cost for the hybrid propulsion), crew, insurance, maintenance costs and other running costs over the lifecycle of the vessel. Major part of OPEX are the electricity cost (for the batteries as a main source) caused by the open water and ice resistance/required powering, and the crew salary. Much effort was made to reduce resistance and propulsion by CFD. CAESES used the resistance/propulsive power as a response surface obtained from HSVA's CFD studies for the double-ended ferry.

Propeller type (POD or conventional propeller) and size, position and even the number of the propulsive devices were important; for example, the required power for ice was higher for two PODs than for four PODs according to Finnish-Swedish ice class rules. It was estimated that the OPEX was over 1.2 M€ per year.

As mentioned in Sect. 12.1.1, the estimated numbers of cars travelling daily onboard is 480. It is assumed that the daily income from each car is 15 €, which include the ticket price and money spent by passengers onboard. Total daily income is 7200 €.

In the optimization process, constraints need to be defined in order to identify the feasible solutions. In the double-ended ferry model, the main constraint was the capacity of 150 cars. Combinations of length and beam that could not result in general arrangements with less than 150 cars were disregarded.

Different optimization algorithms were tested for NPV optimisation in CAESES. These were mainly based on genetic algorithms. Figure 12.10 presents the results of optimizations using the Non dominated Sorting Genetic Algorithm (NSGA) available in CAESES. The listed green design variants are acceptable configurations for which the number of cars is higher than 150. The row marked with a star produces the best NPV corresponding to a ferry having the length of 119.5 m and a beam of 20.3 m.

	LOA	Bmax	NPV_Optimal	NPV_ME	CarsOver150
Nsga_NPV_31_des0000	115.0435	19.973419	0.23678523	2.0550514	144.4609
Nsga_NPV_31_des0001	106.72596	18.469734	0.15853212	2.5115473	111.67116
Nsga_NPV_31_des0002	109.74313	21.611444	0.30435438	1.8126344	137.04038
Nsga_NPV_31_des0003	127.63586	20.477089	0.36857326	1.6471687	162.0902
Nsga_NPV_31_des0004	109.74313	21.609979	0.30424155	1.8129705	137.04038
Nsga_NPV_31_des0005	127.63586	20.470741	0.36802404	1.6483973	162.0902
Nsga_NPV_31_des0006	122.74333	20.352087	0.30742992	1.8035448	155.24066
Nsga_NPV_31_des0007	114.63566	21.736446	0.34462718	1.7034337	166.61706
Nsga_NPV_31_des0008	127.6184	20.345739	0.35689736	1.6738955	162.06576
Nsga_NPV_31_des0009	122.76078	20.477089	0.31620452	1.7783448	155.2651
Nsga_NPV_31_des0010	127.61682	20.470741	0.36779034	1.648921	162.06354
Nsga_NPV_31_des0011	122.76237	20.352087	0.30847576	1.8004849	155.26732
Nsga_NPV_31_des0012	122.76237	20.352087	0.30847576	1.8004849	155.26732
Nsga_NPV_31_des0013	122.74333	20.289586	0.30337789	1.8155493	155.24066
Nsga_NPV_31_des0014	122.74174	20.352087	0.30838298	1.8007557	155.23844
Nsga_NPV_31_des0015	122.76237	20.477089	0.31622153	1.7782969	155.26732
Nsga_NPV_31_des0016	109.74313	20.289586	0.22577989	2.1045409	137.04038
Nsga_NPV_31_des0017	122.74333	20.352087	0.30742992	1.8035448	155.24066
Nsga_NPV_31_des0018	122.74333	20.352087	0.30742992	1.8035448	155.24066
Nsga_NPV_31_des0019	122.74333	20.289586	0.30337789	1.8155493	155.24066
Nsga_NPV_31_des0020	119.49328	20.289586	0.27849353	1.8949268	150.69059
Nsga_NPV_31_des0021	122.74333	20.289586	0.30337789	1.8155493	155.24066
Nsga_NPV_31_des0022	122.74333	20.289586	0.30337789	1.8155493	155.24066
Nsga_NPV_31_des0023	122.74333	20.289586	0.30337789	1.8155493	155.24066
Nsga_NPV_31_des0024	122.74333	20.289586	0.30337789	1.8155493	155.24066
Nsga_NPV_31_des0025	119.49328	20.289586	0.27849353	1.8949268	150.69059
Nsga_NPV_31_des0026	122.74214	20.352087	0.30743462	1.803531	155.23899
Nsga_NPV_31_des0027	119.49328	20.293492	0.27865796	1.8943677	150.69059

Fig. 12.10 Results of the optimisation

The best NPV is 1.9 M€, which is acceptable because archipelago double-ended ferries usually operate with government subsidies (with tax funds). High profits are not needed when making investment decisions.

12.3.2 Midship Analysis in BV Mars 2000

The goal of this section is to describe the developed *midship section export tool* from Cadmatic Hull to Bureau Veritas Mars2000. We report in the following our hands-on experience of the tools features and its implementation in the double-ended ferry case study.

Using the Export to Mars2000 feature, it is possible to export data from Cadmatic Hull frame views to an *xml file*, which can be then imported to Mars2000 software and be used there for the scantlings analysis. The exported xml file contains the description of the inner construction of the vessel (see Fig. 12.11) and its variation along the ship, translated to a Mars2000 data protocol. The export works only one-way, i.e. from CADMATIC to Mars2000.

Data exported from Cadmatic to Mars2000 consists of the basic ship information, such as name, class notation, main dimensions, material and relevant ship drafts. In addition, the data includes bending moment and shear force distributions. All the data are transferred in xml format.

As the xml file is opened in Mars2000, the cross-section will appear in the project window. Basic ship data can be manually modified, and the transferred values of bending moments and materials can be also corrected, if needed. In BV Mars2000 the user can modify the plates and stiffeners of the cross-section, if the resulting midship section does not comply with classification rules. Possible changes in plate thicknesses and stiffener profiles are then shown to the user, who can modify the Cadmatic model accordingly.

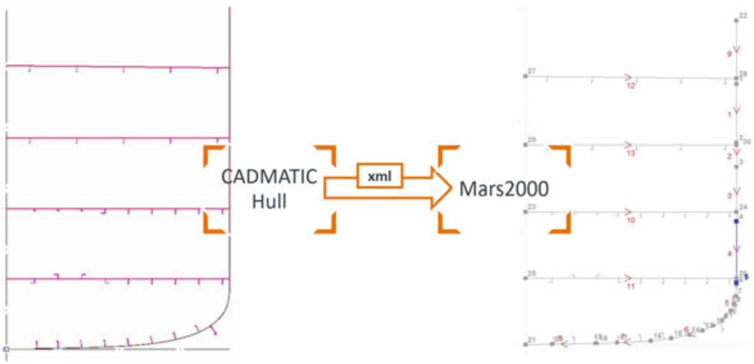


Fig. 12.11 Schematic of Cadmatic Hull and Mars2000 interface

12.3.3 *Ice Belt Optimisation*

The ice belt optimization of the double-ended ferry was carried out among the midship analysis. The focus was the finding of the lightest steel weight in the ice belt region by controlling the spacing of ice frames (secondary stiffeners) and comparing transverse system against the longitudinal one. The second objective was to compare how much the steel weight differs between different ice classes according to the Finnish-Swedish ice class rules (Avellan 2020).

The analysis and optimisation were done in two stages:

1. CAESES was used to generate ice belt area, ice frames and stringers to the 3D model based on user defined parameters and Finnish-Swedish ice class rules
2. Python programming language receives the ship data (main particulars), ice belt area and stiffener lengths from CAESES. Python uses a defined stiffener and steel plate library and formulas of Finnish-Swedish ice class rules to calculate the scantling requirements and the minimum applicable weights.

In CAESES script there were different user controlled (free) variables and formula dependent variables, which were used in the ice stiffening analysis (see Table 12.3). A user defines bulkhead and deck positions, and selects ice class, framing system and

Table 12.3 Variables used in the ice belt optimisation (Avellan 2020)

Variable label	Definition
Control variables	
Hull model	3D ship hull model
LIWL level	Coordinate value to define lower ice water line level
UIWL level	Coordinate value to define upper ice water line level
Displacement at UIWL	Ship's displacement tonnage at UIWL
Deck positions	List of coordinates to define deck pos
Bulkhead positions	List of coordinates to define BHD pos
Transverse floor spacing	Value to define floor pos
Web frame spacing	Value, which is used to create webs
Controlled pitch propulsion	Definition whether the ship has controlled or fixed pitch propulsion [Yes/No]
Number of propellers	Value to define the propeller quantity
Propeller diameter	Value to define the propeller diameter
Independent variables	
Ice class	Value to define the specific ice class [1C, 1B, 1A, 1A Super]
Framing system	Definition of used framing system [Transverse/Longitudinal]
Frame spacing	Value, which is used to create frames
Ice frame spacing	Value, which is used to create additional ice frames
Stringer positions	List of coordinates to create ice stringers

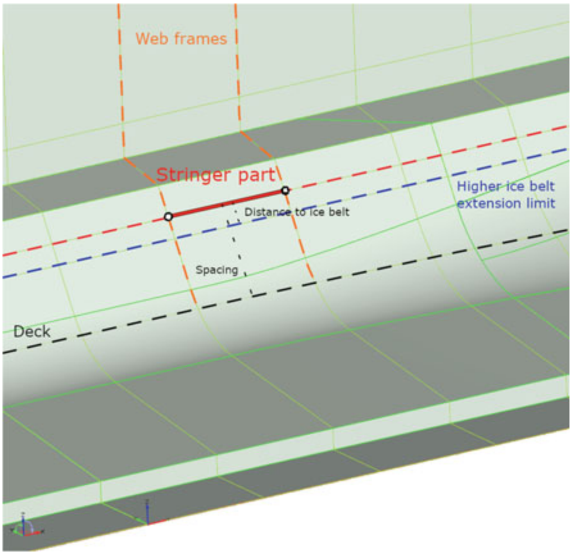


Fig. 12.12 Top ice stringer above the ice belt region (Avellan 2020)

frame spacing in CAESES. Based on calculated draft, CAESES defines Lower Ice Water Line (LIWL) and Upper Ice Water Line (UIWL) set by Finnish-Swedish ice class rules. LIWL and UIWL give vertical limits for the ice belt region, thus defining the positions of longitudinal ice stringers, which are primary stiffeners similar to main webs (see Fig. 12.12) (Avellan 2020).

Bulkheads, floors (bulkheads in the double bottom) and decks are generated by CAESES. In the areas where there are these primary structures, ice frames (secondary stiffeners) are not generated. Primary structures together with ice stringers and web frames also split the span of ice frames (see Figs. 12.13 and 12.14) (Avellan 2020).

Transverse spacing varied between 350 mm (every half frame) and 700 mm (every frame) for ice frames. In longitudinal framing, the spacing varied from 550 to 750 mm. Main webs were on every 4th frame (2800 mm), and longitudinal ice stringer positions were based on vertical limits of the ice belt region. Figures 12.15 and 12.16 present generated designs. Dots in curves split ice frames, ice stringers and main webs into separate objects. The splitting objects are decks, bulkheads and floors.

As presented in Fig. 12.15, longitudinal ice frames extend over the hull both in the double bottom and between decks 1 and 2. Spacing of the dots is denser at the ends of the ferry in the double bottom because transverse floors are located on each frame there.

Transverse ice frames are only in the midship region in the double bottom (see Fig. 12.16). Floors are on every 4th frame in the midship and on every frame at the ends. Main webs are on every 4th frame between decks 1 and 2. Transverse ice frames are not generated in these areas.

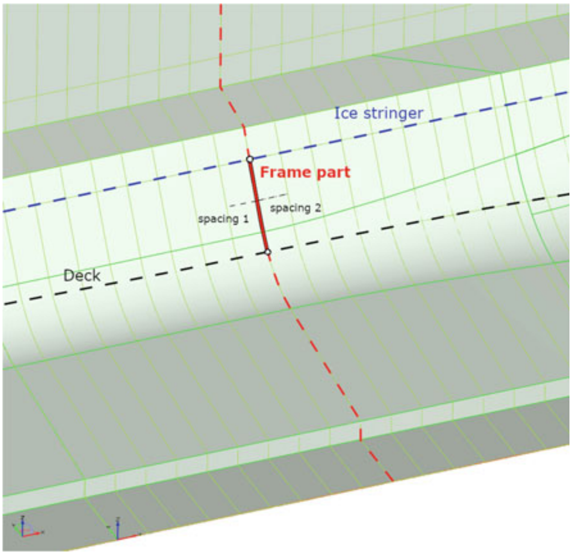


Fig. 12.13 Transverse ice frame in red between a deck and top ice stringer (Avellan 2020)

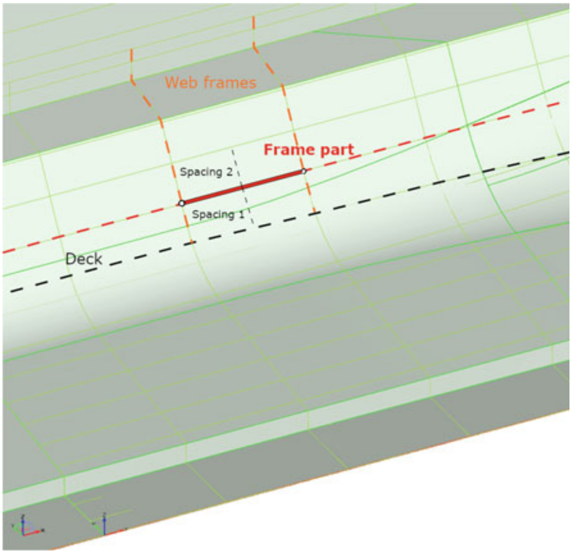


Fig. 12.14 Longitudinal ice frame between two main webs (Avellan 2020)

In case of transverse ice frames, it was compared whether weight savings are obtained by removing ice stringers from the 3D model. The upper ice water limit was near the deck 2 so it was meaningful to extend ice frames directly to the deck 2 instead of the top ice stringer if the weight savings were not so relevant (Avellan 2020).

Figure 12.17 presents obtained steel weights for the ice belt region including hull

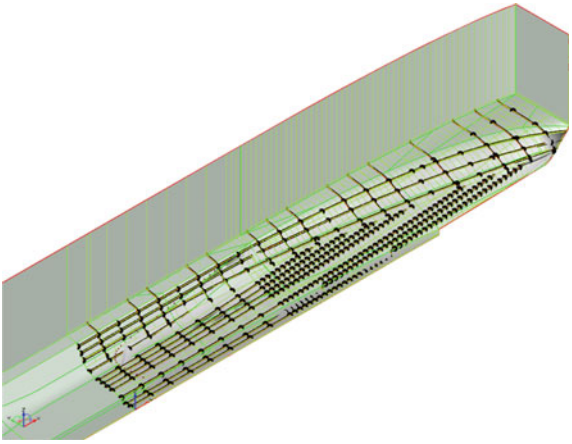


Fig. 12.15 Longitudinal ice frame spacing generated by CAESES script (Avellan 2020)

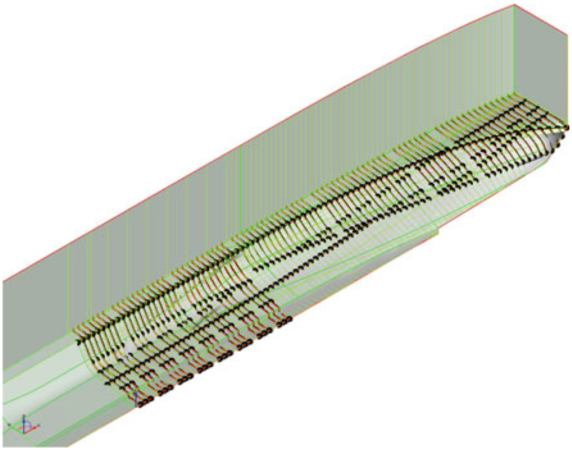


Fig. 12.16 Transversal ice frame spacing generated by CAESES (Avellan 2020)

plate and stiffener weights. Transverse ice framing provides significant weight saving against the longitudinal option. The latter option is only used in very long vessels where the longitudinal strength is critical. The double-ended ferry did not belong to this category.

It was confirmed that transverse ice frames on each half frame (350 mm), is the optimum solution for 1A and 1A Super classes. The optimum spacing was 700 mm for 1B and 1C ice classes.

The significant weight increase was seen in 1A Super ice class where the average steel weight increase was from 40 to 100 t against 1A option (see Fig. 12.18). The significance highlighted in longitudinal ice framing system.

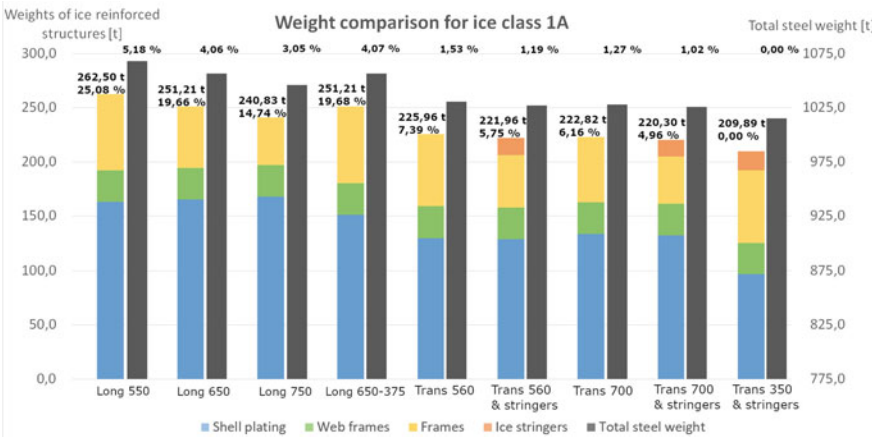


Fig. 12.17 Steel weight results for ice class 1A (Avellan 2020)

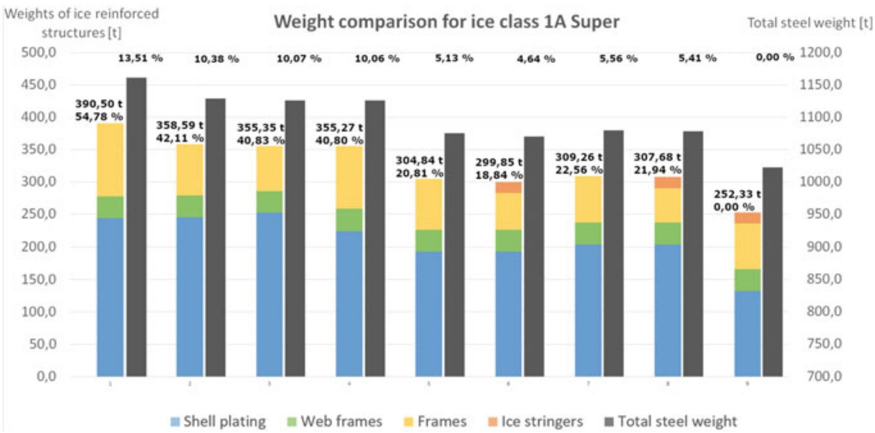


Fig. 12.18 Steel weights for ice class 1A Super (Avellan 2020)

12.3.4 Resistance

In order to support design decisions related to resistance and powering, the Hamburgische Schiffbau-Versuchsanstalt (HSVA) conducted an extensive series of full-scale resistance computations for the preliminary designs of the double-ended ferry. This series addressed design changes in the following aspects:

- number of lanes on the vehicle deck, and associated beam changes
- overall ship length
- presence and positioning of the propulsion units
- changes in draft.

CAESES software coordinated the geometry changes, and executed a fully-automated RANS computation using FreSCo+ (Hafermann 2007). The computations addressed the full-scale resistance, with special attention to dynamic trim and sinkage. Typical results from the RANS computation using FreSCo+ are shown in Fig. 12.19.

The resulting resistance and the associated effective power, P_E, were supplied in the form of a response surface model (RSM) within the CAESES design environment. A visualization of the RSM can be seen in Fig. 12.20.

With this type of *surrogate model*, the designer may investigate all combinations of design parameter changes within the design space, without the need to perform

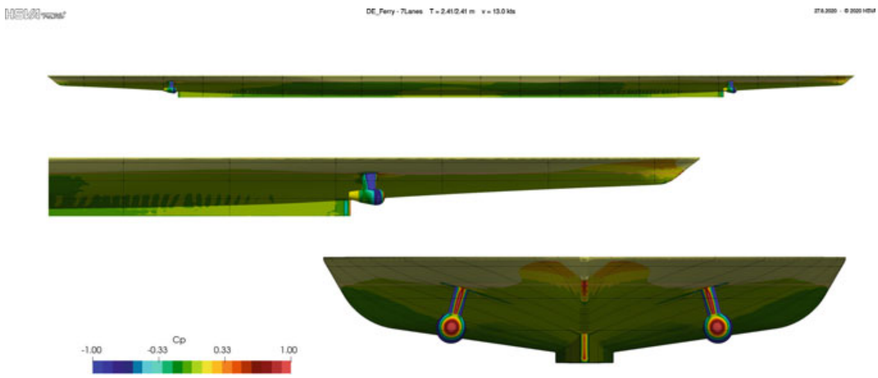


Fig. 12.19 Pressure Distribution on Double-ended ferry model including pod propulsion system: profile (top), bow detail (middle), from ahead (bottom)

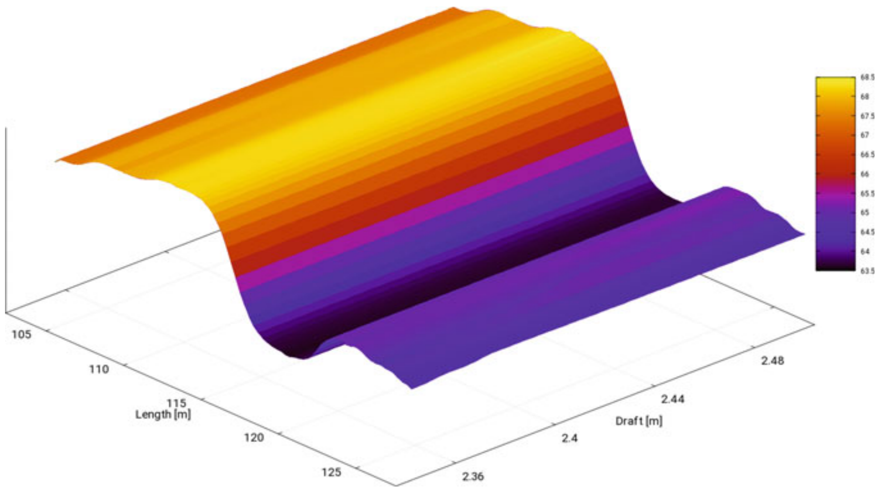


Fig. 12.20 Response Surface Model of resistance [kN] as function of Length and Draft

full RANS computations on each change. Considering the sensitivity of resistance on these design variables, the use of traditional estimation tools, such as empirical models or regression analyses of similar ships, would be redundant.

12.3.5 Analysis of Propulsion System

In this section, an analysis of the propulsion system is pursued by means of numerical simulations. The CFD solver adopted here is the in-house general purpose unsteady RANS tool Xnavis, developed at CNR-INM. Numerical discretization of the RANS equations is achieved in the framework of a finite-volume block-structured grid formulation. Complex geometries and body in relative motions are handled by a suitable (dynamic) overlapping grid (Di Mascio et al. 2006). Several spatial and time integration discretization schemes are implemented in the solver, resulting in a globally second order accurate method (for more details see Di Mascio et al. 2009). The method is based on the pseudo-compressibility formulation, acceleration toward divergence free field at each physical time step is achieved by means of an efficient multi-grid algorithm (Favini et al. 1996). In the solver, several turbulence models have been implemented, among them the one-equation Spalart–Allmaras turbulence mode, which has been employed for the simulations reported in the following. Propeller effects can be taken into account by either a real geometry representation of the propeller or modelled using an actuator disk model (Broglia et al. 2013).

Numerical simulations have been carried out for the double-ended ferry equipped with four PODs (see Fig. 12.21). The open water curve characteristics of the propeller are reported in Fig. 12.22. For this study a general POD geometry and stock propeller have been used, while the geometry is reported in Fig. 12.23.

In the numerical simulations, the struts and the nacelle of the PODs are considered in full-scale geometries, whereas the propeller effects are taken into account by means of a suitable propeller model (Hough and Ordway model). Computational

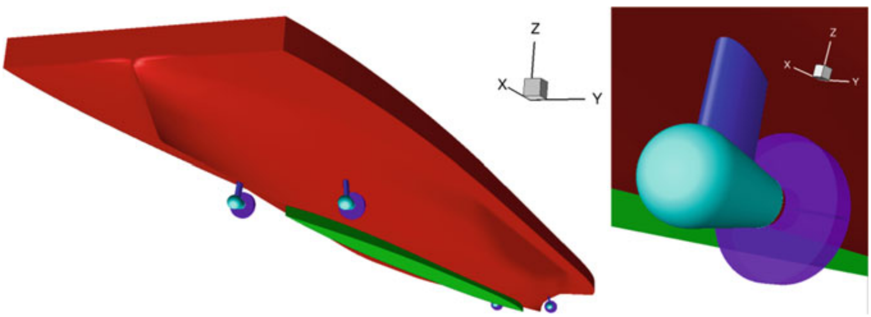


Fig. 12.21 Double-ended ferry model including pods propulsion system, overview and detail of the POD propulsor

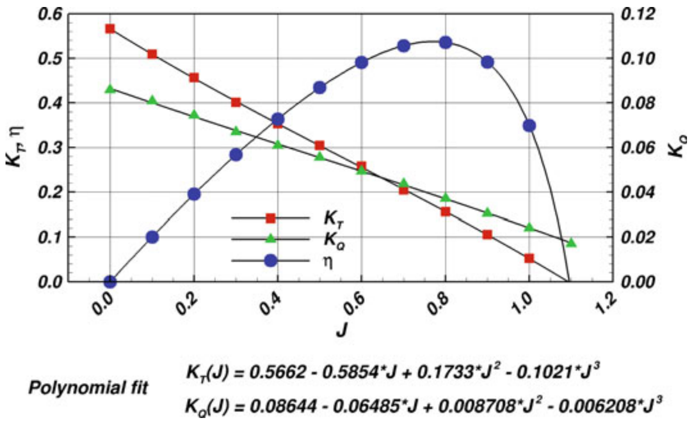
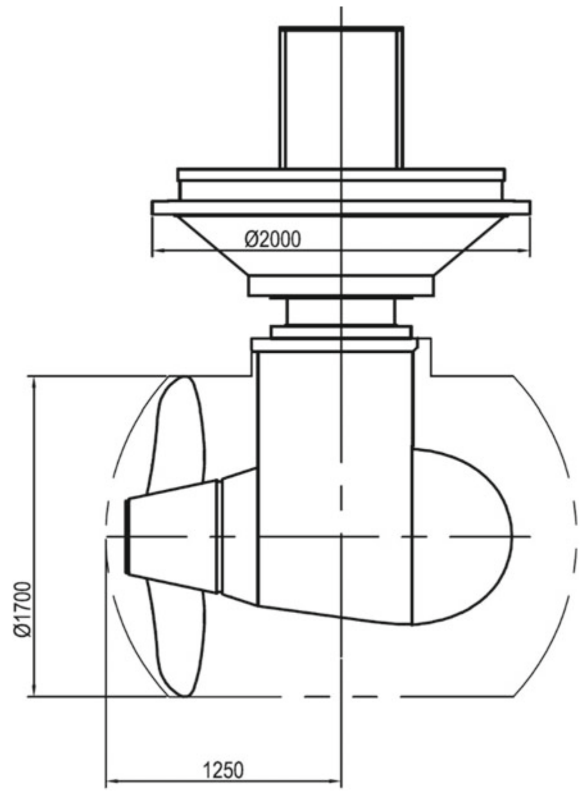


Fig. 12.22 POD propulsor: open water curves for the selected stock propeller. Measured data marked with symbols, continuous lines are third order polynomial fit

Fig. 12.23 Geometry of the fitted POD propulsor



mesh has been generated exploiting *Chimera* grid capabilities; a block structured mesh around the main hull is assembled with a separated block structured mesh for the central skeg. The mesh around the pods is composed by a grid around the vertical strut and a grid around the nacelle. The different parts are assembled and immersed in a background grid which fills the entire computational domain. Usual boundary conditions are imposed on the input, output and far-field boundaries. Points are clustered toward physical boundaries, in order to resolve the thin boundary layer (no wall functions have been used, $y^+ \approx 1$ is guaranteed on all solid walls). Moreover, extremely highly resolved mesh is considered in the space between the fore and the aft pods, in order to take accurately into account the mutual interaction between the fore and aft propulsion systems.

The computational mesh is composed for a total of about 20 million grid points for half geometry (simulations are carried out only for half geometry exploiting the symmetry along the longitudinal vertical plane). The computational grid has been built starting from the CAESES model for both the ship hull and the pods. Numerical simulations have been performed within CAESES framework, which allowed an easy tuning of the operative conditions (i.e. advancement speeds, propulsion point, distribution of thrust and torque between the fore and aft pods).

Numerical simulations were carried out at full scale for and advancement speed of 13 kn, with a corresponding Froude and Reynolds numbers (based on the ship length between perpendicular and the advancement speed) of $Fr = 0.195$ and $Rey = 7.250 \times 10^8$, respectively. Several tests have been pursued to find the best power distribution between the fore and aft pods. Once the power distribution is fixed in terms of percentage of the total thrust to be delivered by the front and aft propellers, computation is carried out to find the self-propulsion point.

The torque is then obtained from the open water curves. The procedure is repeated with a new resistance estimation at the actual propulsion point. The iterative procedure is stopped when a negligible difference in the resistance estimation is seen between two consecutive simulations. The result of the iterative procedure, allowed to find the following propulsion points for the different fore/aft load balance.

As it will be shown in the following, due to the large distance between the two propulsion systems, a rather weak influence has been seen by the front pod on the aft pod (and vice versa). Therefore, the perfect balance of the required power between the front and rear pods is driven by the total resistance; in particular it has been found that the acceleration and the swirl imposed to the flow by the front propeller cause an increase of the resistance; as a consequence, a minimum of the total power requirement is seen when the major fraction of the thrust is provided by the aft PODs. Total power required and fractions between fore and aft propellers are reported in Table 12.4, and graphically in Fig. 12.24.

In order to better illustrate the flow field and the propeller working conditions three simulations in fully appended configuration is presented here, namely:

1. *Both propellers turned off* ($\alpha_1 = 0.0$, $\alpha_2 = 0.0$)
2. *Only the fore propellers turned on* ($\alpha_1 = 1.0$, $\alpha_2 = 0.0$)
3. *Both propellers turned on* ($\alpha_1 = 0.5$, $\alpha_2 = 0.5$)

Table 12.4 Propulsion points at speed $U_\infty = 13kn$

Balance fore/Aft	Fore propellers					Aft propellers					Total
	J	K_T	K_Q	η	P [kW]	J	K_T	K_Q	η	P [kW]	P [kW]
1.0/0.0	0.68	0.21	0.044	0.52	1302	1.1	0.00	0.000	–	0	2604
0.9/0.1	0.70	0.20	0.043	0.53	1132	1.01	0.05	0.023	0.32	205	2675
0.8/0.2	0.73	0.19	0.041	0.53	989	0.95	0.08	0.027	0.44	298	2573
0.7/0.3	0.75	0.18	0.040	0.54	848	0.90	0.11	0.031	0.50	394	2484
0.6/0.4	0.78	0.16	0.038	0.54	729	0.85	0.13	0.034	0.52	500	2458
0.5/0.5	0.82	0.14	0.035	0.53	586	0.82	0.14	0.035	0.53	586	2343
0.4/0.6	0.86	0.12	0.033	0.52	479	0.79	0.16	0.037	0.54	694	2348
0.3/0.7	0.90	0.10	0.030	0.49	381	0.76	0.17	0.039	0.54	811	2383
0.2/0.8	0.96	0.08	0.027	0.43	282	0.74	0.18	0.040	0.54	904	2372
0.1/0.9	1.02	0.04	0.022	0.31	196	0.72	0.19	0.041	0.53	1009	2409
0.0/1.0	1.10	0.00	0.000	-	0	0.71	0.20	0.042	0.53	1105	2210

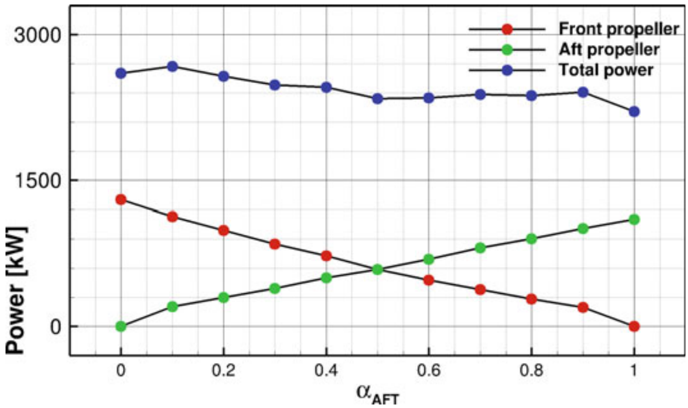


Fig. 12.24 Fore, aft propeller and total required thrust versus aft propeller fraction thrust

The aim of the first simulation is the estimation of the nominal wake for the fore propeller, for the second one is the estimation of the nominal wake of the aft propeller, for the last one is, obviously, the analysis of the entire system working in the real operative conditions.

In Fig. 12.25, the nominal and effective wakes for the fore and aft propellers from the three simulations are reported. Nominal wake for the fore propeller is the panel at top left (i.e. when both propellers are off, that for the aft propeller is the panel at bottom in the middle (i.e. when only the fore propeller is on). As it can be seen, both propellers are in the wake of the strut of the pod; for the fore propeller the trace of the junction vortex can also be seen. Clearly, the inflow to the aft propeller is also

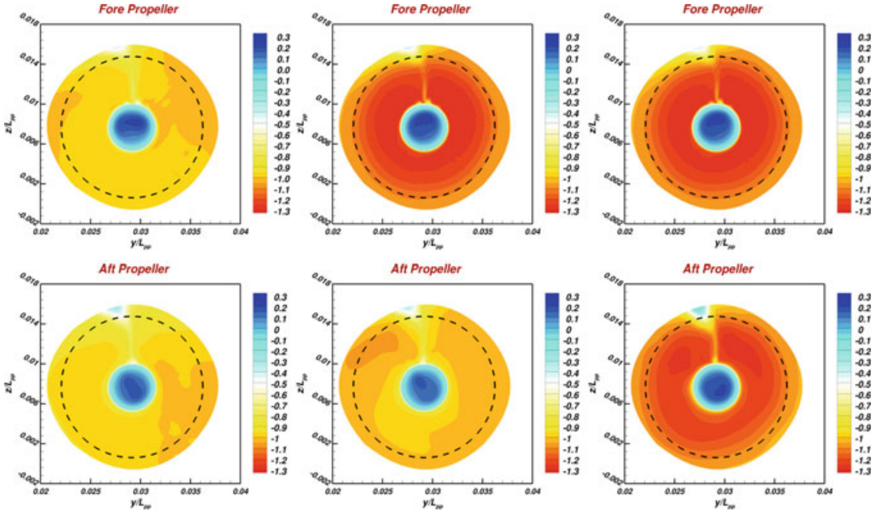


Fig. 12.25 Nominal and effective wakes for the fore (top row) and aft (bottom row) propellers. Left column is with propellers off, middle with only fore propelled turned on, right column is with both propellers turned on (ratio ($\alpha_1 = 0.5$, $\alpha_2 = 0.5$))

characterized by a larger presence of the hull boundary layer. However, the structure and wake fraction of the two inflows are rather similar. Moreover, comparing the inflow on the aft propeller with or without the fore propeller turned on, similar flow field is seen; confirming the negligible effect of the fore propeller wake on the aft propeller. Looking at the flow in front of the two propellers when they are turned on (right column), the acceleration of the flow imparted by the propellers is evident. The wake of the strut is strongly thinned, and the trace of the junction flow is stronger (at least for the fore propeller).

12.3.6 Intact and Damage Stability

Stability analysis as integral part of the ship design process was performed for the double-ended ferry design study by use of the software package NAPA. The stability analysis process was integrated into the process and design optimization framework CAESES using the parametric hull description, as described in sub-Sect. 12.2.1, which formed the basis for the intact and damage stability calculations by NAPA.

The approach for using NAPA by CAESES is shown in Fig. 12.26. CAESES provides the hull form and wind profile in IGES-format and additional parameters and calculation control information in text format as ASCII-files. These additional parameters as well as calculation control options contain among others the main ship particulars, not provided with the hull geometry, like side depth to main deck, the draughts to be considered in the calculations, the service speed and the number

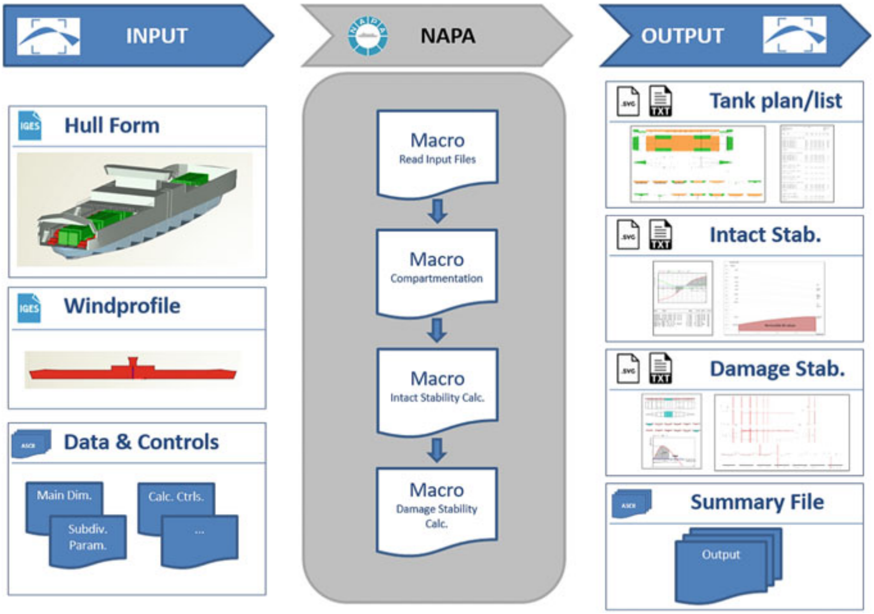


Fig. 12.26 Process map for intact and damage stability analyses using CAESES and NAPA

of passengers as well as details of the watertight subdivision. NAPA is called by CAESES in batch mode and runs a number of internal macros to set up the calculation model, to perform the intact and damage stability calculations for each design variant and to generate a series of output files, as text files with calculation results and graphic files for visual inspection, like tank plan, subdivision arrangement and KGmax curves. This information is generated in NAPA and is transferred back to CAESES for evaluation. Additional result files with more details concerning intact and damage stability calculations can optionally be generated and be stored in the folder of each design variant.

The described process for intact and damage stability analyses can be applied in the design process in different ways:

- Calculate and evaluate single design variants: Within a design optimisation process stability can be considered as a constraint, which has to be met in order to have a valid design. In this case the stability analysis is performed for each variant and the only feedback to the optimisation process could be the information on the validity of the design with respect to stability (pass or fail).
- Establish design dependencies: In early ship design the process can be used to establish most influential main parameters on intact and damage stability. Especially for vessel types not familiar to the ship designer and/or for new or upcoming stability regulations this approach could be a very beneficial source of information.
- Generate surrogate models: In case of time-consuming stability calculations (probabilistic damage stability rules) the generation of surrogate models for an

Table 12.5 Range and limits of design variables used in the design space exploration

Design variable	Unit	Lower limit	Baseline value	Upper limit
Length over all/Loa	[m]	110.00	122.00	130.00
Max. Beam/Bmax	[m]	15.50	19.20	22.50
Design Draught/Tdwl	[m]	2.20	2.50	2.60
Depth to Car Deck/D	[m]	4.00	4.20	6.00
Bilge Radius	[m]	0.50	2.10	3.00
Deadrise Angle	[deg]	0.0	8.3	10.0
Flat of Bottom Ratio	[–]	0.00	0.10	0.35
Number of compartments	[–]	9	14	19

estimation of the stability results based on input parameters might be an adequate option in a design optimization process. These surrogate models can be based on response surfaces or multiple non-linear regression formulas.

As a measure to assess the stability requirements the maximum permissible vertical centre of gravity KGmax of the laden ship on design draught as described in Zaraphonitis et al. (2019) is used. This KGmax value can be compared with the total KG derived from the weight calculation for the respective design variant considering a suitable margin for free surface effects and uncertainties.

The described approach for determination of KGmax can also be applied for other draughts of interest, like scantling draught or a number of draughts between a minimum and a maximum draught. This allows for analysis of an operational profile with respect to differing loading conditions.

To investigate design dependencies with regard to intact and damage stability of a double-ended ferry and to provide support for design decisions a design space exploration applying a SOBOL algorithm with 500 variants was performed with a parameter range for the parametric hull form and the internal subdivision as per Table 12.5.

In addition to supporting design decisions by establishing design dependencies the design space exploration could be utilized to generate surrogate models on basis of response surface techniques or multiple non-linear regression analyses to generate estimation formulas for KGmax, to be applied fast and efficient in early design optimization (Zaraphonitis et al. 2019).

12.3.6.1 Relevant Rules and Regulations

The double-ended ferry is designed for operation within domestic waters of Finland, a member state of the European Union. Therefore, Directive 2009/45/EC of the European Parliament and the Council on Safety Rules and Standards for Passenger Ships

(European Commission 2009) was applied.[1] The Directive regulates—among other safety related issues—freeboard requirements as well as intact and damage stability standards for passenger vessels engaged in domestic operations within European waters.

Due to the range of operation and the weather conditions to be expected in the area of operation the vessel is defined according to the Directive as a 'class D' vessel. Vessels of 'class D' are designed for operation in sea areas where the probability of exceeding 1.5 m significant wave height is less than 10%, the distance to a place of refuge is less than 6 miles and the distance to the coast line is less than 3 miles. The vessel is designed for 400 passengers and 8 crew members.

As per Directive the following regulations are to be fulfilled for 'Class D' vessels:

- Freeboard: 1966 International load line convention (as amended) with exemption of the minimum bow height requirement;
- Intact Stability: IMO Resolution A.749(18) as adopted on 4 November 1993; the Severe Wind and Rolling Criterion might be replaced by an alternative approach ensuring satisfactory stability; and
- Damage Stability: requirements on subdivision and stability as per rules of the Directive (deterministic approach). Alternatively, IMO Resolution A.265 (VIII) may be used in their entirety.

12.3.6.2 Intact Stability

Intact stability analyses in accordance with the existing Directive are to comply with IMO Res. A.749(18) (IMO 1993). The code contains mandatory stability criteria for all vessels and recommendatory stability criteria for certain vessel types. The mandatory requirements for the double-ended ferry are listed in Table 12.6 and are identical to those defined in the 2008 Intact Stability Code.

Alternatively, for ships with a wide beam and small depth ($B/D \geq 2.5$) the administration may allow the application of alternative intact stability criteria (IMO 2008) for the position of the maximum righting lever and the area under the GZ curve up to 30° as shown in Table 12.7.

Due to the uncertainty of the decision of any administration the standard and alternative criteria for the position of the maximum righting lever and the area under the GZ curve up to 30° are analysed and compared in this study.

Within the presented design study, the hull form is generated by the parametric hull model in CAESES and contains the hull up to main deck (car deck). The wind profile is also generated in CAESES based on the size and arrangement of the deckhouse and the lateral area of the trucks or the side shell/bulwarks.

[1] Recently the Directive was amended by the Commission Delegated Regulation (EU) 2020/411(European Commission 2009). For ships with keel-laying date on or after 19 September 2021 the rules on stability and subdivision will be changed in order to make reference to SOLAS Chapter II-1 B to B-4.

Table 12.6 Standard intact stability criteria for passenger vessels (IMO 1993)

Criterion	Requirement
Min. Intact Stability GM	$GM \geq 0.15\,\text{m}$
Max. Righting Lever GZ	$GZ_{max} \geq 0.20\,\text{m}$
Position of max. Righting Lever	$\varphi_{GZ_{max}} \geq 25°$
Area(s) under GZ Curve	$A_{30°} \geq 0.055\,\text{m rad}$
	$A_{40°} \geq 0.090\,\text{m rad}$
	$A_{30°-40°} \geq 0.030\,\text{m rad}$
Weather Criterion	$b \geq a$
Max. Heel due to wind moment	$\varphi_0 \leq 16°$ or
	80% of angle of deck edge immersion
Max. Heel due to passenger crowding	$\varphi_{Pax} \leq 10°$
Max. Heel due to turning at speed	$\varphi_{Turn} \leq 10°$

Table 12.7 Alternative intact stability criteria for wide beam and small depth vessels with B/D $\geq$ 2.5 (IMO 2008)

Criterion	Requirement
Position of max. righting lever	$\varphi_{GZ_{max}} \geq 15°$
Area under GZ curve up to 30°	$A_{30°} \geq 0.055 + 0,001(30° - \varphi_{GZ_{max}})$ m rad

Results of the intact stability analysis with respect to the different criteria concerning the position of the maximum of the GZ-curve parameters and with respect to parameter depth are shown in Fig. 12.27.

For the design parameter side depth, the results of a sample investigation are shown in Fig. 12.27. For both—standard and alternative stability criteria—increasing the depth leads to higher permissible KG values. At higher depth a decrease of the KGmax values for vessels with small breadth can be observed.

The red dashed line in Fig. 12.27 represents an assumed centre of mass/gravity for the laden ship to be at car deck level (KG = Depth).[2] Thus, these graphs could be used in supporting design decisions. Based on the application of the standard stability criteria a designer could draw the conclusion from the graph that a depth of at least 4.50–5.00 m would increase the probability of complying with the intact stability criteria. For the alternative criteria it is obvious that for depth up to approximately 5 m a very comfortable safety margin of about 2 m between the permissible KG value and the assumed centre of gravity exists.

[2]KG = depth is a simplified formulation based on a rough estimate of the centre of gravity of the laden ship for the baseline design.

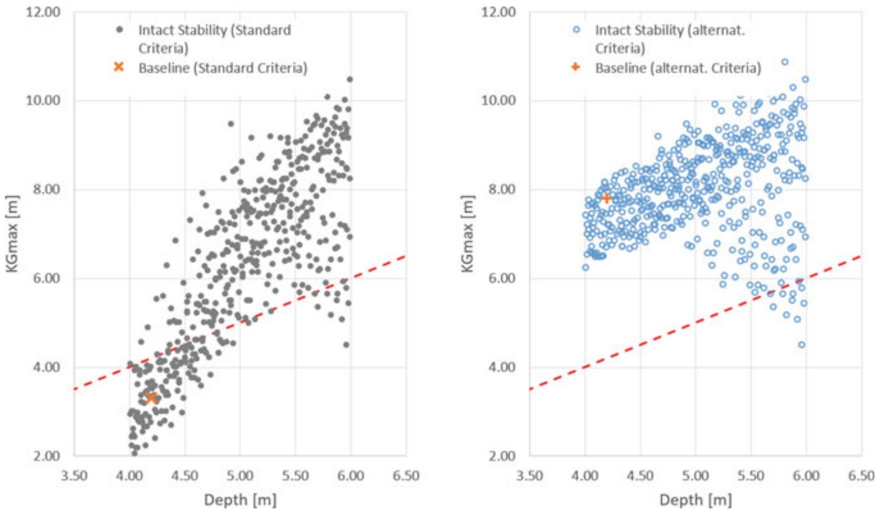


Fig. 12.27 KGmax values to fulfil intact stability requirements with respect to depth for standard criteria (left) and alternative criteria (right)

For the samples of the design space exploration the limiting criteria were analysed and clustered to show the relevance of the applied intact stability criteria for the double-ended ferry. The results are presented in Table 12.8.

In applying the alternative stability criteria a shift from the position of GZmax criterion to the weather criterion could be observed. The weather criterion for the analysed vessel allows for much higher KGmax values. For the baseline design the standard criteria would allow a KGmax of 3.30 m while applying the alternative criteria KGmax could be increased up to 7.80 m. Depending on the applied criteria the design of the double-ended ferry would vary. If the standard criteria are to be complied with the hull design can be expected to require changes due to the very low permissible KG. For the alternative criteria a very comfortable permissible KG is reached. Thus, a designer should seek the discussion with the administration very early in the design process, if the alternative criteria would be accepted for the vessel and the area of operation.

Table 12.8 Limiting criteria for KGmax with respect to intact stability as percentage of all samples

Criterion	Standard criteria (%)	Alternative criteria (%)
Pos. of GZ max (>25° or >15°)	65.1	0.4
Heel due to wind	10.8	10.8
Weather criterion	16.0	74.4
Other criteria	8.1	14.3

12.3.6.3 Damage Stability Analysis

Damage stability assessment in accordance with Directive 2009/45/EC is based on a *deterministic approach* for side damages and requires proof of compliance with floodable length requirements for the floating position as well as compliance with stability requirements in damaged condition. For vessels of 'class D' with 400 and more persons on board a subdivision factor of 0.50 is to be applied, which results in a maximum compartment length of half the floodable length calculated for a margin of submergence of at least 76 mm below the bulkhead deck (i.e. the car deck in case of the double-ended ferry). Compliance with the stability requirements has to be demonstrated for all service conditions by adequately withstanding the flooding of any two adjacent compartments for vessels with required subdivision factor of 0.50.

The extent of side damage to be applied can be seen from Table 12.9 and the stability requirements to be complied with in the final stages of flooding are stated in Table 12.10.

Pre-calculations showed that the final stage of flooding imposes the highest requirements on stability. Furthermore, the multi-compartment damages proofed to be more severe than the one-compartment cases. Thus, to speed up calculations, the study was performed by analysing multi-compartment damages in the final stage of flooding only.

The floodable length requirement was reviewed in a pre-design study and proved not to be a critical requirement. Therefore, floodable length calculations were not part of the SOBOL study. However, due to the stability requirement which requires the margin line in the final stage of flooding not to be submerged the floodable length requirement is comparably covered. For the baseline design the curve of floodable length on design draught and for a permeability of 0.95 is shown in Fig. 12.28. To proof compliance, the compartment triangles for the two-compartment status are included.

For the study a generic watertight subdivision model allowing for the analysis of different arrangements with respect to double bottom and double hull configurations was developed and applied. The model uses a simplified room arrangement based on void spaces, tanks and machinery rooms only. The room arrangement was defined to be symmetrical about L/2 and centre line. Small tanks inside machinery rooms and rooms subdivided with A-class boundaries were neglected in the model.

Table 12.9 Extent of damage to be applied (European Commission 2009)

Side damage	Extent of damage
Longitudinal extent	Min. (3.00 m + 3% length of the ship, 11.00 m; 10% length of the ship)
Transverse extent	B/5 from ship's side at the level of deepest subdivision load line
Vertical extent	From the base line upwards without limit
Lesser extent	Any damage of lesser extent, which results in a more severe condition is to be considered

Table 12.10 Stability requirements in the final condition after damage (European Commission 2009)

Criteria (final stage of flooding)	Requirement
Range of positive righting lever	$Range \geq 15°$[a]
Area under GZ-curve	$Area\ 22° \geq 0.015\,\text{m} \cdot \text{rad}$ (one-comp. flooding) $Area\ 27° \geq 0.015\,\text{m} \cdot \text{rad}$ (two-comp. flooding)
GZmax	$GZmax \geq 0.10\,\text{m}$
GZmax taking into account max. heeling moment due to: – passenger crowding – launching of survival craft – wind pressure	$GZmax \geq \frac{heeling\ moment}{displacement} + 0.04$
Heeling angle	$Heel \leq 12°$
Margin line	Not submerged
Progressive flooding	No progressive flooding

[a]the range can be reduced to a minimum of 10° in cases where the area under the righting lever curve (Area22° and Area27° respectively) is multiplied by the ratio 15/range. This alternative was not used in the study

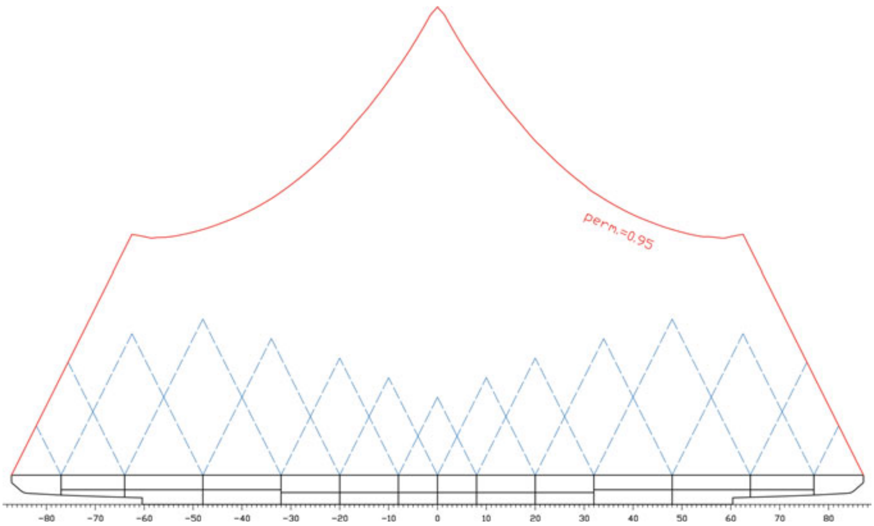


Fig. 12.28 Floodable length calculation for the baseline design

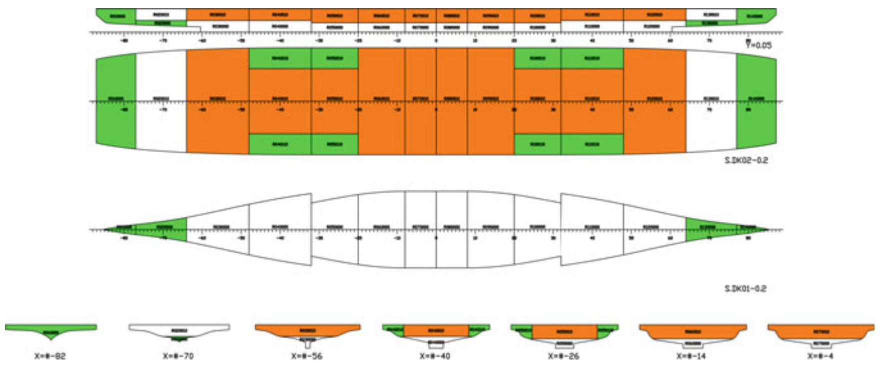


Fig. 12.29 Tank and room arrangement for the baseline design

The generic room arrangement model allows for adaptation of:

- the number of compartments (between 9 and 19)
- the double hull arrangement:
  - double hull (yes/no)
  - trim and heeling tank arrangement (4 tanks/8 tanks)
  - width of double hull (numeric value)
- double bottom tanks within B/5-limit (yes/no)

The room arrangement of the baseline design is shown in Fig. 12.29. The flexibility of the generic subdivision model with respect to the double hull arrangement is presented in Fig. 12.30.

For the ship model applied in the design space exploration a simplified watertight subdivision arrangement with equidistant[3] compartment length in-between the collision bulkheads with double hull arrangement between compartment 4 to N_c-3 (where N_c denotes the number of compartments) and no additional tanks in the double bottom was applied. The room arrangement for a vessel with 9 and 19 compartments can be seen in Fig. 12.31.

Based on the baseline design a pre-study was performed to show the influence of varying subdivision parameters on the result of the damage stability calculation. It was observed that the influence of the internal subdivision for the baseline design is relatively small. However, a double hull arrangement is disadvantageous due to unsymmetrical flooding while the arrangement of tanks within the B/5 limit in the double bottom shows no effect on the KGmax value.

As expected, the maximum permissible KG on design draught increases with increased number of compartments based on the study for the baseline configuration (see Fig. 12.32, right). Interesting to see is that KGmax is increasing with the number

[3]The bulkheads are positioned from the collision bulkheads inward according to the given transverse frame spacing of 700 mm. This approach can in some cases cause slightly differing compartment length for the center compartment(s) due to rounding differences.

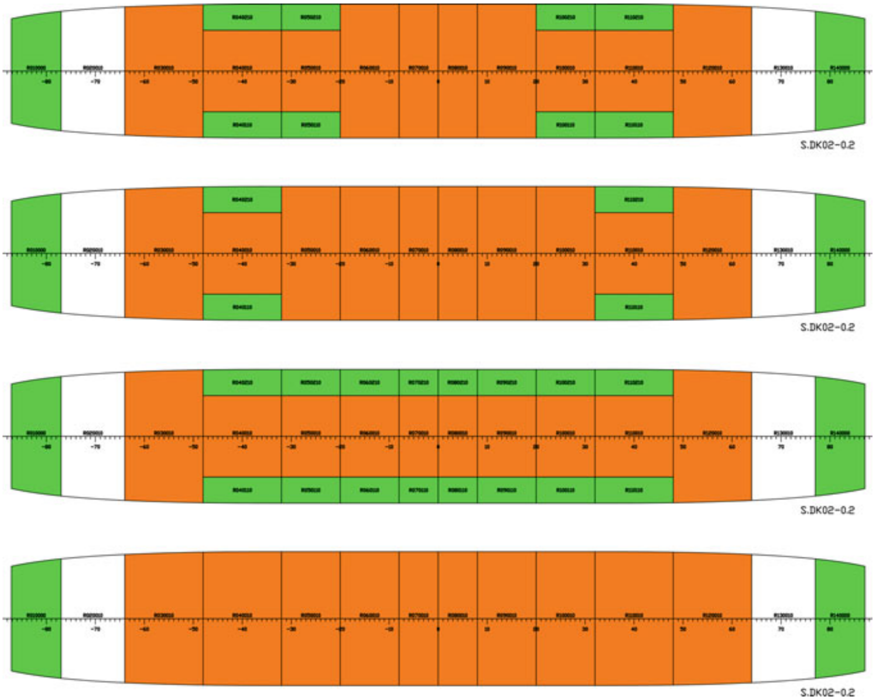


Fig. 12.30 Double hull arrangement for the baseline design with 8 trim and heeling tanks (top), 4 trim and heeling tanks (centre up), double hull (centre down), w/o double hull (down)

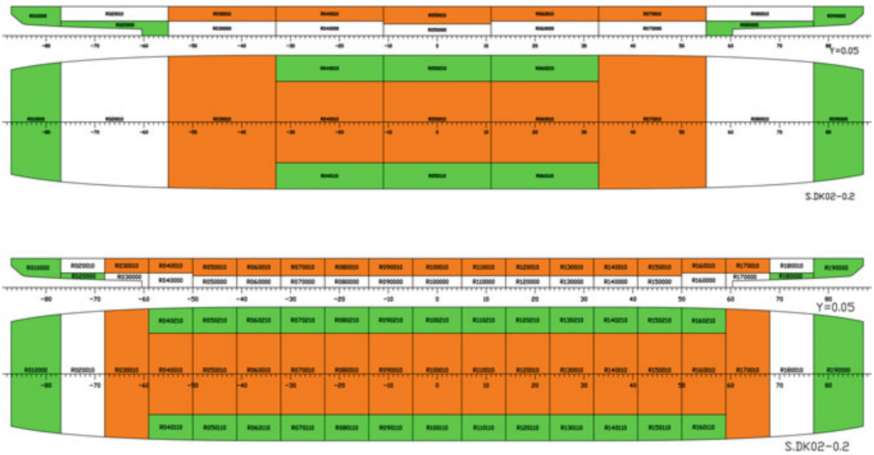


Fig. 12.31 Model used in the study: number of compartments from 9 to 19 compartments (evenly spaced between collision bulkheads), double hull arrangement and no double bottom tanks

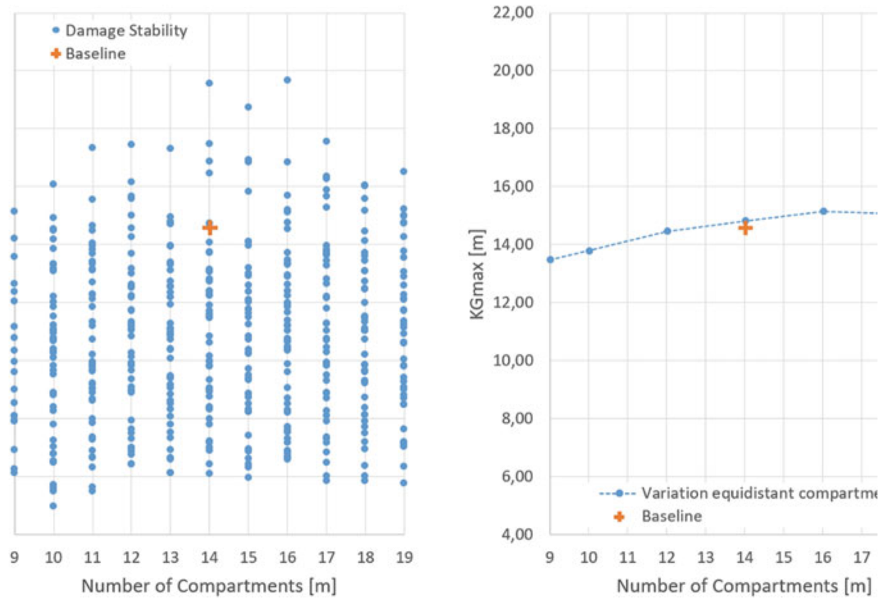


Fig. 12.32 Variation of number of compartments for the design exploration study (left) and a study derived from the baseline design

of compartments up to 16 compartments and then is decreasing again. This is due to the required damage length to be applied and which causes in case of more than 16 compartments the flooding of three compartments instead of two.

Having a look at the results from the design space exploration no clear tendency for KGmax concerning the number of compartments can be observed (see Fig. 12.32, left). It is obvious that other main parameters have a much higher influence on the permissible KGmax value with respect to damage stability.

The influence of the parameter depth can be seen in Fig. 12.33. Increasing the depth for this vessel is disadvantageous with respect to damage stability. This phenomenon is caused by the increased wind lateral area. Looking at the ratio Bmax/Depth a clear tendency can be observed for KGmax with respect to damage stability. With increasing B/D ratio the permissible KG to fulfil the damage stability requirements increases.

Generally it can be stated that the double-ended ferry has a hull form which is beneficial in case of damage. Due to the sharp V-shaped form with additional wing extentions on car deck level to increase the deck space area, submergence in case of damage is very limited. Asymmetrical flooding is also not critical for the double-ended ferry, since asymmetries only exist in the watertight subdivision above the double bottom and the volumes of these rooms are small.

Comparing intact and damage stability requirements for the double-ended ferry identifies that intact stability implies more severe requirements resulting in a lower KGmax value. Independent of the intact stability regulations (standard or alternative

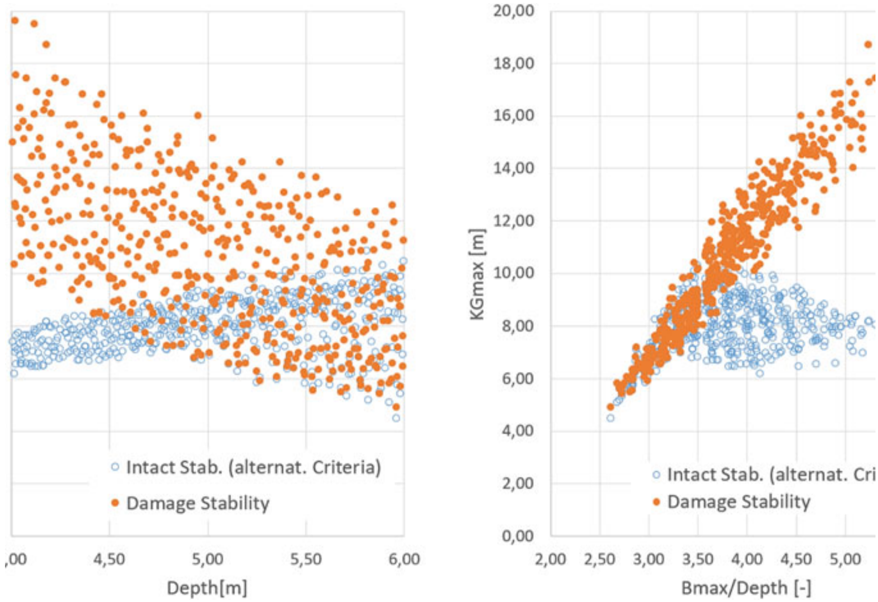


Fig. 12.33 Influence of depth (left) and B/D ratio (right) on KGmax with respect to intact and damage stability

criteria) intact stability is in 85% of the cases of the design exploration study the limiting requirement.

A comparison of intact and damage stability requirements with respect to main parameter depth and B/D ratio is presented in Fig. 12.33. These diagrams may help the designer to find optimum main parameters with respect to stability. However, it is to be noted that the ship design process requires the fulfilment of multiple criteria and optimisation goals can also differ. Therefore, stability can be an optimisation goal but will in most cases act as a constraint. For the designer in the early design stage it is helpful to be aware of the possible design space to avoid problems and cost during design and construction.

Design studies as presented can further be used as a basis for developing surrogate models. These models can be either regression formulas or response surfaces and can help speeding up an optimisation by simplifying the calculation procedure and by decoupling the calculations from expert tools. However, it has to be considered, that surrogate models generate only estimates based on the underlying model and the parameters involved.

For exact calculations, the presented method can be implemented as is in the optimisation analysis. In the case of the double-ended ferry the time for performing intact and damage stability calculations in NAPA is in the range of one minute per variant and thus allows for a direct coupling to the optimisation.

12.3.7 Operational Profile and Battery Dimensioning

An electric balance study was made for the dimensioning of the batteries of the double ended ferry. The energy consumers are divided into groups as shown in Table 12.11. Loads are divided into different stages of the ship operation. These are maneuvering, cruising and harboring. Cruising and maneuvering stage loadings are calculated for summer and winter conditions. In addition, consumers in emergency are identified and calculated.

Propulsion and auxiliaries are the main energy consumers, which consume almost 90% off total energy. Summer propulsion powering of 1323 kW is obtained from CFD analysis, and winter propulsion powering 2123 kW is based on Finnish classification society's (Trafi) ice class propulsion requirements. Table 12.11 loading data is used to define the operation profile at summer and winter conditions, and thus to define the required battery capacity and/or auxiliary diesel generator set capacity.

Table 12.11 Electric consumers

Speed		13 kn	13 kn	2 kn	2 kn		
No	Group	Summer cruise (kW)	Winter cruise (kW)	Maneuv & moor Summer (kW)	Maneuv. & mooring Winter (kW)	Emergency (kW)	Harbour (kW)
1	Propulsion and auxiliaries	1323	2123	173	323		61
2	Engine rm auxiliaries	3	3	3	3		2
3	Ship system auxiliaries	18	18	18	18	48	15
4	HVAC	14	14	14	14		14
5	Heating and Cooling	84	63	84	63		32
6	Deck mach			113	113	23	
7	Cargo systems						
8	Galley	9	9	9	9		5
9	Lightning and automation system	18	18	18	18	9	11
10	Navigation and control	8	8	8	8	8	2
11	Spec. systems						
Total [kW]		**1477**	**2256**	**439**	**568**	**87**	**142**

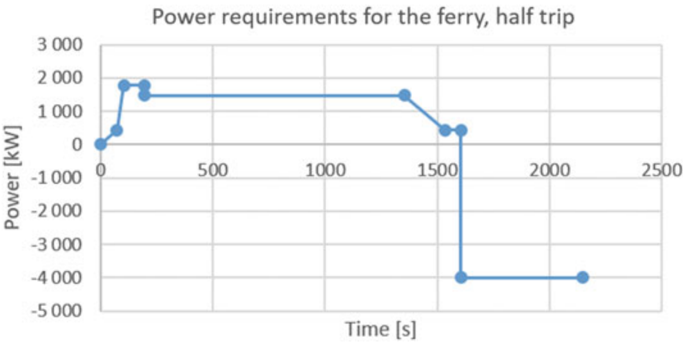


Fig. 12.34 Summer operation profile for half trip

As introduced in Sect. 12.1.1, the length of the round trip is 10 nautical miles, and the ship operates from 5 am to 11:30 pm every day. The double ended ferry recharges its batteries on each half trip. The ship stays at the harbour for 10 min, and recharges the batteries for approximately 9 min at ports. One minute goes to “lock” the recharging unit to the ship. Additionally, three longer breaks (30 min) were taken into account after every 8 trips.

Figure 12.34 shows the operational profile of the double-ended ferry at summertime. It describes the power consumed during each stage in the half trip from port A to B. Operational stages are divided into maneuvering, acceleration, cruising, deceleration and harboring. Required powers are based on the data of Table 12.11 where the magnitude of propulsion and hotel loads are shown at each stage. The power requirement is getting negative after 1600 s, which corresponds to the time in a harbor. During this time, the ferry recharges its batteries using a land-based electricity grid, of which total recharging capacity is 4350 kW. The land-based net supplies 142 kW to run systems onboard. The net 4000 kW goes to the recharging of batteries, while approximately 200 kW is transfer loss.

According to the electrical balance described above, certain battery specifications were considered to fulfil the power demand. Thiswas performed through Bureau Veritas’ Ship Energy Efficiency Calculation and Analysis Tool (SEECAT), both for the full electric and the hybrid systems as well as considering summer and winter seasons. This enabled to take into account the charging dynamic of the batteries where the power is modulated in order to avoid overcharging. The higher the C-rate of the battery, the faster the battery can be charged.[4] This is generally implemented in the battery for safety reason and to keep the battery life long. Consequently, higher battery capacities need to be considered compared with the supposed capacity obtained without accounting for such charging dynamics.

For each design strategy, a specific SEECAT model was built, see Fig. 12.35. Most

[4]The C-rate characterizes the rate at which a battery is being charged or discharged given a specific capacity. Operationally, the battery can be charged/discharged at any C-rate value provided that it remains lower than the value presented by the battery manufacturer.

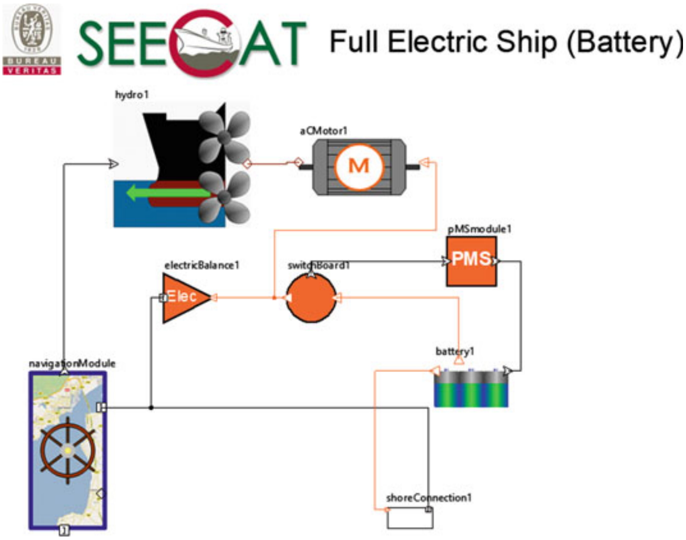


Fig. 12.35 Fully electric SEECAT model for a double-ended ferry

of the components were already existing in SEECAT or were developed during the HOLISHIP project. However, in compliance with the requirements of this application case, some components needed to be developed, like a shore charging facility, as shown in Fig. 12.35.

The battery model chosen by Elomatic for this application case is the Corvus Orca Energy. From the maker's datasheet (Corvus 2020), the battery capacity per pack is 125 kWh, the peak C-rate is 6C and the continuous C-rate is 3C. Through iterative process, the required battery capacity to be installed on-board for the full electric system was found to be 9406 kWh. This can be fulfilled by 76 packs leading to a total installed battery capacity of 9500 kWh.[5]

From the battery specification above, high C rate of battery specification is considered by the mean to sufficiently charge the battery with limited charging time. Figure 12.36 presents the State of Charge (SOC) level of batteries in summer operation. As previously mentioned, the longer lines at 5th h, 10th h and 15th h represent the energy obtained during longer harbor charging breaks. From Fig. 12.36, it appears that 9500 kWh of battery capacity is able to respond to the power demand over one day of operation while fulfilling the class requirement of always having at least 50% SOC (Norway Brevet n° DNVGL-RP-0043 2017). Here in the end of the day, the lowest SOC level is 76%.

[5]Considering the battery sizing and specifications, the peak power 57 MW and continuous power 28.5 MW can be derived through the product of the battery capacity and its respective C-rate value. This figure is the maximum charging or discharging power that can be achieved by the battery according to the manufacturer. This is well above the requirements either for the charge or in order to fulfil the operational profile. This comes as a consequence of the important capacity of the installed battery in comparison with the energy required to perform one half trip.

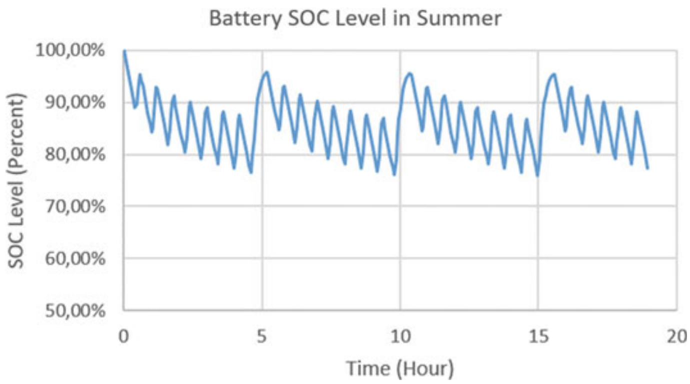


Fig. 12.36 Battery SOC level during summer operation for full electric system

The double-ended ferry is supposed to operate in winter as well. Thus, it has an ice class 1A, which sets certain demands for minimum power. For example, for the ferry with four PODs, the required power for resistance is 2123 kW. With hotel loads included, the winter operational profile is as shown in Fig. 12.37.

The battery capacity sizing is highly dependent on charge debt, which cumulates if the vessel cannot fully (100%) recharge its batteries during the harbor time. Because of this, it is crucial to realistically evaluate the actual power required for the ferry operating in icy conditions.

It is considered that the power requirement is highest in the first round of the day because after the first round the ferry has created cracks in ice, thus lowering ice resistance for the remaining trips. In addition, it is considered that Trafi's (a classification society) power demands are very conservative because in many years there has been no ice in the ferry's operation area. The probability for very thick ice is very low in the future due to global and local climate change.

Based on winter's operational profile, lower level of battery SOC is obtained during winter operation than in the summer operation due to the requirement for higher propulsion power, as visualized in Fig. 12.38. However, the battery SOC level

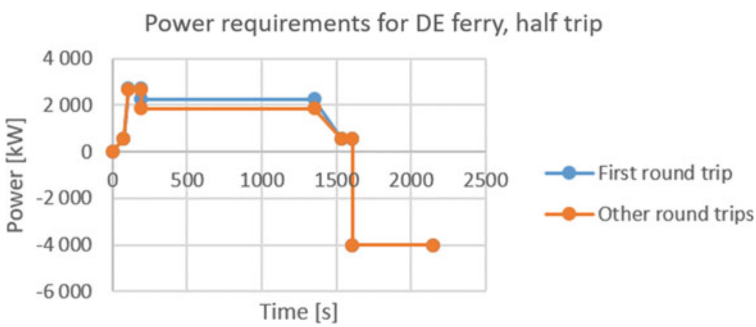


Fig. 12.37 Winter operational profile for the double ended ferry

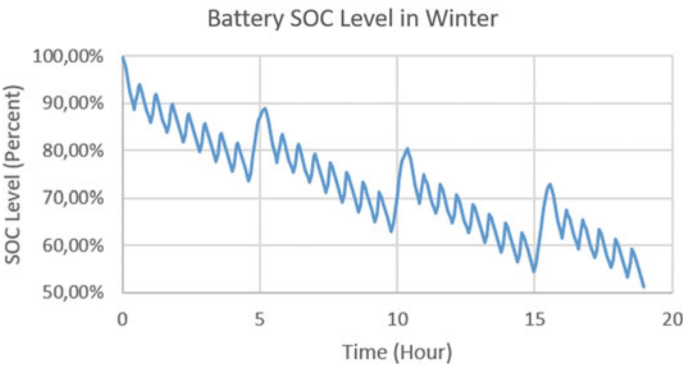


Fig. 12.38 Battery SOC level during winter operation for the fully electric propulsion system

never reaches below 50% of its capacity. At the end of the daily operation, 51% of battery SOC represents the lowest SOC level, meaning that 9500 kWh of battery capacity is also able to respond to the winter power demand in an appropriate manner.

Hybrid system.

Aside from the full electric energy system, a hybrid system was also considered. The reason why hybrid was considered is that this system requires a smaller battery capacity together with producing emissions in acceptable level. Within this hybrid system, two sources are considered to fulfil the power demand i.e. battery system in summer operation and battery system as well as a couple of generator sets in winter operation. Similarly, to the full electric system case, a tailored model for hybrid system was also built in SEECAT and is visualized in Fig. 12.39.

As mentioned, there are a couple of generator sets with the specifications as follows in Table 12.12.

Through an iterative process again, the battery specifications for the hybrid system was found to be[6]:

[6]Peak power and continuous power for full electric system are obtained 17 MW and 8.5 MW, respectively.

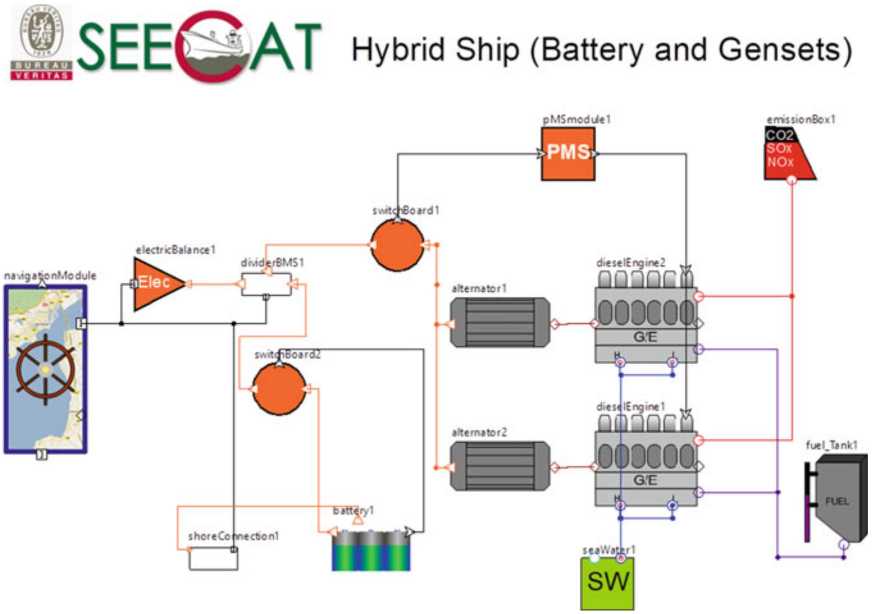


Fig. 12.39 Hybrid SEECAT model for a double-ended ferry

Table 12.12 Generator set specifications of hybrid energy system for a double-ended ferry

Brand	Wärtsilä
Type	Genset 14, type 12V14
Rated power	675 kW
Efficiency	0.95
Output	641 kW
Number of generator sets	2
Total output	1283 kW
Load factor	0.73 kW

– Required battery capacity: 2777 kWh
– Battery capacity per unit: 125 kWh
– Number of batteries: 23 units
– Total battery capacity: 2875 kWh.

Figure 12.40 visualizes that 2875 kWh of battery capacity is able to fulfil the power demand, it is proven from the lowest level of SOC at 55% of its total capacity.

Similar values are also obtained for the winter operation. The winter hybrid configuration, i.e. battery system and a couple of generator sets, prove also sufficient to respond the winter power demand, owing to the fact that the battery SOC level is 72% at the lowest level, Fig. 12.41.

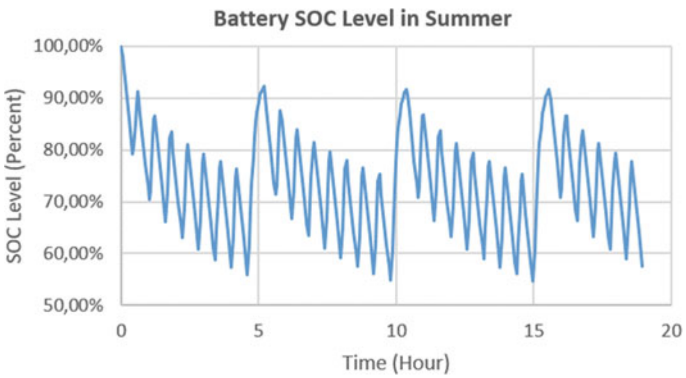


Fig. 12.40 Battery SOC level during summer condition in hybrid configuration over one day operation

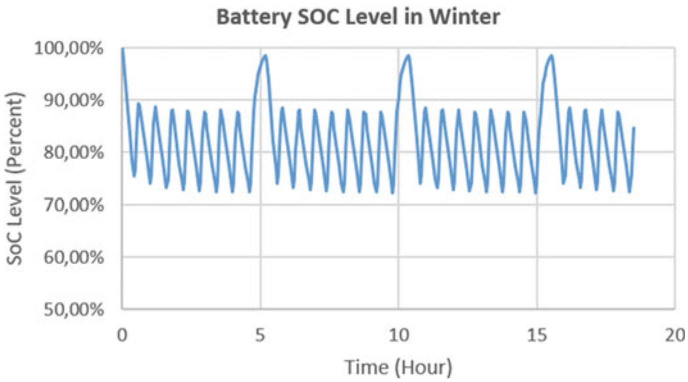


Fig. 12.41 Battery SOC level during winter condition in hybrid configuration over one day operation

12.3.8 Energy Performance Analysis

A comparative study was made between the fully electric and the hybrid system alternative, based on the electrical balance and battery specifications described in the previous chapter. Comparison is performed regarding the energy demand for both designs on a similar operational profile. Emissions for the hybrid architecture are also reported.

12.3.8.1 Energy Comparison

Both design options are compared in terms of energy consumption. This comparison allows to understand which system has the highest efficiency to respond to the same power demand. The simulations were performed over 30 trips as specified in the operational profile.

Concerning the full electric system, the SOC of the battery considering the summer operating profile is shown in Fig. 12.36. The total amount of energy consumption per day operation is 81637 MJ as reported in Fig. 12.42. For the winter operations, the SOC is illustrated in Fig. 12.38. The total amount of energy consumption per day operation is 108021 MJ (see Fig. 12.42).

The differences with the summer operations lie in the higher propulsion power demand which affects the electrical balance. Regarding the gas emissions level, the fully electric system obviously does not produce any gas emissions when the emissions of manufacturing batteries are not taken into account.

Concerning the hybrid system, the energy consumption during summer operation is similar to that of the fully electric system i.e. 81,637 MJ as illustrated in Fig. 12.42. However, the hybrid total energy consumption is higher than the full electric system during the winter operation, 1,239,767 MJ/day vs 108,022 MJ/day. This is due to the internal combustion engine's efficiency that is lower, around 40%, than the efficiency of the electrical configuration, i.e. for a Lithium-Ion battery system, around 80–90%, Vaolen and Shoesmith (2007).

Another interesting aspect to compare is the battery cycling, in terms of Depth of Discharge (DOD) for each operational profile. DOD is defined as the fraction or percentage of the capacity which has been depleted from the fully charged battery (Kurzweil and Brandt 2019). DOD is generally one of the main considerations to maintain the battery lifetime, as the deeper DOD, the shorter the battery lifetime. For the two systems above, the battery energy was consumed differently, as shown in Tables 12.13 and 12.14, for full electric system and hybrid system, respectively:

From Tables 12.13 and 12.14, it appears that the battery needs to perform 30 short cycles, 3 medium cycles and 1 long cycle on a daily basis. A short cycle corresponds

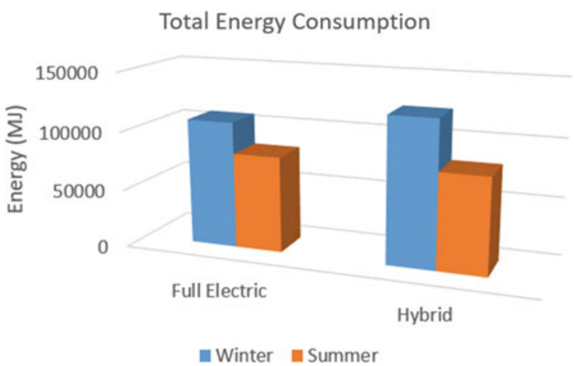


Fig. 12.42 Comparison of daily energy consumption

Table 12.13 Battery cycles and DOD for full electric system

Mode	Short cycle	Medium cycle	Long cycle
Summer	30 @ 6%	3 @ 14%	1 @12%
Winter	30 @ 7%	3 @ 25%	1 @49%

Table 12.14 Battery cycles and DOD for hybrid system

Mode	Short cycle	Medium cycle	Long cycle
Summer	30 @ 20%	3 @ 37%	1 @42%
Winter	30 @ 14%	3 @ 28%	1 @27%

to a half trip, which consists of a short charging at port and half trip of discharging, a medium cycle is defined every 8 short cycles where charging at port is longer (30 min) while a long cycle is defined as the whole trips on a daily basis.

Comparing the two designs, it appears that the expected lifetime of the fully electric battery should be longer than that of the hybrid. This is due to the size of the battery which is smaller in the hybrid case. However, the smaller battery will also be less expensive to replace.

Once again, it proves that full electric system provides more advantages. With better battery lifetime, full electric system consumes less energy and produces zero gas emissions level and eventually leads us to achieve an eco-ship.

12.3.8.2 Emissions

The generator sets in the hybrid system are fitted to fulfil the power demand. Figure 12.43 illustrates the delivered power repartition to responds to the power

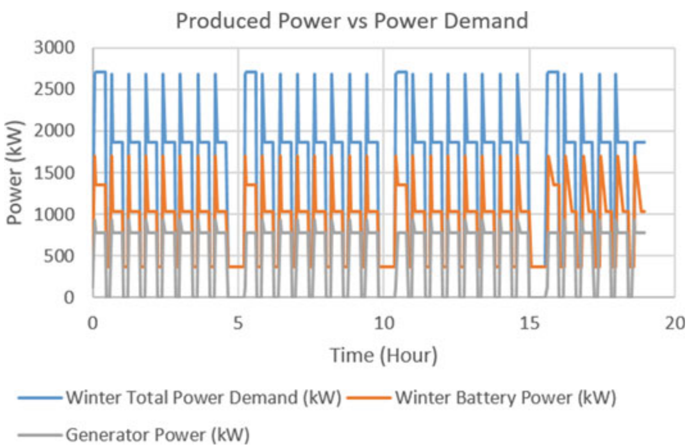


Fig. 12.43 Delivered power by the battery, generator sets along with its power demands

demand, where the red curve illustrates the battery power, the green curve illustrates the generator sets power and the total power demand is illustrated by the blue curve.

Fuel and energy consumption, as well as gas emissions, are also presented in this section. According to Wärtsilä's project guide, the diesel generator engine has a specific fuel oil consumption rate of 205 g/kWh in ISO condition, with Light Fuel Oil as fuel. The instantaneous fuel oil consumption rate obtained from simulations is presented in Fig. 12.44. This corresponds to about 2.1 ton/day of total fuel consumption to fulfil the winter power demand.

Furthermore, since these generator sets consume fossil fuel oil, a certain level of gas emissions is also produced. As such, this combustion process produces 6.5 t/day of CO_2, 134 kg/day of NOx and 145 kg/day of SOx, as visualized in Fig. 12.45.

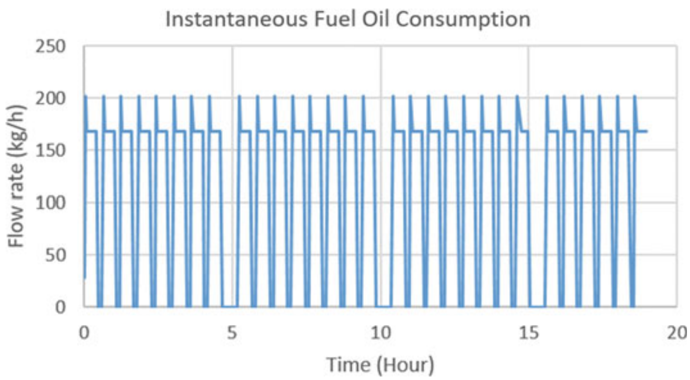


Fig. 12.44 Instantaneous fuel oil consumption during winter condition in hybrid configuration

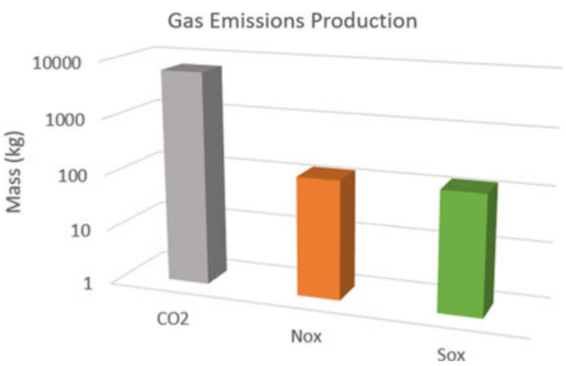


Fig. 12.45 Gas emission production from hybrid system

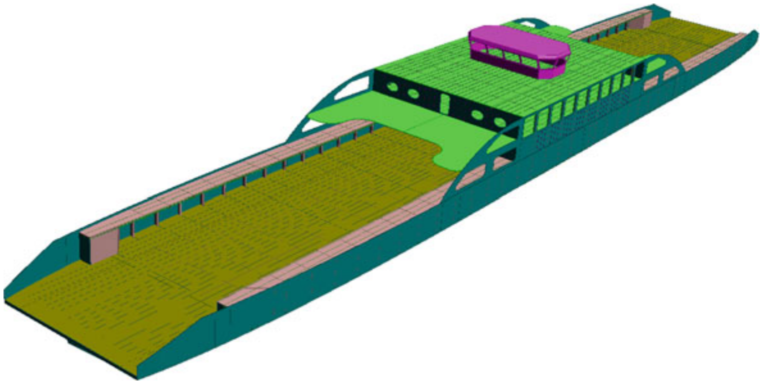


Fig. 12.46 Double-ended ferry in Cadmatic

12.4 End Product of the Design Synthesis

The outcome of the conducted design optimisations is elaborated in the present section. 3D views of the vessel are shown in Figs. 12.46 and 12.47, whereas the midship in Fig. 12.48. The overall length of the ship is 122 m and maximum breadth is 19.1 m. The length and breadth remained almost the same, namely length of 121 m and breadth of 19.4 m were obtained from the optimisation (see Sect. 12.3.1), which almost corresponds to the highest NPV. Some minor adjustments were later made for the functionality of vessel. These refer, for example, to the crew and passenger flows and emergency exit. A structural optimization with certain continuity of structural design also demanded some changes in the final design.

The lightweight is 1342 t, the deadweight 380 t and the displacement 1722 t. Frame spacing is 700 mm, thus the ship extends from frame #-87 to #87, assuming the origin amidships. The double-ended ferry has five decks and 10 watertight bulkheads. Number and positions of the bulkheads are based on IMO's fire regulations, stability analysis (see Sect. 12.3.6) and the functionality of the GA.

12.4.1 Deck 1

The midpart of the machinery (battery) deck 1 is located 1700 mm above the baseline (B.L.) between frames #-32 to #32. Aft and fore parts of the deck 1 are at 2100 above B.L. due to the need of the propulsion systems in ends. The battery capacity has been assessed both for summer and winter needs. In Sect. 12.3.7, it was calculated that a fully electric double-ended ferry requires 76 battery units, each having capacity of 125 kWh. Thus, the total battery capacity is 9500 kWh.

On deck 1 the drives for four PODs are considered. The diameter of the PODs is 1.7 m. PODs are located on frames #-60 and #60 and 3.8 m off C.L. They are as close

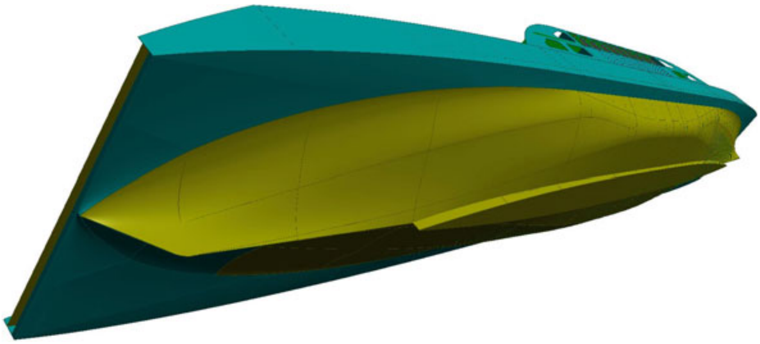


Fig. 12.47 Bottom shape of double-ended ferry

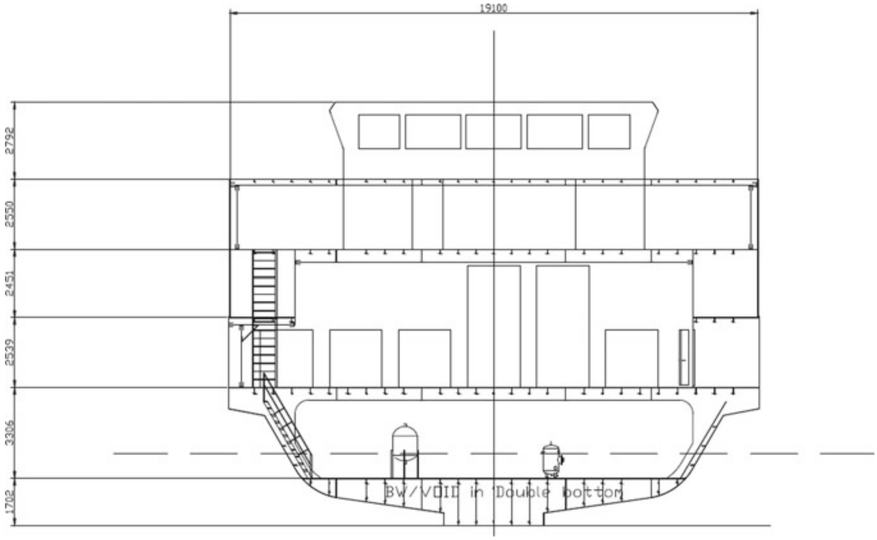


Fig. 12.48 Midship

to the ship's ends as possible in order to provide maximum maneuverability in turns and as far away from each other as possible, so that generated flows do not interfere to each other. The distance of the the PODs of 3.8 m off C.L. was determined by CFD simulation and the risk that propellers may take air in rough seas. CFD simulations also revealed that aft propellers shall be loaded more than fore propellers (see Sect. 0).

Deck 1 also includes an air compressor for batteries (air cooled), a boiler to heat water from the ice sea chest, a heat exchanger and room for necessary pumps. The heat exchanger can be used to transfer hot water from the boiler for the heating and cooling of PAX areas on deck 4.

12.4.2 Deck 2

The height of the car deck 2 is 5 m above B.L. The decision was based on the conducted stability analysis (see Sect. 12.3.6), considering the vertical center of gravity, structural considerations (manufacturability), the required free height for POD supports and auxiliary systems, and the demand for more space for escape ladders at midship and in frames #62 (POD compartments). The car lane length is 750 m, which can take up to 150 cars.

The deck 2 is the main deck enclosing the watertight hull. It has stairs and ladders leading to the machinery deck 1, and to the PAX deck 4 and wheelhouse deck 5. The deck 2 has winches at ends, anchoring equipment and an elevator for disabled passengers.

12.4.3 Superstructure Decks

The deck 3 is a walking platform for passengers between the car deck below, and the PAX area above. It is designated to be the evacuation area. The double-ended ferry has life rafts on deck 3, which take less space than traditional lifeboats.

The deck 4 has a bar and lounge area and includes toilets and an equipment room for HVAC equipment and emergency batteries. The wheelhouse is located on the deck 5, where it is good visibility to both directions of movement.

12.5 Conclusion

The double-ended ferry was a good case study vessel for the HOLISHIP project purposes. It is a quite simple vessel from the GA perspective, but the hull shape and propulsion proved to be a very challenging optimisation task, having many parameters to be optimised. The need to have an ice breaking capability and a keel gave an extra challenge to the optimisation tools.

During the case study, the interaction between CAESES and Cadmatic, CAESES and NAPA, CAESES and CFD tools (surrogate models), Cadmatic and BV Mars 2000 and the functionality of BV SEECAT software was tested. The surrogate model concept allowed concurrent design and analysis, which is the core of the HOLISHIP design synthesis. The double-ended ferry project demostrated the use of a mixture of new type of parallel design/optimisation procedure and of the traditional serial design spiral. Inputs and outputs were exchanged efficiently between design team participants thanks to simple data communication protocols.

Tools used were effectively allowing the exploration of the design space very quickly. However, due to complexities of the general arrangement that cannot be represented by mathematical functions, the need for an user intervention remained. The overall goal to explore a larger design space and to have optimised solutions has been achieved. In this way, the envisaged Intelligent GA worked as initially planned. It worked as a decision-making tool helping designers to explore the functionality of the generated GA and will be a significant tool for Elomatic Oy to efficiently respond to the future demands of the maritime industry.

Acknowledgements The double-ended ferry case within the HOLISHIP was a collaboration project between several companies and universities. ELOMATIC Ltd as a project leader in the double-ended ferry case, gives special thanks to the partners involved, which were BUREAU VERITAS, CNR, FRIENDSHIP SYSTEMS, HS-BREMEN and HSVA.

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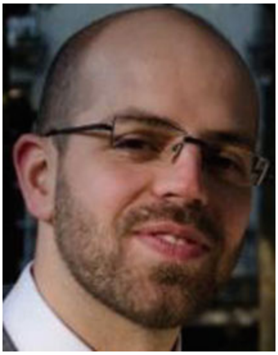

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Chapter 13
SHIPLYS (Ship Life Cycle Software Solutions) Concept for Ship Newbuilding and Retrofitting Bids

Ujjwal Bharadwaj

Abstract The SHIPLYS (Ship Life Cycle Software Solutions) (2016–2019) project was an EU funded HORIZON 2020 project in response to needs of Small and Medium-sized Enterprises (SME), of design offices and naval architects, shipbuilders and ship-owners who need to make improvements in order to survive in the highly competitive maritime world market. The improvements that this project focused on are at the early bidding/tendering stage, during which the ability to respond quickly with reliable cost estimates, and from a life cycle perspective, is increasingly important to remain competitive. Key tasks in the SHIPLYS project were: the development of software for rapid virtual prototyping of design and production, life cycle tools, a multi-criteria decision analysis tool (taking account of life cycle cost, environmental impact and risk based criteria) and a software platform with the ability to integrate the tools developed within the project and other tools (third-party or to be developed in the future). The software tools were developed to provide specific solutions to problems posed by three shipyards in the SHIPLYS consortium, with potential for generic application within the marine industry and across sectors. Apart from being guided by the shipyards within the consortium, the project had an advisory committee comprising experts from major stakeholders who provided periodic feedback during the project. This chapter describes key activities and software tools developed within the project, and is targeted towards industry stakeholders without prerequisite specialized knowledge of the topics discussed.

Keywords Early-stage ship design · Rapid virtual design and production prototyping · Life cycle cost · Environmental impact · Risk assessment · Multi-criteria decision support · Software platform

Abbreviations

AES	Atlantec Enterprise Solutions GmbH, Germany

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A. Papanikolaou (ed.), *A Holistic Approach to Ship Design*,
https://doi.org/10.1007/978-3-030-71091-0_13

AS2CON	Alveus L.L.C, Croatia
ATD	Astilleros de Sandander SA, Spain
BMT	BMT Group Ltd, UK
DMT	Design Management Tool
FERG	Ferguson Marine Engineering Ltd, UK
ISO	International Standards Organisation
IST	Instituto Superior Tecnico, Portugal
LCC	Life Cycle Costs
LCCA	Life Cycle Costs (LCC) analysis
LR	Lloyd's Register EMEA IPS, UK
MCDA	Multi Criteria Decision Support Analysis
NTUA	National Technical University of Athens, Greece
PPT	Production Planning Tool
QFD	Quality Function Deployment
RIT	Requirement Identification Tool
RSET	Rapid Ship Evaluation Tool
SAC	SHIPLYS stakeholders Advisory Committee
SHIPLYS	Ship Life Cycle Software Solutions
SME	Small and Medium-sized Enterprise
SOERMAR	Fundacion Centro Technologies, Spain
TWI	TWI Ltd, UK
USTRATH	University of Strathclyde, UK
VARNA	Varna Maritime Limited, Bulgaria
WP	Work Package

13.1 Background

Small and Medium-sized Enterprise (SME) naval architects, shipbuilders and ship owners need to compete in the global maritime market. The study calculations and modelling they are required to perform during the early design stage when they are responding to tenders for new-build ships or repair/ retrofitting are often difficult and time-consuming. This is particularly true for SMEs without large numbers of trained staff and tools.

The overarching aim of the SHIPLYS project was to develop software solutions to support such stakeholders during the early stages of new-build design or repair so that they can make reliable estimates of the scope of work and the costs involved. SHIPLYS also enables specific concerns of various stakeholders to be taken account of at the very initial stages of ship design or retrofitting. Thus, the ambition in the project was not just to help shipyards in making rapid and reliable estimates in response to tenders, but also to enable them to add value to the services that they provide by giving them the ability to assess and provide costing for different options with corresponding LCC, environmental impact and risk profiles.

The SHIPLYS consortium, led by TWI Ltd, was formed by 12 partners from 7 EU countries: (TWI) TWI Ltd, UK; (SOERMAR) Fundacion Centro Technologies, Spain; (AES) Atlantec Enterprise Solutions GmbH, Germany; (USTRATH) University of Strathclyde, UK; (ATD) Astilleros de Sandander SA, Spain; (NTUA) National Technical University of Athens, Greece; (IST) Instituto Superior Tecnico, Portugal; (VARNA) Varna Maritime Limited, Bulgaria; (FERG), Ferguson Marine Engineering Ltd, UK; (AS2CON) Alveus L.L.C, Croatia; (BMT), BMT Group Ltd, UK; (LR) Lloyd's Register EMEA IPS, UK.

There was an external industrial advisory group—the SHIPLYS Stakeholders Advisory Committee (SAC)—comprising experts from major stakeholders who provided feedback from time to time. The stakeholders included designers, shipyard operators, ship owners, operation and maintenance professionals, repairers, classification bodies, researchers and consultants. More information on the SAC members can be obtained from Bharadwaj (2017).

13.2 Introduction

Within the SHIPLYS project, SHIPLYS Platform and associated software suite of tools (called 'SHIPLYS Applications'), were developed and applied to certain Scenarios (called SHIPLYS Scenarios, described later). SHIPLYS aims to help the ship designers, shipbuilders and ship-owner members, who, in order to survive in the highly competitive world market, need to:

i. improve their capability to reduce the cycle time and costs of design and production,
ii. obtain adequate estimates of work content, raw materials and costs, as well as adequate production process planning of the work to be carried out,
iii. reliably produce better ship concepts through virtual prototyping, and
iv. meet the increasing requirements for Life Cycle Cost Analysis (LCCA), environmental assessments, risk assessments and end-of-life considerations as differentiators.

The development within the project was carried out according to the work package (WP) scheme as shown in Fig. 13.1.

13.3 Shiplys Scenarios, Applications and Platform

For the benefit of readers with no prior knowledge of the SHIPLYS Project, the following terms used in this chapter and other SHIPLYS documents have special meaning as described here:

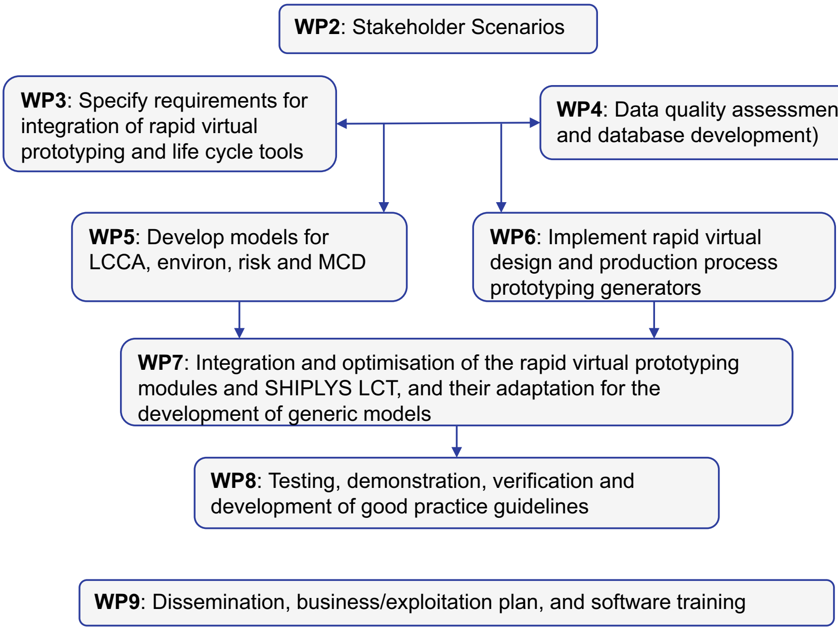

Fig. 13.1 SHIPLYS technical work package scheme (WP1 was on project management)

SHIPLYS Scenarios: These are issues posed by the three Shipyards present in the SHIPLYS Consortium that the project addressed. There were three SHIPLYS Scenarios; one requiring the optimisation of a hybrid propulsion system used in a short route ferry ship (Scenario 1), another requiring support during early design stages of new building ship through inputs from risk-based life cycle assessments (Scenario 2), and the third requiring support during early planning and costing of ship retrofitting accounting for life cycle costs and risk assessments. These three Scenarios were mooted and elaborated upon by Ferguson Marine Engineering Ltd (UK), Varna Marine Engineering Ltd (Bulgaria) and Astilleros de Santander SA (Spain) respectively. More information on the SHIPLYS Scenarios is available in Bharadwaj et al. (2017).

SHIPLYS Applications: These are software modules developed within the SHIPLYS project, or enhanced versions of existing software owned by SHIPLYS Consortium members. Table 13.1 shows these Applications, where apart from RSET, CAFE, SeaSafe, RulesCalc that pre-existed and where 'glue code' and/or certain enhancements were made during the project, the other Applications were developed within the project.

SHIPLYS Platform: Software developed within the project to enable the integrated use of a variety of software modules (or Applications) that have a 'glue code' allowing for such integration.

It must be noted that not all Applications were equally applicable to all SHIPLYS Scenarios because of inherent differences in the Scenarios. Within the project, Applications were applied to those Scenarios where they, in their state of development during the time, were most applicable i.e. where their full functionality could be demonstrated.

13.4 Shiplys Applications and Their Role in Ship Design Cycle

This section briefly describes the SHIPLYS Applications developed within the project and the context in which these are applicable. The development process of the applications and their detailed features are not mentioned here due to space constraints, but can be obtained from the technical papers published and the publicly available SHIPLYS deliverables. An overview of the approach can be obtained from Bharadwaj et al. (2017).

The different software applications integrated into the SHIPLYS platform are listed in Table 13.1.

Figure 13.2 shows a typical ship design workflow and the related software Applications to carry out specific activities within the SHIPLYS platform; iterations are possible within the software but are not depicted for simplification purposes. It starts with an Application supporting the early production planning. The SHIPLYS rapid prototyping Applications use the established workflow methodology based on the ISO Activity Model activities; more information is available from Koch and Kreutzer (2017).

Table 13.1 List of different SHIPLYS applications

Software (applications)	Developer organisation
DMT	BMT
SHIPLYS platform	AES
RIT	AES
ConceptShip	IST
RSET	BMT
CAFE	AS2CON
SeaSafe	LR
RulesCalc	LR
PPT	AES
ShipLCA	SU
SHIPLYS MCDA	TWI
RiskShip	IST

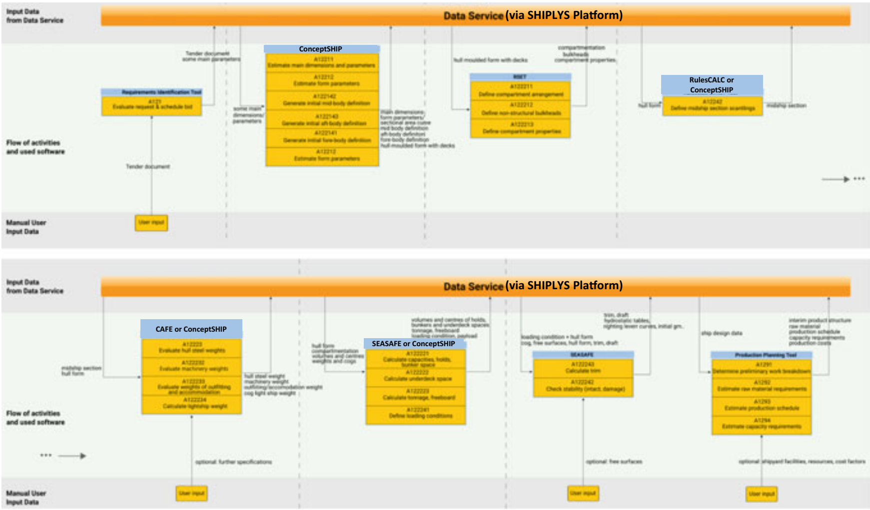

Fig. 13.2 Typical New Build Ship Design Workflow and the related software applications within SHIPLYS platform

This chapter will not go into the details of each software. Only some key features are mentioned here. For more information, please refer to SHIPLYS publicly available deliverables, particularly (Reddy et al. 2019).

13.4.1 SHIPLYS Applications

The Design Management Tool (DMT) acts as a user interface entry-point Application to facilitate visual interaction and connection with the SHIPLYS platform for access to local or remote services and resources. Users of the DMT can connect with and access the SHIPLYS platform, and launch the integrated software Applications. The DMT's visual representation of the database containing the SHIPLYS project data and activity models can be used to enable a designer or spectator in accessing the current state of a project.

The Requirement Identification Tool (RIT) represents the very first step within the whole ship design process and requires only the tender document to be provided by the owner. The tender document can be easily imported into the Application to create requirements linked to relevant text positions in it. Once the requirements are created, they are machine-readable which provides various advantages.

ConceptSHIP is a software Application for the early stages of ship design and is implemented as an add-in to Excel® spreadsheets. The main objectives of such a choice are to take advantage of the familiarity of naval architects with this type of software, reducing the learning process, to enable the immediate evaluation of the impact of changes in some basic parameters in the global characteristics of the ship ("what if" type of assessment). In addition, as all the data introduced and computed is directly available, it can be exchanged with most software Applications used for the next step in the development of the design. Functionalities for the direct export, in commonly used file formats, of extensive numeric data related to hull form and compartments definitions are also included.

The Rapid Ship Evaluation Tool (RSET) is a system that allows users to rapidly explore the design space of general arrangement in the early stages of ship design. Given a hull form, from ConceptSHIP or an external file, RSET allows the user to import or generate bulkheads, decks, and superstructure, as well as detail a list of functional spaces (compartments) for arrangement within the available spaces defined by the decks and bulkheads of the ship.

A set of user-defined constraints for compartment placement allows RSET to automatically generate a general arrangement that satisfies design requirements, facilitating the rapid evaluation of various constraints and layouts. Employing a 3D view of the general arrangement, RSET allows a user to visualise and experiment with combinations of chambers and constraints to meet various design objectives, such as maximising utilisation of available space, minimising hull form size, or reducing construction cost.

CAFE is a ship modelling software for fast developing of preliminary ship structure and positioning of the main equipment in order to obtain a preliminary estimate of the lightship weight, centre of gravity and provide the structural design that will be checked according to the classification societies' rules and input needed for calculating preliminary trim and stability. Also, CAFE generates a list of equipment and bill of materials.

The ShipLCA Application is an evaluation software that can be used to estimate the 'life cycle cost, environmental and risk impacts' in order to determine the optimal solution amongst different design alternatives. Due to lack of life cycle software specific for the marine/ship building industry, it becomes time consuming and difficult to carry out the life cycle assessment. The ShipLCA software fills the gap in existing LCA software with the consideration of ship life stages and various activities. Within ShipLCA the three most significant impacts are included: life cycle costs (mainly building, operational, maintenance and end of life costs), impact on environment, and risk during operation and maintenance stage (demonstrated in Scenario 1 using Risk Priority Numbers). The software can be used to help shipyards, ship owners and operators, and policy makers to estimate the life cycle impacts during the early design stage. The software will help to determine optimal alternatives while selecting engines, configuring systems or applying different sources of electricity.

The SHIPLYS MCDA (Multi Criteria Decision Support Analysis) application provides a mathematical approach for end-users to assess and evaluate different options based on a variety of criteria corresponding to life cycle costs, risk and environmental impact. SHIPLYS MCDA Application was applied to Scenario 1, in which assessment results from ShipLCA for each alternative in terms of economics, environmental impact and risks, are input into the MCDA Application for a comprehensive comparison to be carried out. As a result, an optimised design alternative is suggested.

SEASAFE Professional creates precise 3D vessel models, conducts naval architectural calculations and produces reports. It delivers designs complying with IMO and national safety regulations. It can generate manuals and Trim&Stability booklets within hours. It can also build 3D wind models, produce KG/GM limit curves and calculate damage stability, both deterministic and probabilistic.

RulesCalc is a design and Rule compliance Application that can integrate the assessment within the design spiral. RulesCalc enables the user to verify Rules compliance, track down Rule failures, and rapidly identify areas of concern and the design modifications that might be required. RulesCalc can be used as a standalone system or in conjunction with other design software packages, including Napa, Tribon and Lloyd's Register ShipRight SDA.

The Production Planning Tool (PPT) tool supports production assessment during the early bidding stage so as to predict more precisely the overall costs over the lifetime of a ship. Once structural data has been generated by rapid prototyping Applications for design, it can be used by PPT to generate production relevant data, starting with the derivation of interim product structure in the case of new building projects. In the case of retrofitting projects where the interim product structure plays a minor role, the first input can also be just a specification document provided by the owner, which in the same way as described for the RIT can be imported and linked with specific retrofitting tasks. Independent of project type, PPT enables rapid definition of tasks, scheduling, planning of material and equipment and estimation of related costs. Rapid definition is made possible by the integrated catalogue management system providing general data such as task templates to be used for various projects. Another important feature of PPT is the schedule optimization allowing, for instance, minimisation of the overall project duration and costs. Once all the required data has been defined, appropriate reports can be automatically generated such as a cost report that is structured according to SFI grouping codes and represents a bid to be provided to the owner.

13.5 Steering by and Benefits to SHIPLYS Stakeholders

13.5.1 SHIPLYS Stakeholders

The SHIPLYS Consortium had representation from a variety of stakeholders in the early ship design process. SHIPLYS partners included three shipyards, a classification body, and service providers such as software developers, consultants and researchers in ship design, life cycle assessment and planning. Apart from these in-house stakeholders, SHIPLYS interacted with SHIPLYS Stakeholders Advisory Committee (SAC) members (Bharadwaj 2017) and held annual meetings with them (the first and the last being physical meetings and the second an online meeting). Additionally, SHIPLYS gained from the interaction with representatives from other related H2020 projects such as LINCOLN (LINCOLN Consortium), HOLISHIP (HOLISHIP Consortium) and RAMSSES (RAMSSES Consortium) through held joint workshops.

13.5.2 Understanding End-Users' Needs and Priorities

During the early stages of the project, SHIPLYS followed a formal approach using Quality Function Development (QFD) to identify and prioritise user requirements in order to develop software functionality corresponding to such requirements. Different stakeholders were involved and their opinions led to a better understanding of end-users' needs and the development of a product that fulfils their requirements (Milat and Golik 2017). Towards the completion of the project, the needs and priorities identified during the QFD task were revisited in light of the development done within the project. Whilst it is not possible to list the benefit of every functionality developed corresponding to the endusers' requirements, some are mentioned in the next section.

13.5.3 Benefits to SHIPLYS Stakeholders and Wider Industry Stakeholders

13.5.3.1 Designers

One of the SHIPLYS Platform benefits is reducing the time involved in the ship design which leads to improving competitiveness of ship design offices. In addition, the designers can use different modules within the platform and therefore they can be involved in different ship design processes and combine them.

Although SHIPLYS is targeted towards the very early design stages of ship design, when designers and shipyards are responding to tenders, one of the benefits of the application of SHIPLYS is that such early work can be more readily also used in the later stages of design when the bid is successful and the newbuilding or retrofitting project is launched.

13.5.3.2 Shipyard operators

SHIPLYS will support shipyard operators in optimising the use of their resources (time, personnel and costs) in the production of new building or retrofitting/ repair projects. Project risks/ hotspots can be identified and managed by the PPT (Production

Planning Tool) Application. Production planning tool supports a shipyard to make reliable estimations regarding the duration of new building or retrofitting projects and related costs. Amongst others, it contains a scheduling component and a functionality to generate work breakdown structure to support the early production planning and costs.

Typically, shipbuilding tenders, new building or retrofitting/ repair projects, need quick response in the limited time and data available. It is to provide support in this challenging situation that SHIPLYS will enable SMEs shipyard to make more reliable estimates based on the owner tender requirements, in the early stage of inquiry, and the shipyard‘s existing production capacity. The shipbuilding sector is actually a ship owner governed market; this means that the shipyards need to have enough flexibility to adapt to the requirements of the ship owners in their response to the offer request. SHIPLYS tools are versatile enough to support this important requirement.

At the same time, the possibility of analysing during the pre-contractual period, the implementation of alternative technological and production solutions, the evaluation of their effectiveness taking into account the risk-based life cycle assessment, the environmental impact, the cost and the planning, gives a competitive advantage to the SME shipyards.

13.5.3.3 Ship owners

By providing a life cycle perspective, the SHIPLYS approach and supporting tools encourage long-term thinking that is often required to justify high initial costs. By including environmental impact in assessments in the SHIPLYS approach (in the ShipLCA Application), ship owners can be conscious of the environmental footprint of different options. The MCDA module presents ship owners different perspectives based on life cycle costs, environmental impact and risk at the early design/ tendering stage.

13.5.3.4 Operation and maintenance professionals

SHIPLYS includes the concept of risk-based inputs during the early design stage. Such inputs have significant potential to reduce operation and maintenance costs, and also provide some indication as to which parts of the structure are more susceptible to damage though the life of the ship.

13.5.3.5 Classification bodies

The use of SHIPLYS streamlines the approval process by collating all the data in a central place in well-defined data formats. This potentially allows classification bodies to perform validation assisted by automation.

13.5.3.6 Researchers

The SHIPLYS project has supported several PhD researchers and will give further opportunities to continue the research in advanced shipbuilding technologies.

13.5.3.7 Software developers

The SHIPLYS project offers the ability to integrate other software applications into the SHIPLYS platform and software developers will be able to promote their applications and expand their customer base and market infiltration.

13.6 Concluding Remarks

This chapter provides an outline of work done within SHIPLYS and its legacy in terms of benefits that it brings to a variety of stakeholders. The project was in response to needs of SME naval architects, shipbuilders and ship-owners who need to make improvements in order to survive in the highly competitive world maritime market. The improvements that this project focused on are at the early bidding/tendering stage during which the ability to respond quickly with reliable cost estimates and from a life cycle perspective is increasingly important to remain competitive.

Whilst the software tools were developed to provide solutions to problems posed by the three shipyards in the SHIPLYS consortium, there is potential for their generic application within the marine industry and across sectors.

Acknowledgements It is not possible to acknowledge here the individual contribution of participants from the organisations in the SHIPLYS consortium, but the project could not have accomplished what it set out to do without the team spirit, competence and professionalism of all involved. The SHIPLYS consortium is grateful to the HOLISHIP consortium for providing this opportunity to disseminate its project outcomes through this chapter. The project received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 690770, for which the SHIPLYS consortium acknowledges its gratitude.

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Chapter 14
LINCOLN—Lean Innovative Connected Vessels

Brendan P. Sullivan, Monica Rossi, and Sergio Terzi

Abstract The maritime industry has been working to apply unique solutions capable of improving design and development performances. Over the past several decades, the industry has faced changes related to the increasing complexity of the dynamic global market. LINCOLN project successfully developed three new value-added vessels by following a highly customizable lean design methodology that combined series of innovative sensor arrays, on-board equipment, and IoT solutions to support the design and development of efficient and sustainable maritime vessels. Through this integrated approach to vessel development, innovative solutions that have not previously been combined were able to support designers/engineers transform the design process for the extension of serviceability and reduction of design time. This chapter describes the innovative design framework, based on the comprehensive usage of design methodologies, (economic and environmental) sustainability analysis and Internet of Things (IoT) in vessel design.

Keywords LINCOLN · HPC simulation · Lean design · Lean transformation · LTF · Maritime design · Collaborative design · Case study · SysML · Lifecycle assessment

Abbreviations

AP	Acidification Potential
CED	Cumulative Energy Demand

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A. Papanikolaou (ed.), *A Holistic Approach to Ship Design*,
https://doi.org/10.1007/978-3-030-71091-0_14

CFD	Computational Fluid Dynamics
EERV	Emergency Response and Recovery Vessel
EP	Eutrophication potential
FEM	Finite Elements Method
GWP	Global Warming Potential
HPC	High Performance Computing
IMO	International Maritime Organization
IMU	Inertial Measurement Units
IoT	Internet of Things
KbeML	Knowledge Based Engineering Modelling Language
LCA	Life Cycle Assessment
LDM	Lean Design Methodology
LINCOLN	Lean Innovative Connected Vessels
LTF	Lean Transformation Framework
PM	Particulate Matter
PoE	Power-over-Ethernet
SBC	Single Board Computer
SBCE	Set-Based Concurrent Engineering
SCP	Sustainable Consumption and Production
SysML	Systems Modelling Language
UMG	Universal Marine Gateway
VftF	Vessels for the Future

14.1 Introduction to LINCOLN Project

The maritime industry is and has historically been a critical factor both socially and economically. Surrounded by 136,000 km of coastline, 5.4 million jobs and almost €500 billion a year of gross added value, Europe has historically been a world leader in maritime vessel development and transportation. Over the past several decades, the maritime industry has faced changes related to the increasing complexity of the dynamic global market. Like other industries it has become increasingly important for companies to improve their processes to maintain competitiveness, prosperity, and survival. The European vessel construction industry - in response to fierce competition from Asian ship builders (especially South Korea, Japan, and China) – European builders have begun restructuring, repositioning on the high-end market, characterized by specialized design and production with high complexity / high technological content. In an effort to facilitate and increase the competitiveness of the European maritime sector, lessons learned from the naval and specialized vessel industry have served as a key element in future development.

Recently European maritime industry has been dealing with increased competition, due to ports becoming strategic poles of distribution for maritime traffic to/from new emerging countries. To facilitate and increase the competitiveness of the European maritime sector, lessons learned from the naval and specialized vessel industry have served as a key element in future development. This includes the incorporation of new technologies, materials and optimization processes into the engineering and design practices of the greater industry (Luglietti et al. 2018; Thanopoulou and Strandenes 2017). At the same time, the European Maritime sector must diversify their business offerings and be capable of integrating these advanced technologies into design processes to be competitive in the global market (Milanovic 2016). However further work remains beyond application alone to identify and develop value-added solutions, products and services that can accommodate changing demands in the sector. To remain competitive in this changing market the industry must deal with cost reductions, improved design, optimal production time and the ability to diversify its business offer. This includes the incorporation of new technologies, materials and optimization processes into the engineering and design practices of the greater industry (Barthwal and Agarwala 2019; Mirović et al. 2018; Sullivan et al. 2020). The Product-Service paradigm is well suited for this task as it promotes new vessel development that emphasizes service to stakeholders, while creating new market segments that can be targeted.

This chapter presents a set of unique methodologies and tools developed under the joint H2020 EU Funded Project Lincoln—Lean Innovative Connected Vessels (LINCOLN 2018), to support the integration of Internet of Things (IoT) and real time data collection for advanced vessel sustainability (economic and environmental). The objective was to make it possible for designers and engineers to leverage the value of Lean Design, KbeML, and LCA for the articulation and management of digital solutions.

The Lean Design Methodology and digital solutions developed within the project worked to improve the design process as well as to increase the user information (information related to vessel use) that shipbuilder have access to. This information strengthens the design decision-making process, by leveraging data from integrated sensors, so that functions and analysis of the vessel can be used to validate models and vessel behavior (von Stietencron et al. 2017). The combination of these components leads to the introduction of an innovative design framework for supporting lean development of eco-innovative vessels through a real time IoT data driven approach. To facilitate a product design process that is based on experience (looking backwards) and input from certain customers or key persons, thus reducing subjective judgments. This closes the loop of information between vessel design and its operation phase, by including data derived from real product usage into the design phase and also providing tools to support continuous improvement of the vessel throughout its development and operation. This unified capability increases the ability for different methods and technical quantitative tools to function in an efficient manner while storing and improving design variations. Through this articulation of usage information, designers can be aware of the strengths and issues of the vessel in accordance with real conditions during operation. In short, the following objectives were achieved:

- The development of a maritime design methodology that leverages lean principles to incorporate real-time data from IoT devices, to improve the development, management, and testing of maritime vessels.
- The establishment of highly efficient novel digital tools and IoT solutions capable of relaying, processing, and interpreting real-time data to record and manage the testing of designs.
- The integration of Knowledge Management and Lifecycle Thinking to improve the identification and selection of materials and technologies to improve operational efficiency, reduce emissions, and extend vessel value.

14.1.1 Approach for Intelligent Vessel Design

The LINCOLN approach was developed to support vessel designers, shipbuilders, operators, researchers, and digital analysts in their joint daily activities by providing a sustainable lean development methodology that integrates data and knowledge-based engineering into the ship design development process. To facilitate this, the development process integrates a set of novel technologies that work together to provide for improved usability, analysis, and process improvement. Through the integration of real-time data and optimized digital technologies LINCOLN functions to leverage this information in the most efficient manner during the design phase to extend the value of maritime systems throughout their lifecycle. This requires that usage information and design parameters or component attributes be considered through the project conception phase and expanded to encompass data collection, and design variation testing (Fig. 14.1).

The LINCOLN Vessel Design Approach considered 5 main points that were then implemented throughout the project.

- **Customizable Lean Design Methodology** for Maritime: supports vessel design and development through the integration of design aspects and lean tools to provide a value focused solution to support the design phase.
- **IoT**: a set of digital tools and IoT solutions to support specialized vessel design and operations, enabling SMEs to record, manage and test prototypes.
- **KbeML**: provides a formal approach for articulating engineering knowledge to improve reuse, establish design parameters, and support design optimization.
- **High Performance Computing** Virtual Towing Tank: simplifies the process for CFD analysis by providing a semi-automated virtual towing tank that allows for designers to simulate hull behavior and test design variations.
- **Lifecycle** environmental and economic assessment: supports the sustainable design of vessel through the evaluation of materials and technologies of the system over lifecycle.

The methodology employed was based on a systemic approach. It employs a closed-loop-system to support the exchange of information between vessel designers, shipbuilders, and users. Focusing on the design phase of the development process it allows for new and innovative tools to be used to support continuous improvement and strengthen the vessels value proposition. Figure 14.2 shows the steps followed during the project. This unique design process deviates from traditional maritime vessel approaches by integrating user derived data to improve the decision-making process. Along this process a lean set-based design methodology was developed support the development process, represented in the figure by the funnel in the middle of the loop.

1. The Universal Marine Gateway (UMG) which provides the backbone for the data-oriented framework allowed for a range of sensors and vessel monitoring equipment to be installed for real-time data related to the operating conditions, and vessel performance to be collected (step 1).
2. This data was imported into KbeML to facilitate the improvement of the vessels designs. New vessel concepts were then developed based on the obtained sensor data, in order for improvements and codified knowledge to be better leveraged (step 2).
3. Novel designs and design variations were then developed based on the results and outcomes from the previous steps (step 3).
4. Each design was then validated through a novel High-Performance Computing (HPC) system that utilized real vessel data to analyze different CFD and FEM simulations datasets (step 4). The simulation utilized data collected under real operating conditions, enabling designers to run tests with varying designs, which could then provide support for a more detailed and accurate design.

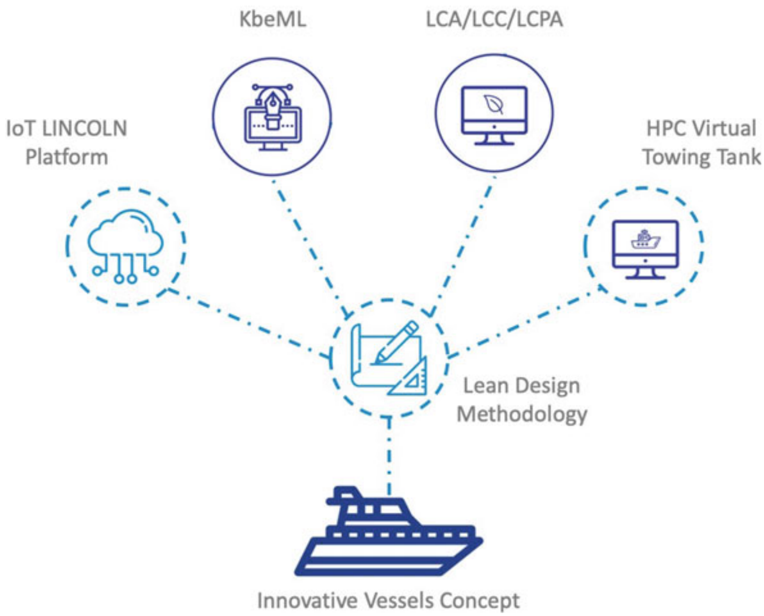

Fig. 14.1 LINCOLN vessel design approach

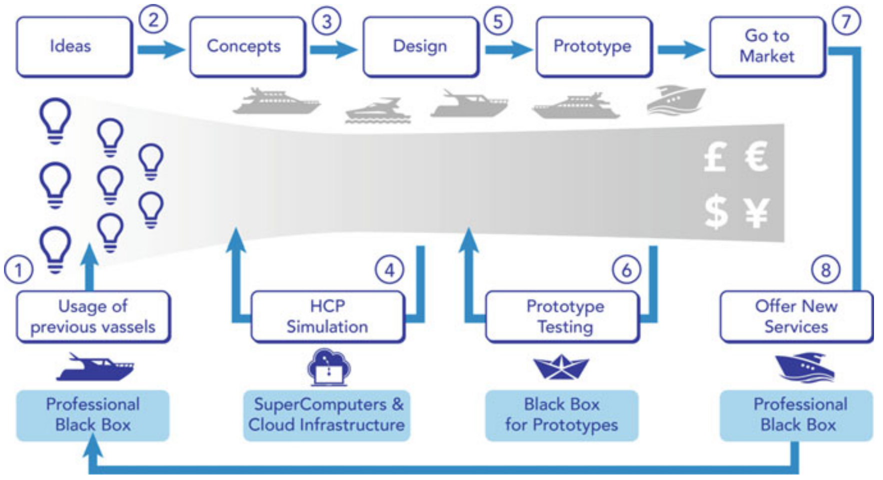

Fig. 14.2 LINCOLN design process

5. Steps 2, 3 and 4 were repeated to test different design options, to optimize the design and increase the value of the vessel (step 5).
6. Once virtual testing and optimization of the vessel was completed, a physical prototype was built and tested for three industrial application cases to validate and confirm the reliability of the previous steps. The UMG was utilized to test the various designs under normal operating conditions (step 6).

    - A flexible multiplatform catamaran that was designed to serve as a Service crew vessel, and survey vessel. The design incorporated a hybrid propulsion system, an innovative crew transfer system (gangway), and a mechanical system integrated in the ship hull to improve safety during people transfer.
    - A modular based high-speed patrol boat designed for reconfigurability, to support flexible and agile changes according to the needs of different operational requirements. The design platform facilitated the development of several design variations of this vessel based on real operational data to enhance value.
    - An Emergency Response and Recovery Vessel (EERV) series for coastal rescue activities that integrated a set of digital technologies to develop an enhanced automatic and low cost Integrated Dynamic Position System.

7. The physical vessels digital data was then collected in order for the next system variations to be improved according to the distinct operational profile and stakeholders' requirements (step 7).

Based on the evaluations conducted in Step 7, the final design underwent further analysis (LCA, value, and service) whereby historical and real data was utilized for predictive maintenance and after-sales services.

14.1.1.1 Key Performance Indicators

The use of KPIs allows for both business and project management improvement tracking, to measure the success of the implemented process and technologies. Traditionally, improvement measures have specifically targeted financial performance—in terms of e.g. costs, effort, capital expenditures and profit. However by focusing solely on financial measures makes it difficult to illustrate the complexity of the engineering design process. For this reason a set of strategic performance indicators were developed so that changes, improvements and managerial considerations met during the design process could be better visualized and measured.

By leveraging the experience of the three use cases within the LINCOLN project it was possible to identify specifically what managers and owners wanted to know about the design process, and how a lean transformation could be evaluated during implementation. Based on the areas of performance identified, performance areas were formulated to facilitate continuous improvement, in a measurable (quantifiable) manner. The performance areas listed below were utilized to serve as identified areas where KPIs for each Business Case can consider, these however are not strict as there is the possibility for measures to be followed.

- Design Cost—The cost of designing the vessel (can be measured in different phases of the process).
- Design Time—Total time to design the vessel from start to finish including the integration of design changes or redesign time.
- Drawing Approval—Minimum set of drawings to be sent for approval, before duplication of work.
- Design Change—The number of design changes that occur during creation of the vessel.
- Internal—Changes due to the organization
- External—Changes due to the customer
- Redesign Time—This metric is the percentage of project time spent repairing, redesigning, or modifying a vessel to correctly satisfy requirements or regulations.
- Production Cost—The comprehensive total cost of all works, efforts, and processes.
- On-Time Delivery to Commitment—This metric is the percentage of time that manufacturing delivers a completed product on the schedule that was committed to customers.
- Customer Retention—This metric is the reflective number of customers that make/place repeat orders.
- Employee Retention—This metric is applied to all employees in the organization, for evaluating and determining the ability of the organization to retain its employees.
- Employee Satisfaction—this metric can be related to the employee retention rate, to calculate the satisfaction levels of employees throughout the organization.
- Testing—number of times it takes to perform necessary tests to verify design parameters.

- Defect Density—The percentage of product failures in relation to total output.
- Unit Cost—The relative cost of each vessel designed or developed within the organization (individual level).

Through the implementation and adoption of the methods described later in this chapter, the KPIs listed above were successfully able to measure both process improvements and for metrics to calculate the long-term benefits of the changes proposed. This supported the objective of the project, while improving the ability for customized specifications to be more easily adapted by teams, like in other engineering disciplines.

14.2 Customizable Lean Design Methodology

The lean design methodology introduced in Sect. 14.1 of this chapter supports the inclusion of unique digital solutions to improve development efforts. To facilitate the optimization of this initiative, an evaluation of diffused strategies was undertaken to develop a Lean Transformation Framework (LTF), that incorporates Set-Based Concurrent Engineering (SBCE) as to maximize vessel value while minimizing waste and resources in a sustainable manner. The lean transformation was developed to have a broader scope than previous lean design efforts, so that all levels of the development process were addressed. This was necessary due to the critical distinction between the creation of a methodology that dictates the technical procedures/considerations for vessel design and the managing process of the design that describes how tools and approaches should be chosen to successfully implement lean. In addressing the latter, this methodology combats delays, and barriers faced in lean implementation by supporting the integration of data and knowledge into the decision-making process.

Through a holistic, question-based approach the methodology considers a customizable set of tasks and steps that are easily adjustable to facilitate implementation of lean in various maritime design processes or organizations.

- What problem has to be solved?
- What is the value for the stakeholder?
- How can the organization improve to better deliver the identified value?
- What skills, attributes, or characteristics are necessary to engage in these processes to best deliver value to the stakeholder?
- Is the current management system capable of supporting this way of working, and what management system is this?

The lean transformation framework is centered around three socio-technical elements that collectively affect an organization's ability to achieve goals and objectives due to the interrelated and interdependent nature of product development: process, people, and technology (Morgan and Liker 2006a, b). The cases considered in the LINCOLN project stressed a need for improvements that could reduce costs and time in the design and development process through a comprehensive, long-term,

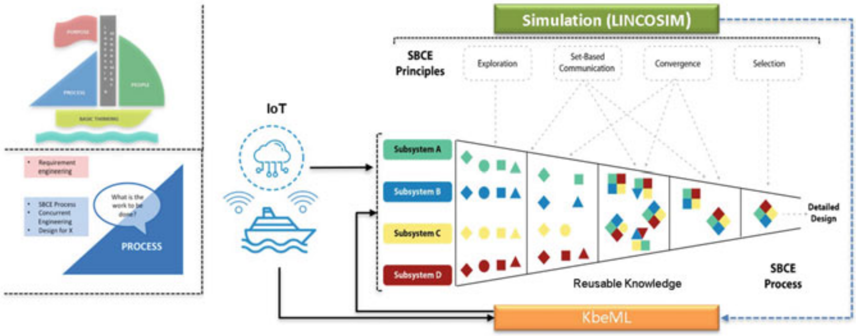

Fig. 14.3 Integrated lean design methodology

improvement methodology. The Customizable Lean Design Methodology (Fig. 14.3) was developed to address the management of vessel development through a sequential waste reducing process for decision-making to better support designers/engineers leverage their resources.

The Customizable Lean Design Methodology targets SMEs in the maritime vessel design and engineering sector, that are seeking to improve or implement elements of lean into their organization. Through a systemic approach, established business needs and high-level methodological requirements identified within LINCOLN were utilized to frame the basis for how the methodology would behave and interact throughout implementation. The culmination of business needs consider the greater organization involved in vessel development, while the outputs correspond to the industrial case interviews and waste analysis. Through this process, an easy-to-implement methodology was developed that allows businesses to adapt the methodology to satisfy their specific needs. The methods, practices and approaches focus on the outputs they facilitate to deliver and increase stakeholder value. Through a series of questions, the LTF methodology (Fig. 14.4) for maritime focuses on obtaining support within the organization to promote a path for continuous improvement in the design process (Rossi et al. 2012; Shook 2018).

- **Purpose**: What is the value for the stakeholder?
- **Process**: How can the industry/organization improve to better deliver the identified value?
- **People**: What skills, attributes, or characteristics are needed/required to engage in these processes to best deliver value to the stakeholder?
- **Leadership and Management**: What is the management system and leader behaviors utilized to achieve goals and objectives?
- **Basic Thinking**: What considerations and values/goals will be used to guide the lean transformation of the organization? The set of foundational things such as how to carry oneself, “attitude”

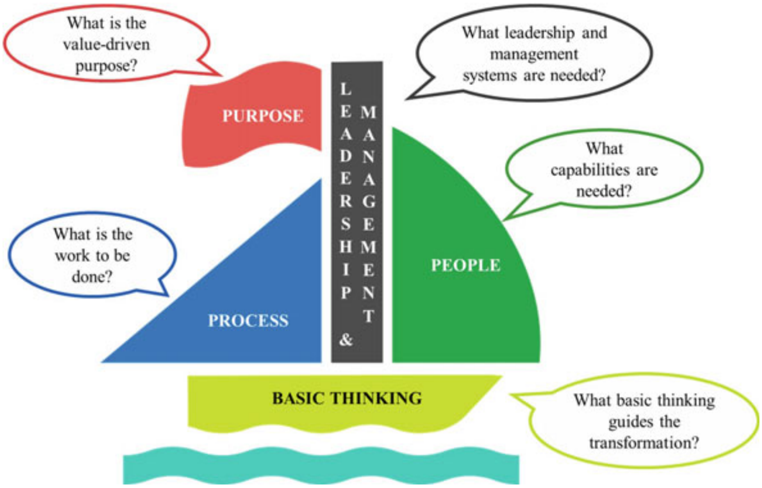

Fig. 14.4 Customizable lean transformation methodology (LTF) for maritime

With respect to the selection of independent methods that were consolidated to create the LTF, they were identified based on their suitability to deliver skills or approaches based on the business needs and high-level requirements. The listed methods and practices focus on the outputs they can facilitate. The outputs adopted correspond to the five areas of organizational improvement related to the five LTF principles to distinguish how they could be best leveraged. Through this process, an easy-to-implement methodology was developed that allows businesses to adapt the methodology to satisfy their specific needs.

14.2.1 Purpose

In considering ways to address 'Purpose' there are several tools and approaches, which have been identified in the state of art and practice could be included. One such approach that is well suited to meet this area and is based on a review of the literature, is the improvement of customer involvement in the design process. This relates to the identification customer requirements through increased user involvement.

User involvement allows for the identification and accurate definition of system requirements to maximize value. Clear calculation of the 'purpose' addresses customer needs and attributes of the stakeholders regarding the product/system, by articulating what the customer wants to have in the vessel and the functions they want it to perform in a specific environment. Needs in this context are a wish list based on the expectations that stakeholders have for the system. In determining and considering this list, it is critical to recognize that a wide range of stakeholders can affect the product development process, a successful design must consider all those stakeholders involved: designers, engineers, shipyards, suppliers and end-users. Through greater customer involvement the following approaches were found to be well suited for cost-minimization, and increased design efficiency.

- Requirement Engineering
- Customer Value Integration and Definition

Recognizing that the maritime development process is a sequence of steps and activities that are employed to conceive, design, and successfully deploy a vessel. To succeed in these efforts, designs must maximize customer value, while ensuring careful conformity to regulations and safety concerns.

14.2.2 Process

'Process' is the manner how work can be done and organized to fulfil business goals and objectives to support the delivery of value (Sullivan et al. 2018). It refers not only to how a process should be performed, but also how the work can be continuously improved. It is a value stream map from raw materials (customer need, past product characteristics, competitive product data, engineering principles) to finished goods. The principles and solutions belonging to this include:

1. **Establish customer defined Value** to separate Value Activity from Waste. The customer should always be the starting point in a lean system, so defining waste starts with defining what a customer (both internal and external one) values. Any activity that takes time and money but does not add value from the customer's perspective can be divided into two types of waste (Morgan and Liker 2006a, b):

    a. created by poor engineering that results in low levels of products or process performance. The best antidote to this category of waste is a deep and concrete knowledge of how to create customer-defined value at each level of the organization (a hierarchy of value).
    b. in the product development itself. Product Development value stream mapping can contribute to eliminate these wastes.

2. **Improve Product Development Process** through *set-based-concurrent-engineering* to explore thoroughly alternative solutions while there is maximum design space. The greatest opportunity to explore alternatives is early in the product development program, where integrated cross-functional engineering resources can be easily implemented; the aim is to keep the "design space" as open as possible before making decisions.
3. **Create a Balanced Process Flow** Once value has been defined, decision making, knowledge use/reuse and gates should be evaluated in order for rework and over engineering to be reduced to a minimum and activities synchronized across functional departments. This balanced flow allows for the functional

and non-functional requirements of the system to be compared against known metrics whereby manufacturing/assembly/changeability can be supported to enhance and extend value (Design for X).

4. **Standardization** to reduce variation and create flexibility and predictable outcomes. The aim of this principle is to reduce variation in product development while preserving creativity (through knowledge-based engineering and MBSE). This supports the implementation of formal regulations and allows for knowledge-based engineering principles to be leveraged in order to allow for:
   a. design validation to verify that the architecture and functions of the system meet all requirements.
   b. process standardization which reduces variability found in having many non-standard tasks, analysis, or calculations.
   c. engineering knowledge is modeled so that decision makers have a systemic understanding of the problem and the system.

Each implementable process was identified according to its ability to fulfil the overarching business needs of each organization in a transparent and systemic manner, namely supporting flexibility, while promoting efficiency, without creating or establishing non-value (wasteful) efforts, allowing for the use of fewer/less resources. These approaches when integrated in the design process can be adapted to ensure customer needs are met and to allow for the integration of user data for future improvement.

14.2.3 People

In considering ways to address ‘People’ it is critical for the purpose and process of the transformation that they are well understood by all employees. This verifies that the necessary skills, and attributes, can be offered during every stage of design process so that designers and engineers have the appropriate and necessary skills to tackle problems effectively utilizing product usage information and experience to generate and evaluate alternative designs in a collaborative and efficient manner.

- Skill Training and Engagement.
- Knowledge Sharing.

Through training and knowledge sharing in the vessel design process, communication facilitates a pull event where teams can visualize risk and opportunities to improve and enhance design efforts. ‘Serious Games’ have also been identified as a successful approach, which allows players to assume different roles and engage them in simple and complicated decision-making processes. This process of gamification also makes it possible for a safe and entertaining environment to be established, where players are openly encouraged to investigate processes without fear of interfering in actual design.

14.2.4 Basic Thinking

Basic thinking considers the values/goals that will be used to guide the lean transformation of the organization. Based on the business needs value delivery efforts, it is possible to continually improve the design and development process, in a sustainable and environmentally responsible manner. In considering the values/goals that can be used to guide the lean transformation, the following approaches were identified:

- 5-step methodology for continuous improvement.
- Fostering an Innovative Culture.

These approaches serve to integrate all parts of the transformation and facilitate the improvement of the design process (no matter if it is lean or not) through a lean perspective.

14.2.5 Leadership and Management

The leadership aspect represents the fifth part of the transformation and represents the soft skills, behaviors, and tools to be utilized by leaders and everyone within the organization so that they can meet the objectives of the process improvement effort in an effective and collaborative manner. It has been found that the way peoples engage and interact with one another directly impacts the amount of respect, empowerment, and support in the organization. In involving people, the leadership can directly increase employee-driven participation (strongly related to Fostering an Innovative Culture).

In pursuing these aims every program/project (the entire transformation and smaller projects) should use a Chief Engineer role to lead and integrate the program from start to finish. Through the utilization of a chief engineer, leaders are responsible for defining, translating, and communicating the purpose, strategy, and goals throughout the organization to everyone, ensuring that a clearly crafted message is developed. Which provides flexibility for those involved to determine how to best accomplish and measure them. Failure to provide such a collaborative approach has limited efficacy and staying power if the right people are not assisted and supported at the right time.

14.3 Digitalization and IoT

The LINCOLN IoT platform allows for the transfer and storage real-life data for vessels and weather conditions and includes the ability to import data from other sources (like e.g. operating manuals, vessel build-info, etc.). The system also enables analyses of data and provision of answers to data enquires from users. In this approach, the product information originating from any phase of the vessel's life-cycle could be reused in another one, generating a closed-loop PLM. The installation of the Marine Gateway (MG) a modular data acquisition system supported the integration of sensor digitalization, the IoT platform and the comprehensive Innovative LINCOLN Vessel.

Despite the increasing amount of generated data, a challenge remains in how to leverage this information in the most efficient manner during the design, the maintenance phases and the upgrade of maritime systems. Addressing this challenge, the efficient use of usage-data and information requires that the relationships between data-analysis, filters and the system dependencies be well established and documented. This requires that usage information and design parameters or component attributes be considered from project conception to data collection, and design alterations. Thus allowing for the transferring of usage-data into reliable parameters, in turn facilitating the successful inclusion of data streams into marine vessel design.

Today's challenge is not necessarily to find data to aid the design process but rather how to define the right parameters necessary for assuring the quality of the data behind the parameters for designers and engineers. To leverage innovation and data in an effective and meaningful way, the necessary engineering effort required has increased, which due to a lack of research into the systematic transfer of usage-data, can create challenges. However, this allows for traceability between data streams and design decisions, which assure that the quality of the data used throughout the design process is reliable.

The design framework (Fig. 14.5) integrates different data driven activities to support vessel designers, shipbuilders and digital developers involved in vessel and maritime design throughout the development process and allows the testing of designs based on real vessel data and not only experience (subjective knowledge). This demonstrates the ability to reduce the cost and time required throughout the design and development process in a comprehensive, long-term, improvement methodology. A framework has been developed that integrates a Customizable Lean Design Methodology (LTF) and the traditional maritime vessel process to support the development of a structured data oriented decision-making process.

Each of the vessels (1 for each industrial case) was equipped with an on-board IoT based technology and digitalization platform to allow for profile data (equipment) and Personal User Information (PUI) data to be collected in a manner pursuant to the framework. In accordance to stakeholder's specifications, the vessel designer will have access to the vessel data based upon the established data types specified for the vessel. This collected information can be utilized for future vessel designs and simulations, as well as for verifying the quality of the data being collected. The information available to the designer is accessible via the UMG (Universal Marine Gateway) operating within the data management structure (Figs. 14.5 and 14.6).

Through consideration of the framework (Fig. 14.6), information and processes pursuant to vessel design are considered based upon a multitude of choices and iterations used in decision-making activities. When considering the necessary processes for data from real vessels to be converted into knowledge, whether it will be PUI or sensor-generated data, the following challenges related to the process are considered:

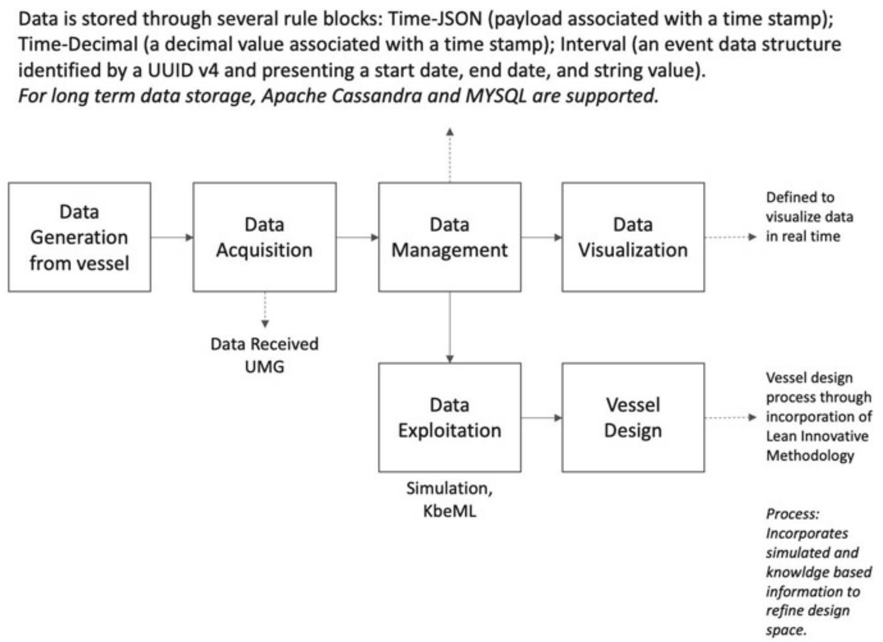

Fig. 14.5 Data Oriented Design Structure (data visualization representative of real-time feedback interface)

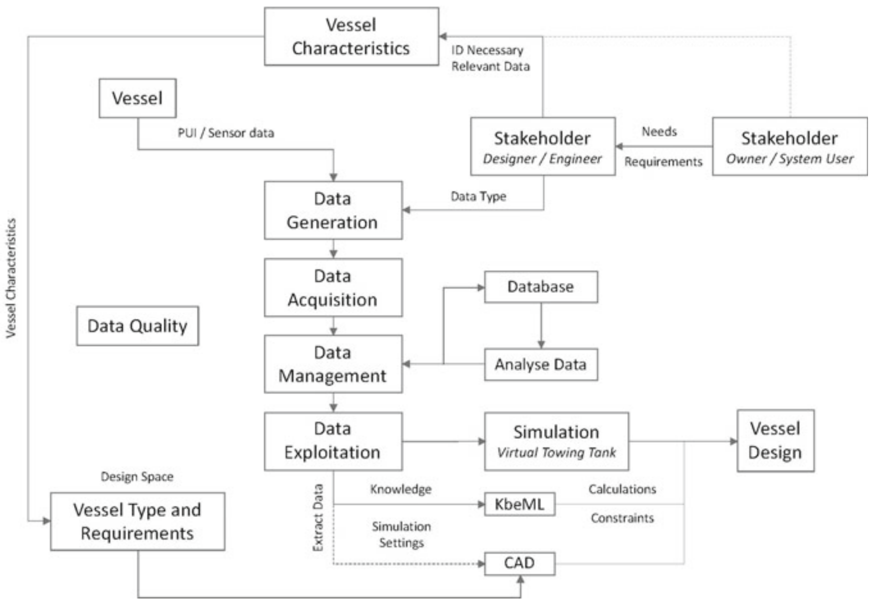

Fig. 14.6 Data-Oriented Vessel Design Framework Block Diagram

- **Data Quality**: Is the determination of the appropriateness of data source in relation to design parameters and application. The challenge is to effectively combine large amounts of data from different sources, with the experience and inherent (tacit) knowledge among current designers and other key personnel in the organizations; thereby ensuring that the data is relevant and related to parameters and/or to analysis being performed. The quality of information that is being generated and collected is of paramount importance for taken proper decisions making. Failure to meet this can result in a negative value for those involved, if the "context understanding" during data collections is unclear.
- **Data Generation**: Specification and identification of data types to be generated from onboard systems (sensor & embedded devices), pursuant to vessel and stakeholder specifications.
- **Data Acquisition**: Process for the collection of information from different on-board systems. A lack of reliability in the acquisition system intersects with data quality. Particularly due to the possibility that if the solution falters, belief in the truthiness of data, and thus of the whole systems is impacted.
- **Data Management**: Process of storage, processing, and management of the vessel data; requiring that the data be available to all personnel involved in the design process, whilst respecting privacy and delivering data security to vessel stakeholders.
- **Data Exploitation**: interfacing PUI and sensor generated data into analytics and product development related applications (e.g. CAD) for decision-making and design improvement; facilitating the establishment of the direct transfer from data to knowledge and support of design and development related decisions to allow e.g., comparisons between simulated vessel behaviors and physical tests.

The framework considers not only specialty vessels but also different product generations (a pilot product and its successors), which could extend the usefulness of the data and information gathered from each real case, facilitating relevant components to be assessed, ensuring integration compatibility, performance, and their ability to fulfill stakeholder requirements. This, for instance, could relate to speed data, which during the usage phase is captured from the engine (or GPS sensor), but in the design phase of the vessel serves as a required value for calculations referring e.g. to the shape of the hull.

14.3.1 Universal Marine Gateway

The Universal Marine Gateway (UMG) is a data acquisition system that has been developed previously in the frame of the EU-funded research projects "BOMA-Boat Management" (EU-FP7 2013), "ThroughLife" (EU-FP7 2014) and "Fortissimo – HighSea Experiment" (EU-FP7 2018). It has the ability to meet the aforementioned requirements of integrating different sensors and on-board systems. It provides a wide range of hardware and software interfaces that facilitate the integration of different

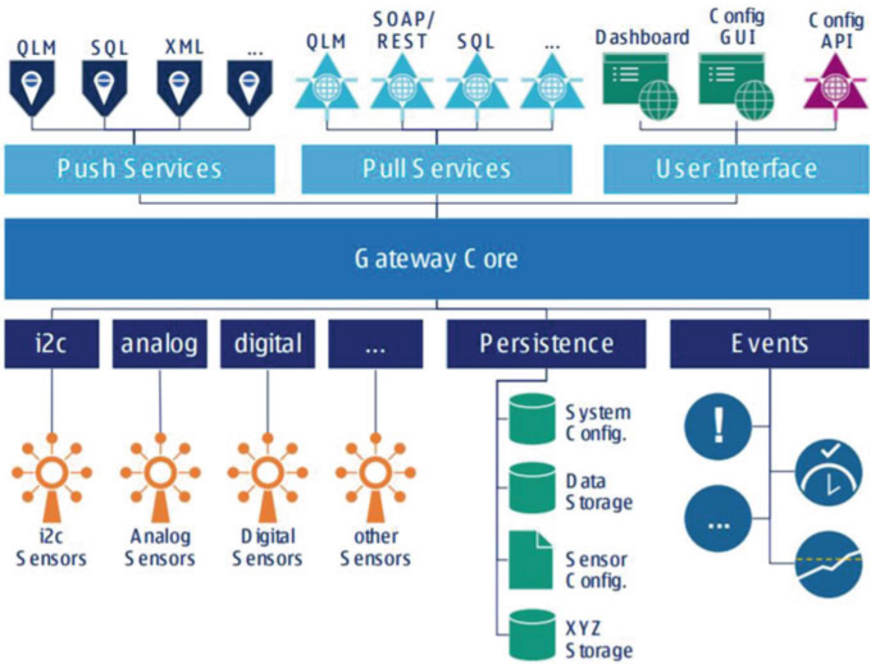

Fig. 14.7 Universal marine gateway architecture diagram

analog and digital data sources like sensors and on-board systems. Figure 14.7 illustrates the architectural overview of the UMG. It consists of a Gateway Core, which is an industrial grade Single Board Computer (SBC) with a custom operating system. It is capable of storing persistent information from data sources into a Time-Series Database (TSDB). The TSDB comprises of measurements successively added to it through various data sources and validated through timestamps during acquisition.

The UMG leverages the power supply from the vessel for its operation and has the ability to form an Ethernet network with the so-called UMG Nodes through a Power-over-Ethernet (PoE) switch. The UMG Nodes are sensor nodes comprising of a small microcontroller and the ability to interface digital and analog sensors directly to them through standard interfaces. These nodes then pre-process the data from the sensors and send the information to the UMG, which in turn saves the information to the TSDB. A finite number of such nodes with the UMG form a sensor network that is deployable on the vessel. The challenge for providing power supply to each of the sensor nodes individually is overcome using the Power-over-Ethernet (PoE) switch. PoE also provides plug-and-play networking abilities for easier integration of multiple UMG Nodes on the same network making placement more flexible at desirable locations of the vessel. Figure 14.8 provides a block diagram of the UMG network that is formed using UMG Nodes and other Ethernet compatible devices. As opposed to other open-source data acquisition boxes like Signal K, the UMG

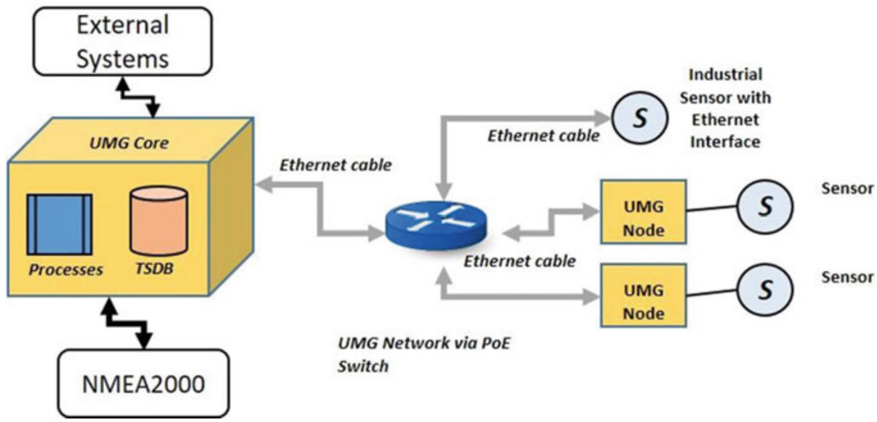

Fig. 14.8 A typical UMG network setup block diagram

along with the UMG Nodes provides more data sources that can be more critical and desirable for vessel design as opposed to only on-board systems like NMEA2000 or NMEA0183.

The UMG Nodes for the LINCOLN project comprise of IMU (Inertial Measurement Units) sensors integrated into them, which provide vector measurements in three-dimensions (X, Y, Z directions). These sensors include a magnetometer,

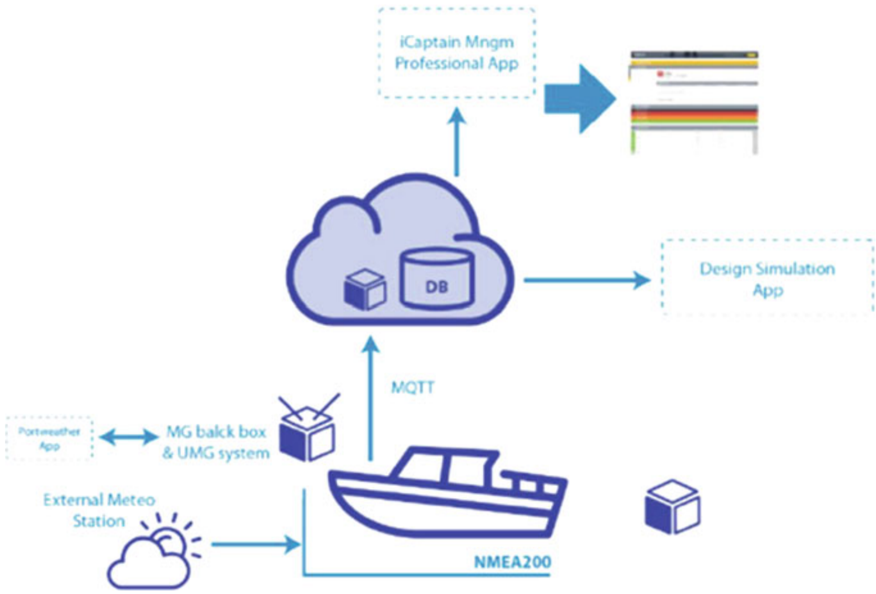

Fig. 14.9 Visualization of the platform and applications correlations

accelerometer and gyroscope which provide orientation of the boat i.e. Yaw, Pitch, Roll (Euler Angles) at the point of installation. Installation of such UMG Nodes within the vessel at specific points are important from design or test perspective in order to obtain large sets of orientation as well as acceleration data, which can then be post-processed to obtain more concrete results or inferences of the vessel's sea trials / voyages.

14.3.2 Port Weather

Port Weather is a web-based application, gathering and providing marine weather monitoring and forecasting to support marine traffic as well as to rescue operations. The Port Weather solution will operate as an autonomous system to provide specific meteorological conditions and forecasts able to be integrated in LINCOLN platforms, to combine vessel behavior with sea and weather conditions at a specified geographical position. For this a weather station was installed on board of a pilot vessel and it operates continuously, providing all the needed initial data. The weather application algorithm which is designed, developed and tested to provide wind speed (and in future wave height) forecasts including early warning for extreme wind potential (Georgoulas et al. 2016; Karvelis et al. 2017; Kolios et al. 2015) is integrated with the MG on board of the vessels. Major benefits from the development and the operational use of this system are:

- Provision of added value to the IoT platform through real-time monitoring of meteorological parameters and early warning regarding extreme weather.
- Improvement of activities and services of vessels.
- Enhancement of safety in ports and vessel services (Fig. 14.9).

The weather application forecasted the speed of the wind, minutes/hours ahead, based on previously recorded values and other measured parameters. It utilizes a small memory footprint Machine Learning (ML) algorithm, which runs in a low power, low CPU frequency, low memory microcontroller. It produces warnings reports and provides the forecasting values to the i-captain black box user. The data is collected online from an on-board weather station and used as input to an advanced Machine Learning Algorithm, which provides Wind Speed prediction for 1–2 h ahead.

This weather application exploits real-time measurements from a meteorological station of high accuracy which is installed onboard of a pilot vessel. All the measurements of the latest hours are used from an internal algorithm of the application in order to produce contiguously short-range forecasts and warnings regarding wind speed and the wave height. The final outputs of the system can be transmitted automatically to a cloud service which supports ("i-captain" black box platform) offering an integrated packet of valuable information regarding a vessel either when is anchored or at sea. It is also mentioned that this application is easily transferable and can be installed in PC units or embedded systems with basic programming features. Nevertheless, this application is a prototype and expertized people with programming skills can efficiently install and operate it, up to now. A main future objective is to create a portable version which can be transferred and installed in a few steps from stakeholders without the need of expertized people.

The weather application is a stand-alone application, developed to operate continuously, especially on board of rescue boats. Major benefits from the development and the operational use of this application can be considered (1) the provision of added-value in services onboard of vessels through the real-time monitoring of meteorological parameters and the early warning about extreme weather (2) the upgrading of the operational capabilities of rescue boats (3) the improvement of activities and services on board of vessels (4) the enhancement of the safety in ports and of the vessels.

14.4 Knowledge Based Engineering

Knowledge Based Engineering (KBE-systems) provides an interface to capture and codify the knowledge in terms of logical rules, algorithms, or constraints, and in addition an output module to trigger (control) adjacent CAx-functions. Accordingly, the main outcome of a KBE project is the generation of automated design applications, which are software modules, which support the designer in generating product model configurations and adoptions automatically, through the execution of a set of rules and procedures, which are translated into source code. The outcomes of these applications are typically new CAD files of products and parts, which inherit properties from an underlying master product, if not designed from scratch by the IT-system.

The codified knowledge can be used for the automated creation of geometry but may also cover analysis tasks in terms of validation or quality checking, such as compliance to required safety parameters, or ISO standards. In fact the findings can be partially extracted from standards and compliance perspectives as well, since these are directly related to the ABS. Further, through the ability to leverage and codify knowledge solutions derived from real data can enable a broader variety of detailed design studies of a given master-concept by usage of a rule-based approach for an automated detailing and examination of design variants and in consequence extensively support the optimization of a given (mechanical) design against defined constraints and requirements (e.g.). Referring to the CFD simulation as a service, the unique capabilities of an integrated approach for vessel improvement allows for design variants to be developed and be tested quicker based on pre-defined rules. In this way an automated evaluation of a range of design considerations can be compared under real conditions to improve the overall vessel's performance.

The approach for the integrating real sensor generated data into codified rules is based on a formal extension of SysML, to facilitate a formal and neutral representation of engineering knowledge. This ability to leverage a MBSE approach functioned to capture codified knowledge, such as rules and equations extracted from regulations and standalone calculations (Dabkowski et al. 2013). These elements supported the use of operational data, that could then be mapped directly to design related elements such as equations or rules. By integrating unique real data from operational vessels and established rules the knowledge based approach to design served to simplify the codification of design & engineering knowledge in a graphical way so that different element types could be represented with their own unique appearance, based on the inherent type of knowledge (PUI or engineering) and thus allow easy recognition by the domain experts.

Following the principles of MBSE and SysML, usage related parameters are linked to the calculations and enable direct linkages between usage and design related parameters (Piaszczyk 2011). For example, typically, in traditional design the speed is treated as a precondition (e.g., customer specifications require that the boat should have a maximum or service speed of 20 knots). In reference to the above approach, this parameter can also be extracted from the usage phase and be provided to the vessel designers, namely allowing for the speed to be linked to a dataset referring to the measured speed over water values, thus to provide an empirical average speed set by statistical data.

Accordingly, the sample indicates that when engineering knowledge (equations and rules) is captured in KbeML/SysML the data can support the identification of user operation and predictive maintenance. The analysis of the way the data is processed in terms of a mean or max or min value (or other statistical functions) has been used to feed design information that influences the overall calculation. Through LINCOLN by linking the UMG with the LTF a broad range of calculations were linked to PUI and real sensor data to evaluate design variations and support the decision-making process. Further, the formal notation and its underlying semantic meaning allow the post-processing and linkage to the design and development which facilitates transparency in terms of what kind of usage data analysis has been conducted for which part and/or step of the design process.

14.5 Environmental and Economic Assessment

Lifecyle thinking is an integral part of the LINCOLN project, as the sustainability of maritime vessels is becoming an increasingly important consideration for shipbuilders. The objective of the LCPA-Tool is to support the design process by allowing for vessel variations to be evaluated early in design stage using a sustainable approach. This included consideration of the following elements:

- The economic viability of design alternatives using the net present value (NPV) concept and the payback time.
- The environmental impact from construction, operation, and recycling of different vessel design variations by measuring their global warming potential (GWP), acidification potential (AP), eutrophication potential (EP) and particulate matter release (PM 10).

- Measurement of the Cumulative Energy Demand (CED) for the way from the well to tank for fuel, material production and energy expense of the shipyard for building and operating of the ship. This ensures that all energy consumption (including their related GHG-emissions) related to production of fuel, relevant materials and shipyard energy consumption is considered.
- The societal impact of emissions from energy provision and conversion that constitute the vessel designs external costs (ExterneE, NEEDS, UBA). To analyze the economic impact of emissions or to consider the effect of internalizing external costs in the LCPA-Tool, corresponding assumptions were made.

The LCPA-Tool provided the designers a method to quickly assess different designs against the baseline system and propose solutions and design options. This ability to support the decision-making process on a rational basis using sustainable design aspects improved how materials were selected which directly corresponds to adjustments in the KbeML, allowing for subsequent variations of the vessel to benefit from previous analysis that were carried out.

14.6 HPC for Virtual Towing Tank

The LINCOSIM Virtual Towing Tank web application was developed to enable designers to simulate the performance of vessel hulls early in the design phase, in order to define more precisely reliable design solutions and before moving to hull prototyping and physical towing tank analysis. Emphasizing the need to reduce the time required to perform a CFD analysis and in line with the LTF, LINCOSIM provides designers a tool that would allow them to reach an appropriate level of detail with minimal time commitments. This functions to transform the entire processes of meshing, modelling and post-processing stages as automated tasks (Table 14.1).

The direct benefit of this solution is that it enables the development of designs based on real operational data to be compared instantaneously and thereby allows a 'designer user' to take advantage of CFD tools without the need to handle the inherent complexity of creating suitable meshes, etc.. More precisely, the 'designer user' is able to evaluate a set of key-parameters (KPARs) of the hull hydrodynamics quickly and more efficiently than by traditional methods. Through the Virtual Towing Tank application, the hull resistance curve, hull trimming, hull pressure distribution, waves distribution, wetted surface area and any other derived quantities can be obtained via a web browser in only few hours.

This drastic simplification of the process and reduction in time required to perform an analysis that enables any *designer to effectively analyze a hull* design. There are several factors that this added capability disposes to designers:

- Reliability: a significative number of CFD simulations for the sample design scenario (more than 550) was performed by experts in advance, while consuming a total of 213.000 core-hours of testing.

Table 14.1 Automation levels of different steps of a CFD workflow using a classical CFD approach and *LINCOSIM* based approach

	CAD design	CAD cleaning	Meshing	CFD modelling	Postprocessing	Decision making
Classical CFD						
Human (%)	100	100	80	40	80	100
Automatic (%)	0	0	20	60	20	0
LincoSim CFD						
Human (%)	100	100	0	0	0	100
Automatic (%)	0	0	100	100	100	0

Table 14.2 Monitored statistical results

Category	Quantity	LincoSim values
Geometries	N. Geometries	45
	Average (avg.) simulations per geometry	12.5
Simulations	N. Simulations	563
	N. Failures	39
	Total Computing Time [core hours]	212,998
	Avg. Computing Time per Simulation [core hours]	378
	Total Storage [MB]	1,318,207
	Avg. storage per simulation [MB]	2341
Users and groups	N. Organizations	3
	N. Users	25
	Avg. Users per group	8
	Improvement in Time to Submission	90%
	Improvement in Time to Result	90%

- The average time to submit a simulation by a designer was about 2 min, making the upload time easy for users to manage.
- The average time to analyze the post-processed outcomes was less than 10 min.
- All the acquired statistical data converged through an innovative web portal, that reduces the demand for high computing computational platforms (Table 14.2).

All the acquired statistical data converge to a very positive evaluation of the novel *LincoSim* web application for naval design activities enlightening that there is a clear opportunity to bring together innovative web tools, computational platforms and state of the art open-source numerical tools to support in a new way designers and engineers.

The model allows the designer to minimize the need to manually execute repetitive tasks (LTF waste reduction) by utilizing an automatic software application. The *LincoSim* approach allows to transform the entire process of meshing, the CFD modeling and post-processing stages to automated tasks. This is not only useful for enabling the automation of the CFD process but also to make it directly available to the end-user, who, in the context of ship design, is a *designer* who is interested in evaluating the hull performance in the scenario of a complex design optimization. The standardized *LincoSim* simulation is the basic brick of the platform which includes:

- a web front-end, which allows to easily define the simulation parameters.
- present significant and interactive visualizations of post-processed results.
- select a simulation from a dashboard of the past simulations through a set of back-end web services, which are called by the front-end and are used to interact with the database used to manage users, geometries, simulations, HPC machines and simulation setups; as well as to send jobs and collect results to be visualized by the front-end.

The integration of a relational database allows users to easily manage a large number of geometries, simulations, machines, and simulation setups, minimizing the effort to extract and compare data from different cases even after a long time. Another major advantage of is the integration of interactive 1D, 2D and 3D visualizations which allow to immediately analyze the results focusing on the physics of the problem instead of the technical software details.

As discussed in the introduction, *LincoSim* is aimed at virtualizing a complex engineering application workflow that can be summarized into three main steps:

- Pre-processing: this step concerns the very sensible activity of importing the geometry input file from the user, checking that the geometry is clean and well described.
- Modeling and Computing: this step concerns the building of a suitable mathematical modeling of the physics of the problem that we want to face. In particular, for state-of-the-art planning hulls simulations we decided to model, discretize and solve the 3D Navier–Stokes partial differential system of equations for a global system made of two immiscible incompressible Newtonian fluids (air and water) under turbulent flow regimen with interface surface capturing, including dynamic mesh motion, interface mesh morphing and tracking. Attention to the potential for numerical ventilation was made to overcome problems in hull simulations.

- Post-processing: this step is related to the management, processing and visualization of the mathematical modeling outcomes extracting meaningful synthetic quantities enabling designers and engineers to perform the so-called decision-making step ranking the considered hull performance.

14.7 Conclusions

As technology continues to evolve and becomes ever more critical to the design process it is critical for resources and activities to be value adding. Throughout the LINCOLN project, the challenge of developing innovative and value extended systems was at the core of all work performed and was successfully accomplished. This chapter provided a brief overview to the LINCOLN approach to ship design and the keys elements that were developed to support the development of innovative maritime vessels. It defined the Lean design methodology that guided the process for development and demonstrated how each of the unique solutions created were applied to the design process.

The project was able to accomplish its objectives by introducing a new way of designing vessels, basing on formal knowledge creation and use, thanks to IoT and new technologies. The main 5 elements constituting the project contents (i.e. lean methodology, IoT, LCA, KBLM, HPC) enables a more efficient and effective design as well as ability to use proven knowledge supports the valuable execution of the overall process. In total the LINCOLN project succeeded in reducing the cost of vessel design, production, and vessel operations by roughly 20%. These improvements which are discussed in more detail in the following section, also succeeded in reducing vessel emission by roughly 30%, depending on the specific operational profile of the vessel. Thanks to the collaboration amongst partners, technological providers and researchers, the tools developed and validated during LINCOLN facilitated the creation of new skills to support digital tools usage, for a more efficient and fast design.

14.7.1 Vessel Performance Improvements

The vessel performance achievements evaluation was determined based on the technical and functional elements of the cases evaluated in the project. These improvements are briefly detailed below to illustrate several, but not all of the measured and calculated improvements.

- Hybrid Propulsion system was able to extend the operating range, reduce emissions and provide an easily customizable optimization process.
- The emissions reduction associated to the fuel reduction and operation with the hybrid propulsion system was determined to be up to 50%, depending on the vessels specific operational profile.

- The features of the modular design and production platform have allowed Hydrolift to enter the professional market that previously has been hard to penetrate, increasing the company market competitiveness. (impact 2: reduction of costs by at least 20% compared to current practices taking the entire process including increased productivity and vessel cost into consideration.)

14.7.2 Operations Improvements

The design is optimized for a cost effective small series of boats.". (impact 2: reduction of costs by at least 20% compared to current practices taking the entire process including increased productivity and vessel cost into consideration.)

- The operation cost reduction is estimated at roughly 27%. (impact 2: reduction of costs by at least 20% compared to current practices taking the entire process including increased productivity and vessel cost into consideration.)
- The reduction of waste and residues from reworks during the construction process -18%
- 20% savings in time and cost for maintenance and parts, and even more important up to 30% less "out of order/use".

14.7.3 Design and Construction Process Improvements

The Lean Transformation Framework improved decision-making activities by promoting a stronger relationship between the designer and customer, and by facilitating the integration of knowledge from past designs and real time data created from new vessels. The methodology was implemented during the design stage of the vessels development to improve communication, and accelerate design time, by eliminating and improving aspects of the process that were previously resource intensive and non-value adding. The Lean Transformation allowed for the People, Processes, and Technology to be analyzed so that a more intuitive and collaborative development strategy could be developed. By underlining the need and importance of reducing design, non-value-added activities were reduced, and employee skills were developed to increase the synchronicity of processes. The critical areas for improvement were: reduction of rework, enhanced management of design data, accelerated feedback between stakeholders, and increased collaboration between designers and engineers.

- 20% savings in time and cost for vessel maintenance and parts, and even more important up to 30% less "out of order/use". (impact 2: reduction of costs by at least 20% compared to current practices taking the entire process including increased productivity and vessel cost into consideration.)

- Customization cost was reduced by roughly 50% in terms of hours used for customization compared to previous design model and vessels. Reduction of costs by at least 20% compared to current practices taking the entire process including increased productivity and vessel cost into consideration.)

Acknowledgements The content of this paper is based on the LINCOLN project (EU H2020 727982) (www.lincolnproject.eu). We wish to express our gratitude to all LINCOLN project partners involved in the creation, validation and testing of the solutions developed during the project.

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