

CRANFIELD UNIVERSITY

Amit Batra

DESIGN SPACE EXPLORATION OF
GAS TURBINE BASED SHIP PROPULSION SYSTEMS

School of Aerospace Transportation and Manufacturing
PhD in Aerospace

PhD Thesis
Academic Year: 2015 - 2021

Supervisors: Dr Suresh Sampath
and Dr Theoklis Nikolaidis

December 2021

CRANFIELD UNIVERSITY

School of Aerospace Transportation and Manufacturing
PhD in Aerospace

PhD Thesis

Academic Year 2015 - 2021

Amit Batra

DESIGN SPACE EXPLORATION OF
GAS TURBINE BASED SHIP PROPULSION SYSTEMS

Supervisors: Dr Suresh Sampath
and Dr Theoklis Nikolaidis

December 2021

© Cranfield University 2021. All rights reserved. No part of this publication may be reproduced without the written permission of the copyright owner.

ABSTRACT

The conceptual design of a ship propulsion system, developed during the early stages of the overall ship design process, has a very large impact on the overall design and performance of a ship. Gas turbines are often utilized for warship propulsion systems designed to fulfil requirements of high ship speed and power density. To achieve a high overall system-level efficiency, gas turbines are often used in combined architectures with diesel engines along with geared, electric or hybrid transmission systems driving multiple propulsors. The process for the development of the conceptual design for such ‘combined’ systems, designed to achieve multiple and often conflicting design objectives, is significantly more complex compared to that for systems where a single-engine drives a propulsor.

A number of approaches are currently used in practice towards the conceptual design of a ship, ranging from manual ‘design lanes’ based iterative approaches, to computerized overall ‘ship as a system’ design synthesis approaches. Towards the conceptual design of the propulsion system, both these approaches pose their own limitations, wherein the approach of the manual iterative design process relies heavily on the preferences of experts and approximations based on past experience; while the ship design synthesis approach usually yields good results generally if the candidate propulsion architectures are based on existing designs.

This research work proposes a model-based process for the design space exploration using a model-based ‘Techno-economic & Environmental Risk Assessment’ (TERA) approach. To undertake feasibility and performance analysis of the candidate propulsion system architectures, the process involves building performance models of the candidate propulsion system architectures at this very early stage the overall design process of the ship and utilizing the generated results as the basis of design related decisions.

For undertaking the performance modelling of the multiple candidate propulsion system architectures, an agile modelling and simulation framework was considered essential that could handle the complexity of ‘combined’ propulsion

plants. To achieve this, a component-based modelling software, 'Poseidon +', has been developed as a part of the present work which enables 0-D modelling of gas turbine engines as well as the entire propulsion system in the same framework. A key aspect of this work was the development of an algorithm that analyses the direction of the torque transmission across the complex transmission system of 'combined' plants, based solely on the states of the engine and clutches.

For undertaking TERA, a suite of 'Multiple-Criteria Decision-Making' (MCDM) methods were selected and applied to select a compromise solution from competing propulsion system architectures, using a combination of performance data generated from simulation of developed models, and comparative expert opinions-based metrics for information not available early in the ship design process. To execute the MCDM procedure, a methodology of deriving weights of the competing design criteria using a combination of hierarchal and network structure, considering the degree of relationships between the design criteria, has been demonstrated.

The overall proposed approach for design space exploration of gas turbine based 'combined' ship propulsion systems has been demonstrated towards the conceptual design analysis of two notional ship designs. The results of the analysis show the effectiveness of the proposed procedure for design space exploration of ship propulsion systems.

Keywords:

Ship propulsion system design; conceptual design; model-based design; propulsion system architecture; Gas turbine modelling; ship propulsion system modelling; 'Techno-economic & Environmental Risk Assessment' (TERA); 'Multiple-Criteria Decision-Making' (MCDM); Poseidon+

ACKNOWLEDGEMENTS

The writing of this doctoral thesis has been made possible by the support, guidance and encouragement of many, whom I would like to acknowledge.

My supervisors, Dr Suresh Sampath and Dr Theoklis Nikolaidis, for their continuous advice, guidance, patience and willingness to share their rich knowledge and experience. They were my mentors and role models through this journey with their depth of knowledge, leadership and work ethic. Their guidance on the technical aspects of my work, contribution to the framing of the research proposal as well as helping me focus on the truly important aspects of my work has proven to be invaluable. I would also like to thank Dr Suresh Sampath for having the faith in me and providing me with the opportunity to pursue this work and Prof. Pericles Pilidis for his overall support of this work.

My wife, Dilshad, for her unrelenting support and endless patience through these years and for taking over much more responsibility to give me the time needed to pursue my work. My son, Jehan, for displaying maturity far beyond his years, by supporting my endeavour; seeing me start my work as a little boy up to its completion when he is almost finishing schooling. My parents and family for their encouragement and understanding through all these years of work.

My research colleague, Mr. Gaurav Singh, for providing me with useful data from the commercial shipping industry to my work.

Ms. Petra Briggs, Ms. Abi Brooks and Ms. Suzanne Morris for their kindness and patience in handling all the administrative support, through the course of my PhD work.

TABLE OF CONTENTS

ABSTRACT.....	i
ACKNOWLEDGEMENTS.....	iii
LIST OF FIGURES	viii
LIST OF TABLES	xxi
LIST OF EQUATIONS.....	xxiv
NOMENCLATURE.....	xxix
LIST OF ABBREVIATIONS	xxxiv
1 INTRODUCTION	36
1.1 Background and Motivation.....	36
1.2 Aim and Objectives	37
1.3 Novelty of the Research Work	38
1.4 Thesis Structure	39
2 LITERATURE REVIEW	41
2.1 Conceptual Design.....	41
2.2 Engine and Propulsion Plant Modelling	47
2.2.1 Marine Propulsion System Performance Simulation	47
2.2.2 Cranfield University in the Field of Gas Turbine Engine and Plant Performance Modelling and Simulation.....	48
2.2.3 Dimensioning and Costing Models	51
2.3 Techno-Economic Analysis Procedure	53
2.4 Ship Operating Profile	53
2.5 Multiple Criteria Decision-Making.....	56
2.6 Summary of Literature Review	58
2.7 Identified Gaps in Knowledge	59
2.8 Addressing Gaps in Knowledge.....	60
3 METHODOLOGY AND SCOPE	62
3.1 Establishing the Broad Overall Approach and Framework for Undertaking Conceptual Design of Ship Propulsion Systems	62
3.2 Development of an Integrated, Agile, Performance Modelling Framework for Ship Propulsion Systems	68
3.3 Application of Dimensioning and Costing Models for Propulsion System	70
3.4 Techno-Economic Analysis Using the Concept Of TERA with Application of MCDM	71
4 PERFORMANCE MODELLING AND SIMULATION FRAMEWORK	73
4.1 Development of Generalized Framework for Performance Modelling of Ship Performance	73
4.1.1 Engine Layer	74
4.1.2 System Layer.....	76
4.1.3 Model Layer.....	76

4.1.4 Math Layer.....	76
4.1.5 Physics Layer	77
4.1.6 Data Layer	77
4.2 Gas Turbine Engine Performance Simulation.....	78
4.2.1 Engine Module Overview.....	79
4.2.2 Gas Turbine Performance Calculation Methodology.....	81
4.2.3 Off Design (OD) Calculations	82
4.2.4 Thermodynamic Calculation Models	88
4.2.5 Gas Turbine Component Models.....	90
4.2.6 Component Performance Maps.....	93
4.3 Ship Propulsion System Performance Simulation.....	104
4.3.1 Interaction between Ship and Propulsor	104
4.3.2 Ship Propulsion System Modelling	108
4.3.3 Operating Point Performance Calculation Methodology	110
4.3.4 Hull Resistance.....	115
4.3.5 Propulsive Coefficients.....	125
4.3.6 Propulsor: Propeller.....	125
4.3.7 Initial Design Optimization of Propellers.....	131
4.3.8 Water Properties Model.....	137
4.3.9 Prime Movers	137
4.3.10 Geared Transmission Systems	141
4.3.11 Modelling Operating 'Drive Modes'.....	143
4.3.12 Gearing Energy Loss.....	152
4.3.13 Shafting	154
4.3.14 Electrical Systems	154
5 TERA BASED ON MULTIPLE-CRITERIA DECISION-MAKING (MCDM)....	159
5.1 Overview of Application of the MCDM Process to TERA.....	159
5.2 Establishing Hierarchal, Network Structure for Evaluation Criteria	161
5.3 Calculation of Criteria Weights.....	169
5.4 Determination of Evaluation Scores for Candidate Architecture	173
5.5 Selection of Plant Architecture Using VIKOR.....	173
6 RESULTS AND DISCUSSION	176
6.1 Verification of Developed Performance Modelling and Simulation Framework	176
6.1.1 Gas Turbine Engine Modelling	177
6.1.2 Diesel Engine Modelling	184
6.1.3 Resistance Models	184
6.1.4 Propeller Model and Optimizer.....	185
6.2 Gas Turbine Engines and Simulation Analysis	187
6.2.1 Gas Turbine Engine Performance Simulation Results	187
6.2.2 Effect of Variation of Power Turbine Speed on Engine Performance	201

6.2.3 Effect of Variation of Ambient Air Temperature on Engine Performance	203
6.3 Design of Propulsion System Architectures	204
6.3.1 Engine Propeller Matching	204
6.3.2 Trailed Propeller Operation	207
6.4 Determination of Criteria Weights for MCDM Analysis	209
6.4.1 Using DEMATEL to Determine Local Weights of Objective Metric 'Performance'	210
6.4.2 Using AHP to Determine Local Weights of Cost and Risk Criteria ..	218
6.4.3 Calculation of Global Weights for Set of Criteria	220
6.5 Notional Destroyer Conceptual Design Study	225
6.5.1 Input Data for Design.....	225
6.5.2 Hull Resistance Estimation.....	226
6.5.3 Propeller Design	228
6.5.4 Candidate Propulsion System Architectures	230
6.5.5 Performance modelling of candidate architectures	236
6.5.6 Mass and Dimensional Estimations.....	243
6.5.7 Estimation of Costs.....	244
6.5.8 Calculation of Relative Scores for Qualitative Criteria.....	248
6.5.9 Objective Comparison of Candidate Propulsion System Designs using VIKOR.....	250
6.5.10 Conclusions of the Propulsion System Conceptual Design Study for the Notional Destroyer.....	260
6.6 Notional Light Frigate Conceptual Design Study	262
6.6.1 Input Data for Design.....	262
6.6.2 Hull Resistance Estimation.....	264
6.6.3 Candidate Propulsion System Architectures	267
6.6.4 Performance Modelling of Candidate Architectures	272
6.6.5 Mass and Dimensional estimations.....	278
6.6.6 Estimation of Costs.....	278
6.6.7 Calculation of Relative Scores for Qualitative Criteria.....	279
6.6.8 Objective Comparison of Candidate Propulsion System Designs using VIKOR.....	284
6.6.9 Conclusions of the Propulsion System Conceptual Design Study for the Notional Light Frigate	293
7 CONCLUSIONS AND FUTURE WORK	295
7.1 Achievements.....	295
7.1.1 Model-Based Design Space Exploration for Conceptual Design	295
7.1.2 Analysis of Degree of Relationships between Performance Criteria for Propulsion System Design	295
7.1.3 Development of an Agile Steady State 0-D Component-Based Modelling Framework for Combined Ship Propulsion Plants	295

7.1.4 Application of Model-Based Design Space Exploration to Ship Designs.....	296
7.2 Conclusions.....	296
7.3 Impact	298
7.4 Future Work	299
REFERENCES	301
APPENDICES.....	314
Appendix A Poseidon+ Software Design	314
Appendix B Symbolic Representation of Poseidon+ Model Components ...	325
Appendix C Poseidon+ Input File Format	327
Appendix D Thermodynamic Calculation Models	332
Appendix E Gas Turbine Component Models.....	342
Appendix F Hull Resistance Model	366
Appendix G Propeller Model	384
Appendix H Water Properties Model.....	387
Appendix I Propulsion Equipment Dimension and Mass Estimation Models	390
Appendix J Propulsion Equipment Acquisition and Maintenance Cost Models.....	404
Appendix K Combined Marine Propulsion Plants	408
Appendix L DANP Procedure.....	410
Appendix M AHP Method.....	414
Appendix N VIKOR Method	416
Appendix O Gas Turbine Performance Simulation Results	418
Appendix P Gas Turbine Engine Input Files	460
Appendix Q Propulsion System Model Input Files	479
Appendix R Model Input Files for Validation Resistance Model and Propeller Optimizer	522

LIST OF FIGURES

Figure 1-1 Overview of the structure of the thesis.....	40
Figure 2-1 Design Timeline [1].....	42
Figure 2-2 Traditional ship design spiral vs. modern integrated ship design synthesis approach [11].....	43
Figure 2-3 'Warship Engineering Management' V-diagram [15].....	45
Figure 2-4 Notional concept design process [19].	46
Figure 2-5 Propulsion machinery alternatives[12].	47
Figure 2-6 Iterative process followed to obtain free power turbine work for different rotational speeds [51].....	50
Figure 2-7 Relationship between internal parts life and the power turbine inlet temperature of a marine gas turbine [57].....	52
Figure 2-8 Comparison of 2003 approved (Current) and observed operating profiles (New) [66].....	54
Figure 2-9 Comparison of operating profiles based on mission type [66].....	55
Figure 2-10 Example of operating profile specification for ASW and GP roles [9].	56
Figure 3-1 Context of propulsion system design in the overall ship design process.	65
Figure 3-2 Broad approach towards the conceptual design of propulsion system.	66
Figure 3-3 Overview of the research work.....	67
Figure 4-1 Conceptual Layout of Layered Modules in Poseidon+.....	75
Figure 4-2. Conceptual arrangement of an engine model in Poseidon+	80
Figure 4-3. Engine Module for a sample engine.....	81
Figure 4-4 Overall process for OD solution finding in Poseidon+ for a sample engine	84
Figure 4-5 Poseidon+ Newton Raphson Solver Algorithm Overview.	86
Figure 4-6 Poseidon+ Engine Component Architecture.	91
Figure 4-7 Working line on a compressor map [84].....	93
Figure 4-8 An example of an implemented compressor performance map (for pressure ratio).....	96

Figure 4-9 An example of an implemented compressor performance map (for isentropic efficiency)	96
Figure 4-10 The compressor map reading problem [68].	97
Figure 4-11 Implemented compressor map interpolation method	98
Figure 4-12 An example of an implemented turbine performance map.....	100
Figure 4-13 An example of a turbine performance map (for isentropic efficiency) in Poseidon+	100
Figure 4-14 Combustor performance map in Poseidon+.....	102
Figure 4-15 Implemented Nozzle map.....	103
Figure 4-16 Concept of ship propulsion [70].....	104
Figure 4-17 Components of ship powering – main considerations [70].....	108
Figure 4-18 Conceptual diagram for a steady-state operating point solution for a simple propulsion system.....	113
Figure 4-19 Conceptual diagram for a transient operating point solution for a simple propulsion system.....	114
Figure 4-20 Propeller action [70].	125
Figure 4-21 Propeller geometry [97].	126
Figure 4-22 Propeller geometry [70].	126
Figure 4-23 Geometric pitch [70].	127
Figure 4-24 Open water characteristics of the propeller.....	130
Figure 4-25 Diesel engine map with lines of constant fuel flow [94].	139
Figure 4-26 Both engines driving respective individual propellers.....	147
Figure 4-27 Port engine driving port propeller, starboard propeller trailing	148
Figure 4-28 Port engine driving both propellers.....	148
Figure 4-29 Starboard engine driving both propellers	149
Figure 4-30 COGAG model used to explain the developed algorithm for modelling of operating drive modes.	149
Figure 4-31 Decomposition of the COGAG model by the developed algorithm for drive mode modelling into component nodes and transmission sub-paths.	150
Figure 4-32 Simplified logic block diagram for ‘Engine-Propeller Interface Data’ function of the developed algorithm for plant drive mode modelling.....	150

Figure 4-33 Simplified logic block diagram for ‘Function: Plant Engines Interface Data from Sub-Path Data’ function of the developed algorithm for plant drive mode modelling.....	151
Figure 4-34 Variation of gearbox efficiency with normalised input torque for propeller and alternator applications.....	153
Figure 4-35 Variation of gearbox efficiency with normalised input speed for propeller application.....	153
Figure 4-36 Variation of electric machine efficiency with normalised effective power.	156
Figure 4-37 Variation of frequency converter efficiency with the normalised current.....	157
Figure 5-1 TERA with Multiple-Criteria Decision-Making.....	160
Figure 5-2 Overview of the developed MCDM procedure	161
Figure 5-3 Design criteria for the MCDM problem in a combination of hierarchal, network structure	168
Figure 5-4 VIKOR method for finding ‘compromise’ solution.....	174
Figure 6-1 Model depiction of Turbojet used for design validation	177
Figure 6-2 Comparison of temperatures at engine stations for handle (PCN or N_c) variation from 0.6 to 1.0 for Turbojet, calculated by Poseidon+ and Turbomatch.....	178
Figure 6-3 Comparison of pressures at engine stations for handle (PCN or N_c) variation from 0.6 to 1.0 for Turbojet, calculated by Poseidon+ and Turbomatch.....	179
Figure 6-4 Comparison of Gross Thrust for handle (PCN or N_c) variation from 0.6 to 1.0 for Turbojet, calculated by Poseidon+ and Turbomatch	180
Figure 6-5 Comparison of fuel flow (WF) for handle (PCN or N_c) variation from 0.6 to 1.0 for Turbojet, calculated by Poseidon+ and Turbomatch	181
Figure 6-6 Comparison of inlet air mass flow (Win) for handle (PCN or N_c) variation from 0.6 to 1.0 for Turbojet, calculated by Poseidon+ and Turbomatch.....	181
Figure 6-7 Computed working line on compressor pressure ratio map for Turbojet	182
Figure 6-8 Computed working line on compressor isentropic efficiency map for Turbojet.....	182
Figure 6-9 Computed working line on turbine enthalpy ratio map for Turbojet	183

Figure 6-10 Computed working line on turbine isentropic efficiency map for Turbojet.....	183
Figure 6-11 Normalised medium-speed diesel engine map derived for present research work	184
Figure 6-12 Comparison of results of implemented resistance model with published data.....	185
Figure 6-13 Comparison of results of implemented propeller optimization module with published data	186
Figure 6-14 Superposition of the results of implemented propeller optimization module with published curves [128].....	186
Figure 6-15 Set of open water results from implemented Wageningen B Series based propeller model with P/D varied from 0.8 to 1.4	187
Figure 6-16 Model block diagram for 25 MW MGT.....	190
Figure 6-17 Computed variation of combustor outlet temperature ($T_{B,out}$) against fuel flow (WF) for 25 MW MGT, with power turbine speed (NPT) varying as per propeller law and ambient temperature at $T_{amb} = 35$ °C.	191
Figure 6-18 Computed variation of power turbine inlet temperature ($T_{PT,in}$) against fuel flow (WF) for 25 MW MGT, with power turbine speed (NPT) varying as per propeller law and ambient temperature at $T_{amb} = 35$ °C.	191
Figure 6-19 Computed variation of compressor outlet temperature ($T_{C,out}$) against fuel flow (WF) for 25 MW MGT, with power turbine speed (NPT) varying as per propeller law and ambient temperature at $T_{amb} = 35$ °C.	192
Figure 6-20 Computed variation of compressor outlet pressure (PC,out) against fuel flow (WF) for 25 MW MGT, with power turbine speed (NPT) varying as per propeller law and ambient temperature at $T_{amb} = 35$ °C.	192
Figure 6-21 Computed variation of overall compressor pressure ratio (PR) against fuel flow (WF) for 25 MW MGT, with power turbine speed (NPT) varying as per propeller law and ambient temperature at $T_{amb} = 35$ °C.	193
Figure 6-22 Computed variation of compressor speed ratio (NC) against fuel flow (WF) for 25 MW MGT, with power turbine speed (NPT) varying as per propeller law and ambient temperature at $T_{amb} = 35$ °C.	193
Figure 6-23 Computed variation of power turbine shaft power or engine brake power ($PW_{sh,out}$) against fuel flow (WF) for 25 MW MGT, with power turbine speed (NPT) varying as per propeller law and ambient temperature at $T_{amb} = 35$ °C.....	194
Figure 6-24 Computed variation of combustor outlet temperature ($T_{B,out}$) against compressor speed ratio (NC) for 25 MW MGT, with power turbine speed (NPT) varying as per propeller law and ambient temperature at $T_{amb} = 35$ °C.....	194

- Figure 6-25 Computed variation of power turbine inlet temperature ($T_{PT,in}$) against compressor speed ratio (NC) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35\text{ }^{\circ}\text{C}$195
- Figure 6-26 Computed variation of compressor outlet temperature (TC,out) against compressor speed ratio (NC) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35\text{ }^{\circ}\text{C}$195
- Figure 6-27 Computed variation of compressor outlet pressure (PC,out) against compressor speed ratio (NC) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35\text{ }^{\circ}\text{C}$196
- Figure 6-28 Computed variation of compressor pressure ratio (PR) against compressor speed ratio (NC) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35\text{ }^{\circ}\text{C}$196
- Figure 6-29 Computed variation of power turbine shaft power or engine brake power (PW_{sh}) against compressor speed ratio (NC) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35\text{ }^{\circ}\text{C}$197
- Figure 6-30 Computed variation of combustor outlet temperature ($T_{B,out}$) against engine shaft power (PW_{sh}) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35\text{ }^{\circ}\text{C}$197
- Figure 6-31 Computed variation of power turbine inlet temperature ($T_{PT,in}$) against engine shaft power (PW_{sh}) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35\text{ }^{\circ}\text{C}$198
- Figure 6-32 Computed variation of combustor outlet temperature (TC,out) against engine shaft power (PW_{sh}) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35\text{ }^{\circ}\text{C}$198
- Figure 6-33 Computed variation of compressor outlet pressure (PC,out) against engine shaft power (PW_{sh}) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35\text{ }^{\circ}\text{C}$199
- Figure 6-34 Computed variation of overall compressor pressure ratio (PR) against engine shaft power (PW_{sh}) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35\text{ }^{\circ}\text{C}$199

Figure 6-35 Computed variation of compressor speed ratio (NC) against engine shaft power (PW_{sh}) for 25 MW MGT, with power turbine speed (NPT) varying as per propeller law and ambient temperature at $T_{amb} = 35\text{ }^{\circ}\text{C}$.	200
Figure 6-36 Computed variation of specific fuel consumption (sfc) against engine shaft power (PW_{sh}) for 25 MW MGT, with power turbine speed (NPT) varying as per propeller law and ambient temperature at $T_{amb} = 35\text{ }^{\circ}\text{C}$.	200
Figure 6-37 Applied propeller law expressed as the variation of engine shaft power (PW_{sh}) against power turbine speed ratio (NPT) for 25 MW MGT with ambient temperature at $T_{amb} = 35\text{ }^{\circ}\text{C}$.	201
Figure 6-38 Computed variation of combustor outlet temperature ($T_{B,out}$) with variation of power turbine speed ratio (NPT), when the engine shaft power is maintained constant $PW_{sh} = 25\text{ MW}$, for 25 MW MGT at $ISA\ SLS$ conditions.	202
Figure 6-39 Computed variation of specific fuel combustion (sfc) with variation of power turbine speed ratio (NPT), when the engine shaft power is maintained constant $PW_{sh} = 25\text{ MW}$, for 25 MW MGT at $ISA\ SLS$ conditions.	202
Figure 6-40 Computed limit of engine operation envelope given as maximum engine shaft power (PW_{sh}) with variation in ambient air temperature (T_{amb}), based on limits imposed by compressor speed limit ($NC, corr, DP$) for $T_{amb} > 15\text{ }^{\circ}\text{C}$ and combustor outlet temperature ($T_{B,corr,DP}$) for $T_{amb} < 15\text{ }^{\circ}\text{C}$, for 25 MW MGT.	204
Figure 6-41 Matching of a propeller to a diesel engine [94].	207
Figure 6-42 'AND' arrangement in a plant with no special arrangements for cruise engine[94]	207
Figure 6-43 The effect of a trailing propeller (single shaft operation) on an open water diagram of a propeller [130].	208
Figure 6-44 The effect of trailing propeller (single shaft operation) on operating line of gas turbine [130].	209
Figure 6-45 Network Relationship Map (NRM) for Performance Dimensions.	212
Figure 6-46 Computed local weights for the criteria set belonging to the Performance Objective Metric.	218
Figure 6-47 Computed local weights for the criteria set belonging to the Objective Metrics Cost and Risk	220
Figure 6-48 Relative weights applied for Objective Metrics of Performance, Cost and Risk across the various application cases	221
Figure 6-49 Computed global weights of the set of criteria for Application Case 1	222

Figure 6-50 Computed global weights of set of criteria for Application Case 2A	222
Figure 6-51 Computed global weights of set of criteria for Application Case 2B	223
Figure 6-52 Computed global weights of set of criteria for Application Case 3	223
Figure 6-53 Computed global weights of set of criteria for Application Case 4	224
Figure 6-54 Computed global weights of set of criteria for Application Case 5	224
Figure 6-55 Considered operating profile for conceptual design of propulsion system for notional destroyer	226
Figure 6-56 Calculated calm water resistance for the considered hull form for notional destroyer	227
Figure 6-57 Calculated open water characteristic for the propeller design optimised based on Wageningen B Series for notional destroyer	229
Figure 6-58 Calculated delivered power for each propeller varying with ship speed for the notional destroyer	230
Figure 6-59 Operating profile superimposed with propeller delivered power required for notional destroyer	231
Figure 6-60 Candidate propulsion system architecture alternative A1, COGAG, for notional destroyer.	233
Figure 6-61 Candidate propulsion system architecture alternative A2, CODAG, for notional destroyer.	234
Figure 6-62 Candidate propulsion system architecture alternative A3, CODAG-E, for notional destroyer.	234
Figure 6-63 Candidate propulsion system architecture alternative A4, CODELAG, for notional destroyer.	235
Figure 6-64 Candidate propulsion system architecture alternative A5, IFEP, for notional destroyer.	235
Figure 6-65 Derivation of ship speed at various operating drive modes limits based on nominal torque envelopes of the engines in the COGAG arrangement.....	237
Figure 6-66 Computed overall fuel consumption curves at defined operating drive modes for the candidate architecture alternative A1 COGAG for conceptual design analysis of notional destroyer.....	238

Figure 6-67 Computed overall fuel consumption curves at defined operating drive modes for the candidate architecture alternative A2 CODAG for conceptual design analysis of notional destroyer.....	238
Figure 6-68 Computed overall fuel consumption curves at defined operating drive mode (full operating range) for the candidate architecture alternative A3 CODAG-E for conceptual design analysis of notional destroyer.	239
Figure 6-69 Computed overall fuel consumption curves at defined operating drive modes (low speed operating range) the candidate architecture alternative A3 CODAG-E for conceptual design analysis of notional destroyer.	239
Figure 6-70 Computed overall fuel consumption curves at defined operating drive modes for the candidate architecture alternative A4 CODELAG for conceptual design analysis of notional destroyer.	240
Figure 6-71 Computed overall fuel consumption curves at defined operating drive modes for the candidate architecture alternative A5 IFEP for conceptual design analysis of notional destroyer.....	240
Figure 6-72 Computed maximum surge speed for candidate architecture propulsion system alternatives towards conceptual design analysis of notional destroyer.	241
Figure 6-73 Computed maximum cruising speed for candidate architecture propulsion system alternatives towards conceptual design analysis of notional destroyer.	241
Figure 6-74 Computed endurance (range) based on tank capacity of 500 tons with ship speed of 14 knots for candidate architecture propulsion system alternatives towards conceptual design analysis of notional destroyer. ...	242
Figure 6-75 Computed required fuel tank capacity based on range requirement of 5000 nm with ship speed of 16 knots for candidate architecture propulsion system alternatives towards conceptual design analysis of notional destroyer.....	242
Figure 6-76 Computed mass of the main propulsion and power generation equipment for the candidate architecture alternatives for conceptual design analysis of notional destroyer.	243
Figure 6-77 Computed occupied deck area of the main propulsion and power generation equipment for the candidate architecture alternatives for conceptual design analysis of notional destroyer.	244
Figure 6-78 Computed acquisition cost of the main propulsion and power generation equipment for the candidate architecture alternatives for conceptual design analysis of notional destroyer.	246
Figure 6-79 Computed lifetime maintenance cost for the main propulsion and power generation equipment for the candidate architecture alternatives for conceptual design analysis of notional destroyer.	246

Figure 6-80 Computed lifetime fuel costs of the main propulsion and power generation equipment for the candidate architecture alternatives for conceptual design analysis of notional destroyer. Average fuel price considered 480.3 Euro per ton based on US Defense Logistics Agency (DLA) Energy publication for 2020.	247
Figure 6-81 Computed occupied deck area of the main propulsion and power generation equipment for the candidate architecture alternatives for conceptual design analysis of notional destroyer.	247
Figure 6-82 Computed relative scores of candidate architecture against qualitative criteria (P4-P9) for conceptual design analysis of notional destroyer.	248
Figure 6-83 Computed relative scores of candidate architecture against qualitative criteria (P10-P15) for conceptual design analysis of notional destroyer.	249
Figure 6-84 Computed relative scores of candidate architecture against qualitative criteria (C3, C5, R1-R4) for conceptual design analysis of notional destroyer.	249
Figure 6-85 Sensitivity analysis of VIKOR ν values for Application Case 1 of conceptual design analysis of notional destroyer.	254
Figure 6-86 Sensitivity analysis of VIKOR 'Q' values for Application Case 1 of conceptual design analysis of notional destroyer.	255
Figure 6-87 Sensitivity analysis of VIKOR ν values for Application Case 2A of conceptual design analysis of notional destroyer.	255
Figure 6-88 Sensitivity analysis of VIKOR 'Q' values for Application Case 2A of conceptual design analysis of notional destroyer.	256
Figure 6-89 Sensitivity analysis of VIKOR ν values for Application Case 2B of conceptual design analysis of notional destroyer.	256
Figure 6-90 Sensitivity analysis of VIKOR 'Q' values for Application Case 2B of conceptual design analysis of notional destroyer.	257
Figure 6-91 Sensitivity analysis of VIKOR ν values for Application Case 3 of conceptual design analysis of notional destroyer.	257
Figure 6-92 Sensitivity analysis of VIKOR 'Q' values for Application Case 3 of conceptual design analysis of notional destroyer.	258
Figure 6-93 Sensitivity analysis of VIKOR ν values for Application Case 4 of conceptual design analysis of notional destroyer.	258
Figure 6-94 Sensitivity analysis of VIKOR 'Q' values for Application Case 4 of conceptual design analysis of notional destroyer.	259

Figure 6-95 Sensitivity analysis of VIKOR ν values for Application Case 5 of conceptual design analysis of notional destroyer.	259
Figure 6-96 Sensitivity analysis of VIKOR 'Q' values for Application Case 5 of conceptual design analysis of notional destroyer.	260
Figure 6-97 Considered operating profile for conceptual design of propulsion system for notional light frigate.	263
Figure 6-98 Calculated calm water resistance for the considered hull form for notional light frigate.....	265
Figure 6-99 Calculated open water characteristic for the propeller design optimised for notional light frigate based on Wageningen B Series.....	266
Figure 6-100 Calculated propeller delivered power (for each propeller) for ship speed for the notional light frigate in twin-propeller modes of operation. .	267
Figure 6-101 Operating profile superimposed with propeller delivered power required for the notional light frigate.	268
Figure 6-102 Candidate propulsion system architecture alternative A1, COGAG, for the notional light frigate.....	270
Figure 6-103 Candidate propulsion system architecture alternative A2, CODAG, for the notional light frigate.....	271
Figure 6-104 Candidate propulsion system architecture alternative A4, CODELAG, for the notional light frigate.....	271
Figure 6-105 Candidate propulsion system architecture alternative A5, IFEP, for the notional light frigate.....	272
Figure 6-106 Computed overall fuel consumption curves at defined operating drive modes for the candidate architecture alternative A1 COGAG for conceptual design analysis of notional light frigate.....	273
Figure 6-107 Computed overall fuel consumption curves at defined operating drive modes for the candidate architecture alternative A1 COGAG (low-speed operations) for conceptual design analysis of notional light frigate.	273
Figure 6-108 Computed overall fuel consumption curves at defined operating drive modes for the candidate architecture alternative A2 CODAG for conceptual design analysis of notional light frigate.....	274
Figure 6-109 Computed overall fuel consumption curves at defined operating drive modes [overall] for the candidate architecture alternative A2 CODAG for conceptual design analysis of notional light frigate.....	274
Figure 6-110 Computed overall fuel consumption curves at defined operating drive modes for [low speed range] the candidate architecture alternative A4 CODELAG for conceptual design analysis of notional light frigate.....	275

Figure 6-111 Computed overall fuel consumption curves at defined operating drive modes for the candidate architecture alternative A4 CODELAG for conceptual design analysis of notional light frigate.....	275
Figure 6-112 Computed overall fuel consumption curves at defined operating drive modes for the candidate architecture alternative A5 IFEP for conceptual design analysis of notional light frigate.	276
Figure 6-113 Computed maximum surge speed of propulsion system candidate architectures for conceptual design analysis of notional light frigate.	276
Figure 6-114 Computed maximum cruising speed of propulsion system candidate architectures for conceptual design analysis of notional light frigate.	277
Figure 6-115 Computed endurance (range) based on tank capacity of 500 tons with ship speed of 14 knots for propulsion system candidate architectures for conceptual design analysis of notional light frigate.....	277
Figure 6-116 Computed required fuel tank capacity based on range requirement of 5000 nm with ship speed of 16 knots of propulsion system candidate architectures for conceptual design analysis of notional light frigate.	278
Figure 6-117 Computed mass of the main propulsion and power generation equipment for the candidate architecture alternatives for conceptual design analysis of notional light frigate.....	279
Figure 6-118 Computed occupied deck area of the main propulsion and power generation equipment for the candidate architecture alternatives for conceptual design analysis of notional light frigate.....	280
Figure 6-119 Computed acquisition cost of the main propulsion and power generation equipment for the candidate architecture alternatives for conceptual design analysis of notional light frigate.....	280
Figure 6-120 Computed lifetime maintenance cost for the main propulsion and power generation equipment for the candidate architecture alternatives for conceptual design analysis of notional light frigate.....	281
Figure 6-121 Computed lifetime fuel costs of the main propulsion and power generation equipment for the candidate architecture alternatives for conceptual design analysis of notional light frigate. Average fuel price considered 480.3 Euro per ton based on US Defense Logistics Agency (DLA) Energy publication for 2020.	281
Figure 6-122 Computed life cycle costs of the main propulsion and power generation equipment for the candidate architecture alternatives for conceptual design analysis of notional light frigate.....	282
Figure 6-123 Computed relative scores of candidate architecture against qualitative criteria (P4-P9) for conceptual design analysis of notional light frigate.....	282

Figure 6-124 Computed relative scores of candidate architecture against qualitative criteria (P10-P15) for conceptual design analysis of notional light frigate	283
Figure 6-125 Computed relative scores of candidate architecture against qualitative criteria (C3, C5, R1-R4) for conceptual design analysis of notional light frigate	283
Figure 6-126 Sensitivity analysis of VIKOR ν values for Application Case 1 of conceptual design analysis of notional light frigate.....	287
Figure 6-127 Sensitivity analysis of VIKOR 'Q' values for Application Case 1 of conceptual design analysis of notional light frigate.....	288
Figure 6-128 Sensitivity analysis of VIKOR ν values for Application Case 2A of conceptual design analysis of notional light frigate.....	288
Figure 6-129 Sensitivity analysis of VIKOR 'Q' values for Application Case 2A of conceptual design analysis of notional light frigate.....	289
Figure 6-130 Sensitivity analysis of VIKOR ν values for Application Case 2B of conceptual design analysis of notional light frigate.....	289
Figure 6-131 Sensitivity analysis of VIKOR 'Q' values for Application Case 2B of conceptual design analysis of notional light frigate.....	290
Figure 6-132 Sensitivity analysis of VIKOR ν values for Application Case 3 of conceptual design analysis of notional light frigate.....	290
Figure 6-133 Sensitivity analysis of VIKOR 'Q' values for Application Case 3 of conceptual design analysis of notional light frigate.....	291
Figure 6-134 Sensitivity analysis of VIKOR ν values for Application Case 4 of conceptual design analysis of notional light frigate.....	291
Figure 6-135 Sensitivity analysis of VIKOR 'Q' values for Application Case 4 of conceptual design analysis of notional light frigate.....	292
Figure 6-136 Sensitivity analysis of VIKOR ν values for Application Case 5 of conceptual design analysis of notional light frigate.....	292
Figure 6-137 Sensitivity analysis of VIKOR 'Q' values for Application Case 5 of conceptual design analysis of notional light frigate.....	293
Figure A-1 'Model-View-Controller' (MVC) design implementation in Poseidon+	315
Figure A-2 Simplified overview of overall software architecture in Poseidon+	317
Figure A-3 Simplified overview of gas turbine engine core sub-module architecture in Poseidon+	318
Figure A-4 Simplified overview of ship propulsion system core sub-module architecture in Poseidon+	319

Figure A-5 Currently implemented web-based user interface for Poseidon+ ..	322
Figure B-1 Symbolic representation of Poseidon+ gas turbine model components	325
Figure B-2 Symbolic representation of Poseidon+ propulsion plant model components	326
Figure C-1 Sample Turbomatch model input file [95]	327
Figure C-2 Input file format for gas turbine engine model	330
Figure C-3 Input file format for ship propulsion system model	331
Figure E-1 Typical convergent nozzle characteristic [60]	356
Figure F-1 Definition of lengths L , L_{wl} , L_{os} [109].....	378
Figure I-1 Overview of volumes and dimensions in the dimensioning model [98]	396

LIST OF TABLES

Table 4-1 Data format used for Compressor Maps	95
Table 4-2 Generic Compressor Maps in Turbomatch, Poseidon+	98
Table 4-3 Data format for implemented Turbine Maps	100
Table 4-4 Applied generic Turbine Maps.....	101
Table 4-5 Data format for Poseidon+ Combustor Map	102
Table 4-6 Data format for Poseidon+ Nozzle Map	103
Table 4-7 Fit coefficients for gear loss model [96].....	152
Table 6-1 Primary design point parameters for 25 MW MGT	189
Table 6-2 Description of evaluation criteria	210
Table 6-3 Normalised Direct Influence Matrix for Performance Dimensions.	211
Table 6-4 Direct Influence Matrix for Performance Dimensions.	211
Table 6-5 Degree of relationship values for Performance Dimensions.	212
Table 6-6 Normalized Total Direct Influence Matrix for Performance Dimensions	213
Table 6-7 Normalised Direct Influence Matrix for comparison of criteria set of Performance Dimension D1 with criteria set of Performance Dimension D2	214
Table 6-8 Normalized Total Direct Influence Matrix for comparison of criteria set of Performance Dimension D1 with criteria set of Performance Dimension D2	214
Table 6-9 Unweighted ANP Supermatrix.....	215
Table 6-10 Weighted ANP Supermatrix with Performance Dimensions DEMATEL Weights	216
Table 6-11 Converged Supermatrix.....	217
Table 6-12 Normalized Pairwise Comparison Matrix of criteria set for Objective Metric Cost.....	219
Table 6-13 Normalized Pairwise Comparison Matrix of criteria set for Objective Metric Risk	219
Table 6-14 Cases considered for analysis of alternatives or candidate architectures	221
Table 6-15 Primary parameters of the considered notional destroyer.....	225

Table 6-16 Primary hull parameters of the notional destroyer.....	227
Table 6-17 Input data for propeller parameters optimization.....	228
Table 6-18 Final parameters for the propeller design optimised for notional destroyer based on Wageningen B Series	229
Table 6-19 Combined table of qualitative and quantitative metrics for all candidate design architectures alternatives for conceptual design analysis of notional destroyer, against the complete set of design criteria.....	251
Table 6-20 Ranking determined by VIKOR method, for varying values of ν , for all candidate design architectures alternatives for conceptual design analysis of notional destroyer, for Application Case 1.	252
Table 6-21 Computed VIKOR 'Q' values, for varying values of ν , for all candidate design architectures alternatives for conceptual design analysis of notional destroyer, for Application Case 1.....	252
Table 6-22 Computed VIKOR metrics S, R, Q and determined ranks as per for all candidate design architectures alternatives for conceptual design analysis of notional destroyer, with $\nu = 0.5$	253
Table 6-23 Selection of best suited candidate architecture and test of 'acceptable advantage' and 'stability of decision' for conceptual design analysis of notional destroyer, with $\nu = 0.5$	254
Table 6-24 Primary parameters of the considered notional light frigate.	263
Table 6-25 Primary hull parameters of the notional light frigate.	264
Table 6-26 Input data for propeller parameters optimization for the notional light frigate.	265
Table 6-27 Final parameters for the propeller design optimised for notional light frigate based on Wageningen B Series.	266
Table 6-28 Combined table of qualitative and quantitative metrics for all candidate design architectures alternatives for conceptual design analysis of notional light frigate, against the complete set of design criteria	285
Table 6-29 Computed VIKOR metrics S, R, Q and determined ranks as per for all candidate design architectures alternatives for conceptual design analysis of notional light frigate, with $\nu = 0.5$	286
Table 6-30 Selection of best-suited candidate architecture and test of 'acceptable advantage' and 'stability of decision', for $\nu = 0.5$	287
Table D-1 Values of substance-specific coefficients ak, i	340
Table D-2 Values of exponent bi	340
Table F-1 Coefficients for F&L Method.....	376

Table F-2 Hollenbach resistance coefficients [94].	381
Table F-3 H&M Method: Range of Application [98,106].	382
Table F-4 F&L method: Range of Application [132].	382
Table F-5 Hollenbach method: Range of Application [106].	382
Table G-1 Coefficients for the <i>KT</i> and <i>KQ</i> polynomials representing the Wageningen B-propeller series for a Reynolds number of 2×10^6 [108]. ...	384
Table G-2 Extent of B-Series propeller parameters.	386
Table O-1 Primary design point parameters for 7.5 MW MGT	418
Table O-2 Primary design point parameters for 15 MW MGT	432
Table O-3 Primary design point parameters for 36 MW MGT	446

LIST OF EQUATIONS

(4-1)83

(4-2)84

(4-3)85

(4-4)85

(4-5)85

(4-6)86

(4-7)86

(4-8)87

(4-9)87

(4-10)87

(4-11)87

(4-12)88

(4-13)89

(4-14)89

(4-15)89

(4-16)90

(4-17)97

(4-18)97

(4-19)99

(4-20)101

(4-21)101

(4-22)101

(4-23)102

(4-24)102

(4-25)103

(4-26)105

(4-27)105

(4-28)	105
(4-29)	106
(4-30)	106
(4-31)	106
(4-32)	106
(4-33)	106
(4-34)	106
(4-35)	107
(4-36)	107
(4-37)	107
(4-38)	107
(4-39)	108
(4-40)	111
(4-41)	111
(4-42)	112
(4-43)	112
(4-44)	115
(4-45)	115
(4-46)	116
(4-47)	116
(4-48)	117
(4-49)	117
(4-50)	117
(4-51)	117
(4-52)	121
(4-53)	121
(4-54)	122
(4-55)	122
(4-56)	123

(4-57)	123
(4-58)	123
(4-59)	123
(4-60)	124
(4-61)	124
(4-62)	124
(4-63)	126
(4-64)	127
(4-65)	128
(4-66)	128
(4-67)	129
(4-68)	129
(4-69)	129
(4-70)	129
(4-71)	129
(4-72)	129
(4-73)	130
(4-74)	130
(4-75)	132
(4-76)	132
(4-77)	133
(4-78)	133
(4-79)	133
(4-80)	133
(4-81)	133
(4-82)	134
(4-83)	134
(4-84)	134
(4-85)	135

(4-86)	135
(4-87)	135
(4-88)	135
(4-89)	135
(4-90)	135
(4-91)	136
(4-92)	136
(4-93)	136
(4-94)	136
(4-95)	136
(4-96)	136
(4-97)	136
(4-98)	137
(4-99)	138
(4-100)	138
(4-101)	139
(4-102)	139
(4-103)	139
(4-104)	139
(4-105)	139
(4-106)	140
(4-107)	140
(4-108)	140
(4-109)	140
(4-110)	140
(4-111)	140
(4-112)	140
(4-113)	142
(4-114)	143

(4-115)	152
(4-116)	154
(4-117)	154
(4-118)	155
(4-119)	155
(4-120)	156
(4-121)	157
(4-122)	158
(5-1)	169
(5-2)	170
(5-3)	170
(5-4)	171
(5-5)	171
(5-6)	171
(5-7)	171
(5-8)	171
(5-9)	172
(5-10)	172
(5-11)	172
(5-12)	172
(5-13)	173
(5-14)	173
(5-15)	173
(5-16)	174

NOMENCLATURE

Alphabetic Symbols

Symbol	Definition	Unit
A	Area	$[m^2]$
A_P	Projected frontal area of ship superstructure	$[m^2]$
A_E	Expanded blade area	$[m^2]$
A_O	Propeller disc area	$[m^2]$
A_D	Propeller developed area	$[m^2]$
A_P	Propeller projected area	$[m^2]$
AR	Nozzle Area Ratio	[-]
C_F	Coefficient of frictional resistance	[-]
C_R	Coefficient of residuary resistance	[-]
C_W	Coefficient of wave resistance	[-]
C_D	Air drag coefficient	[-]
CI	AHP Consistency Index	[-]
CR	AHP Consistency Ratio	[-]
c_p	Specific heat at constant pressure	$[J.kg^{-1}.K^{-1}]$
c_v	Specific heat at constant volume	$[J.kg^{-1}.K^{-1}]$
D	Diameter	$[m]$
d	Ship bow thruster tunnel diameter	$[m]$
D_i	Performance Dimension	[-]
E	Error	[-]
F	Thrust Engine (Aero)	$[N]$
F_n	Froude number	[-]
FAR	Fuel Air Ratio	[-]
F^c	VIKOR compromise solution	[-]
F^*	VIKOR ideal solution	[-]
G	AHP Pairwise Comparison Matrix	[-]
g	Acceleration due to gravity	$[m.s^{-2}]$
H	Enthalpy	$[J]$
h	Specific enthalpy	$[J.kg^{-1}]$
I	Current	A

i	Gear ratio	[-]
J	Propeller advance number	[-]
K_T	Propeller thrust coefficient	[-]
K_Q	Propeller torque coefficient	[-]
L	Length	[m]
N_c	Corrected speed ratio	[-]
N	rotational speed	rpm
n	Rotational speed	rps
P	Propeller Pitch	[m]
P/D	Propeller Pitch to Diameter Ratio	[-]
P	Pressure, Total Pressure	[Pa]
p	Static pressure	[Pa]
PS	Static pressure	[Pa]
PW	Power	[kW, MW]
Q	Torque	[N.m]
q_T	Dynamic pressure	[Pa]
R	Resistance	[N]
R	Gas constant	[J.kg ⁻¹ .K ⁻¹]
R_u	Universal gas constant	[J.K ⁻¹ .mol ⁻¹]
Re	Reynolds number	[-]
S	Surface Area	[m ²]
sfc	Specific fuel consumption	[kg.kW ⁻¹ .h ⁻¹]
s	Specific entropy	[J.K ⁻¹ .kg ⁻¹]
T	Temperature, Total temperature, Thrust	[K] or [°C]
TS	Static temperature	[K]
T_D^α	Normalized Total Direct Influence Matrix	[-]
T_c^α	Normalised Influence Matrix	[-]
t	Thrust deduction factor	[-]
U	Voltage	V
V_S	Ship speed	[m.s ⁻¹ or knots]
V_A	Advance velocity of propeller	[m.s ⁻¹]
V_R	Resultant velocity	[m.s ⁻¹]
v	Specific volume	[m ³ .kg ⁻¹]

W	Mass flow	[kg.s ⁻¹]
WF	Fuel flow	[kg.s ⁻¹]
w	Wake fraction	[-]
w_i	Criteria weight	[-]
W_c	Unweighted Supermatrix	[-]
W_c^*	Weighted Supermatrix	[-]
X	DEMATEL Initial Direct Influence Matrix	[-]
x_k	mole fraction (mole/ concentration in mol/g)	[mol. g ⁻¹]
Z	Propeller blade number	[-]
Z_c	Compressor surge margin	[-]
Z_T	Turbine enthalpy ratio	[-]

Greek Symbols

Symbol	Definition	Unit
ρ	Mass density of fluid	[kg.m ⁻³]
η	Efficiency	[-]
ν	Kinematic viscosity	[m ² .s ⁻¹]
γ	Ratio of specific heats	[-]
σ	Cavitation number	[-]
μ	Dynamic viscosity	[kg.m ⁻¹ .s ⁻¹]
θ	Propeller local geometric pitch angle	[deg]
θ	Inlet temperature / 288.15 K	[-]
ϕ	Entropy function	[-]
λ_{max}	AHP principal eigen value	[-]
δ	Inlet pressure / 101 325 Pa	[-]

Subscripts

Subscript	Definition
A	Advance
Air	Air
APP	Appendage
atm	Atmosphere
B	Burner (Combustor)
BT	Bow Thruster
Bur	Burrill
C, c	Compressor
c	Cost
corr	Corrected
D	Delivered
E	Effective
e	Electric
EM	Electric Motor
eq	Equivalent
F	Friction
F&L	Fung And Liebman
FO	Fouling
FW	Freshwater
gr	Gearing
H	Hull
H&M	Holtrop & Mennen
Hol	Hollenbach
in	Inlet
k	Component Of Mixture
Kel	Keller
loss	Loss
n	Nozzle
nom	Nominal
O	Open Water
out	Outlet

P	Propeller
p	Performance
PT	Power Turbine
Q	Torque
R	Resistance, Residual Resistance
R	Risk
ref	Reference
S	Ship
SB	Switchboard
sh	Shaft
SS	Sea State
SW	Seawater
T, t	Turbine
T	Total
T	Thrust
W	Water
WI	Wind

1 LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
ASW	Anti-Submarine Warfare
CCG	Cross-Connect Gear
CFD	Computational Fluid Dynamics
CIL	Compiled to an Intermediate Language
CODAG	COmbined Diesel engine And Gas turbine
CODAG-E	COmbined Diesel engine And Gas turbine with Electric
CODELAG	COmbined Diesel ELeetric And Gas turbine
COGAG	COmbined Gas turbine And Gas turbine
COT	Combustor Outlet Temperature
COTS	Commercial Off the Shelf
CPP	Controllable Pitch Propeller
CVF	Cooling Volume Factor
DANP	DEMATEL-ANP
DE	Diesel Engine
DEMATEL	Decision Making Trial and Evaluation Laboratory
DP	Design Point
EAR	Expanded Blade Area Ratio
ECMA	European Computer Manufacturers Association
F&L	Fung and Liebman
FAR	Fuel Air Ratio
FC	Frequency Converters
FPP	Fixed Pitch Propeller
GB	Gear Box
Gensets	Generators Sets
GES	Dutch abbreviation for Integrated Energy Systems
GP	General Purpose
GT	Gas Turbine
GTA	Gas Turbine Alternator
GTG	Gas Turbine Generators Sets
H&M	Holtrop and Mennen

ICR	Inter-Cooled Regenerative
IDE	Integrated Development Environment
IFEP	Integrated Full Electric Propulsion Systems
ISA	International Standard Atmosphere
ISO	International Organization for Standardization
ITTC	International Towing Tank Conference
LCC	Life Cycle Costs
LV	Low Voltage
MAUT	Multi-Attribute Utility Theory
MCDM	Multiple-Criteria Decision-Making
MGT	Marine Gas Turbine
MISO	Multiple Input Single Output
MoD	Ministry of Defence
MV	Medium Voltage
MVC	Model-View-Controller
NM	Nelder-Mead
NRM	Network Relationship Map
OD	Off Design
OMOE	Overall Measure of Effectiveness
OOP	Object-Oriented Programming
PT	Power Turbine
PTIT	Power Turbine Inlet Temperature
PTO	Power Take Off
PWM	Pulse-Width Modulated
SB	Switchboard
SISO	Single Input Single Output
SLS	Sea Level Standard
TERA	Techno-economic & Environmental Risk Assessment
TNO	Netherlands Organisation for Applied Scientific Research
US NAVSEA	Naval Sea Systems Command
VIKOR	Višekriterijumsko KOmpromisno Rangiranje in Serbian, translates to multicriteria optimization and compromise ranking

1 INTRODUCTION

1.1 Background and Motivation

In the overall design of the ship, the initial design process plays a significant part, with 70-80% of the shipbuilding costs being committed or influenced by the decisions made during this part of the design [1],[2]. One of the key elements of the initial design of the ship is the development of the conceptual design of the ship propulsion system. The conceptual design of the propulsion system and the ship design significantly influence each other, with factors such as propulsion equipment volume, deck area availability, fuel tank volume, occupation of space on upper decks etc. With the increased electrification of ships, the conceptual design of the propulsion system can also subsume the process of the conceptual design of the electric grid system of a ship. Further, while often upgrades are possible for many ship systems during the life span of the ship, the hull and propulsion system designs are developed for lasting through the entire lifespan of the ship. Hence the conceptual design of the ship propulsion system is a key step in the initial design process of a ship, that significantly influences the overall ship design, performance, and costs.

For propulsion systems designed to fulfil a large number of conflicting design criteria such as high speed, large endurance, low acoustic signatures, high flexibility of operation, survivability etc., ‘combined’ propulsion plant architectures provide a good solution. Such architectures basically involve the application of multiple engines and drives integrated by flexible mechanical, electrical or hybrid transmission systems to deliver the specified design criteria derived from the overall ship design objectives based on the operating or mission profile of the ship. Multiple operating modes involving the utilization of different engines or drives are used to fulfil the various design criteria. Increased efficiency at the plant level is a key objective of such ‘combined’ plants. For ships that need to operate at high speeds, the application of gas turbines is preferred due to their very high power to weight ratio compared to other engines [3]. However, the design of such combined plants adds additional complexity to the design process of the ship propulsion systems.

While a large part of the design analysis for ship propulsion systems is based on the requirements to meet the condition of the rated power of the plant, many ship applications like warships spend a majority of their life at very load conditions or 'off-design' conditions. Hence the analysis of the propulsion systems under these off-design conditions should be a key consideration during design. If such analysis is not sufficiently considered during design, significant performance benefits of a combined plant can be lost. However, during the early stages of ship design where the conceptual design of the propulsion system is undertaken, an in-depth performance analysis of the propulsion, especially for the off-design point operation, is often not undertaken. Accurate performance predictions based on simulation studies for off-design conditions, leading to a higher level of certainty in design which can reduce the requirements of multiple safety margins often used in the design practices. On the other hand, there are many design criteria, e.g., acoustic behaviour, for which very accurate predictions are difficult at the early stages of design. However, for such criteria, historic data or expert opinion data could be captured on a relative scale and used in a decision-making model to make better informed decisions.

When the designer is faced with the task of designing a propulsion system architecture to meet a very large number of design criteria and constraints, a systematic procedure for a techno-economic analysis-based exploration of the design space that combines the performance predictions with historic data and expert opinion, could lead to much-improved design solutions. Such design solutions could provide the benefits of lower design risks, life cycle costs and higher plant efficiency over the entire operating envelope of the propulsion plant.

1.2 Aim and Objectives

The aim of this research work was to develop a process for design space exploration of gas turbine based 'combined' ship propulsion systems using a techno-economic model-based approach towards the overall conceptual design of a ship propulsion system based on the defined design objectives and operational profile.

Key objectives that were defined to achieve the above aim are:

1. Establishing the overall framework requirements for undertaking the design space exploration of ship propulsion systems based on techno-economic studies.
2. Development of an integrated, agile, performance modelling methodology for ship propulsion systems that would allow the engines, as well as other elements of the propulsion system including that for multi-engine, combined plants, in a common modelling domain.
3. The modelling environment of the propulsion system should allow for modelling of various operating 'drive modes' where different combinations of engines, clutches and propulsors are used to operate the plant efficiently at various points in the ship operating profile.
4. Validate the developed modelling procedure and apply it to multiple combined plant designs to analyse the overall system performance considering the interactions between the engines and other elements of the propulsion plant.
5. Identify and apply dimensioning and costing models for propulsion system equipment for the economic aspect of the analysis.
6. Identify the key criteria required to be considered for the design of ship propulsion systems and establish the degree of relationships between the criteria.
7. Identification, integration and application of decision-making models required to select the most optimal design from a design space with candidate propulsion system architectures.
8. Application of the overall framework to undertake analysis for notional ship designs of a light frigate and a destroyer.

1.3 Novelty of the Research Work

The primary novelty in the research work undertaken is as follows:

1. Development of a generalized ship performance modelling procedure based on a 0-D component-based approach, with an algorithm to analyse the direction of 'torque flow' based on the states of engines and clutches, giving

the ability to model the large number of 'drive modes' that are typical to combined propulsion plants.

2. Identifying the most often applied design criteria for conceptual design of ship propulsion plants and analysing the degree of relationships between these criteria that affect the decision-making models for selection of preferred plant architecture.
3. Application of multi-criteria decision-making techniques for combining quantitative data based on performance modelling of ship propulsion systems, with qualitative data from expert opinion, for selection of the best compromise solution from the design space populated with candidate propulsion system design architectures.

1.4 Thesis Structure

The overview of the structure of the thesis, divided into seven chapters, is shown in Figure 1-1. Chapter 1 (present chapter) provides a brief introduction to the research work undertaken along with a short description of the novelty of the work. The literature review undertaken towards the primary objectives of the research work is presented in Chapter 2. Chapter 3 presents the overall methodology used for the present research work. This chapter also includes the scope and the boundaries of the applied methods towards the research work.

The overall performance modelling framework developed to undertake the present research work towards performance analysis is described in Chapter 4. This chapter is divided into sections describing the overall concept of performance modelling used, followed by performance modelling concepts used for gas turbine engines and propulsion plant modelling. Considering the wide theoretical background and a large number of relationships applicable for the models used, the content of the chapter focuses more on the developed overall modelling concept while the theoretical background and detailed equations used for the performance simulation calculations are included in the referred appendices.

Chapter 5 describes the integration and application of the selected multi-criteria decision-making methods for undertaking the techno-economic analysis. The chapter also describes the methodology for establishing the network and hierarchy of design criteria for propulsion system design. Chapter 6 describes the application of the established framework for undertaking the concept design of ship propulsion plants for notional light frigate and destroyer designs. The chapter initially describes the results of performance simulations undertaken for various gas turbine engines used for the candidate propulsion system designs. This is followed by performance and further trade-off analysis undertaken for the candidate propulsion system design architectures applicable for the notional light frigate and destroyer designs. The overall conclusions, achievements for the research work and recommendations for future work are included in Chapter 7.

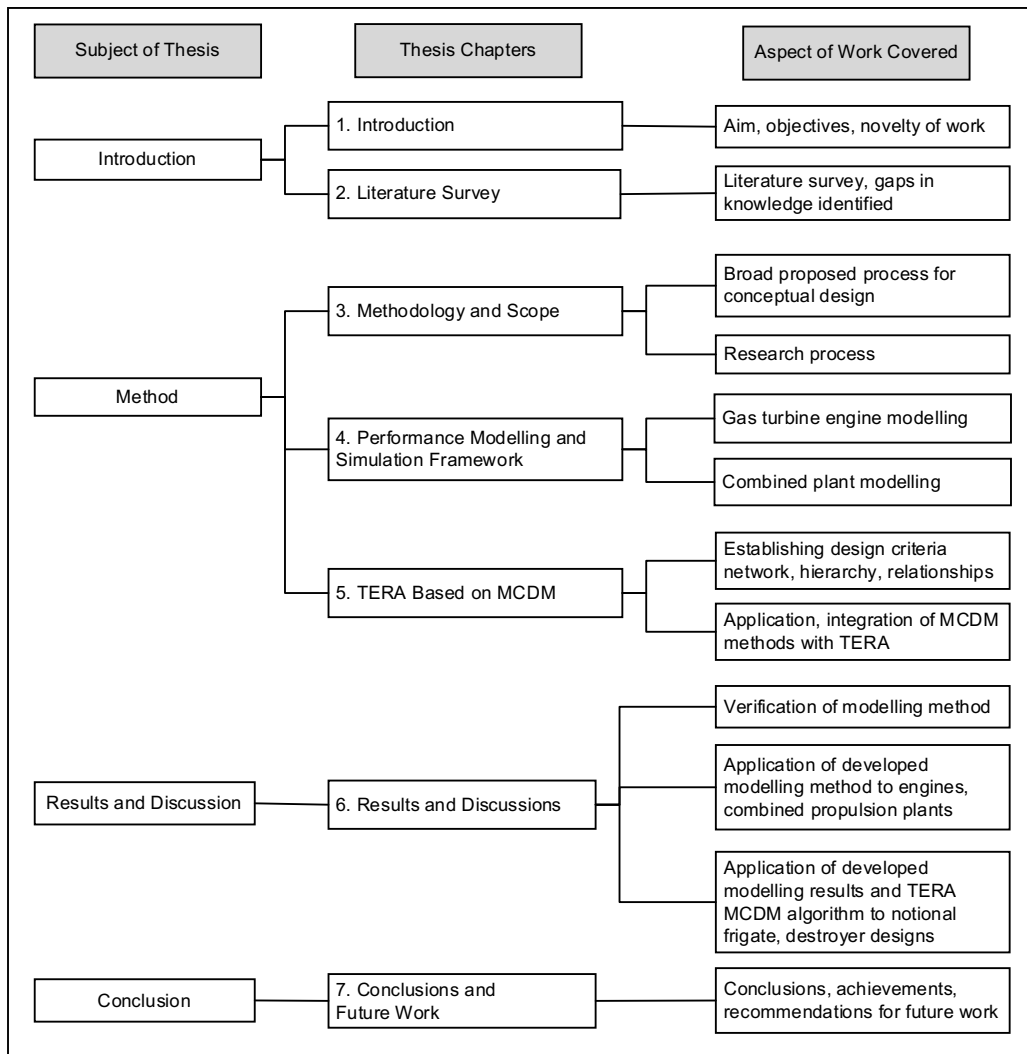


Figure 1-1 Overview of the structure of the thesis.

2 LITERATURE REVIEW

The literature review presented in this chapter focuses on the primary objectives identified towards achieving the overall aim of this research work. References to more specific subjects of the research are included in the respective chapters. The chapter initially describes the current practices towards the conceptual design of a ship propulsion system in the context of the overall ship design process. Thereafter the 'state of the art' methods used to use for performance modelling of ship propulsion systems are briefly discussed. The review also includes the application of TERA, which is widely used for techno-economic analysis across various domains of application. A review of the popular Multi-Criteria Decision Making (MCDM) techniques used for complex decision-making problems has also been briefly presented. This chapter concludes with a summary of the review and the identified gaps in knowledge that are aimed to be addressed by this research work.

2.1 Conceptual Design

Ship design is an iterative process and as the propulsion system is an integral part of the ship, not easily changed once installed, it is important that it is well-considered from the earliest stages of the ship design process [4]. Since the 1960s, the ship design process has popularly been represented by the ship design spiral [5], [6], [7] as shown on the left side of Figure 2-2. The overall ship design process is usually considered to be divided into the stages of 'Conceptual Design' wherein preliminary estimations of the basic ship dimensions and ratios are made, 'Preliminary Design' which involves the accurate determination of the ship's main characteristics based on earlier studies, 'Contract Design' involving the completion of the ship design calculations and drawings, drawing up of the technical specifications for the shipbuilding contract and finally 'Detailed Design' which leads to production level drawings and specifications [8].

For more complex ship designs, like those often typical to warship designs, the timescale from the first conception of requirements to the commissioning of the first ship of the class can be some 12 to 15 years [9]. When framing the role that

the ship will be required to carry out, the naval staff may not be aware of not only of what is technologically feasible at the time of stating the requirement but also of what can confidently be expected to be feasible at some considerable time in the future when the decision to order the ship will be made [9].

The initial design process of the ship plays a significant part in the overall design with 70-80% of the fixed costs of shipbuilding being committed or influenced by the decisions made during this part of the design [1],[2] as shown in Figure 2-1. When considering such factors as weight, volume, manning and cost, the propulsion plant normally has the most significant impact on the ship, and thus upon payload of the ship [10].

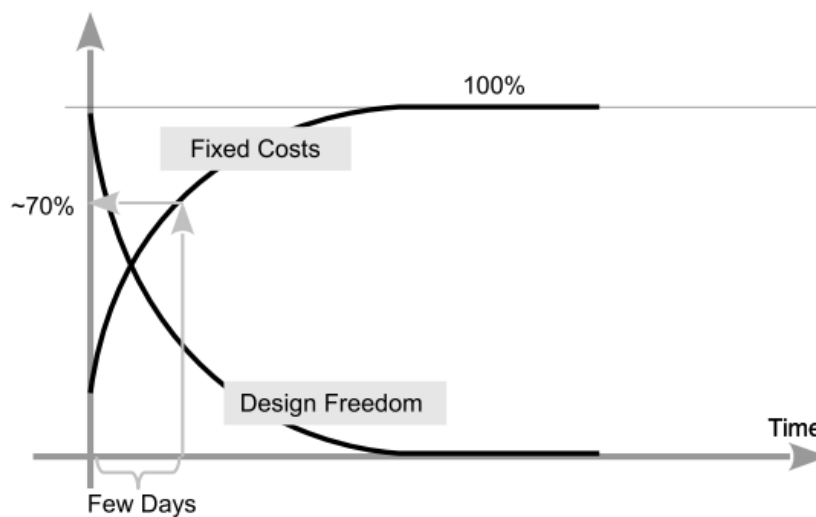


Figure 2-1 Design Timeline [1].

In general, the traditional representation of the ship design process by means of the design spiral reflects the iterative nature of the design process, as is shown on the left part of Figure 2-2, where the design process follows the spiral starting from the outside and is refined as it follows the spiral inward, through the various stages of ship design viz. concept, preliminary, contract and detailed design. The process is based on iterated cycles until the achievement of a satisfactory design solution [1]. The design spiral represents an idealization of the traditional workflow which was indeed to study one issue at a time and to advance in the design step by step, undertaking modifications and establishing refinements iteratively [11]. However, a modern, integrated approach to ship design, as shown on the right side of Figure 2-2, is based on a computer-based synthesis process

which integrates techno-economical databases, calculation and optimization algorithms that allow the exploration of the design space to a much larger extent and leads to new insights and promising new design alternatives [11]. Here the design is not following a stepwise iterative process as for the design spiral, but is being converged upon from the 'outside' towards the 'inside' (in terms of design refinement), using computerized processes, as shown in the right side of Figure 2-2. Both the traditional design spiral and the modern ship design synthesis processes approach the propulsion system design in different ways, embedded in the overall ship design process, as described in the next paragraph.

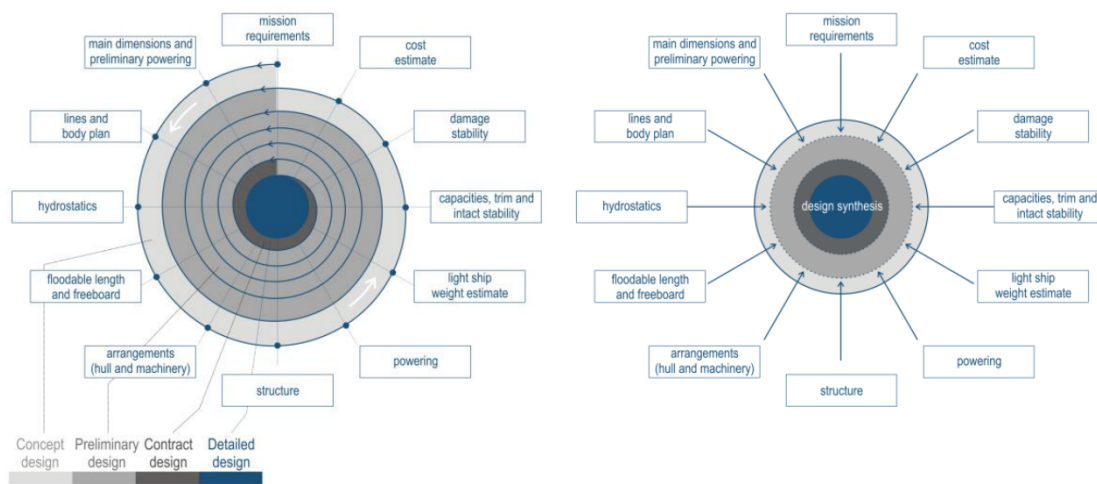


Figure 2-2 Traditional ship design spiral vs. modern integrated ship design synthesis approach [11].

Stepanchick et.al. [12] have noted that the traditional approach to ship design, represented by the ship design spiral, is largely an 'ad hoc' process, where experience, design lanes, rules of thumb, preference, and imagination guide the selection of design concepts for assessment. With such a process often, objective attributes are not adequately synthesized or presented to support efficient and effective decisions [12]. To address these issues, a 'total system approach', represented by the ship design synthesis process, was proposed including a structured search of the design space based on the multi-objective consideration of effectiveness, cost and risk [12].

Stratmann [13] describes the various aspects of engineering management during the early stages of a warship design process where the lead shipbuilder carries

out more in-depth investigations into cost versus capability trade-offs, in the context of the high-level model for 'Warship Engineering Management' published by UK MoD based on the V-diagram as shown in Figure 2-3. In this approach, the overall ship design process is viewed as a 'systems engineering process' 'V-model' with the propulsion system being one of the systems being addressed by the process. The initial trade-off studies to decide the architecture of the propulsion system would need to be undertaken during the stage of 'determining performance system architecture' in the V-diagram.

Palmer [3] highlights that the design of a ship propulsion system requires close collaboration of the naval architect, with the marine engineers, who are principally responsible for the main propulsion plant while naval architects are responsible for the hydrodynamic and hull form characteristics of the ship and propellers. The development of the most effective means of achieving a desired ship's speed also requires trade-offs between naval architects and marine engineers, with due regard for the vessel's intended use [3]. Watson [6], in his textbook on ship design, states that the naval architect, when calculating the propulsive power to specify to the marine engineer, has to rely on a number of assumptions to enable the calculation of quasi-propulsive coefficient which, has a major influence on the required power. The traditional distinctions between naval architecture and marine engineering have been replaced by broader methods of systems engineering and analysis [3].

Combined plants, in configurations commonly termed as COGAG, COGOG, VIKOR, CODOG, CODELOG, CODELAG, IFEP etc. (general description of this terminology is given in Appendix K), are usually used when a single prime mover (a diesel engine, or a gas turbine) cannot acceptably satisfy all the operating conditions and requirements. For example, warships are required to operate for extended periods at low, economical cruising speeds, but upon command may be required to reach maximum power, which can be several hundred per cent higher, in a matter of minutes to respond to an emergency [3]. In combined plants, two different types of prime movers or different sizes of the same type of prime movers are connected to the propeller shaft through a common transmission

system to take advantage of the desirable features of each prime mover [3]. Combined propulsion plant architectures attempt to capitalize on the advantages offered by various combinations of prime movers and power generating systems [10]. The single biggest reason for using combined plants is increased plant efficiency [10]. The efficiency of the system is targeted at a system level by designing for higher efficiency at the speed ranges where the ship would be operated for a majority of its operating time [14].

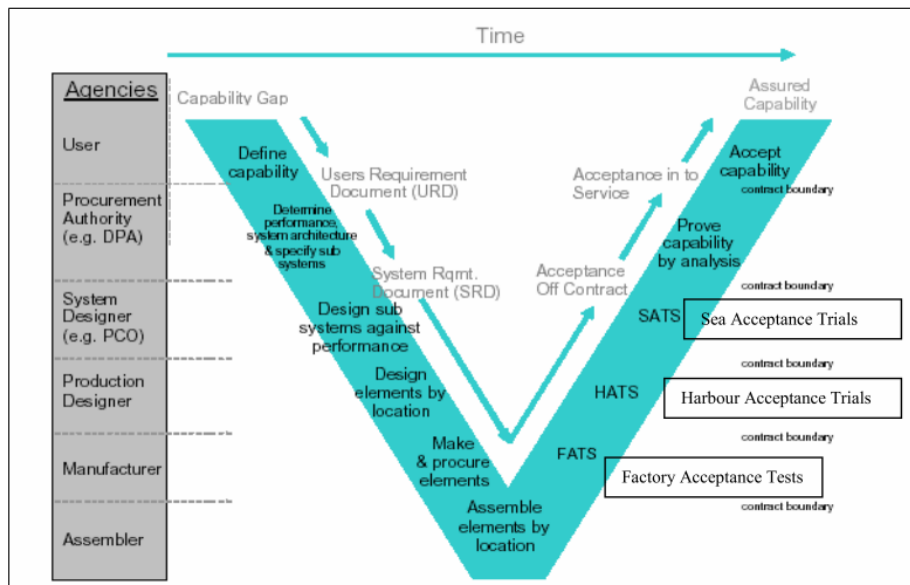
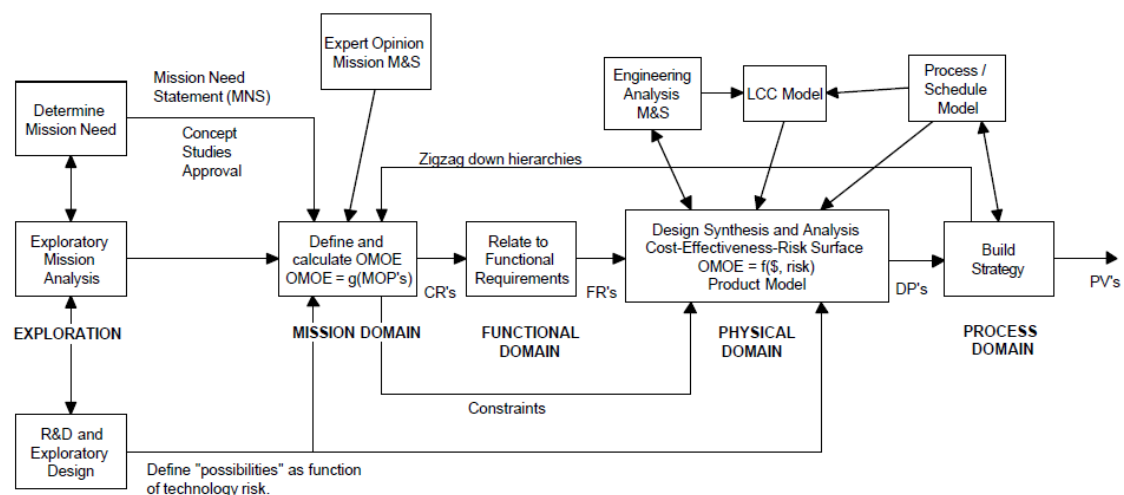


Figure 2-3 'Warship Engineering Management' V-diagram [15].

Plumb [4] notes that while there have been many books, papers and articles on the individual elements that make up a propulsion system but very few on the system design itself or on how to select a system for a ship. The process for integration of ship propulsion systems is well described in the textbook by Plumb [4], comparing the merits and demerits of various propulsion equipment and configurations. Many investigations on the suitability of various propulsion equipment for various applications have been published, like for marine propulsion engines [15] and propulsors [16].

Webster et.al. [17] published the results of a US NAVSEA study undertaken for evaluation of technical and cost impacts of alternative propulsion methods for various types of surface ships based on the fossil fuel-based energy plants contrasted with nuclear energy alternatives. The study included power and

propulsion technologies including gas turbines, diesel engines, mechanical power transmission systems, hybrid power transmission systems, integrated power transmission systems, combined power plants, nuclear power and various propulsor systems. Gully [18] presented an analysis of the performance of hybrid powertrains for naval and commercial ocean-going vessels based on simplified polynomial fit function models for propulsion equipment.



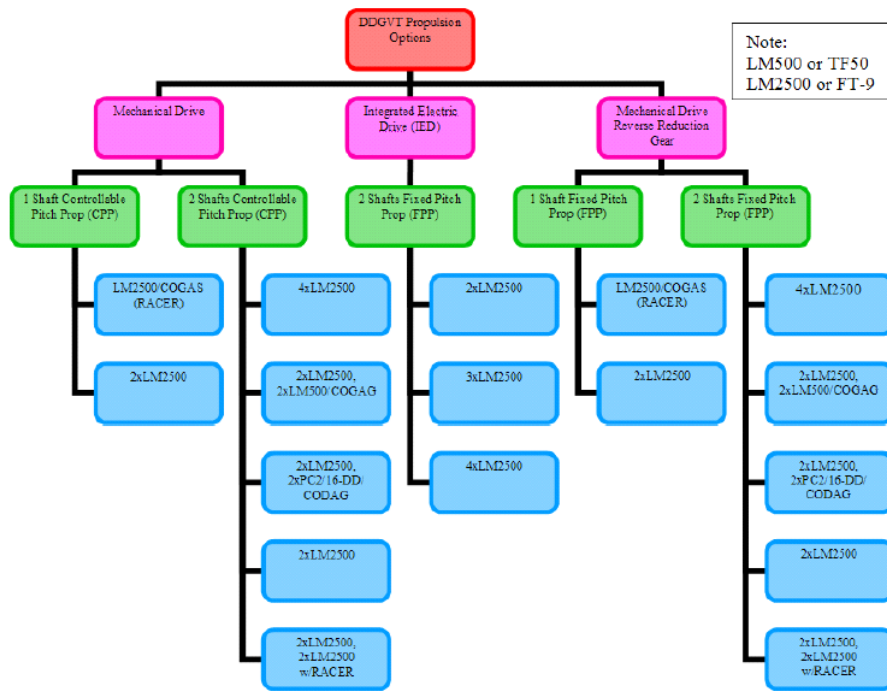


Figure 2-5 Propulsion machinery alternatives[12].

2.2 Engine and Propulsion Plant Modelling

2.2.1 Marine Propulsion System Performance Simulation

Rubis et.al. presented one of the earliest integrated gas turbine and ship propulsion modelling and simulation modelling methods aimed at predicting ship propulsion plant and control system performance for the development of propulsion control systems and their design for protection against excessive torques, thrusts or overspeed conditions [20,21]. Detailed diesel engine component models integrated with propulsion system was presented in the work of Schulten [22] describing the dynamics of interaction between the diesel engines and ship propulsion systems. Benvenuto [23] presented a gas turbine modular model for ship propulsion dynamics. Martelli [24] et.al. published the modelling method of propulsion control systems for a six-degrees of freedom ship motion system.

Figari et.al. [25] presented a methodology for simulation studies to analyse the dynamic behaviour and stability of marine propulsion systems. Campora et.al. [26] presented the method used for full-scale validation of the numerical

simulation of ship propulsion transients. Altosole et.al. [27] published the process used for real-time simulation of a COGAG naval ship propulsion system. Martelli [28], Altosole [29], Campora [30] et.al. have published multiple papers on the propulsion dynamics and control strategies of CODELAG propulsion systems. Menard [31] published a methodology used for the prediction of manoeuvring dynamics for the IFEP based on the US Navy DDG-1000 design. Altosole [32] et.al. presented simulation studies related to propulsion control strategies for ship emergency manoeuvres.

Vrijdag et.al. [33] proposed a systematic approach towards the modelling, verification, calibration and validation of a ship propulsion simulation model to develop a propulsion control system aimed at increased cavitation free time in operational conditions. Geertsma et.al. [34] presented modelling of hybrid propulsion plants with controllable pitch propellers for adaptive pitch control aimed at reduction of emissions.

2.2.2 Cranfield University in the Field of Gas Turbine Engine and Plant Performance Modelling and Simulation

Cranfield University, over the years, has developed a suite of computer applications for gas turbine engines, engine emissions and plant simulation with contributions, from faculty and students, that include Turbomatch, Pythia, Web Engine, Hermes, Poseidon, TERA, Turbo Electric Distributed Propulsion etc.

Turbomatch is one of the primary tools used at Cranfield University for gas turbine simulation. Turbomatch was developed by Macmillan in 1974 [35], based on some of the earliest simulation programmes developed for gas turbine engine simulation such as Palmer's 'Turbocode' scheme [36], 'Simulation of Turbofan Engine' by McKinney in 1967 [37], 'GENENG - A Program for Calculating for Turbojet and Turbofan Engine Design and Off-Design Performance' by Koenig and Fishbach [38,39]. Since its initial development, Turbomatch has been continuously updated by contributions of students and faculty members, some of the most significant being from van den Hout in 1991 [40], Sirinoglou in 1992 [41], Pachidis in 2006 [42], Mucino in 2007 [43], Janikovic in 2010 [44] and

Giannakakis in 2013 [45]. However, through these enhancements, the basic code structure and core design of Turbomatch has remained the same.

Pythia was thereafter developed by Escher in 1995 [35] to provide for the ability to undertake engine diagnostic related studies. A web-based application, 'Web Engine', was developed by Apostolidis and Suresh in 2013 [47], [48] using the Turbomatch as its core, to provide an ergonomic a web-based graphical user interface and offering a key advantage of not requiring any software installation on the user machine for using the application. For undertaking simulation of the integrated aircraft engine performance, Hermes was developed designed to interface with Turbomatch. APPEM (Analysis and Prediction of Pollutant Emissions) was developed for modelling combustor performance and predicting exhaust emissions calculation.

Poseidon was developed by Tsoudis in 2008 [49] as an integrated computational marine vessel operation environment simulation tool with modules for marine vessel power prediction, power plant operation management and journey management. The primary objective for the development was to undertake economic feasibility studies of marine power plants with gas turbines. The TERA analysis using Poseidon is based primarily on a journey management module that looks at the engine and journey or voyage parameters defining ambient conditions dependent on routes taken by commercial vessels. Bonet [39] further developed Poseidon for exhaust pollutant emissions under the effect of varying environmental conditions of long hauled voyages.

To use Poseidon, the off-design operational characteristics of each gas turbine engine need to be initially created by the user using Turbomatch, tabulated into two or three-dimensional look-up tables, which are then used by the Poseidon program by using linear interpolation to obtain the required output engine parameters [49]. Further, Royo Bono [51] observed that Turbomatch does not allow the rotational speed of the power turbine to be used as a 'handle', and hence it is not possible to calculate the required fuel to produce the required power and rotational speed of the engine. To overcome this, Royo Bono [40] used the method as shown in Figure 2-6, which involves the creation of a scaled power

turbine ‘performance map’, for relative rotational speed lines. Using this map, for a given fuel flow, a relative rotational speed is selected and by an iterative ‘matching process’.

Mody [52] published the results of a joint project involving University of Strathclyde (UoS), University of Manchester (UoM) and Cranfield University (CU) aimed at the development of a simulation modelling tool for undertaking gas turbine steady-state and transient performance in Integrated Full Electric Propulsion Systems (IFEP). UoS was responsible for the preparation of the electrical simulation models and integration of electrical and mechanical models, UoM for preparation of models for electrical drives, propellers and ship, and CU contributed by development simulation of prime mover models, techno-economic environmental and risk analysis of marine power plants. This modelling tool was aimed at application in the marine industry in the ‘pre-design’ stage to allow proof of concept and to thus provide technological back-up and risk-mitigation for IFEP plants. The engines models of some specific engines were written in FORTRAN 77 and transformed as a direct link library to a SIMULINK package for running system-level simulations [52].

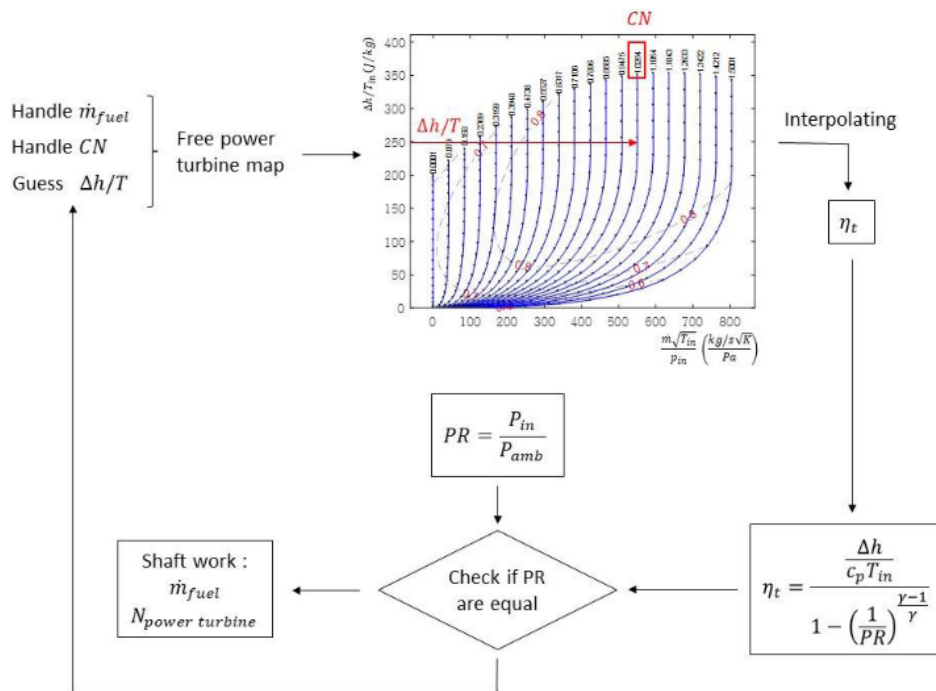


Figure 2-6 Iterative process followed to obtain free power turbine work for different rotational speeds [51].

2.2.3 Dimensioning and Costing Models

The data on the mass and dimensions of standard equipment like engines is usually easily available from the manufactures in the form of technical specs, project guides, brochures etc. However, to use this data for comparative analysis, additional considerations are needed to ensure that the data indicated are based on similar considerations like the mass of base frames, enclosures, auxiliaries etc. The data for mass and dimensions of more custom-designed equipment like geared transmission systems, propellers etc. is not usually readily available. However, it is indeed possible to create simple regression-based models for the propulsion equipment and it is known that such models are built by shipyards, design and research organizations.

The literature review on the subject indicated that, while some generic information on the subject has been published in textbooks [3], [53], such models are not widely published. Stapersma et.al. published an interesting paper on dimension prediction models of ship system components using first principles [54]. A very useful publication on the subject is the regression data models published by van Es [55], where the first principle-based dimensioning and data from the manufacturers are compared. The data used by van Es [55] was mostly derived from software tool GES (Dutch abbreviation for Integrated Energy Systems), developed by TNO (Netherlands Organisation for Applied Scientific Research), from manufacturers' information, literature, expert experience, as well as considerations of the first principles.

The initial purchase or acquisition costs of propulsion equipment are very difficult to predict as the costs are not widely published and are dependent on many factors like volume of equipment ordered, the conclusion of maintenance contracts along with purchase or the intention to buy products in the future, strategic prices etc. Watson [6] has observed that in shipbuilding practice, the machinery material costs are obtained mainly from subcontractor's quotations but partly by costing items either on unit, unit power or unit weight basis. Webster et.al. [17], [56], compared the overall impacts of different concepts of power and propulsion technologies on acquisition cost and overall 'Life Cycle Costs' (LCC)

for the propulsion systems considered, without giving the cost break up for individual equipment. Watson [6] has noted that usually, the most important item of running costs is the annual fuel bill. Another important element for the LCC is that of maintenance costs. Elaborate models for deriving maintenance costs of gas turbines have been extensively published. For gas turbines, the life of the hot section components usually determines the interval between major maintenance actions, resulting in an estimated average maintenance cost [57]. The hot section life is dependent on the power rating at given ambient conditions or the Power Turbine Inlet Temperature (PTIT) as well as the operating profile of the engine. The normal relationship between internal parts life and the power turbine inlet temperature is indicated in Figure 2-7.

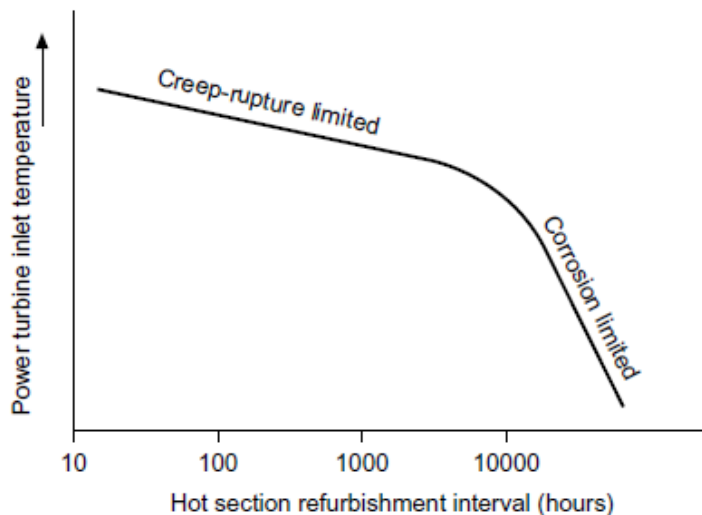


Figure 2-7 Relationship between internal parts life and the power turbine inlet temperature of a marine gas turbine [57].

At higher internal temperatures the component life is determined by creep-rupture and decreases rapidly with increased temperature; at lower internal temperatures the component lives are determined by corrosion and do not vary as rapidly [57]. Elaborate models for gas turbine maintenance and lifing aspects have been built in the framework of TERA analysis in the works such as by Doulgeris [58,59] who used a creep-life prediction method for the life of a marine gas turbine to develop a maintenance cost model and Raja [60] for simulating failure of critical hot gas path components as a function of the thermodynamic performance of the gas turbine and creating maintenance schedules based on failure trends simulated.

2.3 Techno-Economic Analysis Procedure

Techno-economic & Environmental Risk Assessment (TERA) is a concept developed at the Cranfield University that uses a framework of mathematical models to conduct design space exploration and trade-off studies in the areas ranging from taxation policies in civil aviation [61]; to the selection of gas turbine engines for aero [62], industrial [60] and marine applications [59]. The framework is modular in structure and consists of a set of core system models linked to economic, risk and environment models, to objectively assess and compare competing schemes by weighing investment of resources against performance and risk estimations. Gayraud [63] was the first to base his studies on techno-economic assessments of industrial gas turbines at Cranfield University. Whellens and Singh [64] describe how the TERA approach can be used to model the design procedure to make the traditional decision-making process easier. Doulgeris [59] used the approach for the assessment and optimization of marine propulsion systems focussing on emission and cost considerations in his based on the approach developed for aerospace applications. The overall scheme of TERA is usually integrated with optimisers such as real parameter 'Genetic Algorithm' for the optimisation of one or more goal functions which could range from fuel burn, engine noise, engine emissions to operating costs.

TERA analysis of ship propulsion system was presented by Tsoudis, Bonet etc. using Poseidon [49,59] [50,65] primarily focussed on merchant ships, which operate at a high percentage of rated power, except for short periods when approaching or departing ports. Consequently, for merchant ships, economical operation at the sustained sea speed corresponding to the intended trade route is of primary importance [3]. Hence, these studies were primarily based on journey route-based analysis. On the other hand, the power plants for naval ships do not follow specific routes but are usually assigned mission areas. The design of a power plant of such ships must fully reflect the operating profile of a ship [3].

2.4 Ship Operating Profile

The operating profile of a ship is represented by the percentage of time underway spent at various bands of speeds in the ship's speed range as shown in Figure

2-8. Naval ships must be designed to satisfy the highest speed requirements projected for them, but the maximum power capability provided is seldom used. In addition, good economy at the cruising speed is of major importance because the fuel consumption at this speed may control the range of the ship during many operations. This means that for ships that must have a very high-power capability, but only for rare and brief periods, the acceptable component service lives for full-power operation may be relatively low, and the acceptable rate of fuel consumption at full power may be high. On the other hand, economy would be given major emphasis for the more extensively used, lower power, cruising mode of operation [3]. Hence operating profile is a very important design input that should be considered for conducting the trade-off studies for the design of propulsion systems for such applications.

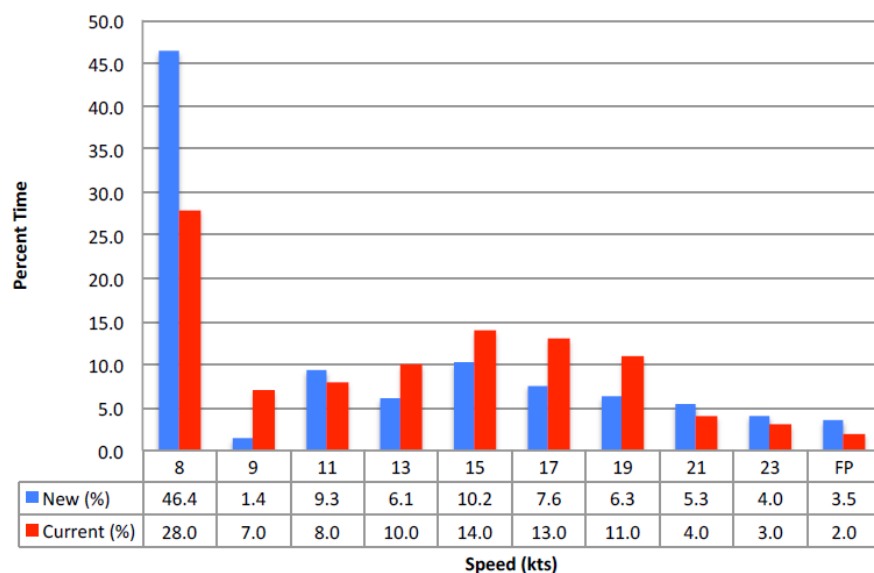


Figure 2-8 Comparison of 2003 approved (Current) and observed operating profiles (New) [66].

While the operating profile is a key design input, it is a complex task to predict such a profile for the entire lifetime of a ship. The profile is usually derived based on the experience of operation of similar vessels. Such data is not usually publicly available. Anderson et.al. [66] presented a very detailed case study of comparing the original speed-time profile for a class of US naval destroyers, DDG-51, considered with the actual operations of the ship, in 2013. This analysis clearly showed a large deviation from the originally considered profile and the approved

profile in 2003. A comparison of the operating profile as derived based on data in 2013, compared to the approved profile of 2003 is shown in Figure 2-8. The analysis also shows that the ship's mission has a strong influence on the profile.

Another way of classifying the operating profile of a warship could be based on its primary role described by the broadest of terms such as 'anti-submarine' or 'anti-surface' etc. and a secondary or peacetime described as 'General Purpose' (GP) [9]. Based on this the operating profile for a ship designed for the primary role of 'Anti-Submarine Warfare' (ASW) could be described as shown in Figure 2-10.

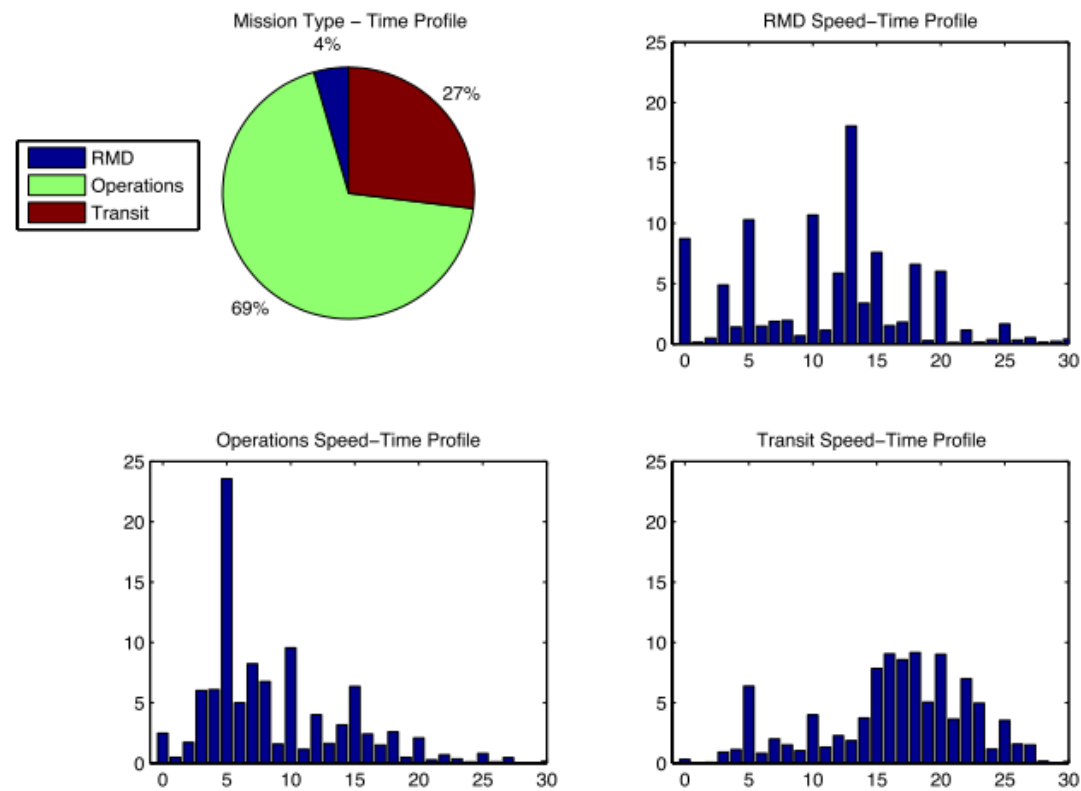


Figure 2-9 Comparison of operating profiles based on mission type [66].

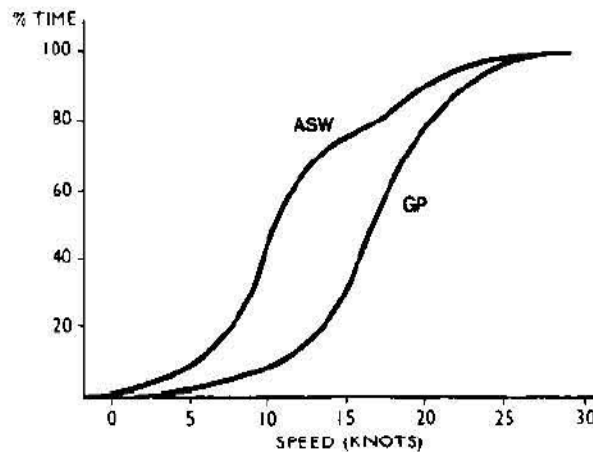


Figure 2-10 Example of operating profile specification for ASW and GP roles [9].

2.5 Multiple Criteria Decision-Making

Multiple criteria decision-making (MCDM) has grown as a part of operations research, concerned with designing computational and mathematical tools for supporting the subjective evaluation of performance criteria by decision-makers [67]. MCDM is one of the most widely used decision methodologies in various fields such as energy and environment, business, economy, production. In more recent times, the development and application of hybrid methods, based on previously developed well-known MCDM methods, is becoming increasingly important [67].

The Analytic Hierarchy Process (AHP) method [68], is used to decompose the decision problem into a hierarchy of subproblems and the decision-makers evaluate the relative importance of the various elements by pairwise comparisons. AHP converts these evaluations to numerical values, which are used to calculate a score for each alternative [69]. Amongst the MCDM approaches, AHP has been used more than other tools and approaches [67]. Ruschmeyer [68] and Shamasundara [69] used AHP for the selection of propulsion plant design based on defined requirements or design criteria. Brown [72] applied a combination of AHP and 'Multi-Attribute Utility Theory' (MAUT) for the overall naval ship concept design process including the propulsion system architecture selection utilizing metrics for quantifying performance and risk. The

utilization of expert-based opinion for such analysis has been used for optimization in ship design by Brown [72] [12].

Analytic Network Process (ANP) is a generalisation of the AHP wherein the decision-making problem is modelled as networks, instead of hierarchies as with the AHP [73]. If dependencies exist between criteria, application of ANP is more appropriate than AHP, as the dependencies and feedback between the decision-making elements can be modelled to calculate more accurate weights of these elements [74]. Rai [75] proposed a combined AHP and ANP method for the selection of alternatives for the procurement of weapons for 'air power potential'.

The pairwise comparison matrix method used in the ANP process, when applied to complex problems can get difficult to implement practically. The 'Decision Making Trial and Evaluation Laboratory' (DEMATEL) method is often used to overcome these difficulties by analysing the cause-and-effect interrelationships between the criteria by analysing the degree and type of influence they exert on each other [76]. There are various methods of integrating the DEMATEL with ANP, with one of the most popular being the DEMATEL-ANP (DANP) method [77], [78]. In the DANP method, the DEMATEL method is used to determine the interrelationship among the main dimensions (criteria clusters) as well as the relationships between the criteria for each dimension instead of the pairwise comparison method. The rest of the process followed in DANP is the same as the ANP process.

The VIKOR method ('Višekriterijumsko KOmpromisno Rangiranje' in Serbian, translates to multicriteria optimization and compromise ranking) is the method used to rank and select the 'best-suited alternative' from a finite set of alternatives in the having conflicting and non-commensurable attributes [79]. This method is based on the concept of a multicriteria ranking index based on the measure of 'closeness' to the 'ideal' solution. Cristóbal [80] used VIKOR for the selection of a renewable energy project from possible alternatives. Demirel [81] applied the VIKOR method for the selection of suitable roll stabilizer type for motor yachts using a hybrid fuzzy AHP and VIKOR methodology. Chiu [82] used a hybrid

DANP with the VIKOR approach for analysing possible measures to improve an e-store business.

2.6 Summary of Literature Review

The overall summary of the literature review undertaken on the primary subjects of the present research work is as follows:

1. The design process of ships, traditionally approached using the ship design spiral, is being replaced with the integrated 'systems approach' for design synthesis. However, the adhoc process for design using 'design lanes', rules of thumb etc. is still prevalent. Even though the design spiral represents the ship design process in a highly simplified sequential, cyclical approach which is far from the actual application, it is still a good representation of the design process represented in a logical way for the sake of understanding.
2. Irrespective of the approach taken during the initial design of a ship, the propulsion system design is embedded into the process as one of the systems being addressed in the overall process. This often masks the considerations required to address all the aspects of the design of the propulsion system. The identified literature on propulsion system design primarily describes the process of integration of propulsion systems. However, the overall process for design space exploration towards the process of the conceptual design of a propulsion system, based on specific design criteria, is not adequately described in the literature.
3. The conceptual design of a ship propulsion system requires close interaction between the marine engineers and the naval architects to evolve an effective design. The traditional approach of using 'design lanes', 'rules of thumb' etc. relies heavily on the preferences of experts or organizations involved in the design process; while the 'systems approach' approach would usually yield good results only if the propulsion architectures used as options are based on existing designs. Most published literature on the 'systems approach' towards ship design treat the entire ship as a system, without providing the necessary level of detail required for the design synthesis of a ship propulsion plant.

4. 'Combined' propulsion plants are often usually designed to meet the requirement of a very wide range of operating speeds and additional performance criteria, at the expense of adding complexity to the overall design. Gas turbines are often employed in such combined plants due to their advantages of high power to weight ratio. due to the added complexity of such plants, more extensive design procedures are required.
5. Most literature on marine propulsion system modelling and simulation can be found for transient analysis where the objective is to assess the dynamic performance of a propulsion plant with the ship propulsion control system. For such simulations usually, a ship-specific propulsion plant model is created and coupled with the model of the ship control system. Such models usually include simplified models of engines as the primary objective is to study the dynamics of the propulsion plant and not engine performance. The transient response analysis usually consists of simulations of 'crash stop manoeuvres', ship turns and additional dynamics from seaway interaction which are used to tune the control system.
6. MCDM is an effective tool operations research, concerned with designing computational and mathematical tools for supporting the subjective evaluation of performance criteria by decision-makers. MCDM is one of the most widely used decision methodologies across many application domains.
7. The limited available literature on the subject of the application of MCDM techniques towards undertaking the conceptual design of a ship propulsion system shows that the design criteria are considered to be independent of each other for the analysis. However, the assumption of design criteria being independent is not fully valid.

2.7 Identified Gaps in Knowledge

Based on the literature survey undertaken, the identified gaps in knowledge that this research aims at addressing are as follows:

1. The current approach for conceptual design of propulsion system designs is based on the traditional approach of 'design lanes' with simplified design point

calculations, subjective expert judgements or low fidelity integration in computerized overall ship design synthesis procedures.

2. Lack of literature on the generalized methodology for steady-state, component-based, performance modelling and simulation for combined ship propulsion systems with complex transmission systems.
3. No published literature found on the application of MCDM models towards the design space exploration of ship propulsion plants, that consider the degree of relationships between criteria for undertaking techno-economic analysis and decision making.
4. Lack of literature on using a combination of 'quantitative' data based on model best analysis and 'qualitative' based on expert opinion for techno-economic analysis of ship propulsion plants.

2.8 Addressing Gaps in Knowledge

The present research work strives to address above knowledge gaps with the following contributions:

1. A generalized model-based design space exploration process has been proposed for approaching the conceptual design of a ship propulsion system, instead of the current approach based on the traditional 'design lanes' based approach or the more modern computerized overall ship design synthesis procedure.
2. To address the model-based design space exploration process, where a large number of candidate architectures would be modelled, the usual approach for modelling observed in the literature, specific for propulsion system architectures was not considered to be practical from a point of view of the involved effort. Also, the usual approach would usually work for a well-developed engine but not if analysis needs to be done for a new development engine whose performance characteristics are not known. Hence, a component-based modelling method and framework has been developed that enables not only the modelling multiple propulsion system architectures in an

agile way, but also the large number of 'drive modes' that are typical to combined propulsion plants.

3. While some literature was found where MCDM methods have been applied to select a ship propulsion system from competing architectures, the degree of relationships between criteria has not been considered for such analysis which may influence the final decision. Hence, the present work proposes application of MCDM methods to consider the degree of relationships between criteria whilst applying the method.
4. Based on the experience of the author, it is often not possible to have mathematical models to generate results for some of the specified criteria in the early stages of design. For such criteria, a relative qualitative data from expert opinion could be used for the analysis. The present work proposes an application of MCDM methods to address the knowledge gap for combination of 'quantitative' data based on model best analysis and 'qualitative' based on expert opinion for techno-economic analysis of ship propulsion plants.

3 METHODOLOGY AND SCOPE

This chapter describes the overall methodology used for the present research work. During the initial studies conducted towards this research work, the broad overall approach for exploring the design space exploration towards the conceptual design of a ship propulsion system, based on a techno-economic model-based analysis was developed. Based on this broad approach, the requirements, as well as scope for the overall framework required for such analysis, was defined, as has been briefly explained in this chapter.

3.1 Establishing the Broad Overall Approach and Framework for Undertaking Conceptual Design of Ship Propulsion Systems

If the design spiral, as shown in Figure 2-2 is unwound, the relevant interdependences of the propulsion system design process with that of ship design can be visualized as shown in Figure 3-1. With this backdrop, the various aspects of techno-economic aspects that need to be considered for the conceptual design of a ship propulsion system can be broadly defined as:

- Ship operating or mission profile.
- Primary performance requirements of the ship at various operating modes of the propulsion system.
- Additional performance requirements other than for those for mobility, like low acoustic and infrared signatures, flexibility in operation etc.
- Constraints in design based on maximum fuel capacity, available deck area, the possible location of propulsion equipment.
- Constraints in acquisition and life cycle costs.

For undertaking the design space exploration of ship propulsion considering the above aspects, the first objective of the research work was to develop an overall framework for undertaking such analysis based on a techno-economic model-based approach. While the term ‘model-based design’ is often used in the context of problems associated with designing of complex control, signal processing and communication systems, the term has been used in this thesis in the sense that the conceptual design of the ship is approached by utilizing an integrated

approach of techno-economic models. Based on the literature survey, the following broad approach towards the conceptual design was developed, shown as a block diagram in Figure 3-2:

- The overall design requirements of the ship are initially processed into design criteria for the propulsion system. The design criteria are classified and organized into a defined network and hierarchy.
- The hull data relevant for the prediction of resistance and ship electrical load is taken as a design input. Based on this, the resistance estimation is undertaken to determine the approximate overall propulsive power required along with the propulsor configuration.
- The process for design space exploration for the propulsion plant is initiated by populating the design space with multiple candidate propulsion system architectures that meet the key design performance criteria for the propulsion system using engines from an existing limited pool of well-developed engines. The design space, consisting of the candidate propulsion system architectures, is thus a discrete domain of these candidate architectures instead of being a continuous domain. This step is expected to be executed by domain experts, to ensure that the elements of human expertise and experience are well integrated within the overall design process. The approach would usually involve starting with simple propulsion system architectures, and then moving towards more complex designs to fulfil the requirements of defined performance criteria.
- The candidate propulsion system architectures are created using well-established steps involving optimization of the propulsor design, and 'matching' the propulsors to the engines using a custom-designed mechanical or electric transmission system. The design feasibility of the candidate propulsion system architectures is tested using performance simulation against the defined key design performance criteria; like maximum speed, endurance targets with consideration to the defined performance envelopes of the considered engines, drives etc.
- A major constraint for undertaking a detailed analysis for certain design criteria, towards the conceptual design of the propulsion system, is the lack

of information at the early stages of the ship design. For such criteria, expert opinion-based is used for a relative grading of the candidate designs against such criteria.

- Dimensioning and costing models are applied to determine the mass, overall dimensions and life cycle costs of candidate designs.
- The candidate propulsion system architectures are then compared objectively by undertaking TERA using MCDM methods to arrive at a 'compromise ranking' of the candidate architectures against the defined criteria for performance, costs, and risks.

The approach described above applies in general to the early stages of the ship design. The early stages of the ship design, as referred to in this thesis, is a combined term that refers to the stages of ship conceptual design and preliminary design. While the described approach in this thesis describes the procedure executed over a single iteration of the ship design process, this procedure would usually need to be repeated over several iterations of the ship design process. The approach could be applied in multiple scenarios of conceptual design ranging from designs that are novel to ones that are based on existing designs.

Based on the requirements of executing the above-defined process towards exploring the design space of a ship propulsion system, the overall framework required to execute these steps were identified, which are described in the following paragraphs. This process can be seen in the context of the overview of the overall research work undertaken in Figure 3-3. The figure highlights the overall relationship of this process with the identified gaps in knowledge, methods used to undertake the analysis, and the key outcomes along with the novelty of the work undertaken.

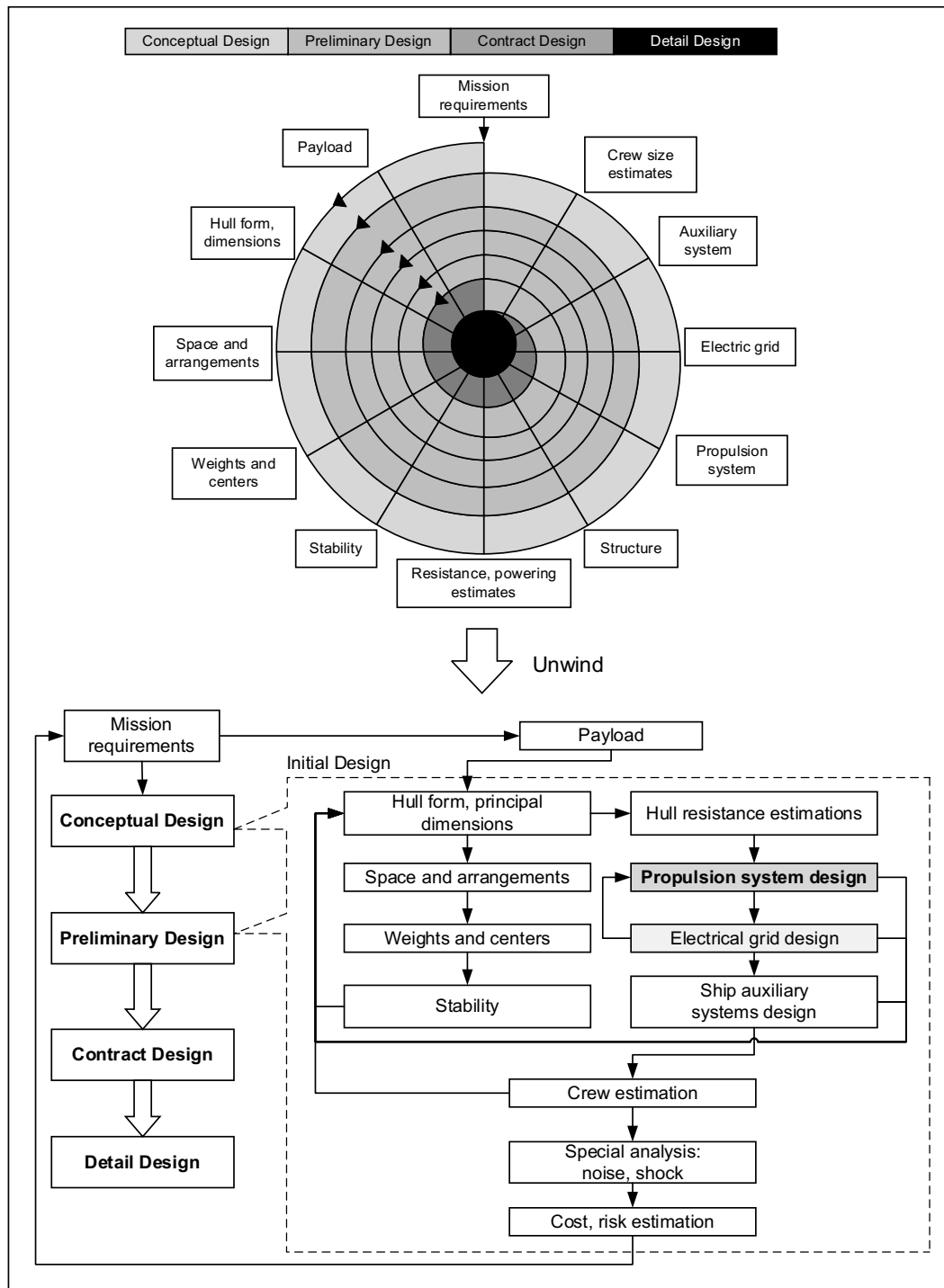


Figure 3-1 Context of propulsion system design in the overall ship design process.

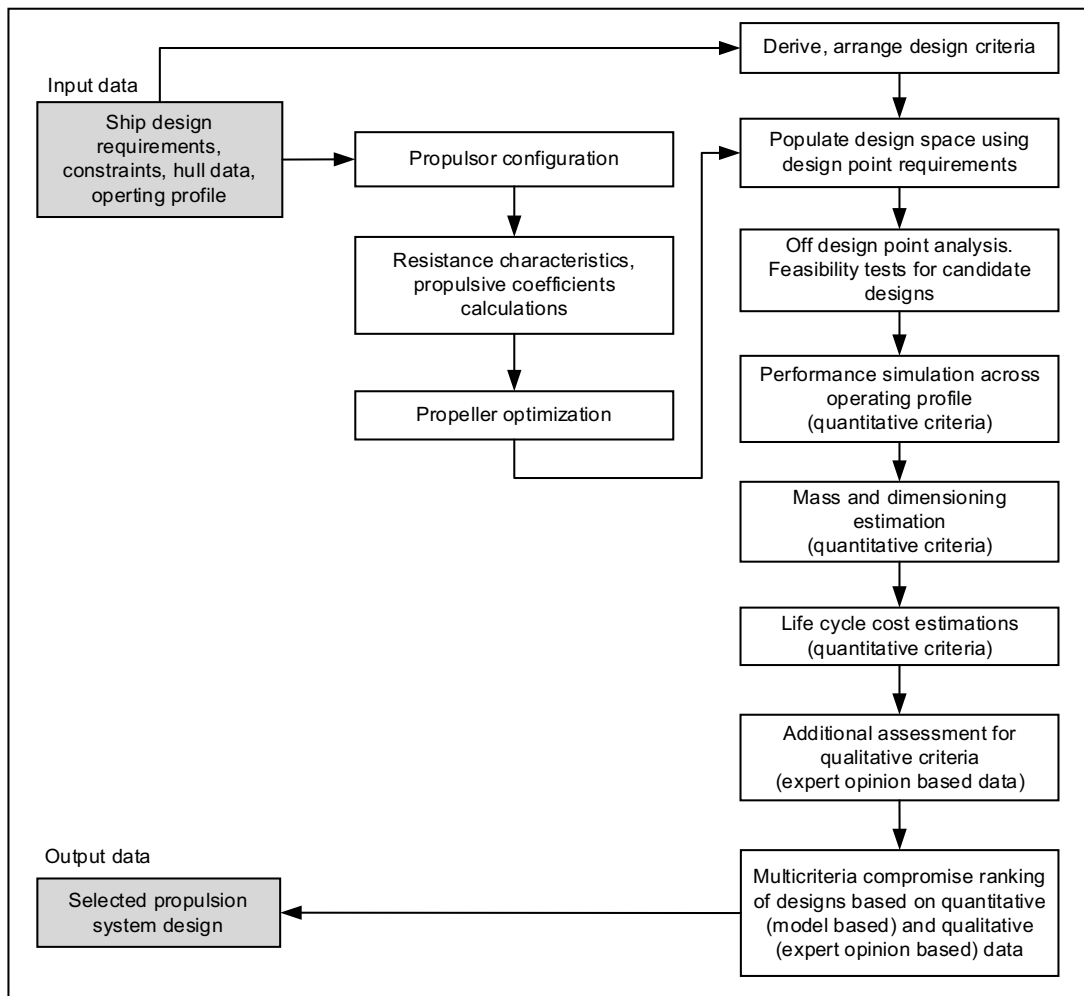
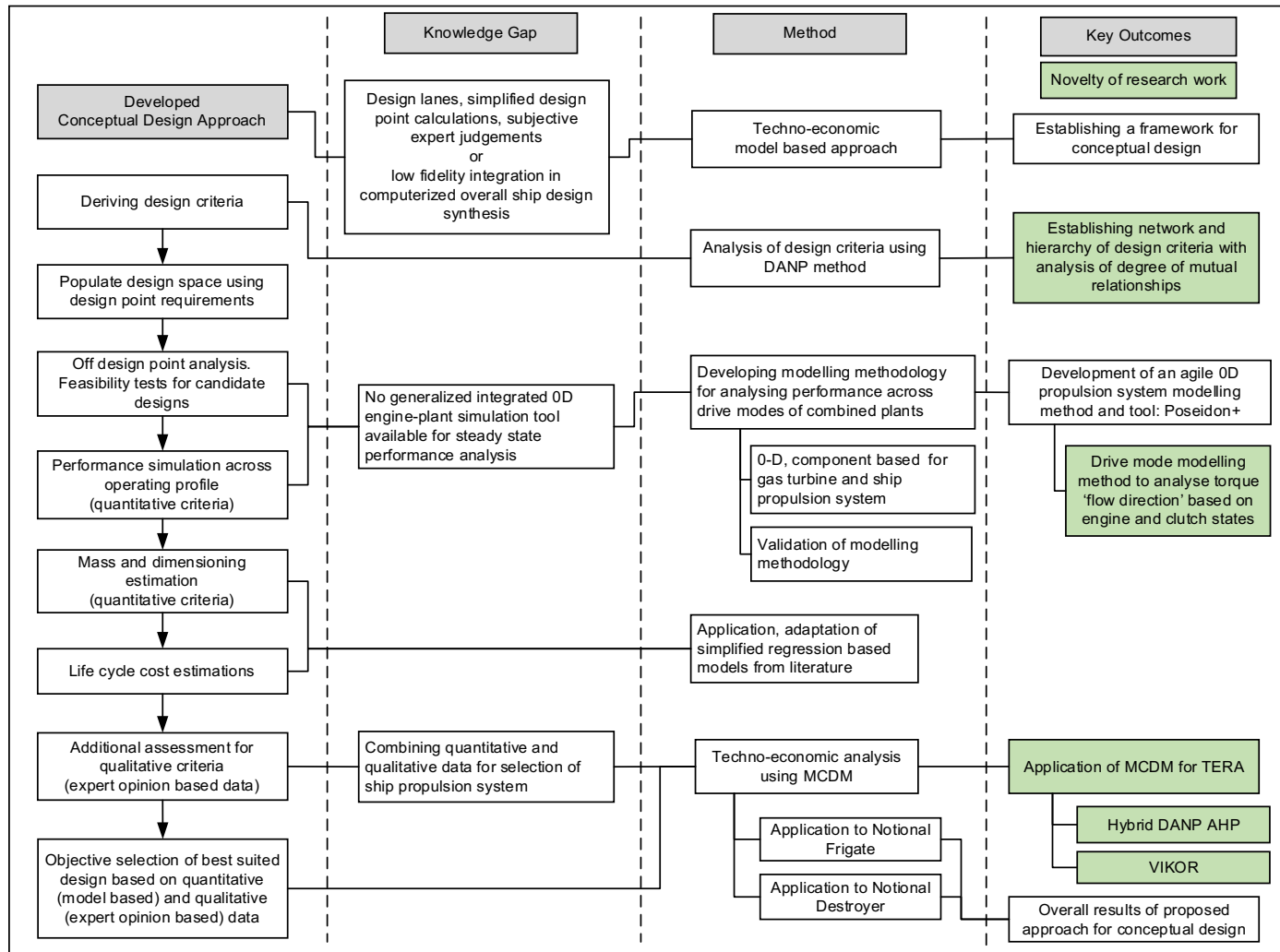


Figure 3-2 Broad approach towards the conceptual design of propulsion system.



1

2 **Figure 3-3 Overview of the research work.**

3.2 Development of an Integrated, Agile, Performance Modelling Framework for Ship Propulsion Systems

To execute the established model-based design approach, an agile modelling and simulation tool was considered essential to enable efficient modelling studies for the multiple candidate architectures under consideration. This would allow the performances analysis of multiple candidate architectures across the operating profile, by simulation studies using developed models. While many individual software tools are available for modelling and simulation of engines, prediction of ship performance etc., an integrated tool that could integrate all these elements into a single modelling and simulation environment without the need to manually process information from the domain of one tool to the other, was considered essential. Due to the limitations of the original Poseidon software [49], as described in section 2.2.2 of this thesis, the same could not be used for the present work.

Further, each of the considered combined plant architecture could have multiple drive modes (different combinations of engines and clutches) at various points in the operating profile, which was an important factor that needed to be considered for these studies. When different combinations of engines and clutches are used in the combined plants, the direction of power transmission through the transmission elements may change based on the states of the engines and clutches. A simplified way of modelling this could be creating individual performance models for each of the operating modes. However, this method of modelling is not a very elegant way of approaching the problem and could be prone to errors of modelling.

The above-mentioned factors with the drivers to develop a novel 0-D component-based modelling and simulation method as a part of the present work, resulting in the modelling software which has been named 'Poseidon +'. Poseidon+ has been 'built from scratch' using object-oriented programming, and the only commonality it shares with the original 'Poseidon' design is some of the basic concepts and, of course, the name.

During the early phase of ship design, towards which the present work is focussed, the selection of the propulsion system architecture is based on the steady state operation of the system across the entire operating range of the ship. The transient behaviour of the plant is assumed to be addressed using the usual design margins used for such designs. The transient analysis is expected to be undertaken in the detailed design phase of the ship where system vibration analysis as well as overall system dynamic analysis of the plant with the effects of the control system would be undertaken. If any risk towards design of a system architecture is seen, this analysis can be undertaken earlier, before finalization of the architecture selection. Transient and dynamic analysis is, however, not a focus of the present work and is not addressed in this thesis. On the other hand, the developed component-based modelling and simulation method has been designed to extend the present steady state functionality to dynamic analysis in the future, as explained later in the text.

The developed modelling method allows assembly of multiple engines (0D gas turbine engine models and simplified map-based diesel engine models) as well as the whole plant in the same framework using predefined components. In the context of the conceptual design procedure, 'Poseidon +' was used to initially check the feasibility of the created designs and then used to compare the performance of the candidate architectures across the design criteria. Towards this, engine and propulsion system models were built to run steady-state performance simulations for the generation of performance simulation data like ship speed, endurance, engine performance, fuel consumption, etc. for the candidate propulsion system architectures. Since the majority of operations of ships are executed at off-design conditions, the performance simulations were not limited to the design point but were undertaken for the entire operating range of the ship. Further details of this modelling approach are described in sections 4.2 and 4.3 of this thesis.

3.3 Application of Dimensioning and Costing Models for Propulsion System

During the conceptual design of the ship propulsion system, the exact equipment that would be included in the final design is not decided. The shipbuilders prefer to have a high degree of competition between the suppliers to have the lowest possible cost for the equipment. The mass, dimensions, and cost estimates for the propulsion equipment during the early part of the design is usually undertaken based on equipment that is most likely to be used in the final application. For the present research work, rather than using data of specific equipment considered in the candidate designs, an average representation of the equipment mass, dimensions and cost in the form of simple regression-based models irrespective of the manufacturer, was decided to be used.

The subject of the application of mass, dimensioning and costing models towards the design space exploration was the primary area of focus rather than the development of regression models for the same. Hence a literature review was undertaken to find such published models which could be directly used for the present work. For the present research work, the mass and dimensioning models used are primarily based on the published data by van Es [55] which is based on results from the TNO's GES software tool, published data as well as considerations of the first principles. The results of the models were compared with some samples in the range of application considered and certain modifications to the models were applied where they were not giving expected results. These models have been applied in the overall framework for the conceptual design with the objective that when more evolved methods are developed or are available to the end-user, these can be easily replaced. The applied models for mass and dimensioning of the propulsion equipment have been described in Appendix I of this thesis.

Due to the scarcity of information available in the public domain for acquisition costs for the propulsion equipment, as mentioned in the introduction to this chapter, for the present work, the acquisition cost models have also been developed from the limited information given by van Es [55] and then corrected

based on publications such as ‘Gas Turbine World Market Forecast’, ‘Forecast International’ etc. To limit the scope of work, simple models which provide maintenance costs as an average cost based on the overall operating hours of the equipment was selected, based again on the regression-based approach from the work of van Es [55]. Further, the maintenance costs have been considered only for the prime movers and not the transmission systems, considering that a relative analysis of systems is being undertaken and it is assumed that the maintenance costs of the various types of transmission systems would approximately equalize and not the drivers for the maintenance costs. It should be noted that the models for costs should be treated as very broad indicative numbers as they are based on a very limited amount of data. The applied models for the costing of the propulsion equipment have been described in Appendix J of this thesis.

3.4 Techno-Economic Analysis Using the Concept Of TERA with Application of MCDM

The process to arrive at the best suited ‘compromise design’ from the candidate propulsion system architectures in the developed approach is based on the foundation of the TERA concept developed at Cranfield University. Towards the application of TERA, an element of novelty in the present work is that the usual optimization algorithms used in TERA have been replaced with MCDM, considering the discrete design space.

The MCDM methods were selected based on the literature survey considering the requirements of the analysis which needed to apply methods where relationships exist between design criteria and the need to use a combination of quantitative and qualitative data for comparison of designs. DANP has been used for determining the degree of relationships between the determining the criteria weights where relationships exist between criteria, while AHP has been used for the same where the criteria are considered to be independent. Once the global weights of the criteria have been determined using the DANP-AHP hybrid method, the alternatives in the form of candidate propulsion system architectures are compared using the VIKOR method using a combination of quantitative and

qualitative data for the selection of ship propulsion system. Further details of the applied models and their integration into the developed process is described in chapter 5 of this thesis.

4 PERFORMANCE MODELLING AND SIMULATION FRAMEWORK

This chapter describes the overall performance modelling and simulation framework developed and applied for the design space exploration of ship propulsion plants, as a part of this research work. In this chapter, initially, the overall concept of the developed performance modelling framework has been described. Thereafter, the procedure used for gas turbine engine performance simulation is described. The chapter then describes the simulation process for ship propulsion plant performance calculations, combining the engine models with hull resistance, propeller performance and additional plant component models. A novel algorithm used for the analysis of multiple operating drive modes of combined propulsion plants, based on the states of engines and clutches has also been described in this chapter. The chapter also briefly describes the theoretical basis of the methods used for performance modelling and the procedures used to apply them. A more detailed description of the modelling methodology used, and the performance calculations are given in the referred appendices. The application of the described procedures in this chapter and the results obtained thereof are described in Chapter 6 of this thesis.

4.1 Development of Generalized Framework for Performance Modelling of Ship Performance

The developed modelling method uses a hierarchal ‘layered modular’ approach enabling the assembly of marine gas turbine and ship propulsion plant by interconnecting of defined pre-programmed components. The overall concept of using pre-programmed components to create the system model has been extended from the 0D modelling concept of Turbomatch. This conceptual layout of layered modules has been shown in Figure 4-1. Further description of the software architecture of the developed modelling software, Poseidon+, is described in Appendix A.

The engine-level model is assembled in a different ‘layer’ while the system-level model is assembled at a higher-level ‘layer’. A separate ‘layer’ has been created

for executing physics-based calculations like fluid thermodynamics calculations etc., math functions like interpolation, optimization, nonlinear solvers etc. and interfacing with data from models and maps. This common layer is accessed by the engine and system layers to undertake the necessary calculations at component, engine or system level, as applicable. The engine-level layer is designed to accept a predefined list of fuels. The ambient conditions, as well as operating point settings, can be specified for the entire system or specific components, based on the modelling scenario.

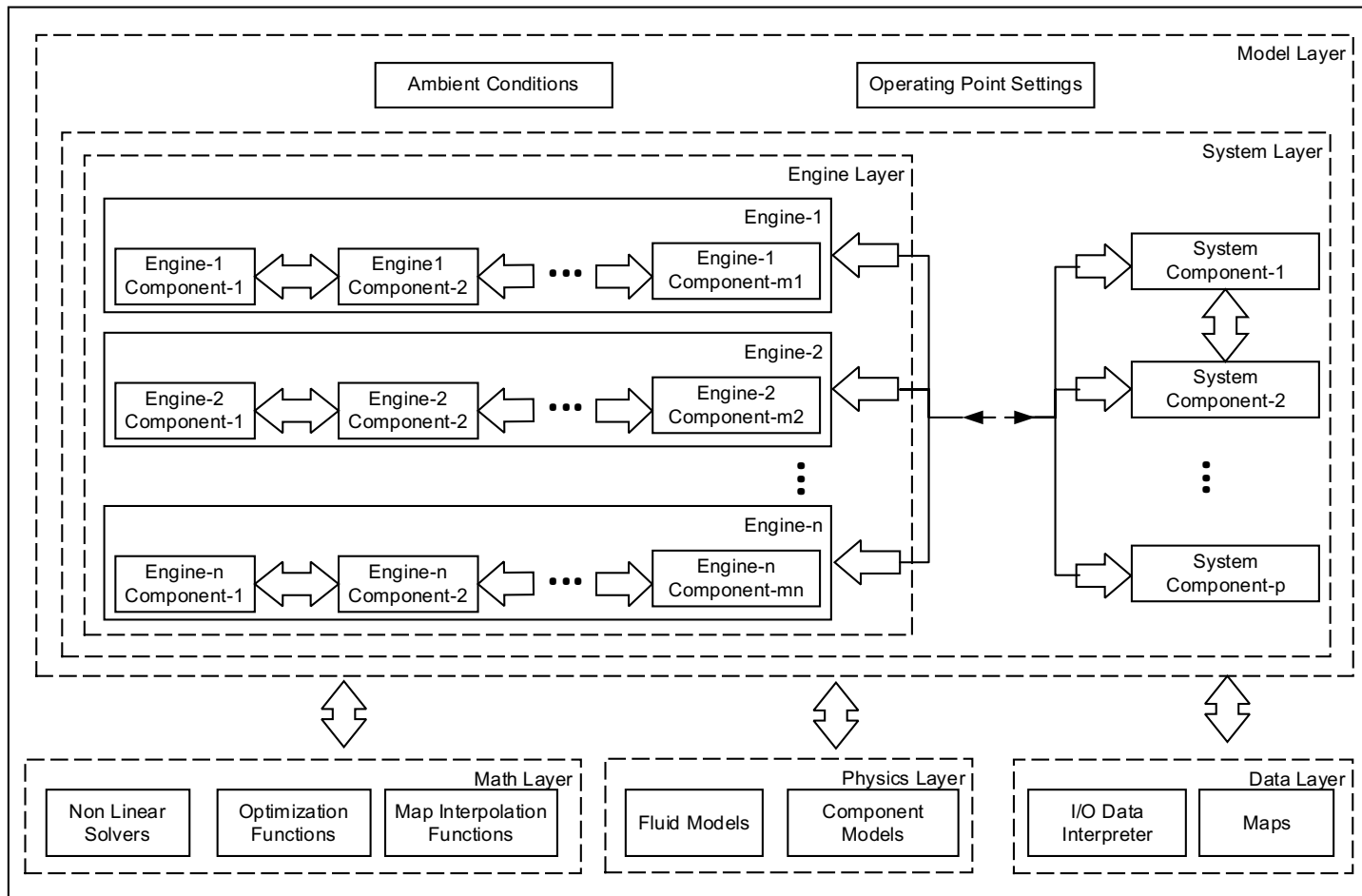
As shown in Figure 4-1, the primary 'layers' of the model and the modelling environment are conceptually divided into:

- Engine Layer
- System Layer
- Model Layer
- Math Layer
- Physics Layer
- Data Layer

The overview of the above layers is briefly described in the following paragraphs.

4.1.1 Engine Layer

The engine layer, as it is currently implemented, is used to undertake calculations to simulate the behaviour of a gas turbine engine. Components of the engine along with their fluid and mechanical connections are defined in the engine model. The engine layer is designed so that the engine models can run independently where the primary objective is to model and simulate the behaviour of a gas turbine engine, or when integrated with a ship propulsion system model.



1

2

Figure 4-1 Conceptual Layout of Layered Modules in Poseidon+

4.1.2 System Layer

The system layer is used to integrate the engine layer with other system-level components like the ship hull, propellers, transmission gearboxes, shafts electric drives with their transmission systems. The system layer interfaces with the engine models which are defined independent of the system layer, so that the same engine model can be reused multiple times. The modelling at the system layer follows the same concept as that of the engine layer where components are created and then connected by electrical and mechanical connections, as applicable.

4.1.3 Model Layer

The model layer is used to connect the engines and the system layers with the overall ambient conditions in which the system operates, as well as the operating point of the plant specified by the user based on which the simulation runs are executed.

The 'Ambient Conditions' block uses the defined conditions of air as well as water in which the ship hull is operating to undertake calculations for providing the interface data as required by the component blocks. 'Operating Point Settings' takes the user-defined plant settings for operation such as engine throttle settings, propeller pitch settings etc. and provides interface data as required by the component blocks.

4.1.4 Math Layer

All the components, as well as integrated engines or systems, use a common 'Math Layer', to undertake all complex mathematical calculations. This layer is primarily composed of the following modules:

- Non-Linear Solvers
- Optimization Functions
- Interpolation Functions

Non-Linear Solvers: ‘Broyden’s’ method and ‘Newton Raphson with Back Tracking and Line Search Methods’ have currently been implemented as the solvers for the system of non-linear equations. Broyden’s method is currently implemented as the default non-linear solver. The details of the implementation of these methods are further described in sections 4.2.3.1 and 4.2.3.2.

Interpolation Functions: Interpolation used by various modules to undertake both one-dimensional and two-dimensional standard interpolation methods for performance maps defined for components, is based on Lagrange’s method as well as the cubic spline method. Special interpolation functions for compressor and turbine maps have been created to read the standard Turbomatch compressor and turbine maps, further described in section 4.2.6.

Optimization Functions: The ‘Nelder-Mead’ method for optimization has been implemented which is used for propeller design optimization, further described in section 4.3.7.

4.1.5 Physics Layer

The physics layer is used to execute all execute all the common thermodynamic and fluid-related calculations for various components of the engine as well as for the system components. Each engine and plant component has its individual calculation module which accesses common functions for the physical calculations like calculation of thermodynamic properties, gas compositions, water properties etc.

4.1.6 Data Layer

The data layer is designed to provide the interface with the external and internal data to the various modules. This layer includes:

- Input/ Output (I/O) Data Interpreter
- Pre-defined component maps, engineering tables and constants

The input data is written to a text file in a specific format as defined in Appendix C. The model data is read through the ‘Input-Output Data Interpreter’ and fed into structures that are accessed by the component engine and system

modules. The results of the simulation calculations are published onto result files in the form of text or 'MS Excel' sheets also using this module. The component maps are stored as individual files while standard engineering constants are stored within a separate class. Further details on these interfaces are described in Appendix A.

4.2 Gas Turbine Engine Performance Simulation

Mathematical models of gas turbines can be categorized according to the level of discretization of space, into 0-D to 3-D models. 0-D models consider the averaged fluid characteristics that are computed at discrete positions inside the engine, generally at the inlet and the outlet of each component such as compressor, combustion chamber, turbine, and exhaust nozzle. 1-D models consider continuity in the computation; the fluid characteristics are still averaged in each plane, where plane means a fluid section perpendicular to the engine axis. They are computed quasi-continuously, limited by the space discretization step, along a mean line representing the average trajectory of the fluid inside the engine. 2-D and 3-D models extend this description by discretizing the whole flow path inside the engine, and not just the mean line of 1-D models. 2-D models consider there is the symmetry of revolution for the stream, while 3-D models make no simplification and use the complete equations of conservation [83].

0-D Models are the most widely used in the industry as they do not require a detailed description of the engine geometry, but still represent the engine model close to 'reality' by considering the engine as a set of 'black boxes', one for each major component of the engine. This method of model greatly simplifies the calculation methods, as the goal is to compute the fluid characteristics only at the interfaces of the components or the 'black boxes' whilst still maintaining a reasonable accuracy of performance calculations. 0-D models are therefore extensively used, but not limited, to the following applications:

- To undertake performance analysis of engines in the early stages of an engine development program.
- Capturing the characteristics of existing engines for which detailed performance models, characteristics are not available.

- Development of 'digital twins' of engines for performance health monitoring of engines and for training simulators.

For application to ship propulsion system modelling, the 0-D modelling approach was selected, due to the following reasons:

- If the engines being considered for the ship propulsion system are underdevelopment engines or engines for which detailed information is not available, 0-D modelling method provides a suitable balance of result accuracy and modelling effort.
- Even if performance characteristics for the engines considered for the ship propulsion system are available, as provided by the engine maker, the characteristics are usually defined for fixed inlet conditions of the engines and fixed power turbine speed or power turbine speed varying as per a cubic propeller curve. Hence for investigation of engine performance over different inlet conditions and more realistic propeller curves, 0-D modelling of the engines provides a good solution.

The overall approach used for gas turbine engine modelling in the developed framework is based on the 0-D modelling approach of Turbomatch. However, all the routines for engine components, engine fluid calculations, enhanced nonlinear mathematical solvers, interpolation routines etc. have been written afresh. The details of the calculation routines used are described in the following paragraphs.

4.2.1 Engine Module Overview

Conceptually, the engine module can be viewed as a part of the layout of layered modules which was briefly explained in section 4.1. Each engine model can be run individually on its own and this scenario can be conceptually represented as shown in Figure 4-2. In the engine module, the various components of the engine model that are connected based on the definition of the engine model input by the user, run sequentially as the fluid would travel in the engine. A sample layout of an engine with the fluid connections of individual components, defined in the

user-created engine model, that would run as a part of the engine module is shown in Figure 4-3.

The engine module is designed to run in both the 'Design Point' (DP) and 'Off-Design' (OD) calculation modes (described further in section 4.2.2), controlled by different algorithms. The DP run is essential also for running OD calculations as this is used to calculate the scaling factors required for the component maps. These scaling factors are then used for the OD performance calculations where the engine model is run over several iterations. It should be noted that the DP run to calculate the scaling factors for component maps is only essential if generic maps for the components are being used. If specific component maps for a particular engine are available, then this step would not be required. Further, if generic component maps are being used and the map scaling factors have been derived using another process, these scaling factors can be directly used to undertake the OD calculation without requiring the DP run.

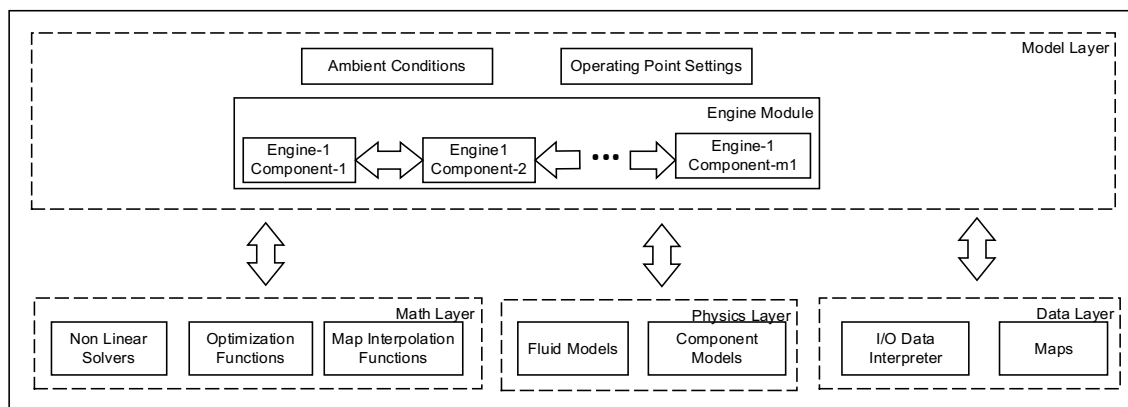


Figure 4-2. Conceptual arrangement of an engine model in Poseidon+

Only the engine component models that are required for the implementation of marine gas turbine modelling have been currently implemented in Poseidon+. Some additional algorithms have been incorporated that apply for aero engines primarily for testing and comparison of Poseidon+ results with Turbomatch. The various engine component models, as well as the ambient air and additional thermodynamic calculation models implemented, have been explained in Appendix E.

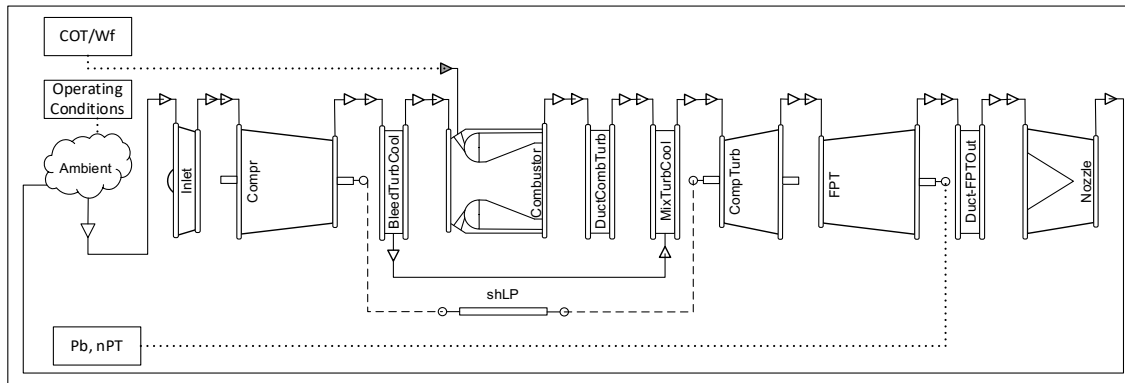


Figure 4-3. Engine Module for a sample engine

4.2.2 Gas Turbine Performance Calculation Methodology

The gas turbine performance simulation analysis can be divided into two categories: 'Design Point' (DP) and 'Off-Design' (OD) analysis. The DP is referred to the single working point in the operating range of a gas turbine when the engine is running at the particular speed, pressure ratio and mass flow for which the engine components have been designed. However, the engine obviously operates at many other operating points than the DP, which are termed as the OD points of operation. To capture the overall performance of the engine over its entire operating range, the performance calculations need to be executed for the DP and set of OD points over the entire operating range of speed and power output [84].

The DP analysis effectively defines the engine geometry in terms of duct and nozzle areas as well as compressor and turbine flow capacities. Most DP calculations are mathematically quite simple to execute as the thermodynamic calculations related to the components can be undertaken sequentially with the assumption that all the conditions of mass and energy compatibility between components are already satisfied. The design point essentially fixes the 'size' of a gas turbine engine, usually defined by the mass flow and overall pressure ratio as well as individual component characteristics to satisfy the overall requirements of Pressure Ratio, Combustor Outlet Temperature, overall thermal efficiency etc. The DP calculation is used to calculate the scaling factor for generic component maps used in the model, which serves as the basis for OD calculations. The DP calculation is executed station by station, in the same order as the one used by

the fluid to pass through the engine. The calculation begins at the air inlet, continues with the compressors, the combustion chamber, the turbines, and ends with the exhaust.

However, in OD simulations the conditions as assumed for DP calculations cannot be assumed. The OD calculation is executed using the geometry of the engine defined by the DP calculation, the changing operating conditions (like ambient temperature and pressure, power setting, bleed, power offtake etc.). Mathematically, this yields a complex non-linear problem that can only be solved iteratively [85].

4.2.3 Off Design (OD) Calculations

The execution of the OD calculations is based on 'component' matching to satisfy the essential conditions of compatibility of mass, work and rotational speed between the various components. Towards this, an engine parameter or a set of parameters are selected as a 'handle' or 'power setting'. This 'handle' is the fixed-parameter based on which the matching conditions of the engine are determined. Suitable 'handles' can be the compressor rotational speed, Turbine Entry Temperature (TET) etc.

The 'component' matching exercise is often described in textbooks assuming constant component efficiencies as well as choked turbines and nozzles, to restrict the number of iteration variables to one or two or to avoid iteration completely. While these assumptions simplify the mathematical problem, they lead to a significant loss of accuracy because the efficiency variation described with component maps is missing [85]. Problems with more than one iteration variable can be solved with the method of nesting iteration loops. However, such a methodology can only yield the result for a single type of simulation problem. Change in engine configuration or iteration variables would usually lead to a new nested loop problem definition.

To have a generic procedure for off-design simulation, a set of 'variables' and 'errors' are defined in the engine model, with an iterative nonlinear solver algorithm employed to vary the values of 'variables' to reduce the 'errors' to an

acceptable level. The iterations commence with an initial guess of the ‘variables’ which are updated in each further iteration. The number of ‘errors’ is equal to the number of ‘variables’. This process has been illustrated using a sample engine in Figure 4-4.

Mathematically, the problem statement for the OD solution root-finding can be defined as follows. Defining E as the error function whose zeros are being searched that gives as a set of N errors for a vector V of free variables $v_1, v_2, \dots, v_N$, which that need to be adjusted to find the ‘zeros’, the problem can be written in the form:

$$E_i(v_1, v_2, \dots, v_N) = 0 \quad (4-1)$$

$$i = 1, 2, \dots, N$$

$$V = v_1, v_2, \dots, v_N$$

This function determines the set of errors in the ‘Engine Module’ as shown in Figure 4-4.

Newton Raphson and Broyden’s methods are perhaps, most popular nonlinear solvers used for such applications [83], [85], [86]. Both of these methods have been implemented in the developed framework. These methods have been also used as the non-linear solvers for the propulsion system simulation calculation as described later in the text. These methods, along with their implementation for the gas turbine engine simulation calculations, is described in the following paragraphs.

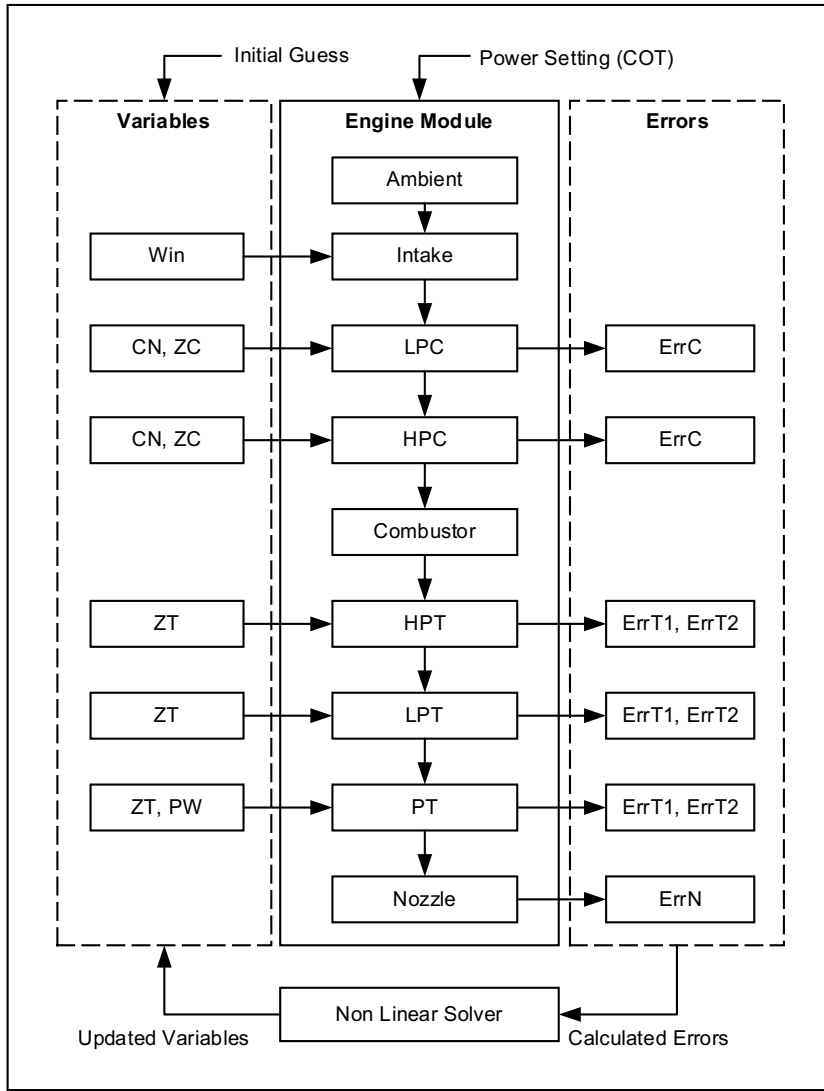


Figure 4-4 Overall process for OD solution finding in Poseidon+ for a sample engine

4.2.3.1 Newton-Raphson Method

The Newton-Raphson algorithm, in its simplest implementation, can be explained as follows. If V denotes the vector of values v_i and E denotes the vector of error functions E_i , in the neighbourhood of V , each of the functions E_i can be expanded based on the Taylor series as:

$$E_i(V + \delta V) = E_i(V) + \sum_{j=1}^N \frac{\partial E_{ij}}{\partial v_j} \delta v_j + O(\delta V^2) \quad (4-2)$$

where δV is the change in variables defined as:

$$\delta V = \delta v_1, \delta v_2, \dots, \delta v_N$$

The Jacobian J , with each element J_{ij} , is defined as:

$$J_{ij} \equiv \frac{\partial E_{ij}}{\partial v_j}$$

$$J = \begin{bmatrix} \frac{\partial E_{11}}{\partial v_1} & \frac{\partial E_{12}}{\partial v_2} & \dots & \frac{\partial E_{1n}}{\partial v_n} \\ \frac{\partial E_{21}}{\partial v_1} & \frac{\partial E_{22}}{\partial v_2} & \dots & \frac{\partial E_{2n}}{\partial v_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial E_{n1}}{\partial v_1} & \frac{\partial E_{n2}}{\partial v_2} & \dots & \frac{\partial E_{nn}}{\partial v_n} \end{bmatrix}$$

The above equation can be written as:

$$E(V + \delta V) = E(V) + J \cdot \delta V + O(\delta V^2) \quad (4-3)$$

Neglecting terms of order δV^2 , setting $E(V + \delta V) = 0$

$$E(V) + J \cdot \delta V = 0 \quad (4-4)$$

$$J \cdot \delta V = -E(V) \quad (4-5)$$

In the expanded form, the above equation can be written as:

$$\begin{aligned} \frac{\partial E_{11}}{\partial v_1} \delta v_1 + \frac{\partial E_{12}}{\partial v_2} \delta v_2 + \dots \frac{\partial E_{1n}}{\partial v_n} \delta v_n &= -E_1 \\ \frac{\partial E_{21}}{\partial v_1} \delta v_1 + \frac{\partial E_{22}}{\partial v_2} \delta v_2 + \dots \frac{\partial E_{2n}}{\partial v_n} \delta v_n &= -E_2 \\ &\vdots \\ \frac{\partial E_{n1}}{\partial v_1} \delta v_1 + \frac{\partial E_{n2}}{\partial v_2} \delta v_2 + \dots \frac{\partial E_{nn}}{\partial v_n} \delta v_n &= -E_n \end{aligned}$$

δV is solved for by LU decomposition, and corrections δV are added to solution vector or the new value of V_{new} as:

$$V_{new} = V + \delta V \quad (4-6)$$

and the process is iterated to convergence.

The Newton Raphson solver, as implemented in the calculation procedure for the engine, follows the algorithm as shown in Figure 4-5. The influence coefficients are given by $J_{ij} \equiv \frac{\partial E_{ij}}{\partial v_j}$ where each element of J , stands for influence on i th error of j th variable. Each variable v_j is varied by a small value to get the j th column of J , which can be written as:

$$\begin{matrix} \frac{\partial E_{1j}}{\partial v_1} \\ \frac{\partial E_{2j}}{\partial v_1} \\ \vdots \\ \frac{\partial E_{nj}}{\partial v_1} \end{matrix}$$

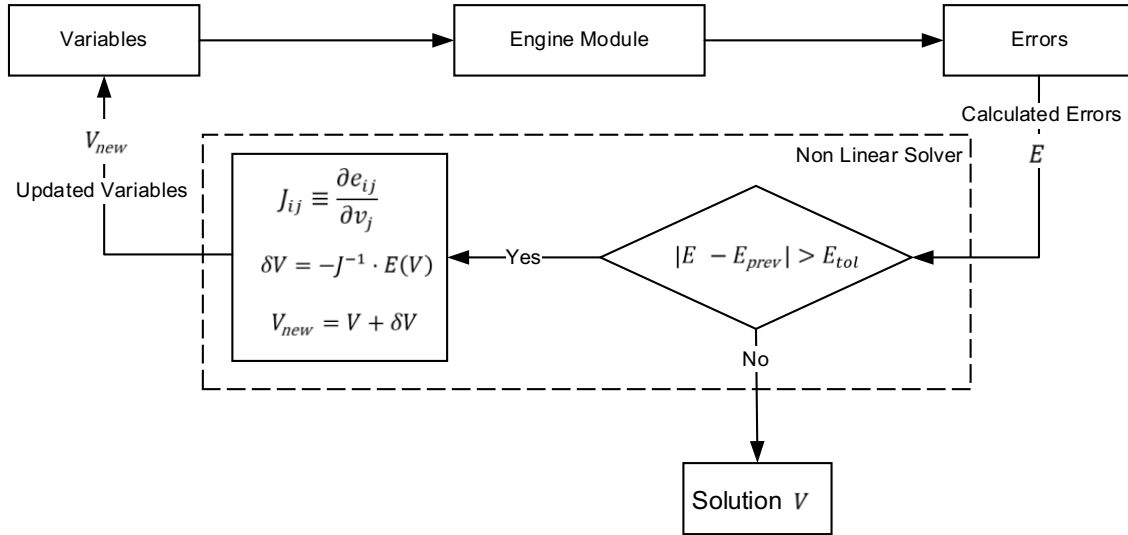


Figure 4-5 Poseidon+ Newton Raphson Solver Algorithm Overview.

At each step error is checked against user-specified tolerance E_{tol} as:

$$|E(V) - E(V_{prev})| > E_{tol} \quad (4-7)$$

To avoid issues of convergence to a solution, the Newton Raphson method implemented includes enhancements for ‘Back Tracking and Line Search’ [87]. The above implementation is a significant improvement over Turbomatch where the solver is embedded in the code [44]. This method implementation keeps the maths well separated from the physical process related calculations. This allows multiple methods for root solving to be easily implemented and integrated with the procedures.

For the implementation of Broyden’s method, an algorithm similar to that shown in Figure 4-5, is implemented with the step for Jacobian calculation replaced with the secant method based finite difference approximation, as described in the next section.

4.2.3.2 Broyden’s Method

Though the Newton Raphson method is powerful, a drawback it has is that the Jacobian matrix is needed to be calculated at every iteration. This finite-difference based determination of the Jacobian can be computationally expensive for the iterative solver. To overcome this, quasi-Newton secant methods can be used to provide cheap approximations to the Jacobian. One of the best-suited methods for this is Broyden’s method [88] [89]. The method makes it possible to avoid the calculation of the Jacobian matrix in every iteration leading to faster calculations. The secant method replaces the derivative from the Newtons method by a finite difference, given as:

$$E'(V_k) \approx \frac{E(V_k) - E(V_{k-1})}{V_k - V_{k-1}} \quad (4-8)$$

$$E'(V_k)(V_k - V_{k-1}) \approx E(V_k) - E(V_{k-1}) \quad (4-9)$$

$$B_k(V_k - V_{k-1}) \approx E(V_k) - E(V_{k-1}) \quad (4-10)$$

$$B_k \cdot \delta V_k \approx \delta E_k \quad (4-11)$$

where:

E is the function whose zeros are being searched,

V_k is the free variable,

k is iteration number.

Broyden proved that:

$$B_k = B_{k-1} + \frac{(\delta E_{i-1} - B_{k-1} \cdot \delta V_{k-1}) \otimes \delta V_{k-1}}{\delta V_{k-1} \cdot \delta V_{k-1}} \quad (4-12)$$

where:

$$\delta V_k = V_k - V_{k-1}$$

$$\delta E_k = E(V_k) - E(V_{k-1})$$

where B_k is the Jacobian calculated for the system of equations, $F(V_k)$ is a matrix with the solution of each equation calculates for V_k .

Using this approximation of the Jacobian, defined by B_k above, the approach as described for the Newton Raphson method is used by the implemented Broyden's method.

4.2.4 Thermodynamic Calculation Models

The properties of the working fluid in a gas turbine engine have a powerful impact on its performance. It is essential that these gas properties are accounted rigorously in calculations, or that any inaccuracy due to simplifying assumptions is quantified and understood. For gas turbine performance calculations, thermodynamic properties are usually calculated, based on the need for accuracy and thus the calculation complexity, as per the following methods [90]:

- Constant, standard values for specific heat (at constant pressure), c_p , and the ratio of specific heats, γ , are defined for cold end gas properties and hot end gas properties. This is the least accurate method, giving errors of up to 5% in leading performance parameters. It should only be used in illustrative calculations for teaching purposes, or crude, 'ballpark' estimates.

- Values for c_p and γ are calculated based on the mean temperature within each component, i.e. the arithmetic mean of the inlet and exit values. This technique is commonly used for hand calculations or simple computer programs.
- Fully rigorous calculations for changes in enthalpy and entropy across components are evaluated using c_p and specific enthalpy, h . This improves accuracy to be within 0.25% for leading parameters at all pressure ratios. Here polynomials of specific enthalpy and entropy are utilised, obtained by integration of the standard polynomials for specific heat.

The performance calculations in the developed method are executed using the method of fully rigorous calculations for changes in enthalpy and entropy across components are evaluated using c_p and h . The thermodynamic properties of the individual elements are evaluated as a function of temperature using defined polynomial laws using the set of equations developed by Bucker et.al. [91] to characterize the thermodynamic properties of interest for the main components of combustion gases. These equations have been developed specifically for gas turbine engine applications, with a high degree of accuracy for gas mixtures at temperatures from 200 to 3300 K. These equations have already been successfully applied in Turbomatch [43]. The thermodynamic properties for the mixtures (working fluid) are calculated as per the equations [91]:

$$c_{p,mix} = \sum_{i=1}^{10} a_{mix,i} \left(\frac{T}{T_0} \right)^{b_i} \quad (4-13)$$

$$h_{mix} = a_{mix,1} + \sum_{i=1}^{10} a_{mix,i} \frac{T_0}{b_i + 1} \left(\frac{T}{T_0} \right)^{b_i+1} \quad (4-14)$$

$$s_{mix} = a_{mix,11} - R_m \ln \left(\frac{p}{p_0} \right) + \Delta^{mix} s^o + a_{mix,1} \ln \left(\frac{T}{T_0} \right) + \sum_{i=2}^{10} \frac{a_{mix,i}}{b_i} \left(\frac{T}{T_0} \right)^{b_i} \quad (4-15)$$

where:

T_0, p_0 are the reference temperature and pressure used across all computations defined as 273.15 K, 0.101325 MPa respectively,

$\Delta^{mix} s^o$ is the change in entropy of the mixture,

b_i are non-substance specific coefficients,

$a_{mix,i}$ are coefficients for the mixture are calculated for $i =$ I, II, 1,2, ...,10 according to:

$$a_{mix,i} = \sum_{k=1}^8 x_k a_{k,i} \quad (4-16)$$

where:

$a_{k,i}$ are substance-specific coefficients,

k denotes the component of the mixture,

x_k is the mole fraction (mole/ concentration in mol/g),

The details of the methodology and the coefficients used, based on the theoretical assumptions, for the same is described in Appendix D of this thesis.

4.2.5 Gas Turbine Component Models

Each engine component module is designed for determining outlet conditions, from knowledge of inlet conditions along with other parameters needed for the simulation as scaling factors and error terms for OD calculations. The overall architecture of an engine component is shown in Figure 4-6.

Each engine component interfaces with other components of the model using the ports shown as grey circles. There are two ports each defined on the inlet and outlet side defined as ‘fluid interfaces’, where the data related to fluid streams is received as input and transmitted as output. The fluid ports are considered directional in nature and the in port and output are indicative of the directional flow of the working fluid stream. Usually, only the ‘Fluid 1’ in and output are in use, but for components where the flow splits or is mixed, the ‘Fluid 2’ ports are used. The mechanical port or ‘torque’ ports are used to make the mechanical

connections between components like connections between compressors and turbines. The mechanical ports obviously have no sense of direction of flow as in the case of flow for fluid ports. The parameters are calculated for each of these ports, akin to the sensor being placed at these ports.

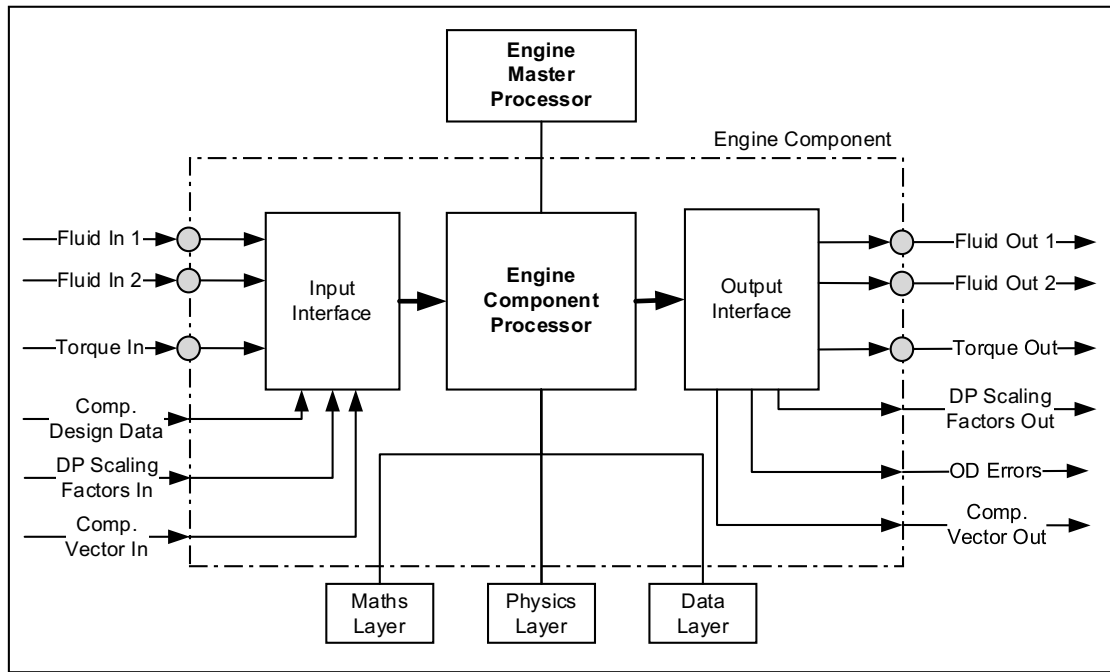


Figure 4-6 Poseidon+ Engine Component Architecture.

In addition to the data that flows through the input ports the design data for the component is received through the 'Component Design Data' interface. The additional input data related to calculations, required to be passed between components, is interfaced through the 'Component Vector'. The scaling factors calculated during the DP run as required for OD calculations is received through the 'Component SF' interface. On the output side, in addition to the data transmitted through the output ports, the scaling factors calculated during the DP calculations as well as error terms for the nonlinear solvers for the OD calculations to be undertaken in further runs is interfaces through the 'DP Scaling Factors' and 'OD Errors' respectively. Additional output data required related to calculations required to be passed between components is interfaced through the 'Component Vector'.

'Input/ Output Interface' blocks are used to format the data at the ports and other interfaces to the defined structure as required by the 'Engine Component Processor'. The 'Engine Component Processor' is the main function that is required to undertake necessary thermodynamic calculations in the module using data from the 'Input Interface' block as well as additional data required from components maps using the 'Data' layer. The 'Engine Component Processor' interfaces with the 'Math' and 'Physics' layer functions to perform the necessary calculations. The overall sequencing control of the 'Engine Component Processor' is executed by the 'Engine Master Processor'.

All the ports and the interfaces use standard data structures. The data structure of the standard fluid port is defined as:

$$\{W_{in/out}, T_{in/out}, TS_{in/out}, P_{in/out}, PS_{in/out}, FAR_{in/out}, V_{in/out}\}$$

This is considered as the standard fluid vector of inputs and outputs at each of the components. The exceptions to this interface are the components intake and exhaust, wherein the intake has its fluid input port connected to the ambient block while the nozzle which has its outlet connected to the ambient block.

The marine gas turbine models are created from the following predefined components:

- Ambient Air
- Intake
- Compressor
- Combustor (Burner)
- Turbine
- Free Power Turbine
- Nozzle
- Splitter
- Mixer
- Duct
- Shaft

The internal calculation methods implemented have been briefly described in Appendix E of this thesis. The symbolic representation of the components to describe the models diagrammatically in this thesis is described in Appendix B. The details of the component properties are defined in models created as input text files, the format for which has been defined in Appendix C.

4.2.6 Component Performance Maps

If component efficiencies are assumed to be constant and equal to the values at DP, the accuracy of simulation can be good only in the neighbourhood of the DP simulation because, in reality, component efficiencies vary along the operating lines by several percent [85]. Hence, 0-D OD simulation is usually undertaken by utilizing 'component maps', which hold the data of performance characteristics of the components under a wide range of operating conditions. Experimental data from actual rig tests or previous experience is usually used in determining these maps. Such data is plotted together in a diagram for representation [84].

The nature of the operating conditions (load, operating conditions) determines the component operating point, calculated iteratively by the 'component matching' undertaken by the simulation program iteratively as already described earlier. The locus of such operating points can be drawn on the component maps as 'working lines' as shown in Figure 4-7.

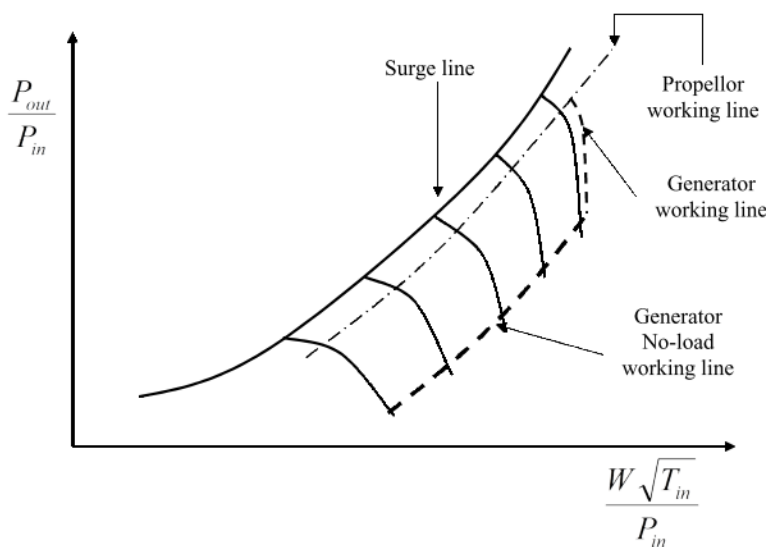


Figure 4-7 Working line on a compressor map [84]

Component maps for specific engines which are the key to accurate OD simulations are not usually available as they are usually proprietary data of the engine maker. However, good approximations can be made by scaling maps of similar components. Turbomatch has several generic maps available covering the usual operating range of components. These maps have been used for several years to model a large range of engines successfully. Component maps used for the present work are based on the well-evolved maps used in Turbomatch. Each map is stored as numerical data in a text file, which is read by Poseidon+ during runtime. A new process for interpolation of data from the maps was developed for Poseidon+ as a part of the present work.

4.2.6.1 Compressor Maps

A compressor map is one of the most important maps required for OD performance calculations. Compressor operation is characterized by the velocity triangles, on which the enthalpy rise (thus pressure ratio and efficiency), and the mass flow depend. Dimensional analysis shows that a velocity triangle similitude must be based on a Mach number similitude. Hence, the compressor operation is usually described by inlet non-dimensional or corrected mass flow and corrected speed [83]. The compressor maps are thus usually represented by plotting non-dimensional mass flow, along each constant corrected speed line, plotted against both pressure ratio and isentropic efficiency (Figure 4-7) of the compressor for a range of operating conditions. The map also usually includes the operating limits in terms of a surge line, as shown in Figure 4-7. The surge line sets an upper limit to the pressure ratio at a given corrected speed because of aerodynamic instability. Compressor maps must be accurate in the region where efficiency is decreasing quickly. The compressor characteristics are generally well known between 75% and 110% of the design speed. Below 75%, theoretical compressor models may lack precision. Cold weather and high-altitude computations often lead to operation at 125% or more of the design-reduced speed [83].

In the developed implementation, the compressor maps are stored in the format as described in Table 4-1 (similar to Turbomatch). A set of corrected speed lines

1,2 ... m given by N_{c_1} N_{c_2} ... N_{c_m} are defined. For each speed line, N_{c_i} , an individual set of data points from 1,2 ... n is defined, with each data point DS_j holding the values compressor pressure ratio, corrected mass flow and isentropic efficiency denoted as PR_{cij} W_{cij} η_{cij} . The speed lines as well as the data points on the speed line, do not follow a uniform density, it being based on the requirement of defining the curves. The data is stored in the files is in the format as described in Table 4-1. It should be noted that the parameters in the map for mass flow and speed are all corrected parameters which are denoted in the shown table without the subscript *corr* for brevity.

Table 4-1 Data format used for Compressor Maps

	DS_1	DS_2	...	DS_n
N_{c_1}	$PR_{c_{11}}$ $W_{c_{11}}$ $\eta_{c_{11}}$	$PR_{c_{12}}$ $W_{c_{12}}$ $\eta_{c_{12}}$	...	$PR_{c_{1n}}$ $W_{c_{1n}}$ $\eta_{c_{1n}}$
N_{c_2}	$PR_{c_{21}}$ $W_{c_{11}}$ $\eta_{c_{11}}$	$PR_{c_{12}}$ $W_{c_{12}}$ $\eta_{c_{12}}$	...	$PR_{c_{2n}}$ $W_{c_{2n}}$ $\eta_{c_{2n}}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
N_{c_m}	$PR_{c_{11}}$ $W_{c_{11}}$ $\eta_{c_{11}}$	$PR_{c_{12}}$ $W_{c_{12}}$ $\eta_{c_{12}}$	...	$PR_{c_{1n}}$ $W_{c_{1n}}$ $\eta_{c_{1n}}$

The data in Table 4-1, when typically plotted for a specific compressor map looks like as shown in Figure 4-8 and Figure 4-9.

A compressor map in the standard format is not straightforward to read, because in parts of the map while reading efficiency the speed lines can be vertical or there could there are two values for corrected flow at a given pressure ratio as shown in Figure 4-10 [92]. The solution to the problem often implemented is the implementation of auxiliary coordinates or the so-called 'β lines' which intersect the speed lines, as shown in Figure 4-10. This makes the reading of the map to be independent from the shape of the speed lines [92].

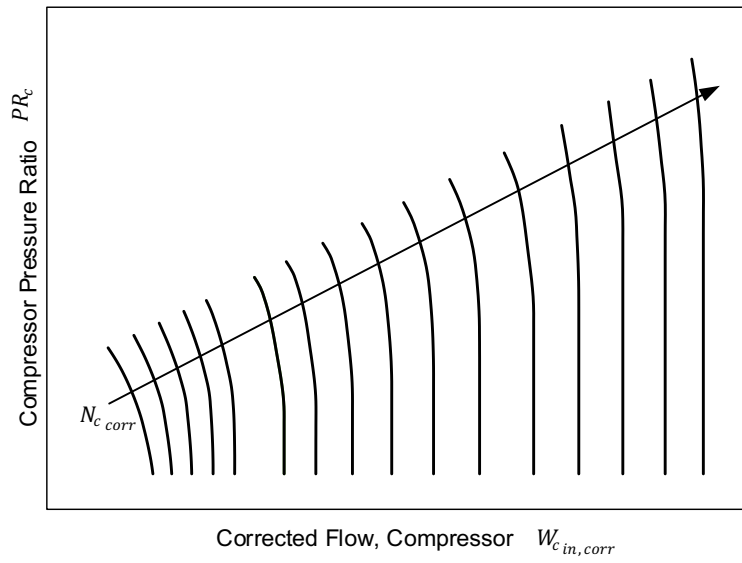


Figure 4-8 An example of an implemented compressor performance map (for pressure ratio)

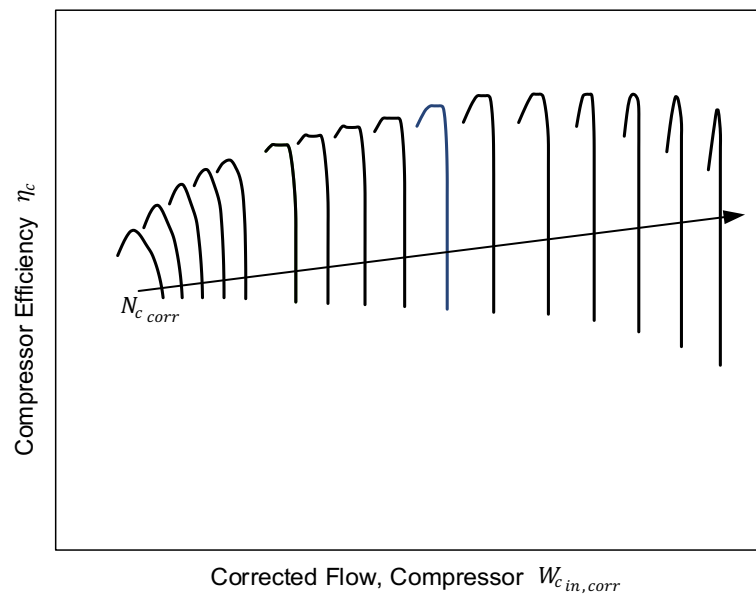


Figure 4-9 An example of an implemented compressor performance map (for isentropic efficiency)

In the developed modelling procedure, like Turbomatch, the concept of ‘ β lines’ is not used. Instead, the operating point on the map is defined by specifying the corrected speed and compressor surge margin ($N_{c,corr}, Z_c$), where Z_c is defined by:

$$Z_c = \frac{PR_c - PR_{c,min}}{PR_{c,max} - PR_{c,min}}$$

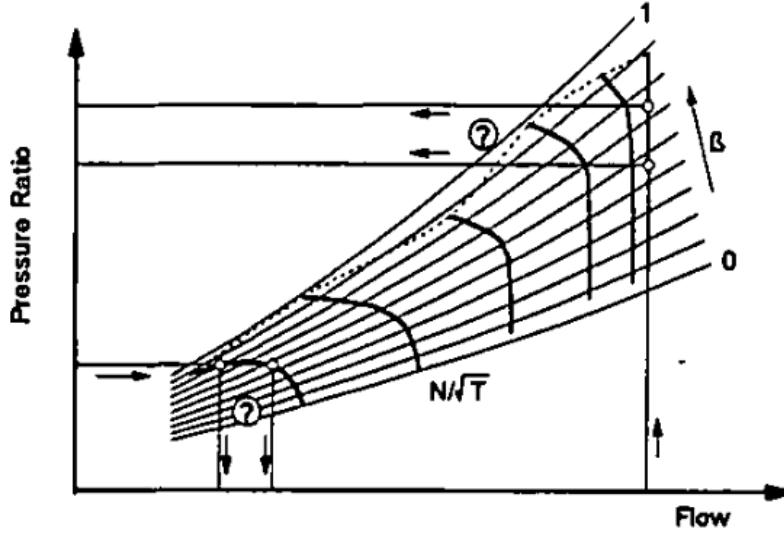


Figure 4-10 The compressor map reading problem [68].

Based on this operating point, the output data is calculated by the implemented map interpolation procedure described as follows. The problem can be defined by:

$$PR_{c_{map}}, W_{c_{map}}, \eta_{c_{map}} = f_{interpTM,C}(N_{c_{corr}}, Z_c) \quad (4-17)$$

Using the given $N_{c_{corr}}$, three encompassing speed data points from the map $N_{c_{corr,1}}, N_{c_{corr,2}}, N_{c_{corr,3}}$ are found. For each of these speeds, the data sets of $PR_{c,ij}, W_{c_{in,corr,ij}}, \eta_{c,ij}$ are extracted.

For each speed $N_{c_{corr,1}}, N_{c_{corr,2}}, N_{c_{corr,3}}, PR_{c,1}, PR_{c,2}, PR_{c,3}$ are calculated based on the definition of Z_c , using:

$$PR_c = PR_{c_{min}} + Z_c(PR_{c_{max}} - PR_{c_{min}}) \quad (4-18)$$

For each extracted speed line $N_{c_{corr,1}}, N_{c_{corr,2}}, N_{c_{corr,3}}$, using the variation of W_c with respect to PR_c on the speed line, $W_{c,1}, W_{c,2}, W_{c,3}$ and $\eta_{c,1}, \eta_{c,2}, \eta_{c,3}$ are calculated using interpolation corresponding to the calculated $PR_{c,1}, PR_{c,2}, PR_{c,3}$ as shown in Figure 4-11 (η_c not shown but approached in parallel based on the same approach).

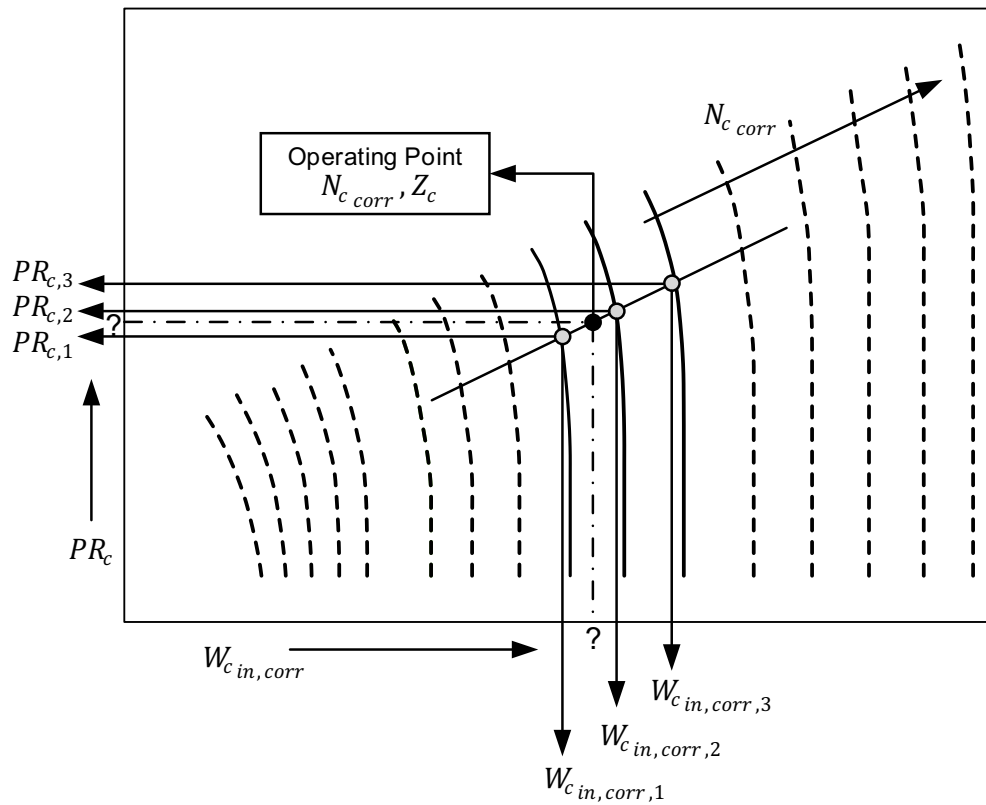


Figure 4-11 Implemented compressor map interpolation method

With the sets of $PR_{c,1}, PR_{c,2}, PR_{c,3}$ and $W_{c,1}, W_{c,2}, W_{c,3}$ for encompassing speed points $N_{c,corr,1}, N_{c,corr,2}, N_{c,corr,3}$ calculated, using the variation of PR_c, W_c with respect to $N_{c,corr}$ the final $W_{c,map}, PR_{c,map}$ are calculated using interpolation based on the three data sets. For the interpolation routines for the data between the points, three options have been included viz. linear interpolation, Lagrange's or cubic splines. The cubic splines method is used by default.

The generic compressor maps used with their recommended range of application are described in Table 4-2 [69]. The choice of compressor map is governed by the maximum pressure ratio on the map since it is desirable to keep the pressure ratio scale factor as near unity as possible.

Table 4-2 Generic Compressor Maps in Turbomatch, Poseidon+

Map Number	1	2	3	4	5
Maximum Pressure Ratio	1.7	2.0	15.0	2.6	11.0

4.2.6.2 Turbine Maps

Turbine maps that have been implemented for the present work, are again based on Turbomatch, represented by enthalpy drop ratio dH/T and isentropic efficiency plotted against the non-dimensional mass flow as shown in Figure 4-12 and Figure 4-13. The turbine maps follow a very similar approach to the compressor maps and hence all the statements made for the compressor maps in the previous section are also valid here. The turbine maps are stored in the format as described here. A set of corrected speed lines $1, 2 \dots m$, given by $N_{t_1} N_{t_2} \dots$ are defined. Each turbine speed line, N_{t_i} an individual set of data points from $1, 2 \dots n$ is defined denoted by DS_j with each data point holding the values of corrected mass flow, turbine enthalpy ratio, and isentropic efficiency denoted as $W_{t_{ij}} dH/T_{t_{ij}} \eta_{t_{ij}}$.

The data in Table 4-1, when typically plotted for a specific turbine map looks like as shown in Figure 4-8 and Figure 4-9. For interpolation of the turbine maps, a similar procedure to the one described for the compressor maps is used and hence is not described again specifically for turbines. The operating point on the turbine map is defined by specifying the corrected speed and compressor surge margin ($N_{t_{corr}}, Z_t$), where Z_t is defined by:

$$Z_t = \frac{dH/T_t}{dH/T_{t_{max}}}$$

where:

$$dH/T_t = \frac{H_{in} - H_{out}}{T_{in}}$$

Based on this operating point, the output data is calculated by the map interpolation procedure defined by:

$$dH/T_{t_{map}}, W_{t_{map}}, \eta_{t_{map}} = f_{interpTM,t}(N_{t_{corr}}, Z_t) \quad (4-19)$$

Table 4-3 Data format for implemented Turbine Maps

	DP_1	DP_2	...	DP_n
N_{t1}	$W_{t11} \ dH/T_{t11} \ \eta_{t11}$	$W_{t12} \ dH/T_{t12} \ \eta_{t12}$	...	$W_{t1n} \ dH/T_{t1n} \ \eta_{t1n}$
N_{t2}	$W_{t21} \ dH/T_{t21} \ \eta_{t21}$	$W_{t22} \ dH/T_{t22} \ \eta_{t22}$	...	$W_{t2n} \ dH/T_{t2n} \ \eta_{t2n}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
N_{tm}	$W_{t1m} \ dH/T_{t1m} \ \eta_{t1m}$	$W_{t2m} \ dH/T_{t2m} \ \eta_{t2m}$	...	$W_{tmn} \ dH/T_{tmn} \ \eta_{tmn}$

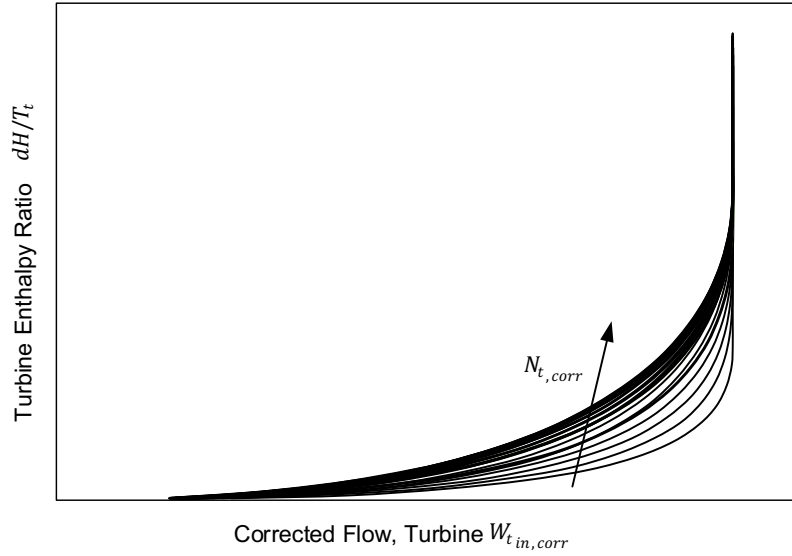


Figure 4-12 An example of an implemented turbine performance map.

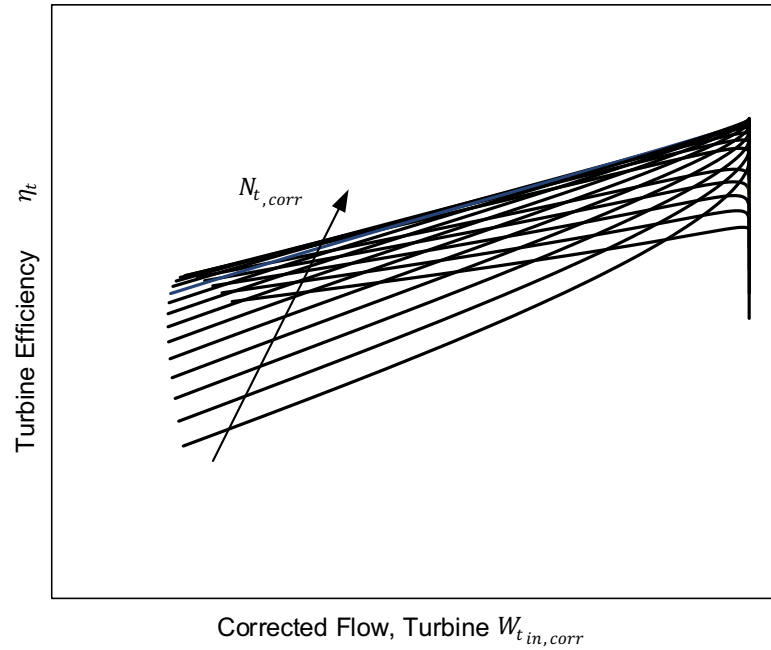


Figure 4-13 An example of a turbine performance map (for isentropic efficiency) in Poseidon+

The generic turbine maps used with their recommended range of application are described in Table 4-4 [93]. The choice of turbine map is governed by the maximum enthalpy drop ratio on the map and the demanded location of choke since it is desirable to keep the enthalpy drop scale factor as near unity as possible [93].

Table 4-4 Applied generic Turbine Maps

Map Number	1	2	3	4	5	6
Maximum Enthalpy Drop Ratio	0.075	0.045	0.065	0.04	0.03	0.13
Choked Area	Rotor	Rotor	Rotor	Mixed	Nozzle	Nozzle

4.2.6.3 Combustor Map

The implemented combustor map is used to calculate the combustor efficiency $\eta_{b,map}$ based on the increase in temperature in the combustor dT_b and the inlet pressure ratio PR_b of the combustor, defined as:

$$PR_b = \frac{P_{in}}{P_{ref}} \quad (4-20)$$

$$dT_b = T_{out} - T_{in} \quad (4-21)$$

Only a single map is currently implemented, which is scaled based on the DP run. The implemented map is shown in Figure 4-14. The combustor map has been adapted from the Turbomatch map to fit it for a standard 2D interpolation process. The data is stored in a text file in a 2D table format as shown in Table 4-5, wherein each PR_{b_i} and dT_{b_j} corresponds to a value of $\eta_{b_{ij}}$. Hence the map interpolation problem reduces to a standard 2D interpolation function defined as:

$$\eta_{b,map} = f_{interp,2D} \left(\frac{P_{in}}{P_{ref}}, T_{out} - T_{in} \right) \quad (4-22)$$

The 2D interpolation is executed using Lagrange's and cubic splines methods.

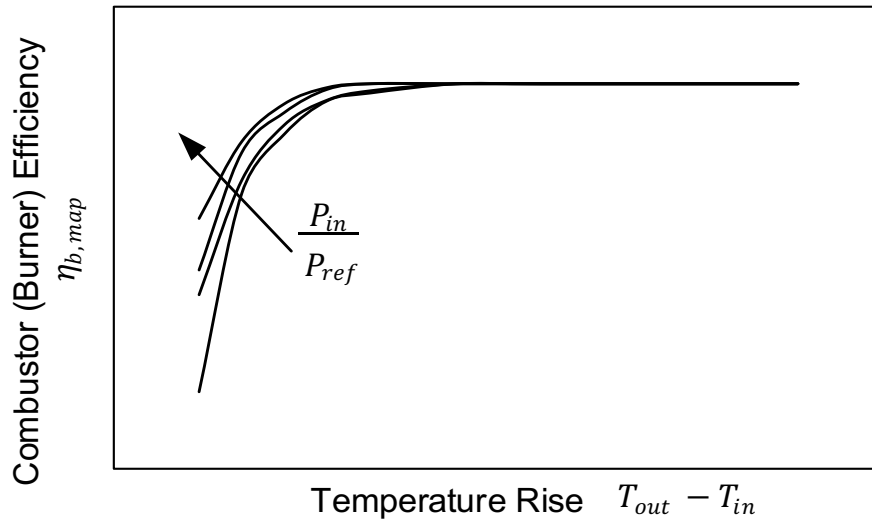


Figure 4-14 Combustor performance map in Poseidon+

Table 4-5 Data format for Poseidon+ Combustor Map

	dT_{b1}	dT_{b2}	...	dT_{bn}
PR_{b1}	η_{b11}	η_{b12}	...	η_{b1n}
PR_{b2}	η_{b21}	η_{b22}	...	η_{b2n}
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
PR_{bm}	η_{bm1}	η_{bm2}	...	$\eta_{bm n}$

4.2.6.4 Nozzle Map

A common nozzle map has been implemented that is used to calculate the nozzle velocity coefficient C_n based on the Nozzle Pressure Ratio PR_n and the Area Ratio of the nozzle, respectively defined as:

$$PR_n = \frac{P_{in}}{P_{S_{atm}}} \quad (4-23)$$

$$AR_n = \frac{A_{throat}}{A} \quad (4-24)$$

where A_{throat} is the throat area, A is the exit area.

This coefficient is used to calculate the Nozzle Thrust T_n (required for aero engines) by multiplying it to V_{out} . The implemented map is generic, shown in Figure 4-14, also includes the data for a convergent-divergent nozzle, and hence various values of AR_n are considered. If the case of convergent nozzles is considered, the value of $AR_n = 1$ is considered. The implemented map is.

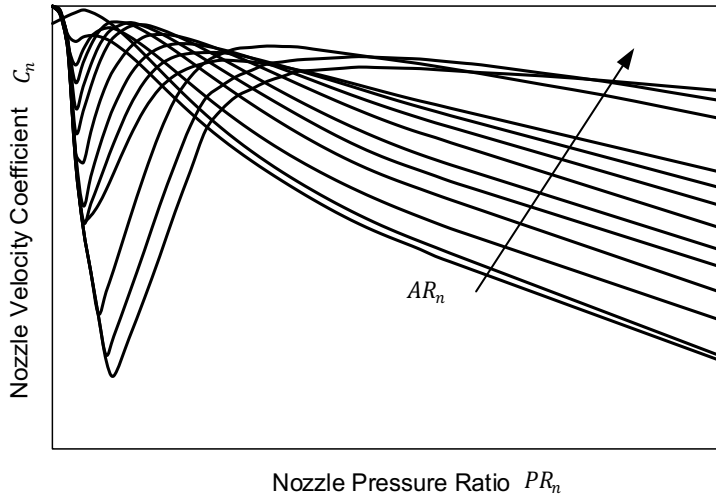


Figure 4-15 Implemented Nozzle map

The nozzle map from Turbomatch has been directly used. The data is stored in a text file in a 2D table format as shown in Table 4-6, wherein each AR_{n_j} and PR_{n_i} corresponds to a value of C_n . Hence the map interpolation problem reduces to a standard 2D interpolation routine defined as:

$$C_n = f_{interp2D,n}(AR_n, PR_n) \quad (4-25)$$

The 2D interpolation is executed using Lagrange's and cubic splines methods.

Table 4-6 Data format for Poseidon+ Nozzle Map

	AR_{n1}	AR_{n2}	...	AR_{nn}
PR_{n1}	C_{n11}	C_{n12}	...	C_{n1n}
PR_{n2}	C_{n21}	C_{n22}	...	C_{n2n}
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
PR_{nm}	C_{nm1}	C_{nm2}	...	C_{nmn}

4.3 Ship Propulsion System Performance Simulation

The ship propulsion system may be seen as a system that converts the energy of the fuel fed to the engines, shown by fuel flow WF , into useful thrust T_S using the propulsor, to match the ship resistance R_T at the required speed V_S , as shown in Figure 4-16.

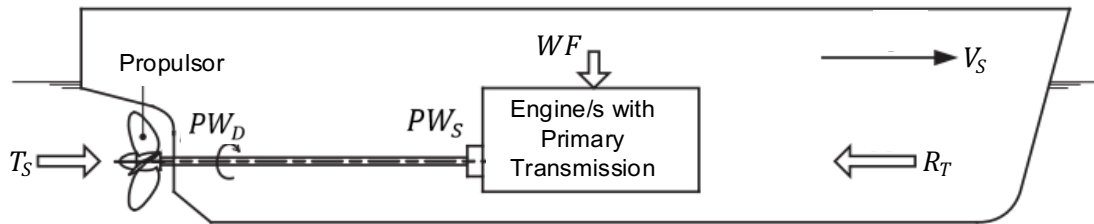


Figure 4-16 Concept of ship propulsion [70]

Therefore, the overall performance of the propulsion system, as seen from the source of power to the final output, depends on [94]:

- Fuel type, properties and quality.
- The efficiency of the engine in converting the fuel energy into useful transmittable power.
- The efficiency of the power transmission system.
- The efficiency of the propulsor in converting the power (usually rotational) into useful thrust.

Hence the performance analysis of the ship propulsion system requires the estimation of the hull resistance, propulsor performance, energy losses in the transmission system and performance of engines.

4.3.1 Interaction between Ship and Propulsor

The following definitions are usually used in the context of the ship propulsion system and the interaction between ship and propulsor, as defined in most textbooks [94–97] on the subject. Different types of propulsors can be used in ship design, but propellers being the most commonly used propulsor, the present work has been restricted to the application of propellers as the propulsor.

The resistance of a ship at a given speed is the force required to tow the ship at a defined speed in smooth water, assuming no interference from the towing ship. The power necessary to overcome this resistance is called effective power PW_E given by:

$$PW_E = R_T V_S \quad (4-26)$$

where:

R_T : total ship resistance

V_S : ship speed

In other words, PW_E is defined as the power required to tow the ship at the required speed.

Based on the general definition of thrust, the thrust power of the propeller PW_T , defined as the product of the propeller thrust T_S and the speed of advance of the propeller V_A , given as:

$$PW_T = T_S V_A \quad (4-27)$$

The thrust T_S measured in a propulsion test is higher than the resistance R_T measured in a resistance test (without propeller) as the propeller induces additional resistance due to [97]:

- The propeller increases the flow velocities in the aft body of the ship which increases frictional resistance.
- The propeller decreases the pressure in the aft body, thus increasing the inviscid resistance.

The thrust deduction fraction t couples thrust and resistance, by the relationship:

$$T_S = \frac{R_T}{(1 - t)} \quad (4-28)$$

The propeller inflow, i.e. the speed of advance of the propeller V_A , is generally slower than the ship speed due to the ship's wake.

The Taylor wake fraction (referred further simply as wake fraction) is defined as:

$$w = 1 - \frac{V_A}{V_S} \quad (4-29)$$

Hence based on the definition of w , the ship speed V_S and the speed of advance V_A are related as:

$$V_S = V_A(1 - w) \quad (4-30)$$

The effective power PW_E can thus be written as,

$$PW_E = \frac{(1 - w)/(1 - t)}{PW_T} \quad (4-31)$$

The ratio of the effective power to the thrust power is called the hull efficiency η_H , given by:

$$\eta_H = \frac{PW_E}{PW_T} = \frac{1 - w}{1 - t} \quad (4-32)$$

η_H is not really an efficiency, and its value can be less or greater than 1.

The thrust power PW_D is related to the delivered power to the propeller PW_T by:

$$PW_D = \frac{PW_T}{\eta_B} \quad (4-33)$$

where η_B is defined as the propeller efficiency behind the ship, which is defined as:

$$\eta_B = \eta_O \eta_R \quad (4-34)$$

where:

η_O is the open-water efficiency of the propeller, measured or computed for a propeller in open water conditions i.e. without hull affecting the flow into the propeller,

η_R is the relative rotative efficiency to account for the differences between the open-water test and the inhomogeneous three-dimensional propeller inflow encountered in propulsion conditions.

In reality, the propeller efficiency behind the ship η_B cannot be measured directly but are accounted for by the between PW_D and the performance in open water and PW_T . All effects not included in the hull efficiency, i.e. wake and thrust deduction fraction, are included in η_R . η_R is not truly an efficiency and its values can exceed 1.

PW_S is the power delivered to the propulsion shaft and it is related to the delivered power to the propeller PW_D by:

$$PW_S = \frac{PW_D}{\eta_S} \quad (4-35)$$

where η_S is defined as the shafting efficiency of the shafting system connecting the geared or electrical transmission system to the propeller.

Defining PW_B as the brake power produced by the ship power plant, it is related to the shaft power PW_S as:

$$PW_B = \frac{PW_S}{\eta_T} \quad (4-36)$$

where η_T is defined as the transmission efficiency of the geared or electrical transmission system.

The term propulsive efficiency η_D , also often referred to as quasi-propulsive efficiency, is used collectively to express the hydrodynamic efficiencies as:

$$\eta_D = \eta_H \eta_O \eta_R \quad (4-37)$$

η_D is used to relate PW_D with PW_E as:

$$PW_D = \frac{PW_E}{\eta_D} \quad (4-38)$$

Based on all defined efficiency terms PW_B can be related with PW_E as:

$$PW_B = \frac{PW_E}{\eta_H \eta_O \eta_R \eta_S \eta_T} \quad (4-39)$$

4.3.2 Ship Propulsion System Modelling

In the preliminary design stage, when the propulsion system needs to be designed to meet the performance requirements of the ship, the hull form of a ship is only vaguely defined by a rough lines plan or in terms of the various form coefficients (e.g. block coefficient, prismatic coefficient, etc.) and principal dimensions (e.g. length, draught, beam, etc.). Further, the propulsor (propeller) design, in terms of its primary parameters, must be optimised within the constraints of the design. In addition, the propulsive coefficients defining the hull propeller interaction must be defined.

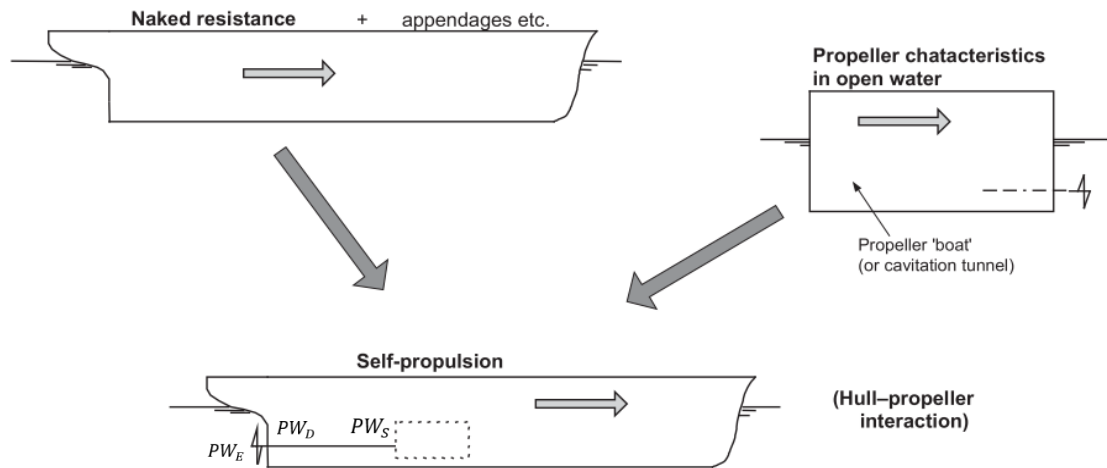


Figure 4-17 Components of ship powering – main considerations [70].

The implemented component-based procedure for modelling the propulsion system follows a similar approach as that used for the gas turbine engine modelling, wherein the propulsion system is modelled as a system of discrete components, parameters for which are defined in the model definition along with the definition of connections, operating conditions and 'handle' or power setting. The discrete ship propulsion components that are defined to model a complete propulsion system are:

- Hull resistance.
- Propellers.

- Propeller shafting.
- Mechanical transmission sub-system consisting of gearing and clutches.
- Mechanical transmission sub-system consisting of alternators, electric motors with frequency converters, switchboards.
- Engine/s: gas turbines and diesel engines.

The hull resistance component is a common component to which the propeller component connects. The engines are connected to a mechanical transmission system or an electrical transmission system, which in turn connects to the propellers through propellers shafts. These connections are made at the defined ports on each component, by mechanical or electrical connections, as applicable.

The overall process used to model the propulsion system should be read in conjunction with section 3.1. Section 4.3.4 of this chapter describes the overall process used by the developed program to calculate the engine and plant parameters for any defined operating point. The brief theoretical background and the implementation of the following specific propulsion system components used to model the entire propulsion plant are described from section 4.3.4 to 4.3.14.

- Hull Resistance, propulsive coefficients
- Propeller
- Propeller Initial Design Optimizer
- Water Properties Model
- Prime Movers
 - Gas Turbines
 - Diesel Engines
- Geared Transmission Systems
- Shafting
- Electrical Systems
 - Electric Machines (motors and alternators)
 - Frequency Converters
 - Voltage System Selection
 - Switchboards

The symbolic representation of the components to describe the models diagrammatically in this thesis is described in Appendix B. The details of the component properties are defined in models created as input text files, the format for which has been defined in Appendix C.

4.3.3 Operating Point Performance Calculation Methodology

The steady-state performance calculation, since it needs to be undertaken using a computer algorithm, needs a generic procedure which can be used for multiple propulsors (more than two are common for waterjet applications) which can be powered with equal or unequal torque from the engines. To enable this, a novel generic method has been developed and implemented as a part of the present work. The method utilizes the same principle of non-linear equation solving as implemented for the gas turbine engines for OD calculations. The algorithm calculates the steady state operating point, iteratively as follows:

- The user inputs the throttle or power setting for the engines (here fuel flow) and the pitch setting of the propellers (here P/D) as well as the environmental condition settings (ambient air, seawater temperature).
- Following variables are defined internally by the program for the calculation: ship speed V_s , propulsor speed for each propulsor in the model: $N_{p_1}, N_{p_2}, \dots, N_{p_m}$, where m is the number of propulsors in the model. Hence, the total number of variables are $m + 1$.
- The solving process starts with an initial guess for the variables, ship speed and the set of propulsor speeds. The values for these variables are thereafter varied by the nonlinear solver for each iteration.
- For each engine Eng_j , connected to a propulsor through a transmission system, the speed of the engines is derived from the propulsor speed as a variable using the transmission system gear ratios.
- Using the derived engine speed and the user-defined power setting of the engine or handle (Hdl), each engine module is run to calculate the engine torque, Q_{eng_j} , for each engine. The Q_{eng_j} from the engines connected to the transmission system are processed by the transmission system model,

to give the total propulsor shaft torque Q_{sh_i} driving the propulsor. The hull module calculates the total thrust T_S and V_A using the variable V_S .

- For each propulsor P_i , the propeller module calculates the propulsor torque Q_{p_i} and propulsor thrust T_{p_i} based on the user-defined P/D , the variables N_{p_i} and V_A calculated by the hull module.
- The thrust of each propulsor is summed up to give the total thrust from the propulsors T_p . Errors for each iteration are calculated as: difference in torque at propulsor based on engine torque: Q_{sh_i} and Q_{p_i} calculated at propulsor end [equation (4-40)], for each propeller, difference in total thrust T_p and T_S [equation (4-41)]. Hence, the total number of errors are $m + 1$, matching the number of variables.

$$Err_{Q_i} = 1 - \frac{Q_{p_i}}{Q_{sh_i}} \quad (4-40)$$

$$Err_T = 1 - \frac{T_p}{T_S} \quad (4-41)$$

While the overall process described is applicable for any type of propulsor, the present work only considers propellers. A conceptual diagram for the described method is shown in Figure 4-18, for a simple propulsion system model with a single CPP being driven by a single engine through a common gearbox and shafting. To find the solution iteratively, the same non-linear solvers as that for the gas turbine calculations, are used. This provides a robust way of solving the equations, even if the initial guess is far away from the solution.

The close resemblance of the schematic used for the steady state analysis at Figure 4-18 in the developed modelling framework, with the one used for dynamic analysis at Figure 4-19 can be clearly seen, wherein the nonlinear solver based on the variables and calculated errors is replaced by the rotor and ship translational dynamics blocks. The ship translational dynamics block integrates the acceleration calculated from the force balance between ship resistance and propeller thrust, ship mass (including entrained water); over time to obtain ship speed [equation (4-43)]. The rotor dynamics block integrates the angular

acceleration calculated from the torque balance between engine output torque and propeller torque, the effective shaft inertia (considering speed reductions in gearing); over time to calculate the propeller speed [equation (4-42)].

$$N_{sh} = N_{sh0} + \int \frac{1}{2\pi I} (Q_{sh} - Q_p) dt \quad (4-42)$$

$$V_S = V_{S0} + \int \frac{1}{m} (T_p - T_S) dt \quad (4-43)$$

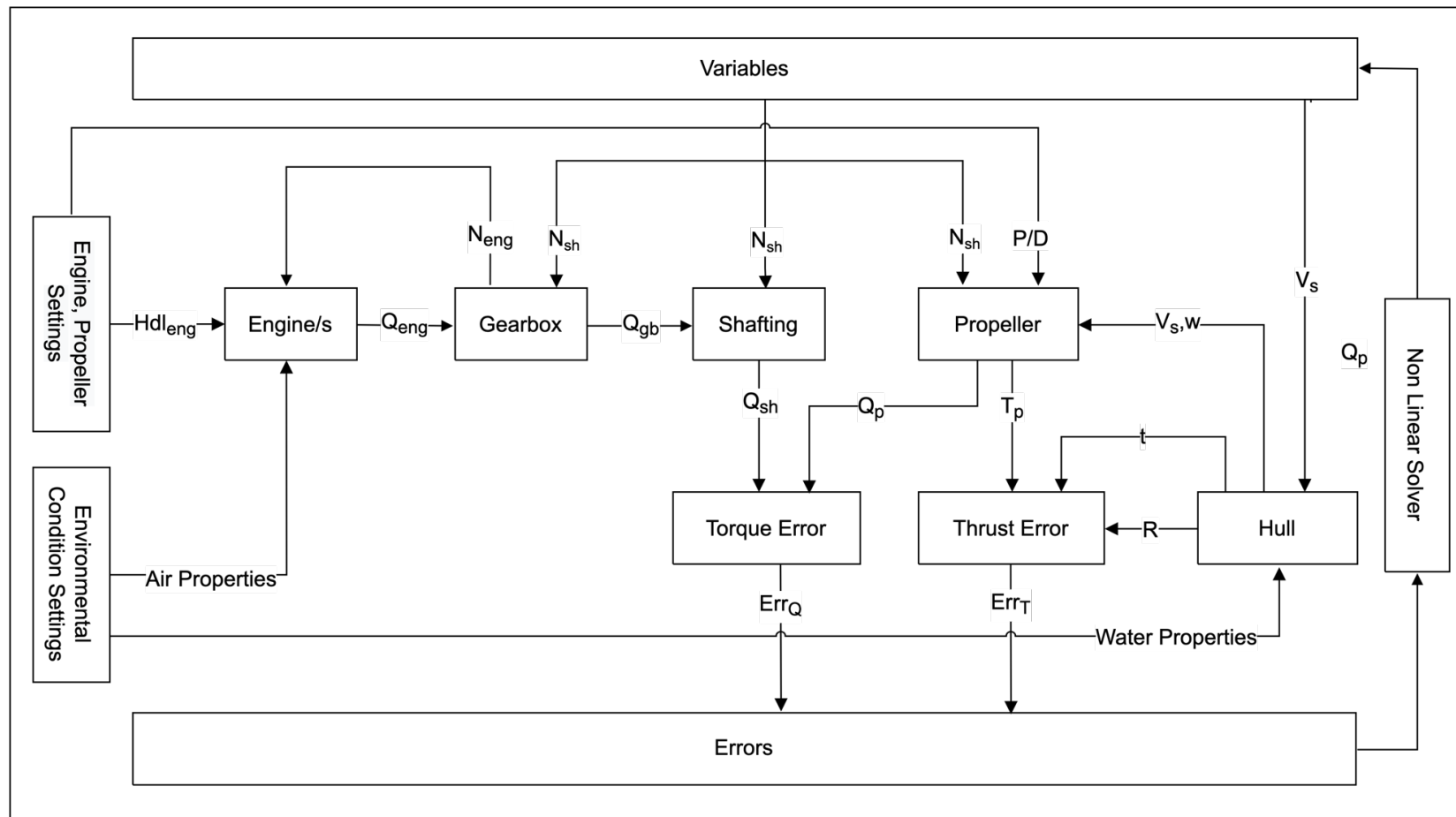


Figure 4-18 Conceptual diagram for a steady-state operating point solution for a simple propulsion system.

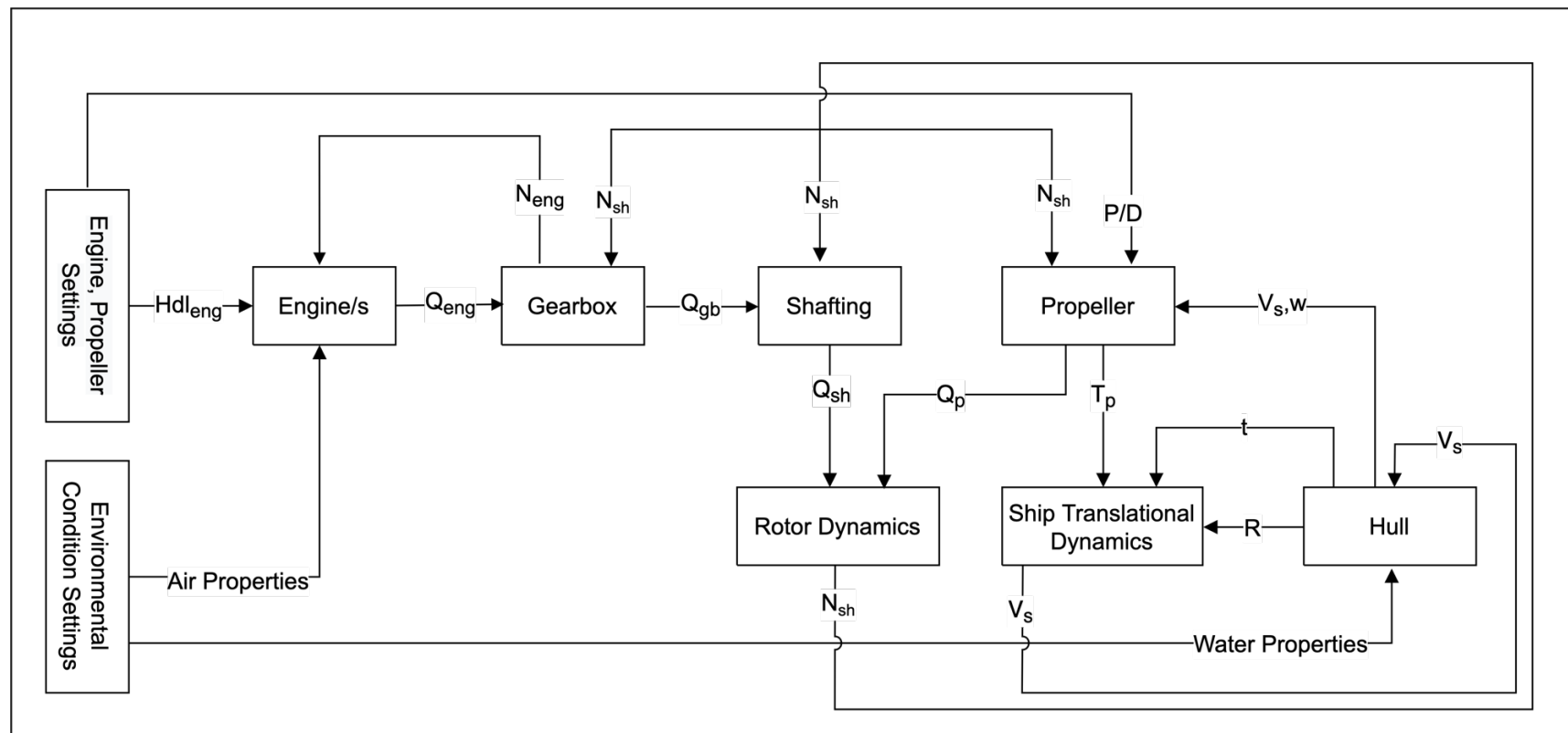


Figure 4-19 Conceptual diagram for a transient operating point solution for a simple propulsion system.

4.3.4 Hull Resistance

4.3.4.1 Brief Theoretical Background

This total resistance of a body moving in water is made up of several components, which are caused by a variety of factors, and which interact one with the other in a complex way. To understand this complex interaction of multiple factors that affect resistance, from dimensional analysis, the resistance of a body in water can be shown to have the following relationship with three distinct groups of variables:

$$R \propto \rho V^2 L^2 f \left[\left(\frac{\rho V L}{\mu} \right)^{-d} \left(\frac{g L}{V^2} \right)^e \left(\frac{p}{\rho V^2} \right)^f \right] \quad (4-44)$$

where:

V : Speed,

L : linear dimension representing the size of the body,

ρ : Mass density of the fluid, (mass per unit volume),

μ : coefficient of dynamic viscosity of fluid,

g : Acceleration due to gravity,

p : Pressure per unit area in the fluid.

From the previous equation, the non-dimensional resistance coefficient $\frac{R}{1/2 \rho S V^2}$ is defined as:

$$\frac{R}{1/2 \rho S V^2} = f \left[\frac{V L}{\nu}, \frac{g L}{V^2}, \frac{p}{\rho V^2} \right] \quad (4-45)$$

where ν is based on the kinematic viscosity of fluid defined as $\nu = \mu / \rho$, and S is the surface area of the body in water.

The above equation effectively states that if all the parameters on the right-hand side have the same values for two geometrically similar but different sized bodies,

the flow patterns will be similar and the value of $\frac{R}{1/2\rho SV^2}$ will be the same for each. Further, it can be seen that the total resistance of a body in water depends upon the various physical quantities involved, associated in three non-dimensional groups:

$$\frac{VL}{\nu}, \frac{gL}{V^2}, \frac{p}{\rho V^2}$$

Considering first the case of a non-viscous liquid in which there is no frictional or other viscous drag, and neglecting for the moment the last group, the second term $\frac{gL}{V^2}$ in equation (4-45) controls the surface wave system. Writing the wave-making or residuary resistance as R_R and the corresponding coefficient as C_R , expressed as:

$$C_R = \frac{R_R}{1/2\rho SV^2} = f_1(V^2/gL) \quad (4-46)$$

This means that geometrically similar bodies of different sizes will have the same specific residuary resistance coefficient C_R if they are moving at the same value of the parameter V^2/gL . It is this property that is used to determine the residuary resistance of hulls based on a scaled-down model test of the hull form.

In the case of a deeply submerged body, where there is no wave-making, the first term $\frac{VL}{\nu}$ in equation (4-45) governs the frictional resistance, R_F . The frictional resistance coefficient C_F is given by:

$$C_F = \frac{R_F}{1/2\rho SV^2} = f_2(VL/\nu) \quad (4-47)$$

As for the third term $\frac{p}{\rho V^2}$ in equation (4-45), since most of the hydrodynamic forces arise from differences in local pressures, and these are proportional to V^2 . Hence these forces are not affected by the atmospheric pressure so long as the fluid remains in contact with the model or ship surfaces. When the pressure approaches very low values, however, the water is unable to follow surfaces

where there is some curvature and cavities form in the water, giving rise to cavitation, which is handled as a separate subject.

The first and the second terms in equation (4-45) lead to two important definitions that are used for such analysis viz. the Froude number and Reynolds number.

Froude number is defined as:

$$F_n = V/\sqrt{gL} \quad (4-48)$$

Reynolds number is defined as:

$$Re = \frac{VL}{\nu} \quad (4-49)$$

Using the equations (4-46) and (4-47), the total resistance coefficient C_T , is defined as:

$$C_T = C_R + C_F \quad (4-50)$$

where:

$$C_T = \frac{R_T}{1/2\rho SV^2} = f_1(V^2/gL) + f_2(VL/\nu) \quad (4-51)$$

Determining resistance through a scaled-down model test should therefore allow determination of the total resistance by estimating the residual and frictional components of the resistance. However, the practical constraint for the conduct of model testing is that the conditions of mechanical similitude for both friction and wave-making cannot be satisfied in a single test. This fundamental difficulty is dealt with by handling the frictional wave-making resistance separately.

In addition to the above, the following components of resistance that act on the hull:

- Eddy Resistance, Viscous Pressure Drag, Separation Resistance and Wave-breaking Resistance.
- Air and Wind Resistance
- Added Resistance due to Waves

- Appendage Resistance.
- Trim Effects
- Shallow-Water Effects

It should be remembered that the components of resistance have complex interactions with each other, and we try to view them as isolated components for the purpose of analysis.

4.3.4.2 Methods for estimating hull resistance

Hull resistance can be predicted with various degrees of accuracy using either experimental, statistical, empirical methods, numerical approaches or a combination of these.

The experimental methods are based on undertaking tests using a geometrically scaled-down model of the full-scale hull to determine resistance. Model testing is an expensive procedure and is therefore generally only carried out in the latter design stages of the ship design [98]. Methodical series are also considered to be an experimental prediction method, wherein the full-scale results are predicted from data extrapolated from a series of tests carried out on a range of models having systematically varied design parameters.

Statistical methods are based on the creation of mathematical models for a certain range of hull parameters, by applying regression techniques to resistance data sourced from methodical series results, results from a wide range of tank towing experiments and actual ship data.

Empirical methods generally comprise one or more relatively simple equations that usually provide an estimate of the overall propulsive power required rather than hull resistance. In many instances, these equations are a combination of theory and 'rule of thumb'. They were extremely popular in the heyday of slide rules and log tables [98] but due to their rather low accuracy, they can be best used for determining initial rough estimates.

Numerical approaches involve primarily using Computational Fluid Dynamics (CFD) for modelling both viscosity and wave-making using Navier Stokes/RANS

solvers. While model tests are still extensively used for resistance prediction of hulls, CFD is finding increasing application for hull forms such as warships, fast ferry etc.

Since the developed modelling procedure focuses on the preliminary part of the ship design when only the basic parameters of the ship are available, the hull resistance component has been implemented based on the following three popular statistical methods for various types of hull forms to be modelled:

- Holtrop & Mennen Method
- Fung and Liebman Method
- Hollenbach Method

The 'Holtrop and Mennen' (H&M) mathematical model was first published in 1977, followed a year later by an improved model which amongst other things, made allowance for bulbous bows and an improvement in estimating the resistance of large waterplane area coefficient ships [99]. The model was then extended, in 1982 to improve the power prediction of ships with high block coefficients, low length breadth ratio and slender naval ships [100]. Despite this, predictions for high-speed craft were often incorrect and, in an attempt to rectify this, the data sample was extended in 1984 to include the Series 64 hull forms [101]. The 1982 mathematical model was developed from 191 random model experiments and full-scale data which increased to 334 for the 1984 model. The method implemented for the present work is based on the publications by Holtrop et.al. in 1982 [100] and 1984 [101].

To support NAVSEA ship synthesis design programs during the early stages of ship design, Fung developed a set of mathematical models to predict the resistance of high-speed transom stern vessels from 1986-1995, typically used for warships [102], [103]. Fung concluded that while Holtrop's regression analysis-based model performed well for cruiser stern ships, particularly at the high end of their operating profiles, the model did not perform very successfully for transom stem vessels and for most tested cases, was likely to underpredict, especially at the lower speeds [103]. Fung developed the model using multiple stepwise regression analysis for 18 different speed-length ratios and data from

three overlapping sets of data which consisted of 529 test conditions. The method implemented for the present work is based on the publication by Fung and Liebman (F&L) in 1995 [104] along with corrections that were published in 1999 [105]. It should be noted that this method uses the imperial system of units with the distance specified in feet and displacement specified in Long Tons.

Hollenbach [106] published a model for predicting resistance in 1998 for more modern ship hull forms than those considered for developing the popular traditional methods considered like Holtrop and Mennen etc. The study evaluated the accuracy of these methods based on the results from a database of model tests from the Vienna Ship Model Basin for the years 1980 to 1995. The model is based on a database that covered 433 models (1218 variants) with protocols of 793 resistance tests and 1103 propulsion tests each for a set of different speeds [106]. Hollenbach method calculates a 'mean' value of resistance which would be expected based on the design inputs as well as and a 'minimum' resistance which might be achieved for good hull lines developed following computational and experimental investigations and a 'maximum' value of resistance that can be expected. For the present work, the 'mean' value of resistance is used for performance calculations. It should be noted that the resistance is decomposed without using a form factor, which can also be seen in the total calm water resistance equation using this method. The method implemented for the present work is based on the publication by Hollenbach from 1998 [106].

While the developed modelling process includes the implementation of the above three methods, the selection of the final method is a subjective judgement that the analyst needs to make based on the limitations of each method and considering the boundaries for these methods defined in terms of the hull forms considered and Froude number, as defined in Appendix F.8. In general, the H&M method covers the widest range of application compared to the other two methods. In the present work primarily H&M as well F&L methods have been used, as would be seen in Chapter 6.

4.3.4.3 Implemented method for modelling hull resistance

Total Resistance

The total resistance of the hull R_H is given by:

$$R_H = R_T + R_S \quad (4-52)$$

where:

R_T is the total calm water resistance, determined by H&M method, F&L method or Hollenbach method,

R_S is the resistance due to the service conditions.

Resistance due to Service Conditions

Resistance due to Service Conditions, R_S , is given by:

$$R_S = R_{FO} + R_{SS} + R_{WI} \quad (4-53)$$

where:

R_{FO} Fouling resistance,

R_{SS} Sea state resistance,

R_{WI} Wind Resistance.

To account for the additional resistance due to the above-mentioned service factors, the exact calculation of these factors is not undertaken in the present work. Instead, the concept of the so-called service factor or service margin is used on the normal continuous power rating to achieve a sustained speed [3]. Hence the determination of resistance due to these factors is not described any further.

Total Calm Water Resistance

Starting with the input data of the hull as shown in Appendix F.1, the total calm water resistance R_T are calculated by the H&M Method, F&L Method and the Hollenbach method, as follows:

H&M Method:

R_T is calculated by H&M method, based on:

$$R_T = R_F(1 + k_1) + R_{R,H\&M} + R_{APP} + R_{BT} + R_A + R_{Air} \quad (4-54)$$

where:

R_F : Frictional resistance,

$1 + k_1$: Form factor to account for viscous resistance of the hull in relation to R_F ,

$R_{R,H\&M}$: Residual resistance calculated by the H&M method,

R_{APP} : Resistance due to appendages,

R_{BT} : Resistance due to bow thrusters,

R_A : Model ship correlation resistance,

R_{Air} : Resistance due to air.

F&L Method:

R_T is calculated by F&L method, based on:

$$R_T = R_F + R_{R,F\&L} + R_{APP} + R_{Air} \quad (4-55)$$

where:

R_F : Frictional resistance,

$R_{R,F\&L}$: Residual resistance calculated by the F&L method,

R_{APP} : Resistance due to appendages,

R_{Air} : Resistance due to air.

Hollenbach Method:

R_T is calculated by Hollenbach method, based on:

$$R_T = R_F + R_{R,Hol} + R_{Air} \quad (4-56)$$

where:

R_F : Frictional resistance,

$R_{R,Hol}$: Residual resistance calculated by the Hollenbach method,

R_{Air} : Resistance due to air.

Further description of these calculation methods based on the defined equations is described in the following paragraphs.

Derived Hull Parameters

Since only the basic hull parameters are defined in the input data, the additional hull parameters are derived using the method defined in Appendix F.2.

Friction Resistance

R_F Frictional resistance is calculated as:

$$R_F = 0.5 \rho V^2 S C_F \quad (4-57)$$

where C_F : frictional coefficients determined by the ITTC 1957 formula, given as:

$$C_F = \frac{0.075}{(\log_{10} Re - 2)^2} \quad (4-58)$$

where Re : Reynolds number.

Air Resistance

Air Resistance R_{Air} due to the superstructure (still air resistance due to the hull frontal area is accounted in R_A for H&M Method) is given by:

$$R_{Air} = 0.5 \rho_{Air} V_S^2 A_P C_D \quad (4-59)$$

where:

A_P : projected frontal area of superstructure

ρ_{Air} : density of air

C_D : air drag coefficient

Model Ship Correlation Resistance

Model ship correlation resistance, R_A , is used to account for hull roughness and still-air resistance in the H&M Method calculations [100]. Model ship correlation resistance R_A is calculated as:

$$R_A = 0.5 \rho V_S^2 S C_A \quad (4-60)$$

Residual Resistance

The residual resistance is calculated using any of the following methods, as defined in the input file:

- H&M Method, calculated as per Appendix F.5,
- F&L Method, calculated as per Appendix F.6,
- Hollenbach calculated as per Appendix F.7.

Resistance Appendage

Resistance Appendage R_{APP} is based on given as:

$$R_{APP} = 0.5 \rho V_S^2 S_{APP} (1 + k_2)_{eq} C_F + R_{BT} \quad (4-61)$$

where:

C_F : coefficient of frictional resistance determined by the ITTC 1957 formula.

Resistance due to the bow thruster

R_{BT} is the resistance due to the bow thruster openings, given by:

$$R_{BT} = \rho V_S^2 \pi d^2 C_{BTO} \quad (4-62)$$

where:

d : tunnel diameter,

C_{BTO} : Coefficient for bow thruster openings.

4.3.5 Propulsive Coefficients

The propulsive coefficients w, t, η_R used to describe the hull propeller interaction have been calculated based on the H&M method [100,101], further described in Appendix F.9. Only the coefficients applicable for twin-screw ships are shown as the cases considered in this work only consider this propeller configuration.

4.3.6 Propulsor: Propeller

4.3.6.1 Brief Theoretical Background

A propeller converts the rotating motion of the shaft into a translating motion of the ship, by creating a thrust force on the water that accelerates a column of fluid passing through the swept disc [94]. The rotation of an airfoil-shaped blade through the water creates a pressure difference between the forward and rear surface, which makes the water accelerate and create a thrust force.

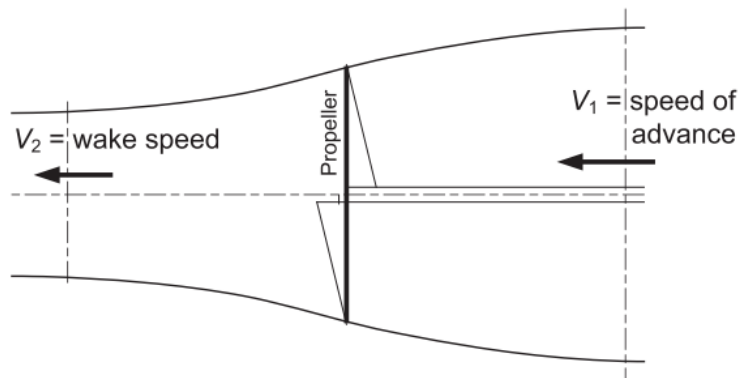


Figure 4-20 Propeller action [70].

Some of the common terms used to describe a propeller are shown in Figure 4-21 [97]. The propeller is often defined in relation to a 'generator line', as shown in Figure 4-23, which may be drawn at right angles to the shaft line, but more normally it is raked [94]. The complex propeller geometry is characterized by many parameters, the primary parameters for the initial design of a propeller being propeller diameter, boss (or hub) diameter, number of propeller blades or blade number, propeller pitch and blade area ratio.

A propeller may be approximated by a part of a helicoidal surface which in rotation screws its way through the water. Propeller geometric pitch P is defined as the distance a screw propeller with geometric pitch angle θ would advance during one revolution. Pitch is normally expressed non- dimensionally as a fraction of propeller diameter D as P/D . For a propeller with radius $R = D/2$ the actual local geometric pitch angle θ at any local radius r (see Figure 4-23) can be calculated as [94]:

$$\theta = \tan^{-1} \left(\frac{P/D}{\pi x} \right) \quad (4-63)$$

where $x = r/R$

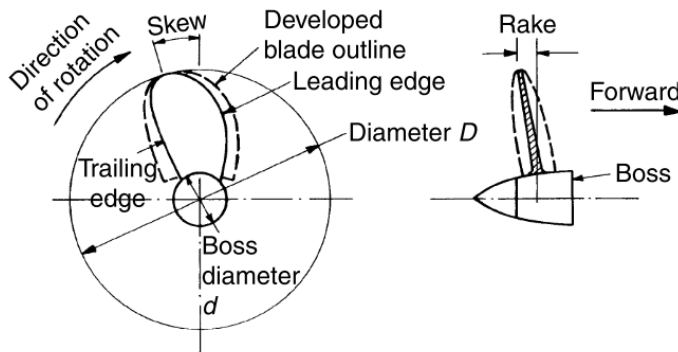


Figure 4-21 Propeller geometry [97].

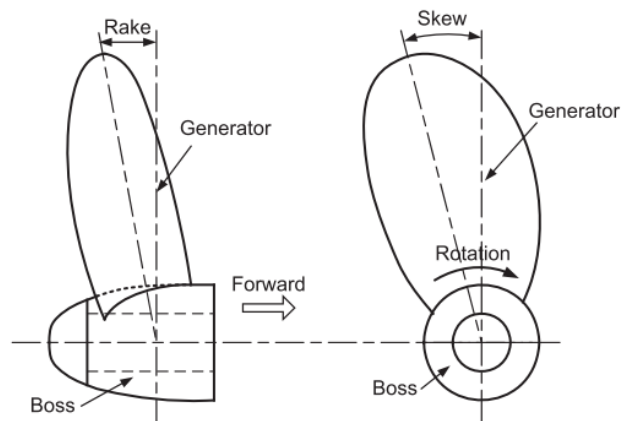


Figure 4-22 Propeller geometry [70].

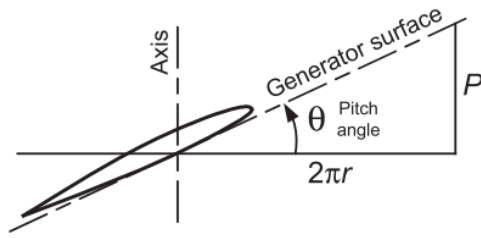


Figure 4-23 Geometric pitch [70].

Propellers do not have a radially constant pitch, and the pitch at one radial position, typically $0.7 R$, is taken as a single value to represent the radial pitch distribution [97].

Expanded blade area A_E is the area formed by the outline if the circumferential chord of the blade is set out against the radius [97]. Expanded Blade Area Ratio EAR is defined as the ratio of A_E , with respect to the propeller disc area A_O as:

$$EAR = \frac{A_E}{A_O} \quad (4-64)$$

where the propeller disc area A_O is defined as $A_O = \pi D^2/4$

Typical Expanded Blade Area Ratios are $0.3 < EAR < 1.5$. Area ratios above 1 mean overlapping blades which are expensive to manufacture. EAR , significantly influences cavitation behaviour. Generally spoken, a larger EAR is better for cavitation behaviour, but on the other hand, the propeller efficiency decreases with an increase in EAR since the increased blade area also increases frictional losses. EAR is chosen such that the blade load is kept low enough to avoid unacceptable cavitation. Therefore EAR increases with propeller load (thrust per propeller area A_O). Larger EAR also often demand higher blade numbers to avoid too small side ratios for the blades [97].

The diameter is a fixed value that is well-chosen in the design phase. For high-performance vessels usually, the highest possible diameter for the propeller is selected taking into account the hull form and the maximum draught.

The blade number Z is an important parameter selected for managing torsional vibration resonant frequency and hull modal frequency response. For large ships, blade numbers of 4 to 7 are typical [97].

In ship applications, FPP or CPP are used based on the design requirements. With FPP, the only operational variable is rotational speed, while CPP provides an extra degree of freedom in its ability to change blade pitch [108]. CPP provides more flexibility of operation wherein controlling of the pitch can be designed for optimum propulsive efficiency, managing engine operation within their operating envelopes, reducing cavitation and for additional flexibility for different modes of operation like constant shaft speed operation etc. On the other hand, CPP systems add complexity to the design, additional mass on and off the propeller to manage the pitch setting as well as costs.

4.3.6.2 Propeller Performance

Guidance on the laws governing model and ship similitude by applying dimensional for propellers is obtained from dimensional analysis. Several systems of non-dimensional coefficients can be used in propeller design work, the most commonly used [94] as based on:

$$f_1 \left[\left(\frac{T_P}{\rho_w n_p^2 D^4} \right), \left(\frac{V_A}{n_p \cdot D} \right) \right] = 0 \quad (4-65)$$

$$f_2 \left[\left(\frac{Q_P}{\rho_w n_p^2 D^5} \right), \left(\frac{V_A}{n_p \cdot D} \right) \right] = 0 \quad (4-66)$$

where:

T_P : thrust developed by the propellers,

Q_P : torque to rotate the propeller,

n_p : rotational speed of the propeller,

ρ_w : density of water in which the propeller is working.

Based on the above functions, T_P and Q_P are given by:

$$T_P = f(D, V_A, n_p, \rho) \quad (4-67)$$

$$Q_P = f(D, V, n_p, \rho) \quad (4-68)$$

Thrust coefficient K_T and torque coefficient K_Q are the non-dimensional forms of T_P and Q_P are given:

$$T_P = K_T \rho_w n_p^2 D^4 \quad (4-69)$$

$$Q_P = K_Q \rho_w n_p^2 D^5 \quad (4-70)$$

Advance number J is the non-dimensional form of advance velocity V_A , defined as:

$$J = \frac{V_A}{n_p D} \quad (4-71)$$

The propeller open-water efficiency η_0 is derived from thrust and torque coefficients and the advance number as:

$$\eta_0 = \frac{J}{2\pi} \cdot \frac{K_T}{K_Q} \quad (4-72)$$

The performance of a propeller is normally expressed in three non-dimensional parameters (K_T , K_Q , J) and presented in a so-called open water diagram or open water characteristics showing the variation of K_T , K_Q and η_0 with J as shown in Figure 4-24 [97]:

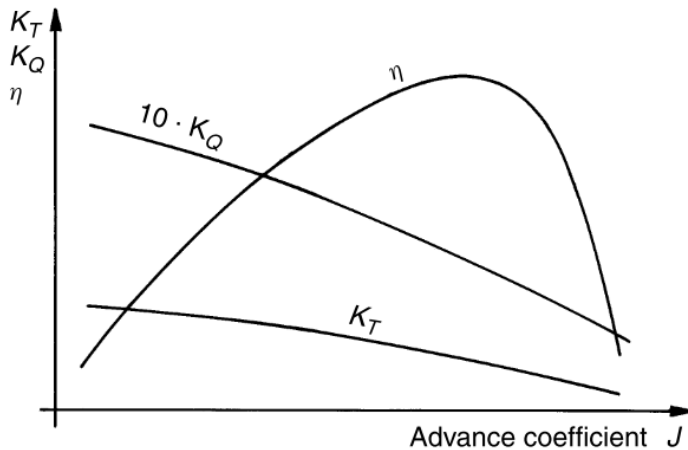


Figure 4-24 Open water characteristics of the propeller.

4.3.6.3 Wageningen B Series Propeller Models

Like for resistance predictions, using standard series propellers as the basis to establish the basic parameters of the propeller, is a good start point of the conceptual design of the propulsion system. Standard series data are regression analysis models based on the results of open-water tests with systematically varied series of propeller models, where the characteristic parameters like $Z, EAR, P/D$ are varied to obtain the open water characteristics of the propeller.

Over the years there have been a considerable number of standard series propellers tested in many different establishments around the world like the ‘Wageningen B Series’, Gawn, KCA, SSPA series, the more modern ‘Wageningen C and D Series’ and others [108]. The series data helps the designer understand the factors which influence propeller performance and the inception and form of cavitation on the blades under various operating conditions while providing models which assist in selecting the most appropriate dimensions of actual propellers to suit full-size ship applications [108].

‘Wageningen B Series’ is perhaps the most extensive and widely used propeller series. The series was originally presented in a set of papers presented by Troost from 1938-1951, and, amongst many practitioners, is still referred to as the ‘Troost series’ [108]. To account for scale effects in the original design diagrams, re-appraisal of the series in which the differences in test procedures were taken into account and the results of this work were presented by van Lammeren et.al. [109]. Detailed regression studies on the performance characteristics given by this model series were thereafter undertaken and computer-analysed data of the Wageningen B-screw series was reported by Oosterveld et.al. [110] at a fixed Reynolds number of 2×10^6 by the equation:

$$K_T = \sum_{s,t,u,v} [C_{T,s,t,u,v}(J)^s(P/D)^t(A_E/A_O)^u(Z)^v] \quad (4-73)$$

$$K_Q = \sum_{s,t,u,v} [C_{Q,s,t,u,v}(J)^s(P/D)^t(A_E/A_O)^u(Z)^v] \quad (4-74)$$

where:

$C_{T,s,t,u,v}$: Table coefficients,

s, t, u, v : Coefficient indices.

The table of coefficients defined for the above equations is given in Appendix G.1. To extend this work further so that propeller characteristics can be predicted for other Reynolds numbers within the range 2×10^6 to 2×10^9 a set of corrections have also been published, shown in Appendix G.2.

For the present work, the 'Wageningen B Series' model has been implemented as the propeller series for the preliminary design of propellers, primarily due to the very large amount of published data available for the series. While applying this series for propellers design the range of validity of propeller parameters for which the series is applicable is extremely important. The extent of applicability of the Wageningen B-screw series parameters [109] is given in Appendix G.3.

4.3.7 Initial Design Optimization of Propellers

The parameters of the propellers need to be fixed for achieving the highest possible open water efficiency of the propellers for the following scenarios:

- With the propeller diameter fixed, determining propeller pitch and speed.
- With the propeller speed fixed, determining the propeller diameter, and pitch.

In most high-performance propulsion system designs, the propeller diameter is fixed to the highest value possible based on the hull profile. The number of blades is fixed based on the requirements of having a low vibration signature. Hence, for such applications, the problem of optimization focuses on determining propeller pitch and speed.

In the present work, to optimize the propeller parameters for the highest efficiency, a numerical optimization method of minimizing an objective function has been implemented on the lines of publications by Biven [111], Gaafary [112,113]. The numerical method implemented for optimization is the Nelder-

Mead (NM) method [114]. The NM method is a method used for minimizing an objective function in multi-dimensional space used to find a minimum without derivative of the cost function, which makes the algorithm attractive for ‘noisy’ problems. The NM method is one of the most commonly used nonlinear optimization algorithms implemented in programs such as MATLAB [115]. To solve the optimization problem, the NM algorithm uses a variable shape simplex which is an n -dimensional convex hull polytope, with $n + 1$ as the number of vertices. The algorithm is based on the iterative shape update of the simplex, made by ‘expansion’ or ‘contraction’ steps, thus ‘adapting itself to the local landscape’ [114]. The following paragraphs describe the implementation of the propeller initial design optimization in the developed procedure.

The optimization process is executed based on the selectable modes:

- Mode 1: Determine propeller speed, propeller diameter fixed.
- Mode 2: Determine propeller diameter, propeller speed fixed.

The objective function for the optimization is written as:

$$\min \eta_o(K_T, K_Q) \quad (4-75)$$

with J , EAR , P/D treated as variables, to calculate K_T, K_Q and thus η_o , from the propeller series-based model.

The optimization process is subject to the constraints:

- Thrust criteria, defined as:

$$K_{T,Prop} - C_{T,OM} J^m \geq 0 \quad (4-76)$$

where:

$K_{T,Prop}$: thrust coefficient calculated from the propeller equations,

$C_{T,OM}$: the thrust constant based on optimization mode,

OM : optimization mode,

m : exponent of J based on OM .

- Limits of the propeller series being used or as per user definition, as:

$$P/D_{min} \leq P/D \leq P/D_{max} \quad (4-77)$$

$$J_{min} < J < J_{max}$$

$$EAR_{min} \leq EAR \leq EAR_{max}$$

Based on the B propeller series, these constraints, imposed irrespective of the user inputs, are:

$$0.50 \leq P/D \leq 1.40 \quad (4-78)$$

$$0.0 < J < 1.8$$

$$0.30 \leq EAR \leq 1.05$$

- Propeller cavitation criteria, defined as:

$$EAR > EAR_{Bur} \quad (4-79)$$

$$EAR > EAR_{Kel}$$

where:

EAR_{Bur} is the EAR calculated using the cavitation criteria defined by Burrill (further described in the following sections),

EAR_{Kel} is the EAR calculated using the cavitation criteria defined by Keller (further described in the following sections).

An initial guess vector for J , EAR , P/D has been predefined in the program. These values set up the initial simplex.

Determination of η_o

Advance velocity V_A , thrust to overcome resistance T_R are calculated based on the user inputs of V , R , w , t , as:

$$V_A = V (1 - w) \quad (4-80)$$

$$T_R = R / (1 - t) \quad (4-81)$$

The subscript R in T_R is used to denote that the thrust has been calculated from the resistance which needs to be distinguished from the thrust calculated from the propeller coefficient in the optimization routine.

It should be noted that the resistance R used here is the resistance as seen by each propeller. For example, if there are two propellers applied for the propulsion system, then each propeller will see half of the whole resistance in ideal conditions.

During each pass of the optimization routine, given variables J , EAR , P/D are varied by the optimization routine, based on which K_T , K_Q are calculated from the series model, from which η_O is calculated.

J , K_T Compatibility

To undertake the optimization, the value of J selected should satisfy the characteristic K_T in the open water propeller diagram. Towards this, an optimisation constant $C_{T,OM}$ is defined such that the unknown variable (to be determined) is eliminated from this constant. For each mode of optimization, different values of $C_{T,OM}$ would thus exist.

For optimization mode 1, $OM = 1$, where n is to be determined, given the value of D , a constant $C_{T,1}$ is defined with the elimination of n as follows:

$$\frac{K_T}{J^2} = \frac{T_R}{\rho D^2 V_A^2} = C_{T,1} \quad (4-82)$$

Hence in the above equation $C_{T,OM} = C_{T,1}$ giving the constraint:

$$K_T - C_{T,1} J^2 \geq 0 \quad (4-83)$$

For optimization mode 2, $OM = 2$, where D is to be found, given the value of n , a constant $C_{T,2}$ is defined with the elimination of D which is an unknown, as follows:

$$\frac{K_T}{J^4} = \frac{T_R n^2}{\rho V_A^4} = C_{T,2} \quad (4-84)$$

Hence in the above equation, $C_{T,OM} = C_{T,1}$ giving the constraint:

$$K_T - C_{T,2} J^4 \geq 0 \quad (4-85)$$

While the above expression uses K_T is used as the parameter for checking compatibility with J for the optimization problem with respect to the requirements of propulsion, a similar approach can be used to derive the expression using K_Q to approach the optimization problem with respect to the requirements of the engine/s.

Determination of EAR_{Bur}

EAR_{Bur} is calculated based on the popular approach of Burrill [94], [108] used for the preliminary design stage of a propeller. EAR_{Bur} is defined as:

$$EAR_{Bur} = \frac{A_D}{A_o} \quad (4-86)$$

where:

A_o is the propeller disk area, given by:

$$A_o = \frac{\pi D^2}{4} \quad (4-87)$$

A_D is the Developed Area, derived empirically by Burrill, given by:

$$A_D = \frac{A_p}{1.067 - 0.229 P/D} \quad (4-88)$$

where A_p is the Projected Area, given by:

$$A_p = \frac{T}{q_T \tau_c} \quad (4-89)$$

where:

T is the propeller thrust, given by:

$$T = K_T \rho n^2 D^4 \quad (4-90)$$

q_T is the dynamic pressure at $r = 0.7R$

$$q_T = 0.5 \rho V_R^2 \quad (4-91)$$

where V_R is the resultant velocity at $r = 0.7R$

$$V_R = \sqrt{V_A^2 + (\pi n 0.7D)^2} \quad (4-92)$$

Burrill and others have plotted data from cavitation tunnel and full-scale tests showing limiting of the Thrust Loading Coefficient τ_c values for a given cavitation number $\sigma_{0.7}$. Empirical relationships have been developed for the various lines on the Burrill chart, as follows [94]:

Burrill Chart Line 1:

$$\tau_c = 0.21(\sigma_{0.7} - 0.04)^{0.46} \quad (4-93)$$

Burrill Chart Line 2:

$$\tau_c = 0.28(\sigma_{0.7} - 0.03)^{0.57} \quad (4-94)$$

Burrill Chart Line 3:

$$\tau_c = 0.43(\sigma_{0.7} - 0.02)^{0.71} \quad (4-95)$$

where $\sigma_{0.7}$ is cavitation number at $0.7D$, given by:

$$\sigma_{0.7} = \frac{p_0 - p_v}{q_T} \quad (4-96)$$

where:

p_0 is the reference pressure given by:

$$p_0 = p_{atm} + \rho_w g h \quad (4-97)$$

where p_{atm} is the atmospheric pressure, h is the depth of the propeller,

p_v is the vapour pressure.

Line 1 is a lower limit, used for heavily loaded propellers on tugs, trawlers etc.

Line 2 is an upper limit, for merchant vessels etc., 2%–5% back cavitation, using aerofoil sections and this line is equivalent to the frequently quoted Burrill line.

Line 3: is an upper limit used for naval vessels, fast craft etc, with 10%–15% back cavitation. This line is for uniform suction type sections and accepts a greater risk of cavitation at full power. This line is just below the likely onset of thrust breakdown due to cavitation.

In the present work, Line 2 has been used for the calculations.

Determination of EAR_{Kel}

The simpler formula by Keller [108] is also often used to estimate the necessary expanded area ratio EAR for preliminary design of the propeller, given as:

$$EAR_{Kel} = \frac{(1.3 + 0.3 Z) T_P}{(p_0 - p_v) D^2} + k \quad (4-98)$$

where k is a constant used depending on the number of propellers and ship type as follows:

- for single-screw ships $k = 0$,
- for twin-screw ships, it varies within the range $k = 0$ for fast vessels through to $k = 0.1$ for the slower ships.

4.3.8 Water Properties Model

The model for calculating what are properties is based on the work of Sharqawy [116] as recommended in the 'ITTC Recommended Procedures: Fresh Water and Seawater Properties' [117]. Details of the implemented model are described in Appendix H.

4.3.9 Prime Movers

Gas turbine and diesel engines have been modelled as mechanical drives for the propellers or alternators in generator set configurations. The modelling approach used in the present work is described in the following paragraphs.

4.3.9.1 Gas Turbines

The gas turbine engine models are integrated into the propulsion plant model by the reference of a filename of the engine model. Hence the engine models exist as individual elements which can be repeatedly used. The gas turbine modelling has been implemented using detailed 0-D modelling, as described in section 4.2.

4.3.9.2 Diesel Engines

To limit the scope of the present research work, the diesel engine model has been implemented based on performance maps of the engine which give brake power of the engine based on engine fuel flow and engine speed. The simplified model of the diesel engine implemented in the present work uses the idea of representing the performance map of the diesel engine shown in Figure 4-25 by polynomial functions. This simplified approach to reduce the complexity of the engine models has been used by Altosole et.al. [118] and W. Shi et.al. [95]. Effectively the simplified model uses the engine speed n_E and the fuel flow WF to determine the brake power of the engine PW_B , which can be written as:

$$PW_B = f(WF, n_E) \quad (4-99)$$

The derivation of the relationships used by the performance model is briefly described here.

At a selected design point with a constant fuel flow WF_d , the engine power $PW_{B,d}$ can be approximated by a third-order polynomial as a function of engine speed, given as:

$$PW_{B,d} = [c_3 n_{E,d}^3 + c_2 n_{E,d}^2 + c_1 n_{E,d}]_{WF_d=const.} \quad (4-100)$$

where c_1 , c_2 and c_3 are the fitting coefficients determined by fitting 3 arbitrary points on the power speed curve for a constant design fuel rate.

To extend the above equation for determining engine power as a function of fuel flow and engine speed at off-design points the following general relations are used:

$$PW_B \propto n_E^3 \quad (4-101)$$

$$\frac{PW_B}{PW_{B,d}} = \left(\frac{n_E}{n_{E,d}} \right)^3 \quad (4-102)$$

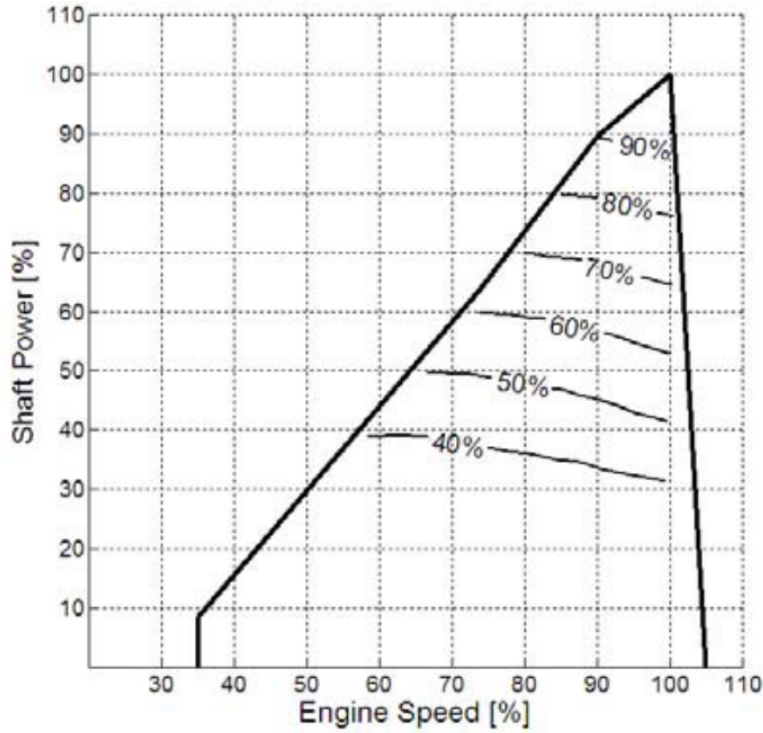


Figure 4-25 Diesel engine map with lines of constant fuel flow [94].

Using the general relations describing the relationship of engine brake torque Q_B with n_E and WF ,

$$Q_B \propto n_E^2 \quad (4-103)$$

$$Q_B \propto WF \quad (4-104)$$

we have:

$$\frac{WF}{WF_d} = \left(\frac{n_E}{n_{E,d}} \right)^2 \quad (4-105)$$

$$\frac{n_E}{n_{E,d}} = \left(\frac{WF}{WF_d} \right)^{1/2} \quad (4-106)$$

We define fuel ratio WF_R , with respect to WF_d as:

$$WF_R = \frac{WF}{WF_d} \quad (4-107)$$

Substituting equation (4-107) in equation (4-106), $n_{E,d}$ can be written as:

$$n_{E,d} = n_E WF_R^{-1/2} \quad (4-108)$$

Combining equations, (4-102) and (4-106), the ratio of engine power at design point to off-design point can be expressed in terms of fuel flow rate by:

$$PW_{B,d} = PW_B \left(\frac{WF}{WF_d} \right)^{-3/2} \quad (4-109)$$

Substituting equation (4-109) in (4-100) and using the relationship in equation (4-108), we have:

$$PW_B WF_R^{-3s/2} = [c_3 n_E^3 WF_R^{-3/2} + c_2 n_E^2 WF_R^{-1} + c_1 n_E WF_R^{-1/2}] \quad (4-110)$$

A shaping constant, s , is defined to adapt the equation to the characteristics of a specified type of engine, and using it in the above equation, upon rearranging PW_B can be written as:

$$PW_B = WF_R^{3s/2} [c_3 WF_R^{-3s/2} n_E^3 + c_2 WF_R^{-s} n_E^2 + c_1 WF_R^{-s/2} n_E] \quad (4-111)$$

To have an equation that works with ratios than absolute values, we define ratios $PW_{BR} = PW_B / PW_{Bref}$ and $n_{ER} = n_E / n_{Eref}$ where PW_{Bref} and n_{Eref} are corresponding points on the power speed curved, at 100% maximum continuous rating (MCR) or 85% MCR, we have :

$$PW_{BR} = WF_R^{3s/2} [c_3 WF_R^{-3s/2} n_{ER}^3 + c_2 WF_R^{-s} n_{ER}^2 + c_1 WF_R^{-s/2} n_{ER}] \quad (4-112)$$

To adapt the above equation, to a medium speed diesel engine, $s = 0.7$ has been used, based on the work of Altosole [94]. For the medium-speed diesel engines

used in the present work, the following constants were derived as a part of this work, starting from the curves defined in the work of Altosole [94]:

	PW_{Bref} $= 85\% MCR$	PW_{Bref} $= 100\% MCR$
c_3	0.6811	0.6811
c_2	-2.6396	-2.6605
c_1	2.9290	2.9756

4.3.10 Geared Transmission Systems

Geared transmission systems are used to transmit torque from engines to the propellers through the shafting system. Geared transmission systems utilize reduction gearboxes to increase the torque output by reducing the rotational speed of the engine to the speed of the propeller. Gearboxes can also be used to add the torque from multiple engines to one shaft or to split the torque from one engine to multiple shafts. In some applications, gearboxes may also be used to implement the reversing the propeller direction of rotation for FPP applications. Cross-connect gearboxes are used to connect two drivetrains. In certain combined plant configurations where engines can operate independently or in combination with other engines, multiple reduction ratios or ‘speeds’ need to be implemented in the gearboxes which are selected based on the mode of operation.

Gearboxes are often classified by the number of inputs and outputs, and connections as:

- Single Input Single Output (SISO)
- Double or Multiple Input Single Output (MISO)
- Cross-Connect Gears (CCG)

To model the combined propulsion system configurations for the present work, the modelling of geared transmission systems needed to have a large amount of flexibility. The initial approach tried was to have preconfigured gearboxes as SISO/ MISO etc., but it was realised that this approach could not provide all the possible configurations that needed to be modelled. Hence the implemented

method for modelling the transmission system is based on the utilization of the following system model components:

- Gearing
- Clutches
- Transmission junction

Clutches are used to connect and disconnect various drives based on the mode of operation and hence has been considered to have 'on' and 'off' states. The 'Transmission Junction' element is primarily used as a torque path connection element. Further details about the application of clutch and the junction models are defined in section 4.3.11.

The implemented model of the gearing, broadly classified into categories of single-speed or twin speed, is based on the following input data:

- Single Speed Gearing:
 - i_{gr} : Gearing Reduction Ratio.
 - $1 - \eta_{gr}$: Gearing Loss Factor.
- Twin Speed Gearing:
 - $i_{gr,1}$: Speed 1 Gearing Reduction Ratio.
 - $1 - \eta_{gr,1}$: Speed 1 Gearing Loss Factor.
 - $i_{gr,2}$: Speed 2 Gearing Reduction Ratio.
 - $1 - \eta_{gr,2}$: Speed 2 Gearing Loss Factor.

The basic relationships used for modelling the gearing are:

$$Q_{gr,out} = \eta_{gr} \cdot i_{gr} \cdot Q_{gr,in} \quad (4-113)$$

where:

$Q_{gr,out}$: gearing output torque,

$Q_{gr,in}$: gearing input torque,

η_{gr} : overall gearing transmission efficiency.

$$i_{gr} = \frac{n_{gr,in}}{n_{gr,out}} \quad (4-114)$$

Energy losses in the gearing are calculated in this module based on the ‘gear loss’ model described later in this section.

4.3.11 Modelling Operating ‘Drive Modes’

One of the primary issues faced during the development of the modelling process for combined propulsion plans was the determination of the direction of transmission of torque in combined plants involving cross-connect gearing. Unlike the case for fluid system components where the in-ports and out-ports clearly define the direction of fluid flow, in the case of mechanical transmission components, this definition cannot be directly applied. It should be noted that the direction of torque transmission being referred to in this context is in the sense of torque being transmitted from the driving side to the driven side.

An example of the above-described phenomenon is shown using Figure 4-26 to Figure 4-29, where the change in direction of torque transmission can be seen based on the states of the engines and the clutches from one drive mode to another. The considered model for this example has a transmission system for two gas turbines, each having its own respective reduction twin speed gearboxes to transmit the torque to the propeller individually. In addition, both the transmission paths are interconnected through a cross-connect gearbox, allowing each engine to individually drive both the propellers using this cross-connect system in separate drive modes. The active part of transmission has been shown by the double arrows while the inactive parts are shown by the crosses. The states of the engines and the clutches defining these operation modes are shown by ‘ON’ and ‘OFF’ in the respective figures. Figure 4-26 shows both the port and starboard engines driving port and starboard propellers respectively. Figure 4-27 shows the port engine driving the port propeller while the starboard propeller is trailing (water milling). Figure 4-28 shows the port engine driving both propellers using the cross-connect gearbox. Figure 4-29 shows the starboard engine driving both the propellers again using the cross-connect gearbox.

To model the above-described behaviour of the change in direction of the torque transmission solely based on the states of the engine and clutches, a novel algorithm was written and implemented in the developed plant modelling framework. Determination of the drive modes using the states of the clutches and driving engines, allows the same combined plant to be used across all the drive modes of the plant and this implementation makes the plant model definition to be very intuitive as it is closely representative of the actual operation of the plant. This developed method with the algorithm is described in the following paragraphs.

The primary components used to implement the modelling algorithm are clutches, transmission junctions and setting of engine to on or off states. These component models are connected in the plant model using the definition of 'mechanical connections' which represent the transmission of torque in a bi-directional way from the point of the driving side and the driven side. The 'Clutch' model component implemented for the present work, models a generic clutch behaviour used to connect/ disconnect engine/driveshaft from the drive train. The implemented clutch model is based on the behaviour of multi-disc or overrunning clutches (not fluid couplings), where there is no slippage between the driving and driven sides of the train. The clutch state (on/off) is individually set in the models to represent the drives modes of operation for the plant. While usually the clutches are housed in gearboxes, for the sake of creating the model plant model flexibly, the clutches are modelled as individual elements. The 'Transmission Junction' component is used as a 'virtual component' to add/ split torque from/to two drive paths. This component has three ports labelled as 1, 2 and C with each port having the same properties. It should be noted that the selection of the port labels has no bearing on the direction of transmission of torque. The transmission junction has been called a virtual component because it does not represent any physical component in the drive train but represents the multiple connections that are possible in gearing to add or split transmission torque.

To explain the implemented method, consider the example of a COGAG plant shown in Figure 4-30. The partial model shown from Figure 4-26 to Figure 4-29,

to describe the direction of torque transmission earlier, is an extract from this very model. A detailed description of this model can also be seen in section 6.6.3 of this thesis. This model is viewed by the implemented algorithm as described in Figure 4-31, where each model component is represented by a node (shown by coloured circles) and these nodes are connected by transmission sub-paths which are assigned specific nomenclature by the algorithm (like a.b, a.b.b etc.). The various components are classified into 'termination' elements viz. engines and propellers where a sub-path can be terminated, 'state elements' viz. engines and clutches whose states can change, 'transmission elements' viz. gearing, shafting and transmission junctions as shown in Figure 4-31.

In the considered COGAG plant, the propellers could be driven or trailed (water-milling propeller, further described in section 6.3.2) or a single engine could be driving one or more propellers. The algorithm needs to assess this overall status by identifying the driven and the trailing propellers, which engines are driving which propellers etc. The developed algorithm consists of the set of functions with their simplified block diagrams shown in Figure 4-32 and Figure 4-33, which are briefly described in the following paragraphs.

The primary function 'Plant Master' that manages the entire simulation of the plant, calls out the 'Engine-Propeller Interface Data' data set for each propeller. This data set includes the data that defines whether the propeller is driven or trailed, and if driven which engines are driving the propeller through which transmission path. The transmission path data includes the overall applicable reduction ratio of the gearing and energy loss data with applicable models of the respective components in the transmission path. This data is compiled by the function 'Engine Propeller Interface Data' as shown in Figure 4-32. This function initially loops through all the components, tracing the transmission path starting from the propeller to create the sub-path data set. This dataset includes the assigned sub-path name by the algorithm, whether the sub-path is active or inactive based on the state of the engines and the clutches, which the sub-paths are connected to the 'termination elements' i.e. engines and propellers, energy loss data and reduction ratio data for the transmission elements.

The addition of individual names to the transmission sub-paths is two-fold. The first objective is to be able to trace the connection of the propeller to an engine by examining if all the intermediate sub-paths in the path are in active state. The second objective is to be able to lump all the reduction ratios of the gearing components to derive the overall reduction ratio applicable for the drive mode and to lump the energy loss data from the respective transmission components in the transmission path. The tracing of the transmission path is undertaken by the algorithm as follows. Based on the propeller identifier received as the input, the algorithm starts the tracing process from the given propeller, systematically assigning names to each of the sub-paths, starting with 'a' as shown in Figure 4-31, where a single loop of tracing from the propeller, FPP-Stbd, has been shown. Each time the algorithm encounters a junction, shown by the red dots, it splits the transmission sub-path into two sub-paths represented by the addition of the 'a' and 'b' to the original sub-path name. The traced paths are later assigned as being active and inactive based on the state of the engines and clutches on the particular transmission sub-path.

After compilation of the data set of all the transmission sub-paths, the 'Engine Propeller Interface Data' function calls the function 'Plant Engines Interface Data from Sub-Path Data', as shown in Figure 4-33. In this function, using the assigned sub-path names, the transmission path from the engine to the propeller is traced, basically with the objective to see which engines are driving the given propeller with what reduction ratio and energy losses. The basic procedure that is used to achieve this is to undertake the systematic reduction of the sub-path names in steps (eg. 'a.b.b' is reduced to 'a.b' in one such step) to trace the path from the engines to the propellers it is driving, described in Figure 4-33. If the engine is driving more than one propeller, it is accounted for in this step by dividing the torque accordingly. Each reduction of the sub-path name corresponds to 'crossing' one component, which is used to lumping of the applicable reduction ratio as well as energy loss data of that component with the overall transmission path reduction ratio and the energy loss data. During each such 'crossing' it is also checked if the overall transmission path is active based on whether each sub-path in the transmission path is active.

After the execution of the function 'Plant Engines Interface Data from Sub-Path Data' hands over the 'Plant Engines Interface Data' back to the function 'Engine Propeller Interface Data' which in turn passes it back to the 'Plant Master' for further processing of the plant model.

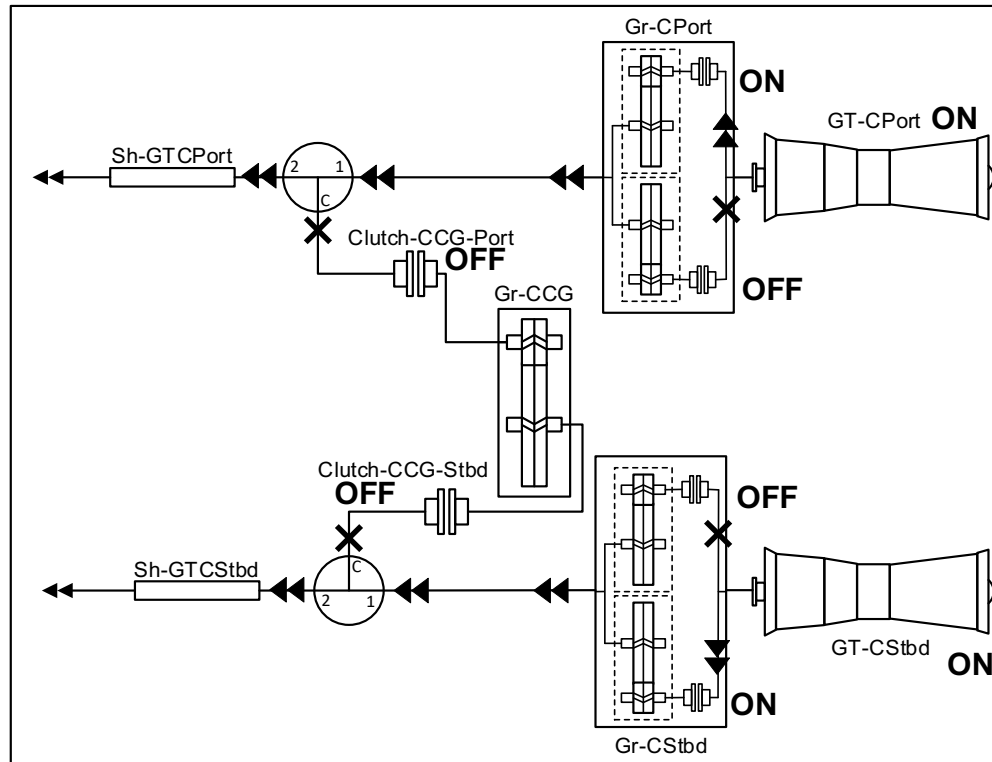


Figure 4-26 Both engines driving respective individual propellers

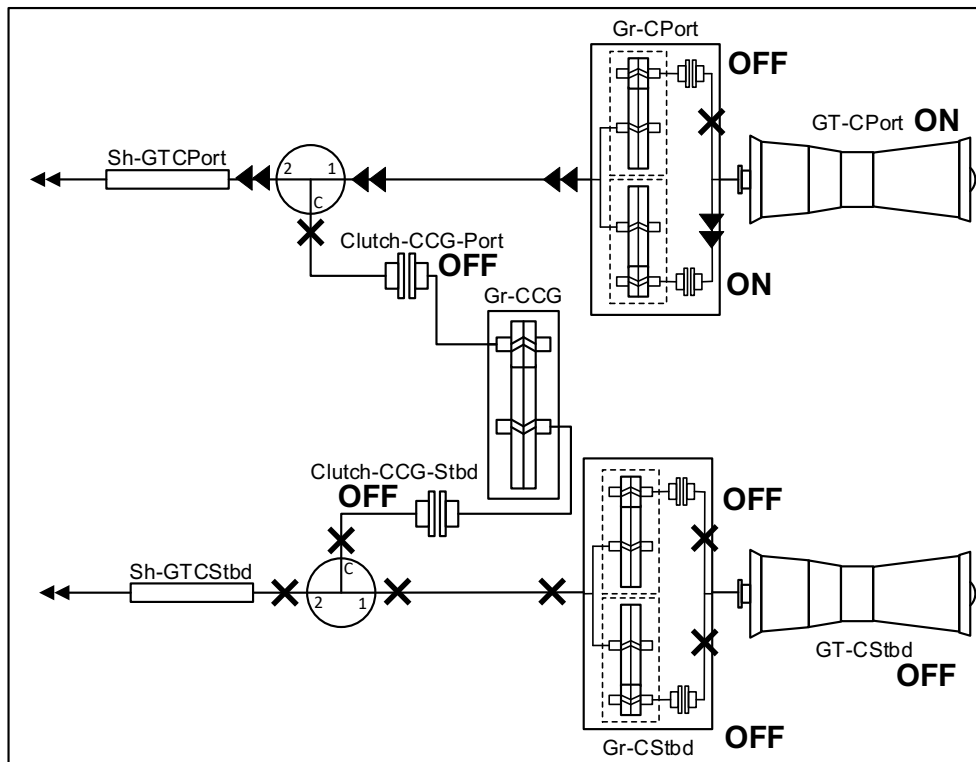


Figure 4-27 Port engine driving port propeller, starboard propeller trailing

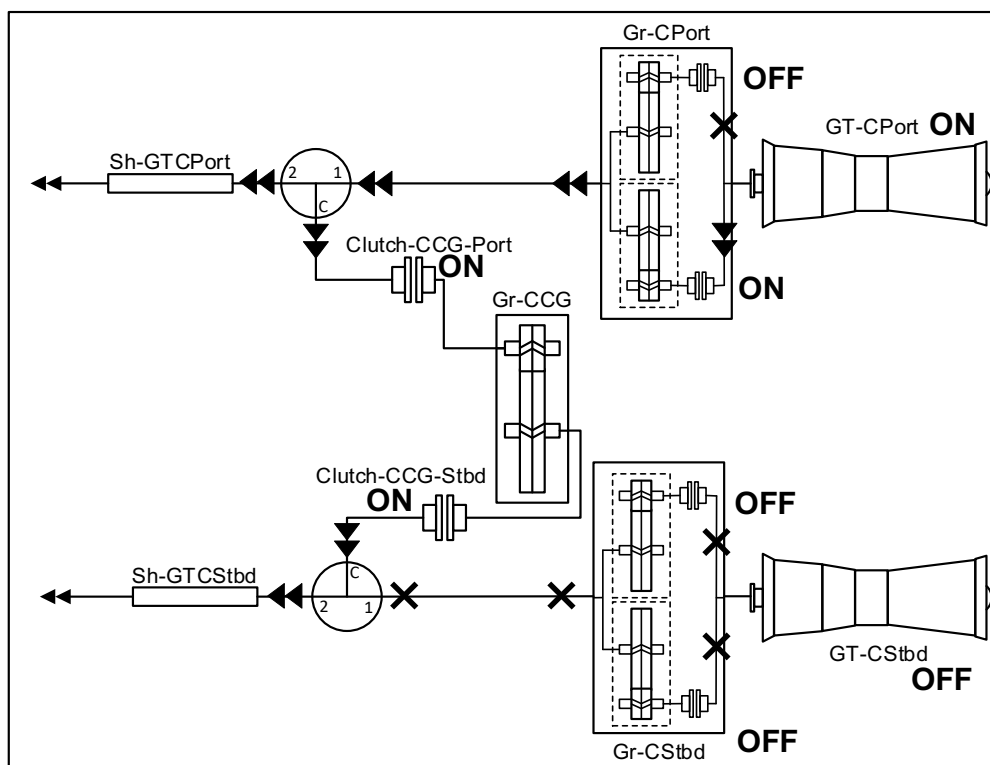


Figure 4-28 Port engine driving both propellers

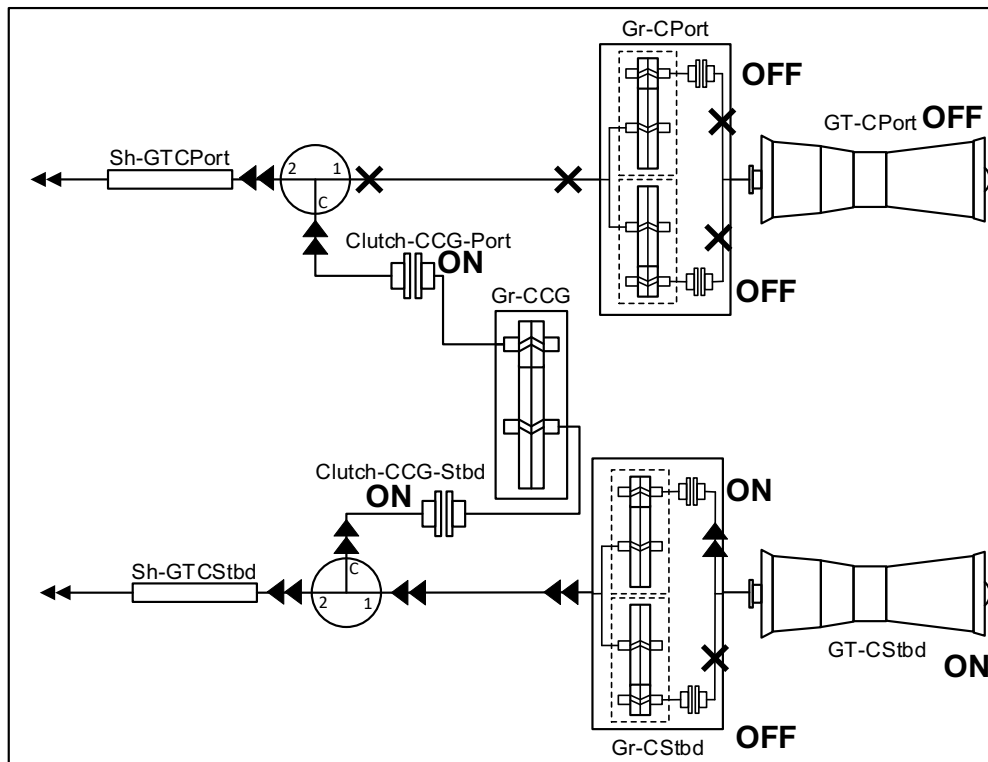


Figure 4-29 Starboard engine driving both propellers

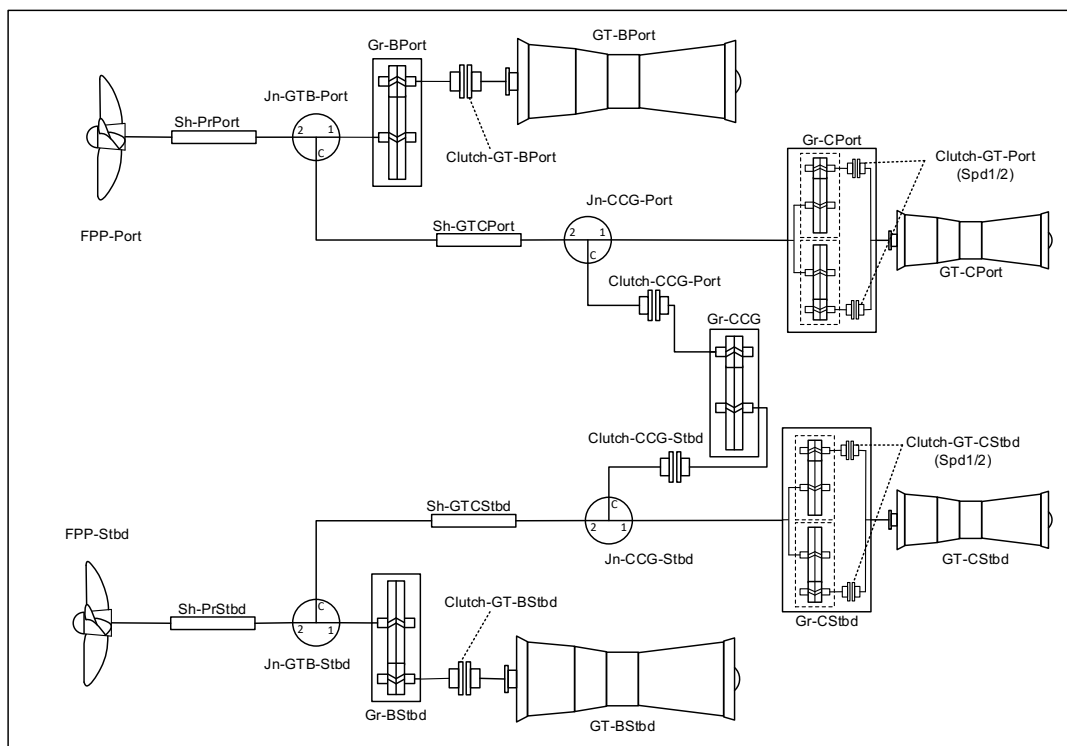


Figure 4-30 COGAG model used to explain the developed algorithm for modelling of operating drive modes.

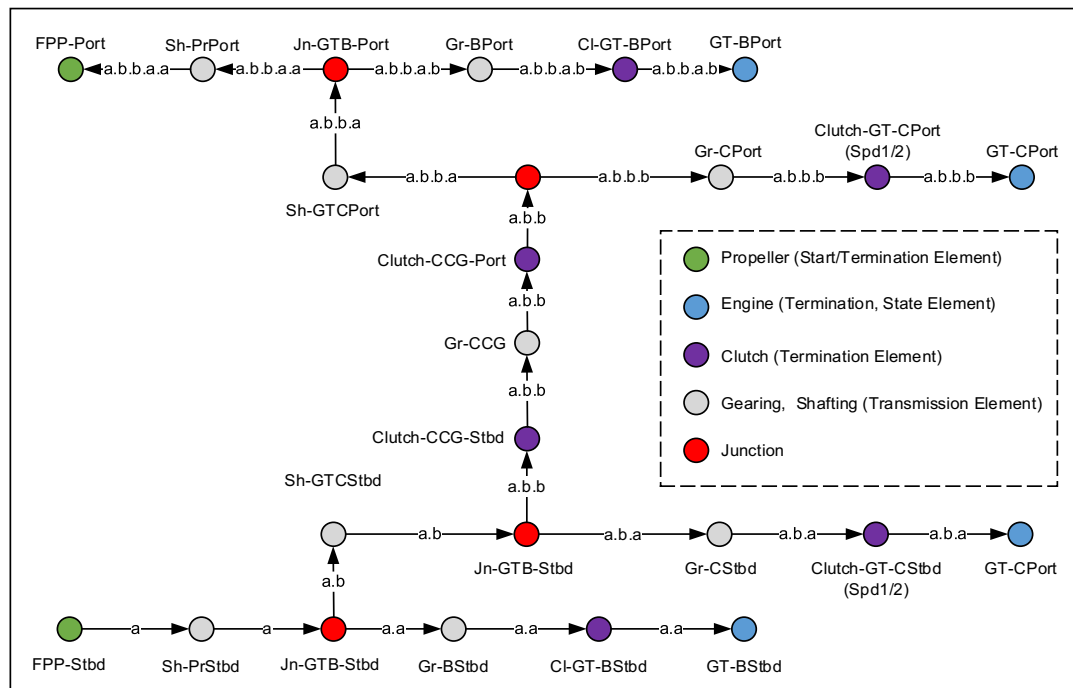


Figure 4-31 Decomposition of the COGAG model by the developed algorithm for drive mode modelling into component nodes and transmission sub-paths.

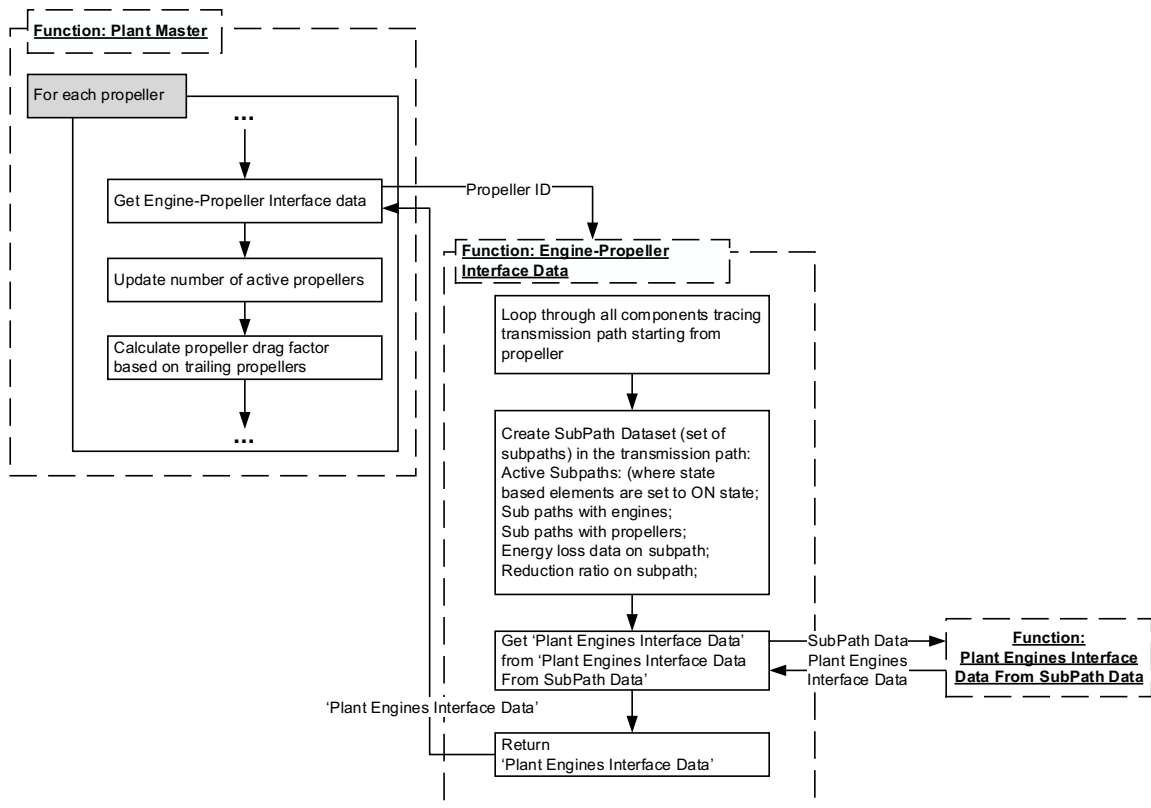


Figure 4-32 Simplified logic block diagram for 'Engine-Propeller Interface Data' function of the developed algorithm for plant drive mode modelling.

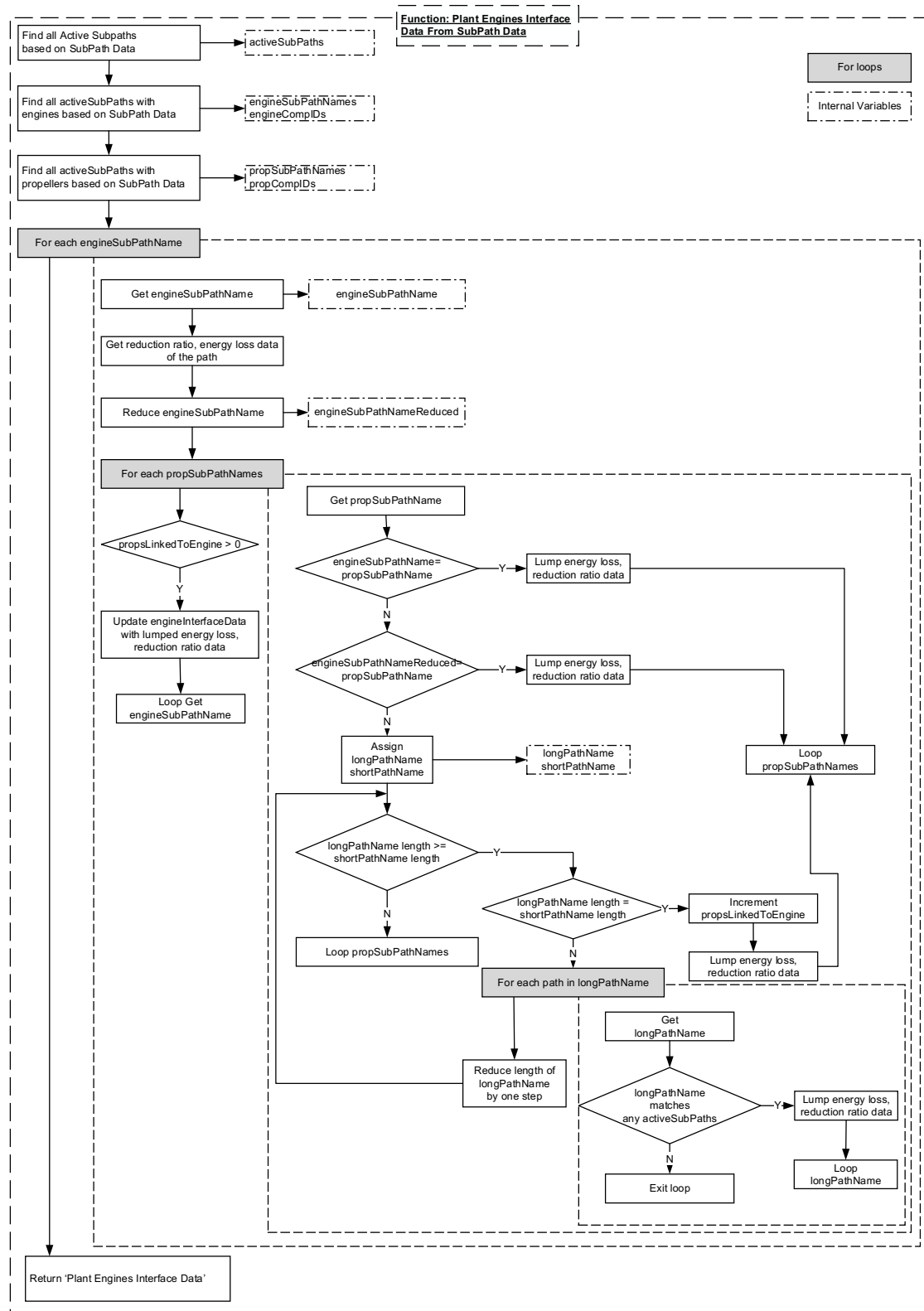


Figure 4-33 Simplified logic block diagram for ‘Function: Plant Engines Interface Data from Sub-Path Data’ function of the developed algorithm for plant drive mode modelling.

4.3.12 Gearing Energy Loss

Gearbox losses are usually considered to be constant through the entire operating range of the gearbox and between 2% and 4% of gear input power or torque. However, in reality, these losses vary in terms of percentage of gear input power or torque, in off-design or part-load conditions. This is a very important consideration as many ships run a vast majority of their life in part-load conditions.

In the present work, the model incorporated for gear losses considers the effect of part load conditions based on the work of Godjevac [96]. The gearing loss is considered as a torque loss consisting of the three elements:

- Element proportional to the transmitted torque,
- Element proportional to the shaft speed,
- Constant element.

Normalized torque loss of a gearbox, $Q_{gr,loss}^*$, is given by the equation:

$$Q_{gr,loss}^* = a Q_{gr,in}^* + b n_{gr,in}^* + c \quad (4-115)$$

where:

a is the fit coefficient related to the torque,

$Q_{gr,in}^*$ is the normalized torque going into the gearbox,

b is the fit coefficient related to the shaft speed,

$n_{gr,in}^*$ is the normalized shaft speed going into the gearbox,

c is the fit coefficient related to the constant torque loss.

The fit coefficients used for the present work in the above equation are given in Table 4-7:

Table 4-7 Fit coefficients for gear loss model [96].

	a	b	c
Propeller Law	0.5	0.4	0.1
Generator Law	0.4	0.1	0.5

The variation of gearbox efficiency η_{gr} with normalised torque input $Q_{gr,in}^*$ for propeller and alternator applications using the shown model is shown in Figure 4-34. The variation of gearbox efficiency η_{gr} with normalised input speed $n_{gr,in}^*$ to the gearbox, based on the applied model, is shown in Figure 4-35.

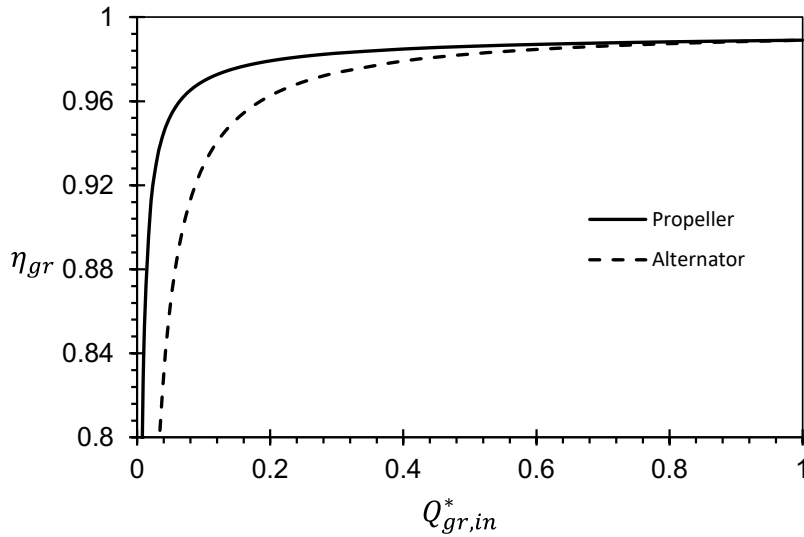


Figure 4-34 Variation of gearbox efficiency with normalised input torque for propeller and alternator applications

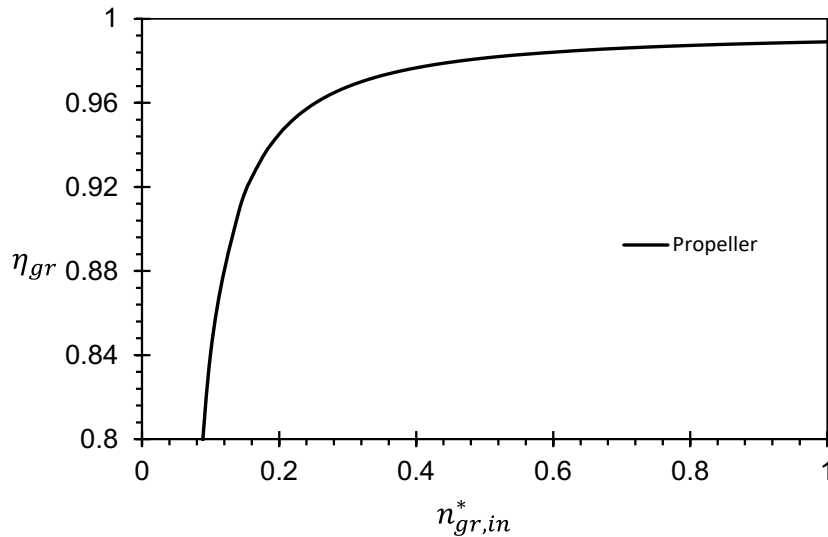


Figure 4-35 Variation of gearbox efficiency with normalised input speed for propeller application

4.3.13 Shafting

The shafting model component is used as a torque or power transmission element and is used to connect the engine with its transmission system to a propeller. The shafting onboard ships is usually supported by bearings and have seals at the interface to the hull which causes power losses. The power loss at the shaft line varies with shaft speed. Shaft losses are usually low, typically 0.5 to 1% of power being transmitted at nominal power.

Since the shaft line losses are primarily caused by the bearings and seals of the shaft, these can be modelled as a constant torque loss. This torque loss $Q_{sh,loss}$ is calculated based on the nominal shaft line torque $Q_{sh,nom}$, as:

$$Q_{sh,loss} = \eta_{sh} Q_{sh,nom} \quad (4-116)$$

where:

η_{sh} : transmission efficiency of the shaft line.

4.3.14 Electrical Systems

4.3.14.1 Electric Machines

The model for electric machines implemented in the present work (here described in the context of electric motors), the brake power from the electric motor at design point (nominal power condition) is described using standard relationships with a defined electrical efficiency, while in off-design points the brake power is corrected based on a predefined function which corrects this efficiency based on the electrical power. Only Asynchronous AC induction motors are considered in the present research work as they find the most common application in ship propulsion with high power application being state-of-the-art for such applications [97].

The nominal effective power $PW_{E,nom}$ for a three-phase AC induction electric motor is written as:

$$PW_{E,nom} = \sqrt{3} U I_{nom} \cos\phi \quad (4-117)$$

where:

U : applied voltage,

I_{nom} : nominal motor current,

$\cos\phi$: power factor,

ϕ : phase difference between U and I .

The nominal brake power $PW_{B,EM,nom}$ of the electric motor is calculated as:

$$PW_{B,EM,nom} = PW_{E,nom} \eta_{EM,nom}$$

The relationship used to calculate the nominal electric efficiency $\eta_{EM,nom}$ of the motor [98]:

$$\eta_{EM,nom} = \frac{1}{1.026 + \frac{0.003162}{\sqrt{PW_{E,nom}}}} \quad (4-118)$$

where $PW_{E,nom}$ is the nominal power given in MW .

For off-design performance, for the given effective power PW_E , $\eta_{EM,nom}$ is corrected based on the following relationship, applicable up to 2% part load [98]:

$$\eta_{EM} = \left[\frac{PW_{B,EM} - (a + b \cdot PW_{EM}^{*c})}{PW_{EM}^*} \right] \cdot \eta_{EM,nom} \quad (4-119)$$

where:

$$PW_{EM}^* = \frac{PW_E}{PW_{E,nom}}$$

$$a = 0.016$$

$$b = -0.01$$

$$c = 0.3$$

While all the above relationships above have been defined referring to an electrical motor, the same relationships apply to an alternator and hence have

not been repeated here. The variation of electric machine efficiency η_{EM} with normalised effective power PW_{EM}^* using the shown model is shown in Figure 4-36.

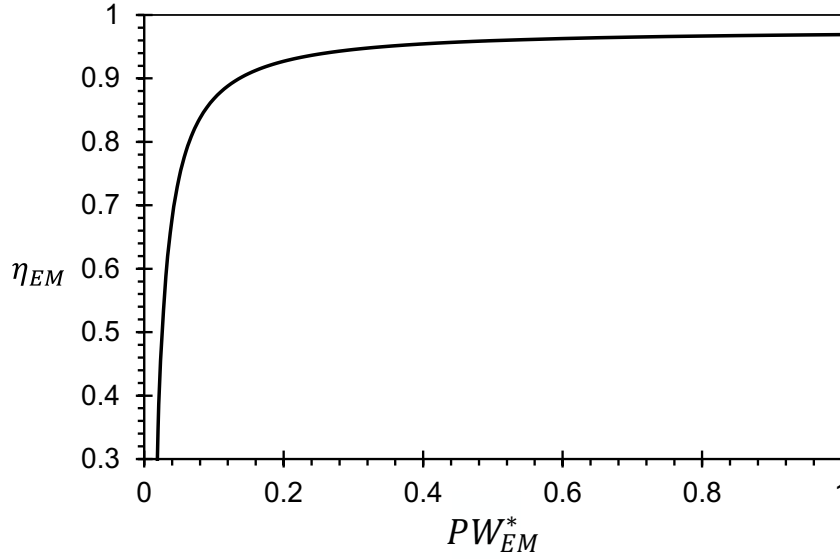


Figure 4-36 Variation of electric machine efficiency with normalised effective power.

4.3.14.2 Frequency Converters

Many types of Frequency Converters (FC) are used, but today's state-of-the-art drives are usually either two- or three-level Pulse-Width Modulated (PWM) voltage source inverters [97]. Hence for the present work, only PWM are considered. Since only steady-state operating points are being modelled in the present work, the frequency converter is modelled as a device that leads to a loss of energy.

The nominal efficiency of the FC, $\eta_{FC,nom}$ is calculated using the relationship [55]:

$$\eta_{FC,nom} = \frac{1}{1.01 + \frac{0.527}{\sqrt{PW_{nom}}}} \quad (4-120)$$

where PW_{nom} is the nominal power of the FC, defined in MW.

At off-design points or at part load conditions, the FC power loss at nominal conditions $P_{loss,nom}$ is corrected by the following relationship, where losses consist of a constant part ($\approx 10\%$), conductor losses proportional with current I ($\approx$

45%) and switching losses proportional to I^2 ($\approx 45\%$) with respect to nominal current I_{nom} :

$$PW_{loss} = PW_{loss,nom} \cdot \left(0.1 + 0.45 \frac{I}{I_{nom}} + 0.45 \frac{I^2}{I_{nom}^2} \right) \quad (4-121)$$

The variation of frequency converter efficiency η_{FC} with normalised current defined as I/I_{nom} using the shown model is shown in Figure 4-37.

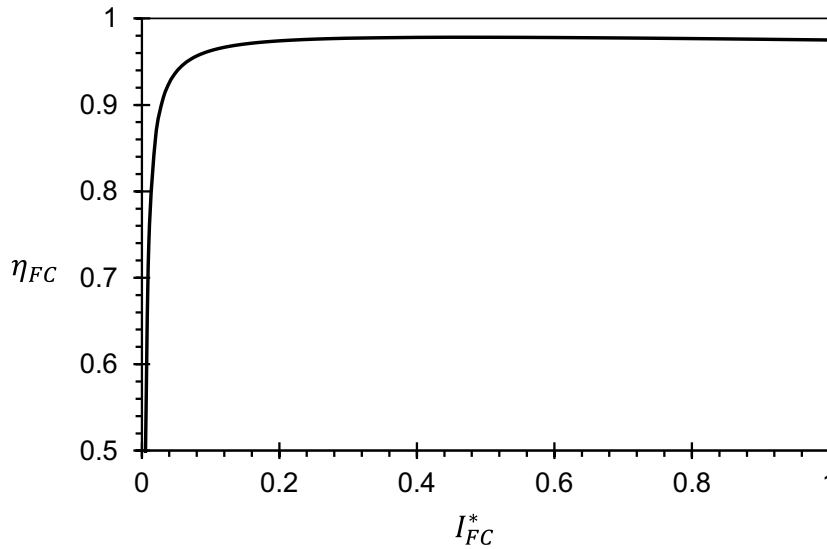


Figure 4-37 Variation of frequency converter efficiency with the normalised current.

4.3.14.3 Voltage System

Only AC systems have been considered for the present work as they are the most commonly used systems onboard ships. The voltage system selected for the electrical system and the electrical machines is dependent on the power being handled by the system, wherein higher voltage systems are selected to limit the current, thus lowering the copper losses and winding temperatures to lower thermal loading of the machines. The current is also a limiting factor for the maximum interruptible fault current capacity of circuit breakers.

System voltage may range from 450VAC to 11kVAC [97]. Systems with rated voltage <1 kVAC are classified as Low-voltage while systems with voltage >1.01 kVAC are Medium-voltage systems (based on the definition by IEC). The typical

low voltage system used onboard ships (NATO standard) is 440 VAC. For medium voltage systems, the typical value of 6.6 kVAC is used, also for commercial applications. For very high-power applications 11 kVAC is also used. 4160 VAC system has also been used in naval applications [99], [100].

4.3.14.4 Switchboards

Based on the voltage system used, the switchboards are also classified into low and medium voltage type switchboards. Losses in a switchboard are low compared to the transmitted power. In the implemented models, like the frequency converter, switchboards are also modelled as devices that lead to loss of energy.

The efficiency of the switchboard is taken as, over the entire range of operation:

$$\eta_{SB,nom} = 0.995 \quad (4-122)$$

5 TERA BASED ON MULTIPLE-CRITERIA DECISION-MAKING (MCDM)

The TERA concept uses a framework of mathematical models to conduct design space exploration and trade-off studies, consisting of a set of core system models linked to economic, risk and environment models, to objectively assess and compare competing schemes by weighing investment of resources against performance and risk estimations. This chapter describes the utilization of the overall concept of TERA and adapting it for the present work, to undertake a techno-economic comparison of the candidate system architectures populating the design space. The chapter also describes the brief theoretical basis of the methods used for MCDM for TERA and the procedures used to apply them. A more detailed mathematical formulation of these procedures is included in Appendix L, Appendix M and Appendix N. The application of these procedures and the results obtained thereof are described in Chapter 6.

5.1 Overview of Application of the MCDM Process to TERA

The overall scheme of TERA is usually integrated with optimisers such as real parameter 'Genetic Algorithm' for the optimisation of one or more goal functions. In the present work, as the design space is considered to be discrete, the optimizer, as usually applied in TERA studies, has been replaced with a hybrid 'Multiple-Criteria Decision-Making' (MCDM) algorithm, as shown in Figure 5-1. The definition of the discrete design space here is that the parameters cannot be continuously varied to have an optimal design, but only discrete points are available in the design space based on existing engine designs.

The primary steps used to execute the applied MCDM procedure are the creation of criteria clusters and organization into a hierarchical and network, calculation of the global weights of the set of criteria, application of criteria weights and evaluation scores across criteria to select the most suitable architecture. Based on the specific characteristics of the various parts of the MCDM process that need to be carried out, specific methods were selected, as described in section 2.5, and integrated to make a robust procedure for executing TERA.

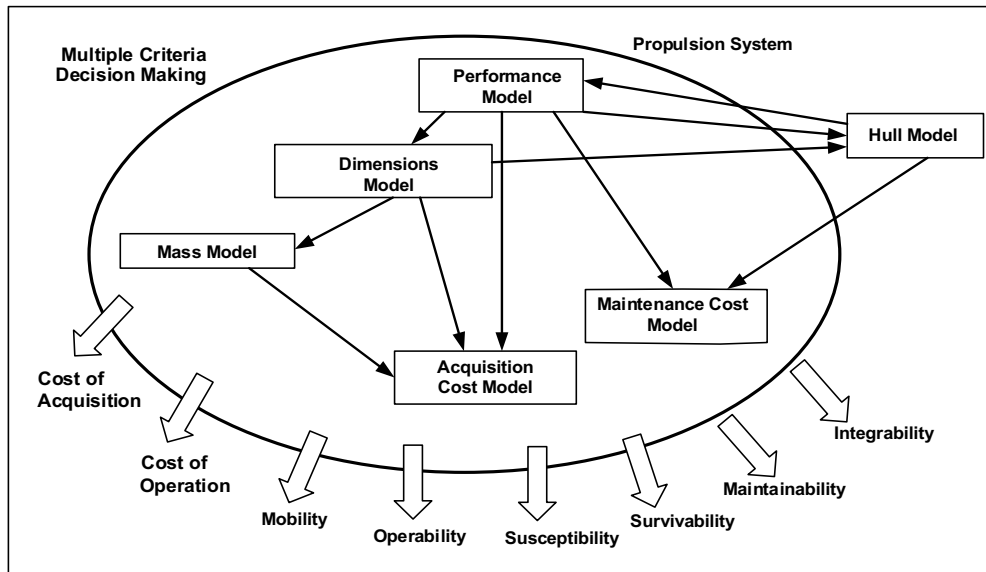


Figure 5-1 TERA with Multiple-Criteria Decision-Making

The overview of the applied MCDM process is as follows. The design criteria is organized into a combination of hierarchal, network structure. The overall objective for organizing the evaluation criteria in this form is to arrive at the global weights of each of the criteria, signifying their relative importance in context of the final decision, against which the candidate architectures would be evaluated. The initial of the MCDM process is to derive the criteria weights using a combination of DANP and AHP. AHP is used to calculate the relative weights of the 'Objective Metric' of 'Performance', 'Cost' and 'Risk'. The individual sets of criteria for 'Cost' and 'Risk', are considered to be independent and thus AHP is used to evaluate the weights of these. All the 'Performance Dimensions' as well their individual sets of criteria are considered to have significant interrelations and hence the entire 'Objective Metric' of 'Performance' is considered as a network as opposed to a hierarchy. The DANP method is thus used for calculation of the relative weights of the criteria under 'Performance'. The relative weights of the 'Objective Metric' of 'Performance', 'Cost' and 'Risk' are then applied to the relative weight of criteria under them to determine the global weights of the entire set of criteria. With the global relative weights of all the criteria as well as evaluation scores of the candidate architectures determined, the VIKOR method is used to find the 'best suited' architecture from the set of candidate architectures. This overview of the developed MCDM procedure is shown in Figure 5-2.

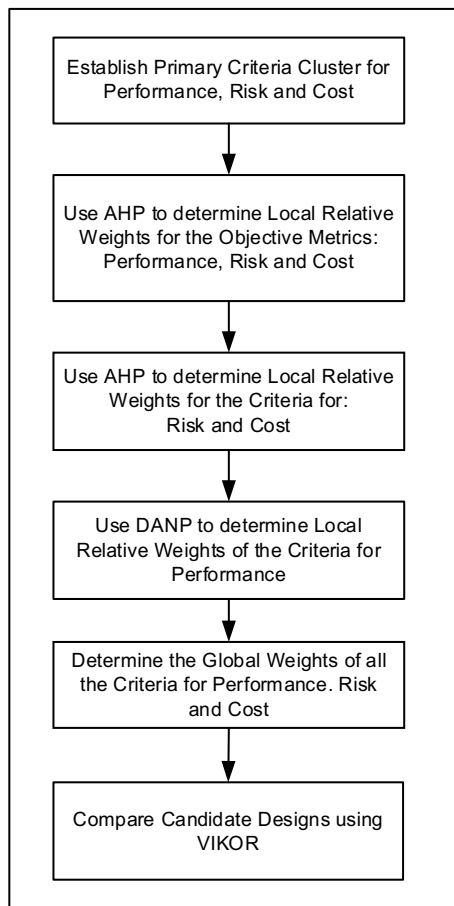


Figure 5-2 Overview of the developed MCDM procedure

5.2 Establishing Hierarchical, Network Structure for Evaluation Criteria

In general, for any ship propulsion plant, the selection criteria for propulsion machinery selection are given in test books like Schneekluth [72] and Papanikolaou [111] as:

- Acquisition cost
- Functional reliability
- Weight
- Space requirements
- Specific fuel oil consumption
- Fuel type and fuel cost
- Emissions

- Repair cost
- Maintenance cost
- Manoeuvrability
- Noise and vibration
- Automation of control

For the present work, the design criteria for the MCDM problem were organized into the combination of hierarchal, network structure as shown in Figure 5-3. In the figure, the hierarchal part of the structure has been shown connected with arrows while the network part of the structure has been shown connected with lines without arrows. The problem was organized with the main 'Objective' defined as 'select the best suited feasible architecture' at top of the hierarchy with the 'Objective Metrics': 'Performance', 'Cost' and 'Risk' at the next level. The 'Objective Metric', 'Performance', were further divided into 'Performance Dimensions' with each 'Performance Dimension' further classified into individual sets of criteria under it.

All the 'Performance Dimensions' as well their individual sets of criteria are considered to have significant interrelations and hence the entire 'Objective Metric' of 'Performance' has been considered as a network as opposed to a hierarchy. Hence, DANP was selected as the preferred method over AHP for calculation of the relative weights of the criteria under 'Performance'. The overall aim is to organize the evaluation criteria in this form is to arrive at the global weights of each of the criteria, signifying their relative importance in the context of the final decision, against which the candidate architecture will be evaluated.

The 'Objective Metrics' of 'Cost' and 'Risk' are directly defined by individual sets of criteria. The individual sets of criteria for 'Cost' and 'Risk', are considered to be independent of each other and thus AHP has been used to evaluate the weights of these. AHP is also used to calculate the relative weights of the 'Objective Metric' of 'Performance', 'Cost' and 'Risk' which are then applied to the relative weight of criteria under them to determine the global weights of the entire set of criteria. Here, a more arbitrary experience-based metric can also be used instead of the application of AHP. The criteria which have been treated as 'quantitative'

and 'qualitative' are also shown in Figure 5-3, with the 'quantitative' criteria distinguished by the dashed boxes. The candidate architectures which are compared for selecting the 'the best-suited architecture' based on the 'evaluated scores' for the individual criteria, weighed against their global weights are shown at the bottom of Figure 5-3. It should be noted that since the candidate architectures have already been tested for 'feasibility' in terms of the basic defined criteria for the ship propulsion plant in terms of achieving 'surge speed', 'cruise speed', 'endurance', the term 'feasible' has been used in the objective. The description of the criteria shown in Figure 5-3 is as follows:

Objective Metric: Performance

Performance Dimension: Mobility

- Surge speed: The defined sustained maximum speed of the ship that can be achieved with a particular candidate propulsion system architecture.
- Cruise speed: The defined economical speed at which the propulsion system architecture is in the region of high efficiency (for example highest speed within the operating range of the cruise engines) for the plant design.
- Endurance: The defined maximum distance the ship can move without the need for refuelling at a specified speed.

While all the propulsion system candidate architectures are designed to meet all the above criteria as minimum input design specifications, a candidate propulsion system architecture may exceed this design specification. These criteria are defined to compare architectures for this aspect, where the candidate propulsion system architectures are exceeding the minimum performance requirements.

Performance Dimension: Mobility

- Operation profile sensitivity: Parameter is used to define how sensitive is the propulsion plant efficiency to the change in operating profile. If a change in operating profile has a very large effect on the propulsion plant

efficiency, then that particular architecture is said to be more sensitive to the operating profile.

- Operating flexibility: Defines the degree of dependence of operation of the plant on operating modes. If the propulsion plant can be operated to cover its entire operating range with a lesser number of operating modes, then the plant is deemed to have higher operating flexibility.
- Manoeuvrability: Comparative contribution of the propulsion system to the manoeuvrability of the ship. In the present context, a propulsion plant that can build up to the rated power in a shorter time is considered to provide better manoeuvrability.

Performance Dimension: Susceptibility

- Underwater signature: Relative contribution of the propulsion system design to the underwater signature of the ship, amongst the candidate architectures.
- Infrared signature: Relative contribution to the infrared signature by the propulsion system design, amongst the candidate architectures.
- Electromagnetic signature: Relative contribution of the propulsion system design to the overall electromagnetic signature of the ship, amongst the candidate architectures.

For all the susceptibility criteria, obviously, the lower the contribution of the propulsion system design to the respective attribute, the better the design is considered.

Performance Dimension: Survivability

- Redundancy: Parameter used to compare the number of backup options for operating the propulsion system in case of single or multiple failures of propulsion plant equipment. The higher the number of backup options available in the design, the better the candidate design is considered.
- Shock resistance: Comparative measure of the propulsion equipment and the plant design to resistance to underwater shock events for the candidate propulsion plant architectures without the requirement of any

special redesign of propulsion equipment. The higher the resistance to shock for a design, the better the candidate design is considered.

- Flooding survivability: Comparative measure of candidate propulsion plant architectures to survive flooding with the plant layout in the preferred engine room layout. The better resistance of a design to flooding, the better the candidate design is considered.

Performance Dimension: Maintainability

- Reliability: Parameter used to compare the overall reliability of the candidate design architectures, based on the individual equipment used and the overall complexity of the design.
- Availability: In the present context is used to compare the availability of equipment based on maintenance intervals defined usually based on hours of operation. In general, candidate propulsion architectures with more frequent and elaborate requirements for maintenance, based on hours of operation would be considered to have lower availability.
- Repairability: Comparative ease of repair of propulsion equipment when such work needs to be undertaken. Here if the propulsion equipment to be repaired needs a large effort to undertake the considered repair work, then its repairability would be considered to be relatively lower.

Performance Dimension: Integrability

- Weight: The overall mass of each candidate propulsion system design architecture derived from individual propulsion equipment is considered to compare the candidate design architectures. A design architecture that would have a lower overall mass would be considered as a better design.
- Space: The overall deck area occupied by each candidate propulsion system design architecture derived from individual propulsion equipment is considered to compare the candidate design architectures. A design architecture that would need lower space would be considered as a better design.
- Fuel capacity: is defined, in the present context, as the overall capacity of fuel required for the propulsion and the power generation systems together

to achieve the minimum specified endurance distance in the design specification at the defined speed. Hence, a design architecture that would need lower fuel capacity to achieve the specified endurance would be considered as a better design.

Objective Metric: Cost

- Acquisition cost: The overall acquisition cost of the propulsion equipment is derived using the individual weight of propulsion equipment and then the candidate designs are compared.
- Maintenance cost: The maintenance cost is derived for each candidate architecture, based on no operating profile which defines the combination of engines to be used in various speed bands, along with the average hourly maintenance rates calculated for individual equipment. Based on the calculated metrics, the candidate designs are compared.
- Manpower: Relative parameter used to compare the overall manpower required onboard to maintain and operate each candidate architecture.
- Fuel: The overall cost of annual fuel consumption rate by each candidate architecture is calculated, using the operating profile and the fuel rate curves calculated based on performance simulation for various modes of operation. Based on the calculated metrics, the candidate designs are compared.
- Support infrastructure: Relative parameter used to compare the extent of ashore support infrastructure augmentation for maintenance of that would be needed if the candidate design were to be selected.

Objective Metric: Risk

- Design: Relative parameter to compare the overall risk to the ship design that would be added if a particular propulsion system design would be selected. If a design architecture is well proven and has been executed by the shipbuilder earlier, it would be considered as a lower risk to the overall ship design.
- Schedule: Relative parameter that defines the overall risk that the selection of a particular candidate architecture would add to the overall

shipbuilding schedule. Here, even if a candidate architecture design is well proven but requires long procurement lead times then this architecture would be considered to be a higher risk to the schedule.

- Crew expertise: Relative parameter that is used to compare the candidate architectures based on whether the requisite crew expertise to operate such a design would be readily available or would there be requirements for specialized crew training. If a design similar to a candidate architecture has been operated by the shipowner's crew earlier, then the risk based on crew expertise would be considered to be lower for the particular candidate architecture.
- Support: Relative parameter used to compare the risk based on the availability of the industrial base required to support the candidate design architecture over the extended life of the ship. In the case of warships, this criterion would be more relevant where an assessment may be needed on the dependence of support from foreign suppliers for the upkeep of particular design architecture.

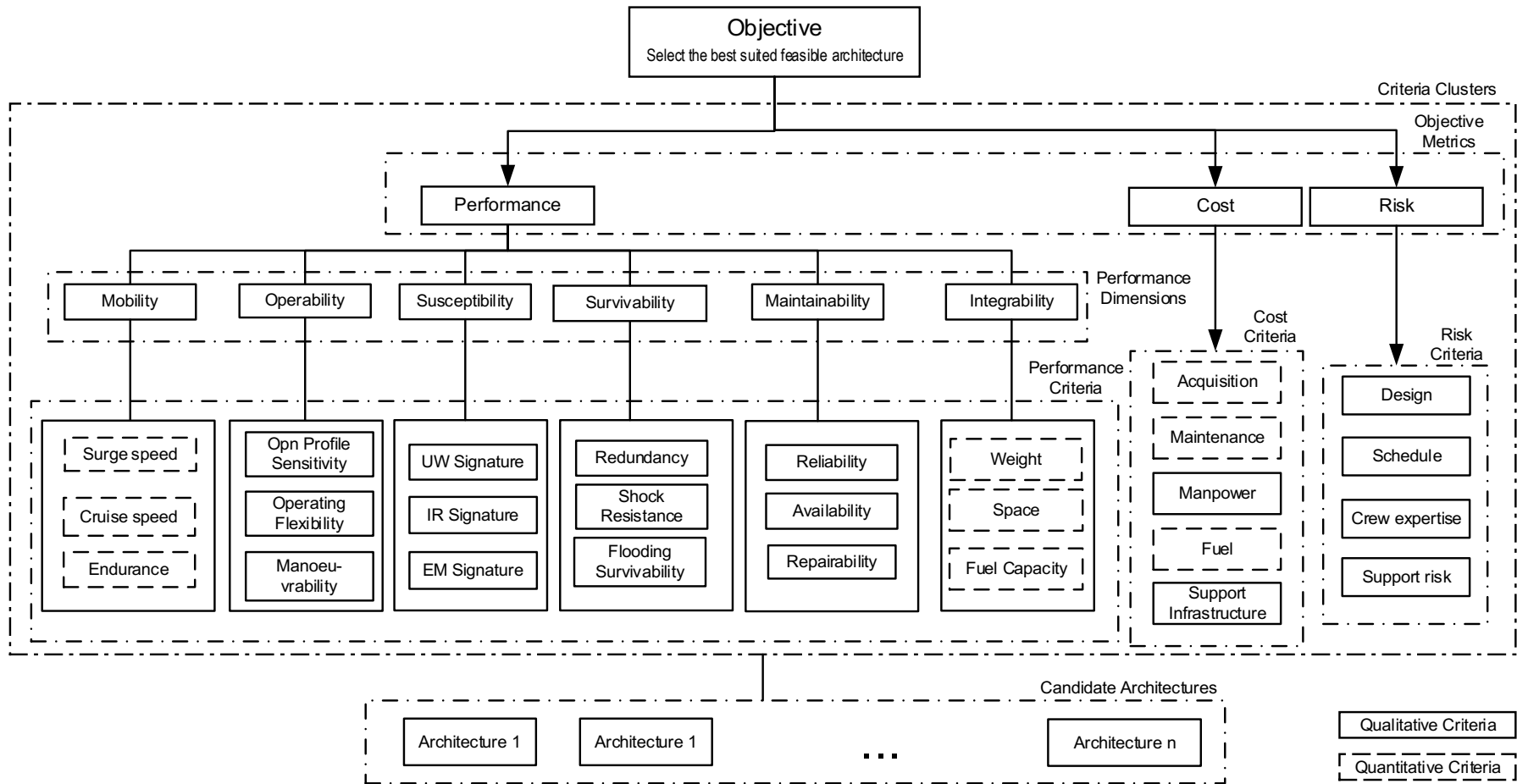


Figure 5-3 Design criteria for the MCDM problem in a combination of hierarchal, network structure

As can be seen in Figure 5-3, the design criteria were also classified into categories of ‘quantitative’ and ‘qualitative’ criteria. The ‘quantitative’ evaluation refers to analysis based on model-based data generation for plant performance as well as mass, dimensioning and cost for the plant. The ‘qualitative’ evaluation refers to analysis based on expert opinion based comparative data of the candidate designs. The ‘qualitative’ evaluation is primarily used for certain design criteria for which it may not be practical to derive exact models for evaluations due to the lack of information at the early stages of the ship design process.

5.3 Calculation of Criteria Weights

The DANP procedure [82,124,125] is used to calculate the local relative weights of the criteria from the ‘Objective Metric’ of ‘Performance’. The detailed procedure applied for the execution of the DANP method is described in Appendix L.

The DEMATEL method is first used to derive the degree of relationships between the ‘Performance Dimensions’ $D_1, D_2, D_3, \dots, D_n$, with each ‘Dimension’ having its respective individual set of criteria under it. The set of criteria of i th ‘Dimension’ is denoted by $c_{i1}, c_{i2} \dots c_{im_i}$ where $m_1, m_2, m_3, \dots, m_n$ are the number of criteria for respectively for each of the ‘Dimensions’. The DEMATEL process starts with the creation of ‘Initial Direct Influence Matrix’, X created by averaging the ‘Expert Direct Influence Matrices’, obtained using the expert-based evaluations of mutual influence for the ‘Dimensions’ $D_1, D_2, D_3, \dots, D_n$:

$$X = [x_{ij}]_{n \times n} = \begin{matrix} & \begin{matrix} D_1 & D_2 & \dots & D_n \end{matrix} \\ \begin{matrix} D_1 \\ D_2 \\ \vdots \\ D_n \end{matrix} & \begin{bmatrix} 0 & x_{12} & \dots & x_{1n} \\ x_{21} & 0 & \dots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \dots & 0 \end{bmatrix} \end{matrix} \quad (5-1)$$

where x_{ij} defines the ‘degree of direct influence’ of D_i on D_j on a scale of 0-4 with each numeric signifying: ‘No influence’, ‘Low influence’, ‘Medium influence’, ‘High influence’ and ‘Very high influence’ in increasing order.

The DEMATEL process is then used to calculate the ‘Normalized Total Direct Influence Matrix’ T_D^α . Using a similar process, as described above, the degree of

relationships between the individual criteria under each of 'Performance Dimensions' is further calculated to create the set of matrices for the criteria, $T_c^{\alpha ij}$, for the sets of criteria under the dimensions. With this set of matrices, the overall 'Normalised Influence Matrix' T_c^α is set up as:

$$T_c^\alpha = \begin{matrix} & \begin{matrix} D_1 & D_2 & & D_n \end{matrix} \\ \begin{matrix} D_1 \\ D_2 \\ \\ D_n \end{matrix} & \begin{bmatrix} c_{11} & \dots & c_{1m_1} & c_{11} & \dots & c_{1m_2} & & c_{11} & \dots & c_{1m_n} \\ c_{11} & T_c^{\alpha 11} & & T_c^{\alpha 12} & & \dots & & T_c^{\alpha 1n} \\ c_{1m_1} & & & & & & & \\ c_{11} & T_c^{\alpha 21} & & T_c^{\alpha 22} & & & & T_c^{\alpha 2n} \\ c_{1m_2} & & & & & & & \\ \vdots & \vdots & & \vdots & & \ddots & & \vdots \\ c_{11} & T_c^{\alpha n1} & & T_c^{\alpha n2} & & \dots & & T_c^{\alpha nn} \\ c_{1m_n} & & & & & \dots & & \end{bmatrix} \end{matrix} \quad (5-2)$$

Each submatrix $T_c^{\alpha ij}$, in T_c^α is written as:

$$T_c^{\alpha ij} = \begin{matrix} & c_{j1} & c_{j2} & \dots & c_{jm_j} \\ \begin{matrix} c_{i1} \\ c_{i2} \\ \vdots \\ c_{im_i} \end{matrix} & \begin{bmatrix} t_{c_{11}}^{\alpha ij} & t_{c_{12}}^{\alpha ij} & \dots & t_{c_{1m_j}}^{\alpha ij} \\ t_{c_{21}}^{\alpha ij} & t_{c_{22}}^{\alpha ij} & \dots & t_{c_{2m_j}}^{\alpha ij} \\ \vdots & \vdots & \ddots & \vdots \\ t_{c_{m_i1}}^{\alpha ij} & t_{c_{m_i2}}^{\alpha ij} & \dots & t_{c_{m_im_j}}^{\alpha ij} \end{bmatrix} \end{matrix} \quad (5-3)$$

with each element $t_{c_{pq}}^{\alpha ij}$ representing the normalized 'influence' $t_c^{\alpha ij}$ of criteria c_{ip} on c_{jq} .

To apply the ANP procedure, 'Unweighted Supermatrix' W_c is arranged as:

$$\begin{matrix}
& & & D_1 & & D_2 & & & D_n \\
& & & c_{11} & \cdots & c_{1m_1} & c_{21} & \cdots & c_{2m_2} & & c_{n1} & \cdots & c_{nm_n} \\
D_1 & c_{11} & \vdots & & & & & & & & & & \\
& c_{1m_1} & & & & & & & & & & & \\
D_2 & c_{21} & \vdots & & & & & & & & & & \\
& c_{2m_2} & & & & & & & & & & & \\
& & & & & & & & & & & & \\
D_n & c_{n1} & \vdots & & & & & & & & & & \\
& c_{nm_n} & & & & & & & & & & &
\end{matrix}
\begin{bmatrix}
W_c^{11} & W_c^{12} & \cdots & W_c^{1n} \\
W_c^{21} & W_c^{22} & \cdots & W_c^{2n} \\
\vdots & \vdots & \ddots & \vdots \\
W_c^{n1} & W_c^{n2} & \cdots & W_c^{nn}
\end{bmatrix}
\quad (5-4)$$

where each W_c^{ij} is calculated as:

$$W_c^{ij} = (T_c^{\alpha ji})' = \begin{bmatrix} t_{c_{11}}^{\alpha ji} & t_{c_{21}}^{\alpha ji} & \cdots & t_{c_{m_j1}}^{\alpha ji} \\ t_{c_{12}}^{\alpha ji} & t_{c_{22}}^{\alpha ji} & \cdots & t_{c_{m_j2}}^{\alpha ji} \\ \vdots & \vdots & \ddots & \vdots \\ t_{c_{1m_i}}^{\alpha ji} & t_{c_{2m_i}}^{\alpha ji} & \cdots & t_{c_{m_jm_i}}^{\alpha ji} \end{bmatrix} \quad (5-5)$$

Thereafter, the degree of relationships between the 'Performance Dimensions' is used to weigh the appropriate portions of the 'Unweighted Supermatrix' in order to get the 'Weighted Supermatrix', using the equation:

$$W_c^* = T_D^\alpha W_c \quad (5-6)$$

The 'Weighted Supermatrix' W_c^* is then solved by raising it to a sufficiently large power h until it converges and becomes a long-term stable super-matrix:

$$\lim_{h \rightarrow \infty} (W_c^*)^h \quad (5-7)$$

This stable super-matrix gives the set of local relative weights of all the criteria in the 'Objective Metric' of 'Performance' under the various 'Performance Dimensions', written as:

$$(w_{p1}, w_{p2}, w_{p3}, \dots) \quad (5-8)$$

The sets of local relative weights of the criteria in the ‘Objective Metric’ of ‘Cost’ and ‘Risk’ are determined using the AHP method since these criteria sets can be considered to be independent.

In the AHP method [68], the relative weights $w_1, w_2, w_3, \dots, w_n$ for n criteria $C_1, C_2, C_3, \dots, C_n$, are obtained by solving the following eigenvector problem:

$$Gw = \lambda_{max}w \quad (5-9)$$

where G is the ‘Pairwise Comparison Matrix’, w is the priority eigenvector associated with the principal eigen value λ_{max} . ‘Consistency Index’ CI and ‘Consistency Ratio’ CR are calculated to verify the consistency of the comparison matrix:

$$CI = \frac{(\lambda_{max} - n)}{n - 1}; CR = \frac{CI}{RI} \quad (5-10)$$

where RI indicates the average consistency index over numerous random entries of the reciprocal matrices with the same orders. If $CR \leq 0.1$, the estimate is accepted; otherwise, a new comparison matrix is solicited. The detailed procedure applied for the execution of the AHP method is described in Appendix M.

The determined local relative weights of the criteria sets in the ‘Objective Metric’ of ‘Cost’ and ‘Risk’ are written as:

$$(w_{c1}, w_{c2}, w_{c3}, \dots), (w_{r1}, w_{r2}, w_{r3}, \dots) \quad (5-11)$$

The AHP method is again applied, in a similar way, to calculate the local relative weights for the comparison between ‘Objective Metrics’ ‘Performance’, ‘Cost’ and ‘Risk’ to get the relative weights:

$$(w_{pe}, w_{co}, w_{ri}) \quad (5-12)$$

The calculated local relative weights for the comparison between ‘Objective Metrics’ ‘Performance’, ‘Cost’ and ‘Risk’; are thereafter loaded onto the sets of

local weights calculated for the ‘Objective Metrics’ to arrive at the set of global relative weights of all the criteria (w_P, w_C, w_R) as follows:

$$w_P = w_{P1}, w_{P2}, w_{P3}, \dots = w_{pe} \cdot (w_{p1}, w_{p2}, w_{p3}, \dots) \quad (5-13)$$

$$w_C = w_{C1}, w_{C2}, w_{C3}, \dots = w_{co} \cdot (w_{c1}, w_{c2}, w_{c3}, \dots) \quad (5-14)$$

$$w_R = w_{R1}, w_{R2}, w_{R3}, \dots = w_{ri} \cdot (w_{r1}, w_{r2}, w_{r3}, \dots) \quad (5-15)$$

5.4 Determination of Evaluation Scores for Candidate Architecture

Once the global relative weights for the criteria have been found, evaluation scores are calculated for each of the candidate architectures against all the criteria. For all the ‘quantitative’ criteria, model-based analysis, as already described, is undertaken to determine the metrics for evaluation for the candidate architectures.

For the defined ‘qualitative’ criteria, a group of experts independently provide a relative evaluation score of each of the candidate architecture. For the present work this relative score is calculated using AHP as follows. Against each of the given criteria, a group of experts give relative scores to each of candidate architectures, compared to another architecture (pairwise comparison) using the using Saaty’s scale of 1 to 9. Here a rating of 1 represents equal rating of compared architectures, while a rating of 9 means that the specific candidate has an extremely high rating compared to the other architecture, for the specific criteria. The scores given by the experts are then averaged or negotiated in a group discussion to a final relative score on the Saaty scale of 1-9. These scores for all the architectures against the specific criteria are then mathematically processed using the method described in Appendix M to arrive at the final evaluated relative score of the architectures against the specific criteria.

5.5 Selection of Plant Architecture Using VIKOR

With the global relative weights of all the criteria as well as, evaluation scores of the determined, the VIKOR method is used to find the ‘best suited’ architecture

from the set of feasible candidate architectures. In the VIKOR terminology, the candidate architectures would be termed as the ‘alternatives’, while the ‘best suited’ architecture would be called the ‘compromise solution’ that is closest to the ‘ideal solution’. The term ‘compromise’ denotes the mutual concessions made between the alternatives [79]. The concept can be illustrated using Figure 5-4, where the alternatives are being assessed across a two-dimensional decision space defined by two criteria with f_i being the ‘evaluated score’ of an alternative for the i th criterion. The ‘compromise solution’ F^c is a ‘feasible solution’ that has been found, ‘closest’ to the ‘ideal solution’ F^* , by mutual concessions, $\Delta f_1 = f_1^* - f_1^c$ and $\Delta f_2 = f_2^* - f_2^c$ [126].

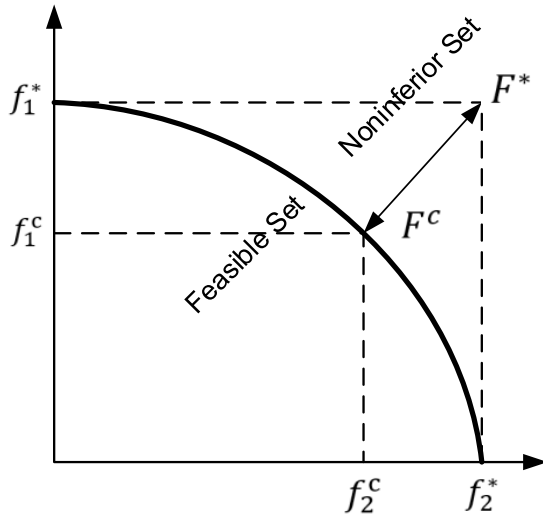


Figure 5-4 VIKOR method for finding ‘compromise’ solution

The VIKOR method is based on the Lp-metric $L_{p,j}$, or the measure of distance to the ideal solution. For a set of alternatives, $(a_1, a_2, \dots, a_j, \dots, a_r)$ being evaluated for criteria $(C_1, C_2, C_3, \dots, C_i, \dots, C_n)$ with corresponding global weights $(w_1, w_2, w_3, \dots, w_n)$, $L_{p,j}$ can be written for the alternative a_j with f_{ij} being its ‘evaluated score’ for the criteria C_i representing a ‘benefit function’ as :

$$L_{p,j} = \left\{ \sum_{i=1}^n [w_i (f_i^+ - f_{ij}) / (f_i^+ - f_i^-)]^p \right\}^{1/p} \quad (5-16)$$

where:

$$1 \leq p \leq \infty; j = 1, 2, \dots, r.$$

$$f_i^+ = \max_j f_{ij}, f_i^- = \min_j f_{ij}$$

As a part of the VIKOR procedure, for each alternative, a_j , being evaluated against a criterion C_i , metrics S_j , R_j , Q_j are calculated using the w_i , f_{ij} and coefficient v . Coefficient v is the ‘strategy coefficient’ set by the decision-maker with $v \in [0, 1]$. The values of v higher than 0.5 indicate that the decision-maker is more focused on satisfying most of the criteria, while values lower than 0.5 indicate that the decision-maker is more focused on minimizing individual differences from the ideal solution. Coefficient v is usually set to a value of 0.5 to start the procedure.

The alternatives $a_1, a_2, \dots, a_j, \dots, a_r$ are ranked in the order of priorities based on the values of S_j , R_j , Q_j with their lower values considered as ‘better’ values. The ‘best alternative’ or the most suitable ‘compromise solution’, is selected as the one ranked by the lowest value of Q . The ‘best alternative’ is checked for validity for having an ‘acceptable degree of advantage’ and ‘acceptable stability in decision making’. If both the conditions are not satisfied, then a set of ‘compromise solutions’ may be selected by the decision-makers based on additional considerations. The detailed procedure applied for the execution of the VIKOR method is described in Appendix N.

6 RESULTS AND DISCUSSION

This chapter presents the results of the investigations made as a part of the present research work towards developing the process for a techno-economic model-based design space exploration of ship propulsion plants. The proposed methodology for undertaking the conceptual design has been demonstrated by application to two ship designs: a notional frigate and a notional destroyer.

The chapter initially describes the verification of the developed performance modelling framework for gas turbine engines and ship propulsion systems. The investigations of performance results, obtained from the developed modelling framework, for the various gas turbine engines applied for the conceptual design investigations for the notional frigate and destroyer ship have then been presented. The verification results of the applied models for resistance and propeller modelling for the ship propulsion systems have then been presented.

The chapter thereafter briefly describes the process of the population of the design space with alternate propulsion plant design architectures. The application of the MCDM methods towards TERA analysis, for both the conceptual design studies towards the selection of the most suitable candidate propulsion plant architecture, has been then demonstrated and the summarised results are presented.

6.1 Verification of Developed Performance Modelling and Simulation Framework

The overall modelling framework developed as a part of the present research work was validated in parts by comparing the results with known performance models. The validation exercise undertaken for the primary parts of the modelling and simulation framework with higher complexity has been described here i.e., the gas turbine engine, hull resistance and propeller optimization modules. The modules for which direct application of models from the literature have been used are not described here. The results of the comparative validation results are described in the following paragraphs.

6.1.1 Gas Turbine Engine Modelling

Towards validating the gas turbine engine modelling and simulation method developed as a part of the plant modelling framework, comparison of the results obtained from the developed modelling framework Poseidon+, were undertaken with the well-proven performance simulation software. Turbomatch, which has been used extensively at Cranfield University for many years, as described earlier in this thesis. For this validation, a simple aero turbojet design was selected for which detailed results were already available from Turbomatch. The description of the model used for this validation is shown in Figure 6-1. The input model file used to run the simulations is included in Appendix P.1.

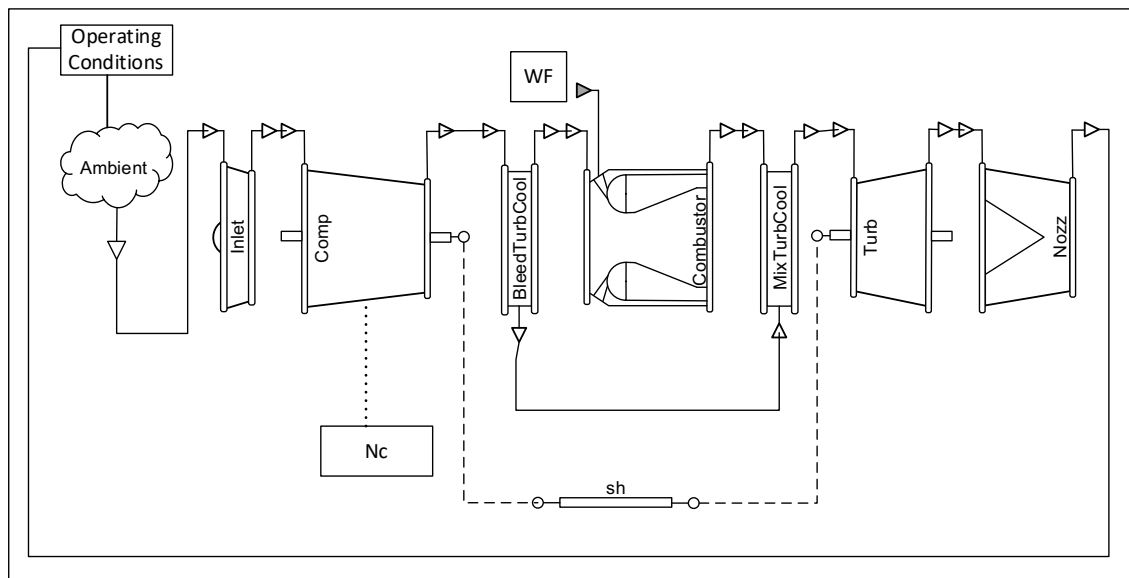


Figure 6-1 Model depiction of Turbojet used for design validation

The correlation of the results from Poseidon+ and Turbomatch was initially undertaken by comparison of the performance of each of the model components at the input and output stations. The results of the overall engine performance were thereafter correlated by comparing variation of temperature and pressure at each station of the engine at various power settings (or handle settings) which in this case was the compressor speed ratio (PCN or N_c) varied from 0.6 to 1. The comparison of the results has been graphically shown in Figure 6-2 and Figure 6-3 for temperature and pressure values respectively, calculated at engine stations.

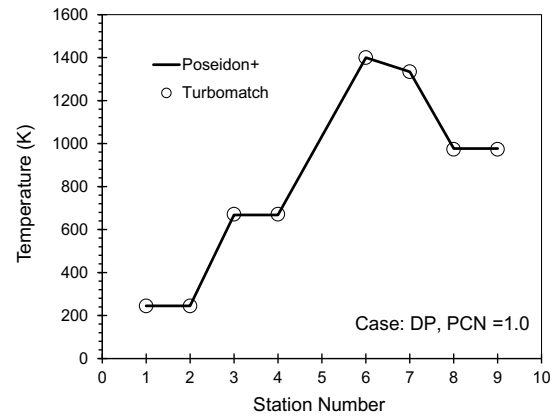
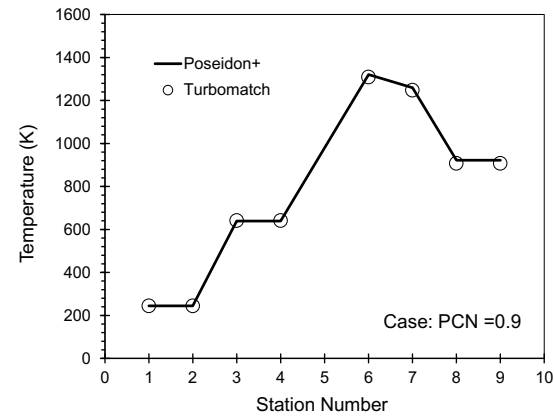
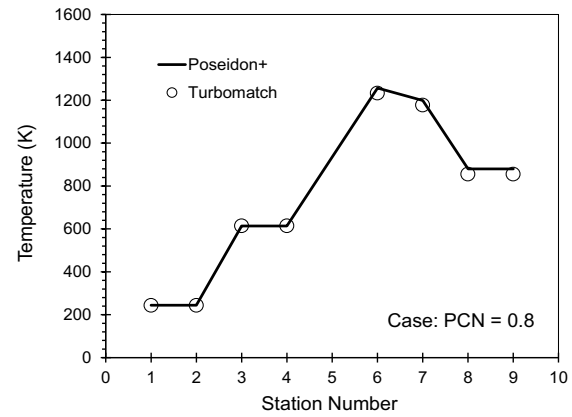
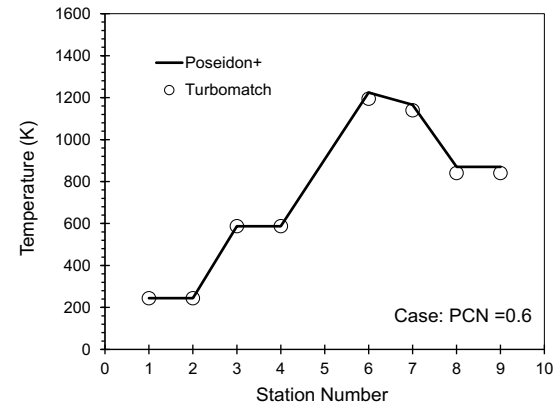


Figure 6-2 Comparison of temperatures at engine stations for handle (PCN or N_c) variation from 0.6 to 1.0 for Turbojet, calculated by Poseidon+ and Turbomatch

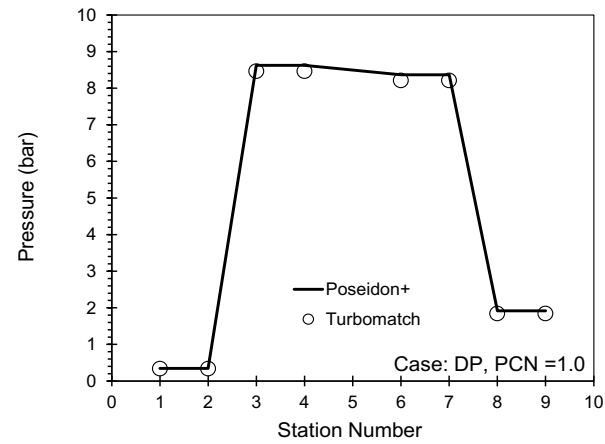
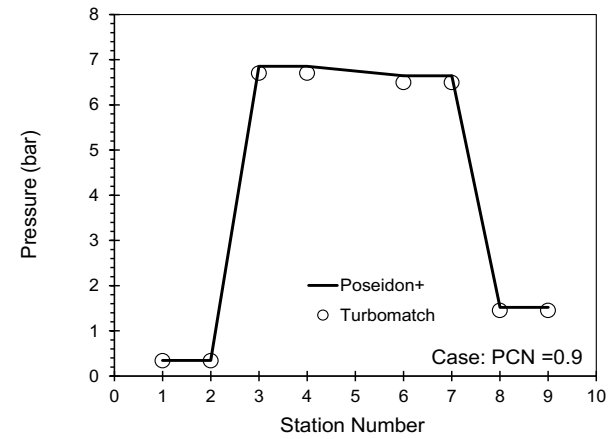
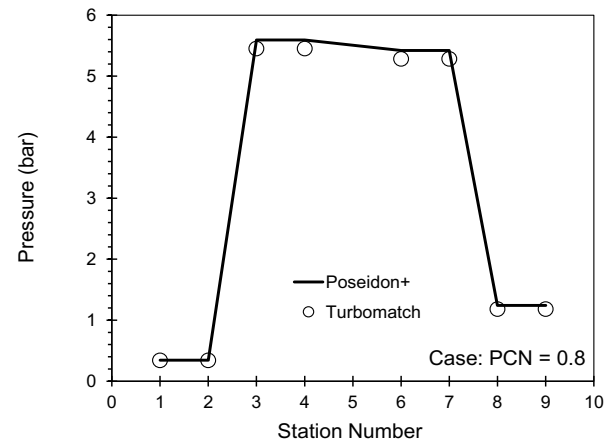
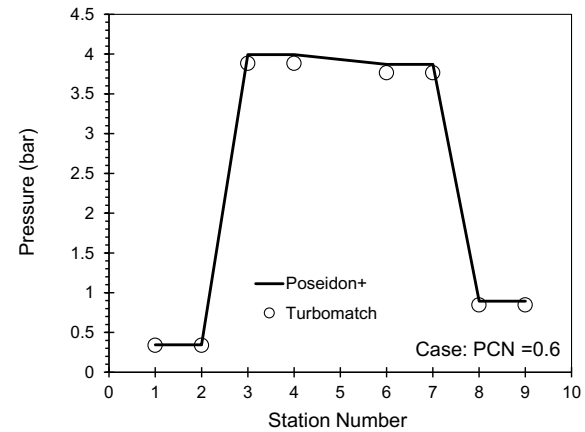


Figure 6-3 Comparison of pressures at engine stations for handle (PCN or N_c) variation from 0.6 to 1.0 for Turbojet, calculated by Poseidon+ and Turbomatch

From the aforementioned figures, it can be seen that the results show a very close correlation. The minor variation in the pressure (up to 3%) at some of the stations can be attributed to slight differences in the fluid model for the DP case and different methods of map interpolation used in Poseidon+ and Turbomatch, leading to slightly different pressure ratios for the OD cases. After comparing the temperature in pressure values at engine stations, the overall performance parameters calculated by Poseidon+ and Turbomatch for the turbojet model were compared. The comparison of the gross thrust, fuel flow, and inlet mass flow across the variation of the handle, calculated by Poseidon+ and Turbomatch are shown in Figure 6-4, Figure 6-5 and Figure 6-6 respectively. As it can be seen from these figures the overall performance parameters also show a very good correlation between the results obtained from Poseidon+ and Turbomatch.

Additionally, the results of the working line on the compressor and turbine maps for the engine are shown from Figure 6-7 to Figure 6-10. It can be seen from these figures these working lines show a good correlation with the expected theoretical values.

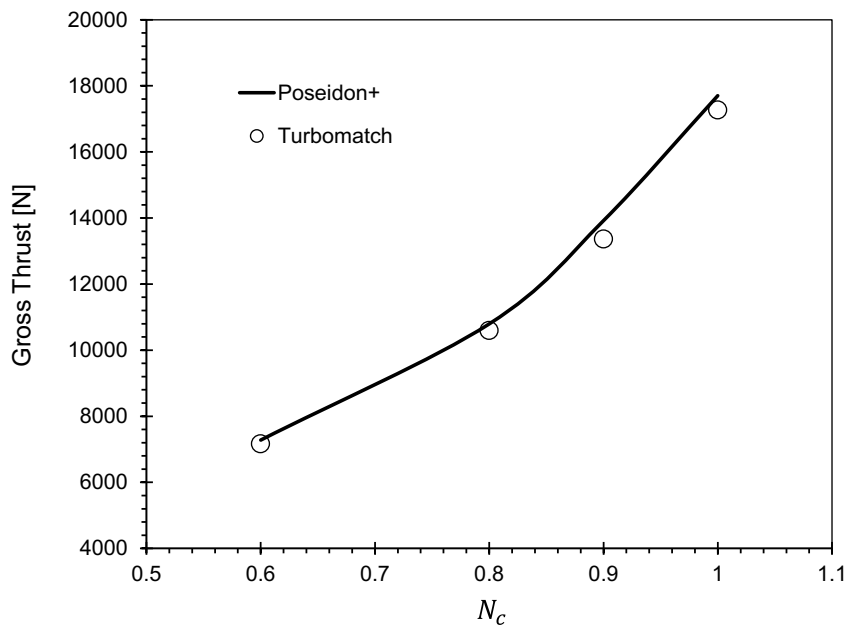


Figure 6-4 Comparison of Gross Thrust for handle (PCN or N_c) variation from 0.6 to 1.0 for Turbojet, calculated by Poseidon+ and Turbomatch

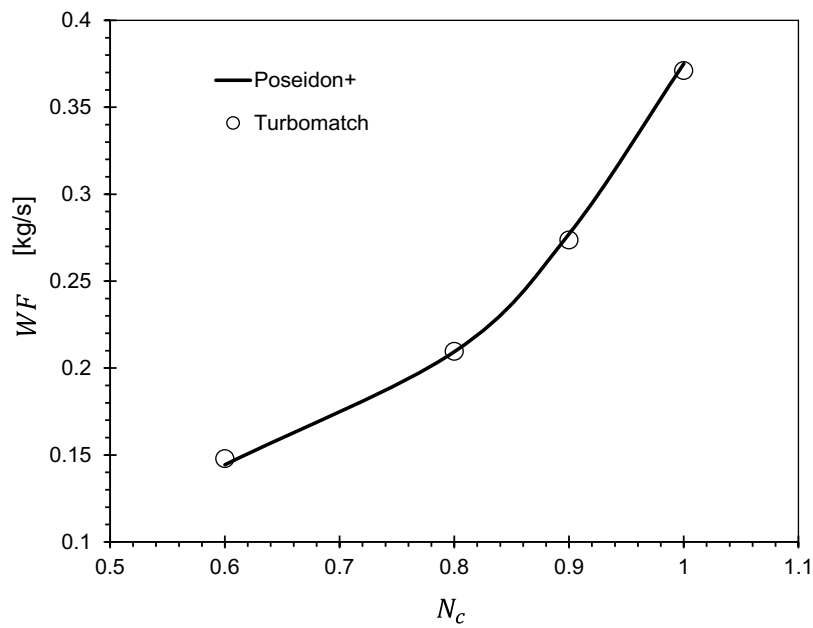


Figure 6-5 Comparison of fuel flow (WF) for handle (PCN or N_c) variation from 0.6 to 1.0 for Turbojet, calculated by Poseidon+ and Turbomatch

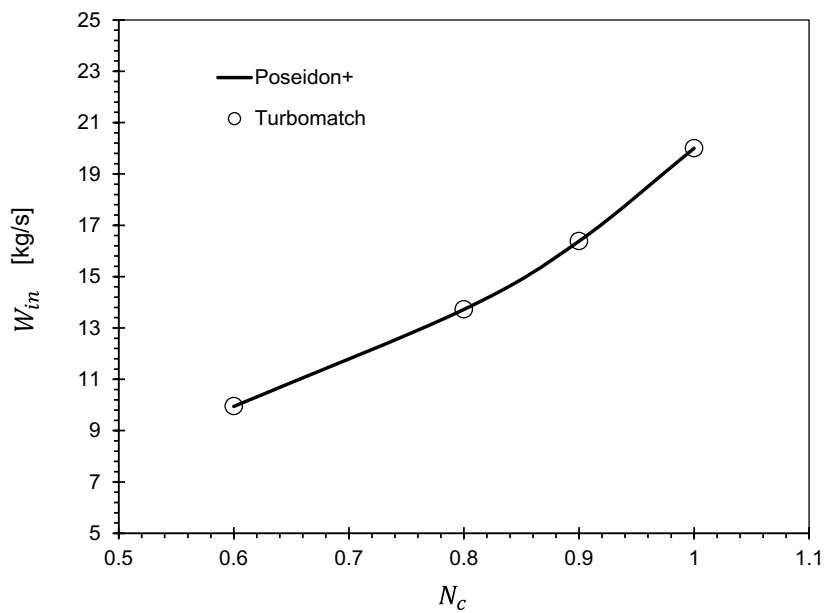


Figure 6-6 Comparison of inlet air mass flow (W_{in}) for handle (PCN or N_c) variation from 0.6 to 1.0 for Turbojet, calculated by Poseidon+ and Turbomatch

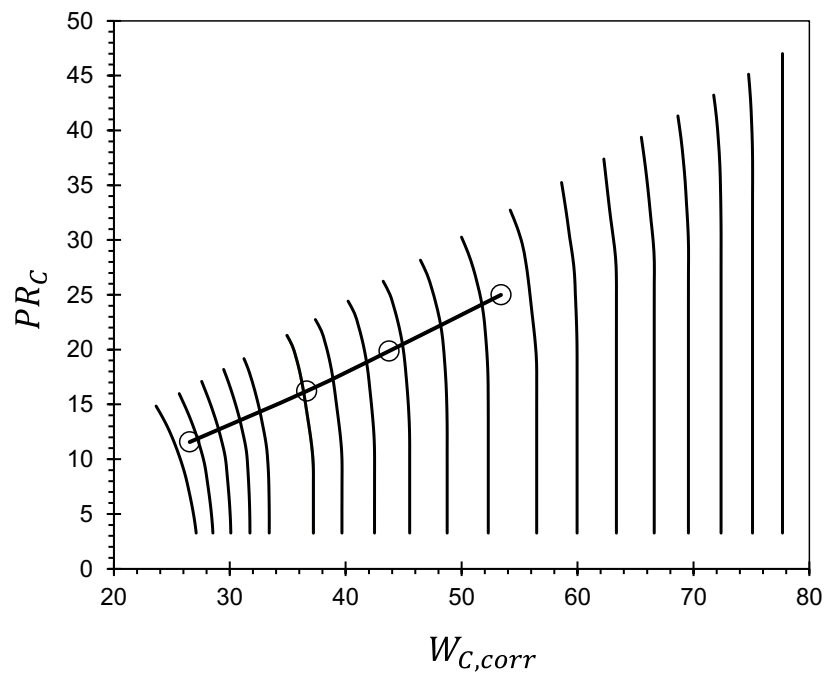


Figure 6-7 Computed working line on compressor pressure ratio map for Turbojet

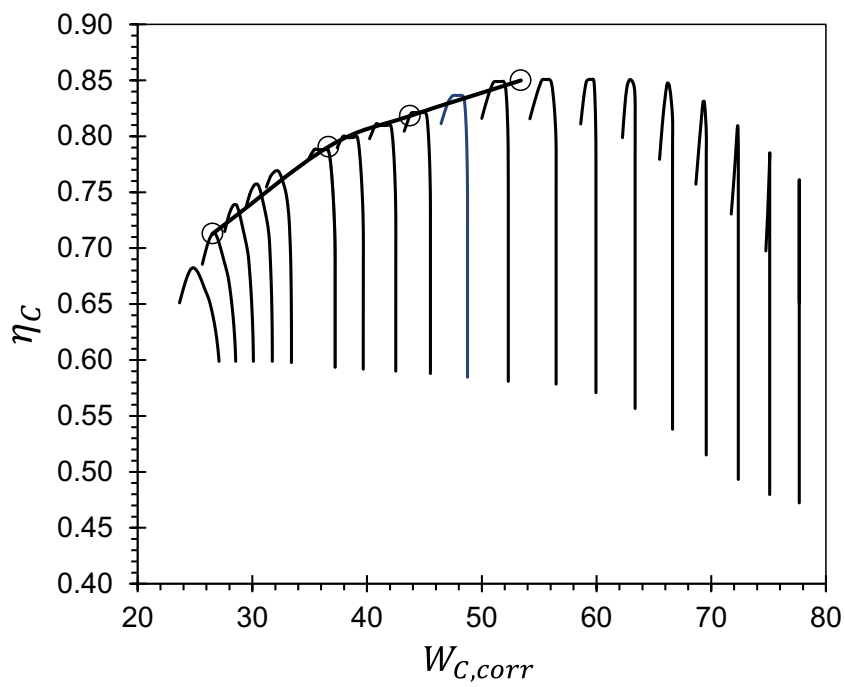


Figure 6-8 Computed working line on compressor isentropic efficiency map for Turbojet

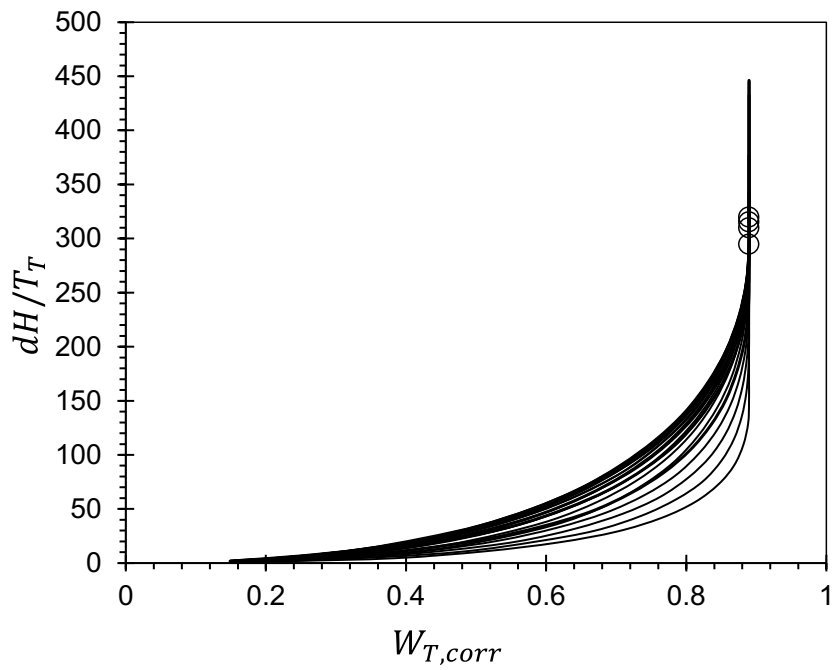


Figure 6-9 Computed working line on turbine enthalpy ratio map for Turbojet

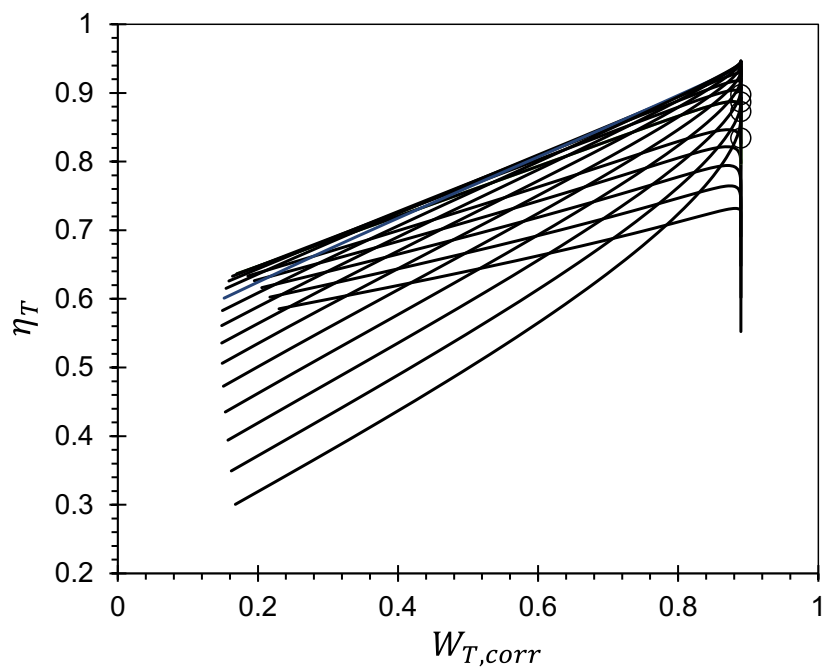


Figure 6-10 Computed working line on turbine isentropic efficiency map for Turbojet

6.1.2 Diesel Engine Modelling

For the present work, a generalized model of state-of-the-art medium-speed diesel engines has been applied in the ship propulsion plant models. As was described in section 4.3.9.2, this generalised model is represented by a normalised map that relates engine speed, fuel flow rate with the brake power produced by the engine. This normalized map is shown in Figure 6-11, generated using the third-order polynomials with the calculated coefficients shown in section 4.3.9.2. The validity of this model was checked against the publication by Altosole et.al. [94], and engine catalogue data which is usually publicly available for a cubic propeller law.

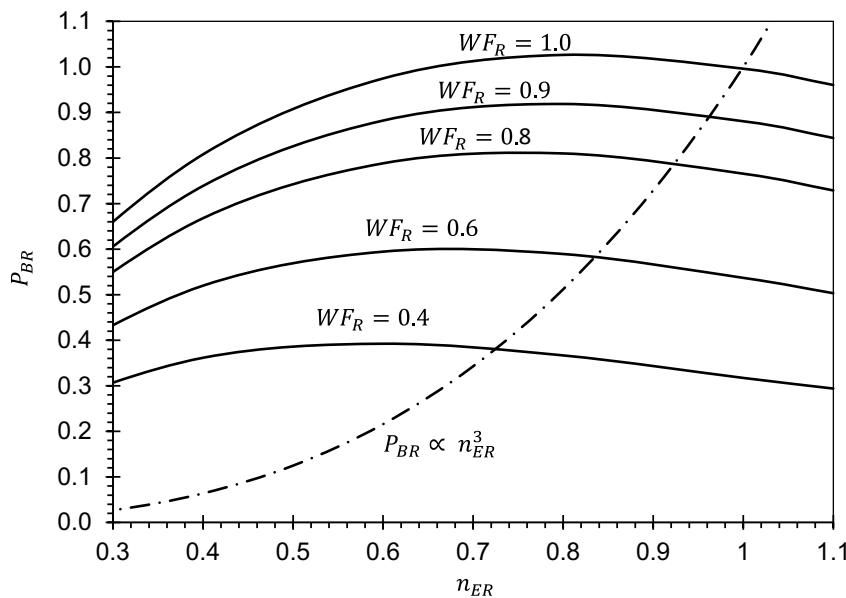


Figure 6-11 Normalised medium-speed diesel engine map derived for present research work

6.1.3 Resistance Models

The resistance models were implemented in the developed framework, as per the description in section 4.3.4, based on the application of the published equations for all three applied methods: H&M, F&L and Hollenbach. After integrating these models into Poseidon+, validation of the implementation was checked by comparing the results with individual examples published in the original papers. Thereafter, the results obtained by all the three implemented

methods were compared with published results for a well-known hull form of the US Navy DDG51 design from literature (UoM: University of Michigan) [127]. The model input file used in Poseidon+ is shown in Appendix R. The results of this comparison as shown in Figure 6-12 and it can be seen that, for the hull form considered, all the results calculated from all three implemented models, show a good correlation with published results.

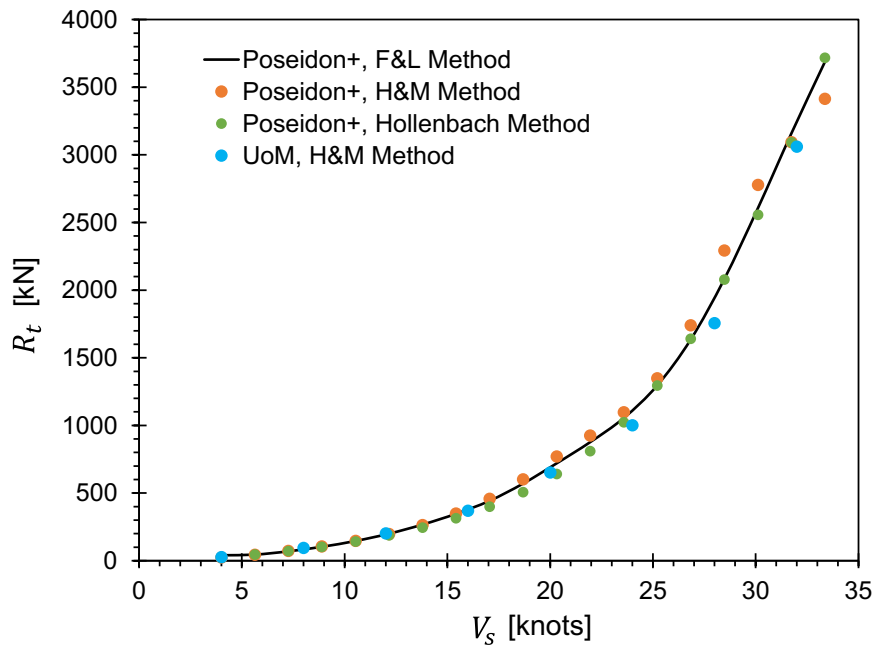


Figure 6-12 Comparison of results of implemented resistance model with published data.

6.1.4 Propeller Model and Optimizer

The propeller optimization module was verified by comparing results from the developed module with Bernitsas [128] and Radojcic [129]. A comparison of the results, generated from the same optimization problem is shown in Figure 6-13. The input model used for the optimization problem is shown in Appendix R.1. The correctness of the implementation of the Wageningen B Series propeller models used in the developed modelling framework was verified by comparing the results with published results as shown by the superposition of calculated results with the published results from Bernistas [128] as shown in Figure 6-14.

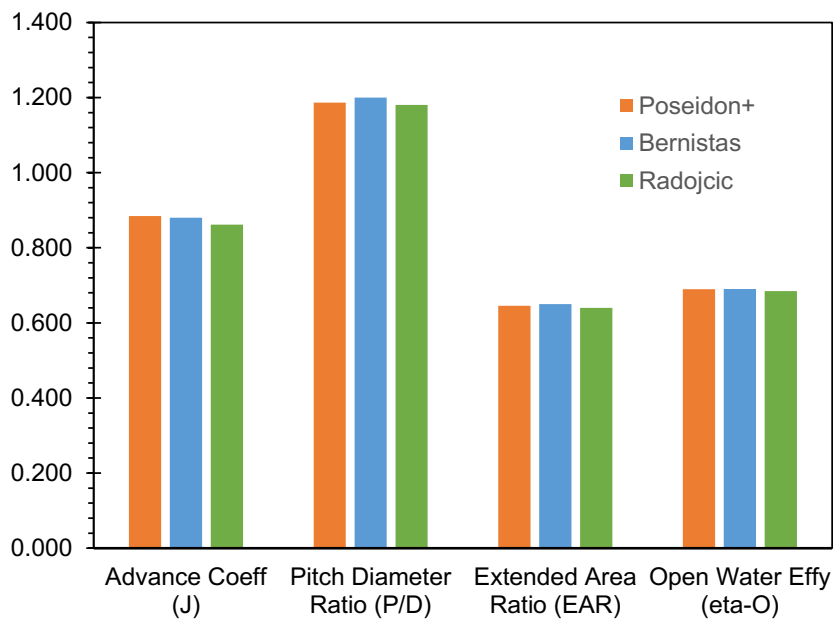


Figure 6-13 Comparison of results of implemented propeller optimization module with published data

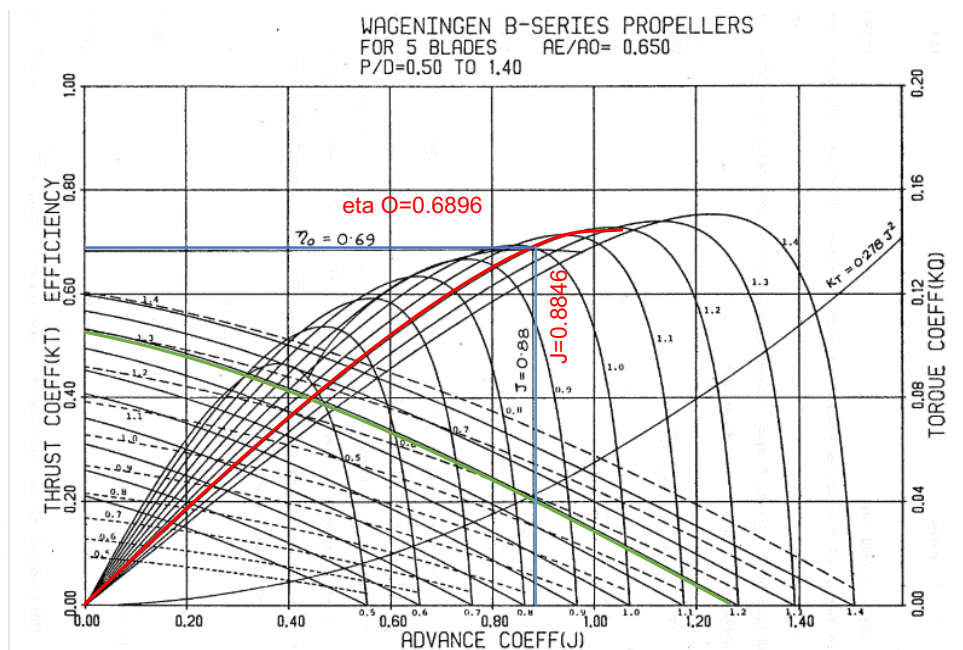


Figure 6-14 Superposition of the results of implemented propeller optimization module with published curves [128]

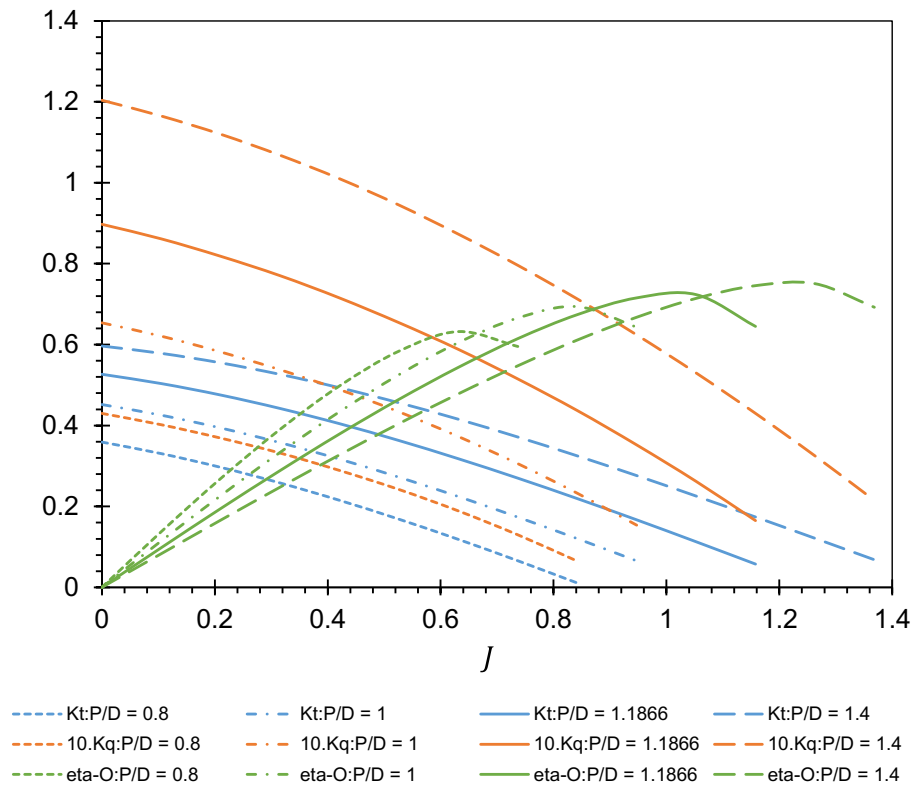


Figure 6-15 Set of open water results from implemented Wageningen B Series based propeller model with P/D varied from 0.8 to 1.4

The effect of variation of the P/D on under open water characteristics of the propeller, as calculated by the implemented model, using the same propeller as that for validation studies above, is shown in Figure 6-15.

6.2 Gas Turbine Engines and Simulation Analysis

6.2.1 Gas Turbine Engine Performance Simulation Results

For the conceptual design investigations, described later in this chapter, for the notional frigate and destroyer, four different Marine Gas Turbine (MGT) engines with rated brake power ranging from 7.5 MW to 36 MW have been modelled. These engine models, as referred to by these names further in this thesis, are:

- 7.5 MW MGT
- 15 MW MGT
- 25 MW MGT

- 36 MW MGT

In all the engine models described, it would be seen that nozzles have been included in the models, which are not applicable for marine applications. Here the nozzle should be seen as a virtual component which is an extension of the free power turbine, for expanding the gas to the atmosphere or the exhaust system of the ship.

The engine models have been run in different scenarios to investigate the behaviour of these engines under various operating conditions. It should be noted that these investigations were independent of the final investigations taken for these engines integrated with the propulsion plants as used for the conceptual design studies presented for the national frigate and destroyer, later in this chapter.

For each engine, the engine characteristics have been calculated and plotted with respect to three primary parameters, for the given operating conditions using the developed modelling tool, Poseidon+:

- Fuel flow (WF)
- Compressor speed ratio (N_C)
- Power turbine shaft power or engine brake power (PW_{sh})

Against each of these primary parameters, the following engine characteristics have been plotted from the simulation results obtained:

- Combustor outlet temperature ($T_{B,out}$)
- Power turbine inlet temperature ($T_{PT,in}$)
- Compressor outlet temperature ($T_{C,out}$)
- Compressor outlet pressure ($P_{C,out}$)
- Overall compressor pressure ratio (PR)
- Compressor speed ratio (N_C)
- Power turbine shaft power or engine brake power ($PW_{sh,out}$)
- Specific fuel consumption (sfc)

In this section the modelling and simulation results of the 25 MW gas turbine engine have been presented. The model description and the simulation results for the 7.5, 15 and 36 MW gas turbine engines have been included at Appendix O.

The 25 MW engine has a single spool gas generator with a free power turbine that is connected to the load or the propeller through the transmission system. The layout of the engine is shown in Figure 6-16. The primary parameters of the engine are shown in Table 6-1. The detailed model input file used is shown in Appendix P.4.

To add some variation to the previous cases, the simulation results presented below for this engine have been run for air inlet temperature of 35 °C conditions with the power turbine speed being varied as per the loading by a propeller, with the load curve shown in Figure 6-37. The OD simulations were undertaken using the power turbine shaft power as the handle. The generated engine characteristics for the engine against engine fuel flow (WF) from Figure 6-17 to Figure 6-23, against compressor speed ratio (N_c) from Figure 6-24 to Figure 6-29 and against power turbine shaft power or engine brake power (PW_{sh}) from Figure 6-30 to Figure 6-36.

Table 6-1 Primary design point parameters for 25 MW MGT

Parameter	Unit	Value
Inlet mass flow	kg/s	68
Compressor pressure ratio	-	19.25
Compressor isentropic efficiency	%	87
Compressor bleed for HP Turbine cooling	%	10
Combustor outlet temperature	K	1550
Fuel type	-	Diesel
Turbine isentropic efficiency	%	89
FP Turbine isentropic efficiency	%	91

FP: Free Power

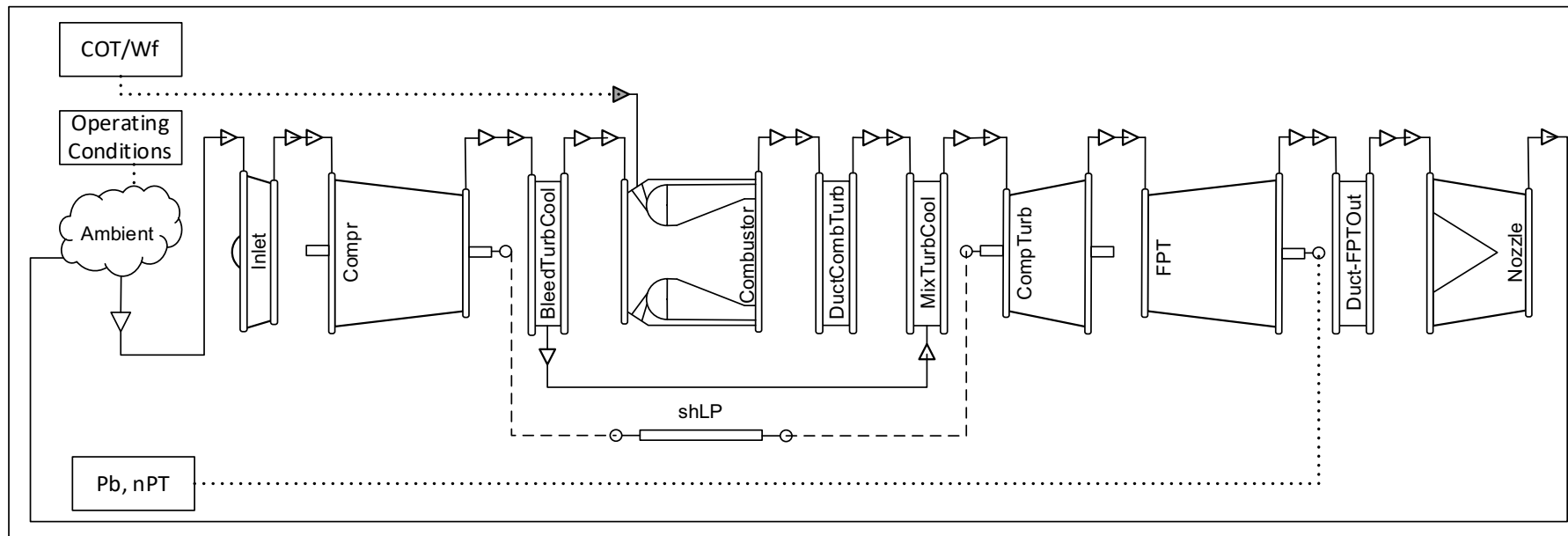


Figure 6-16 Model block diagram for 25 MW MGT

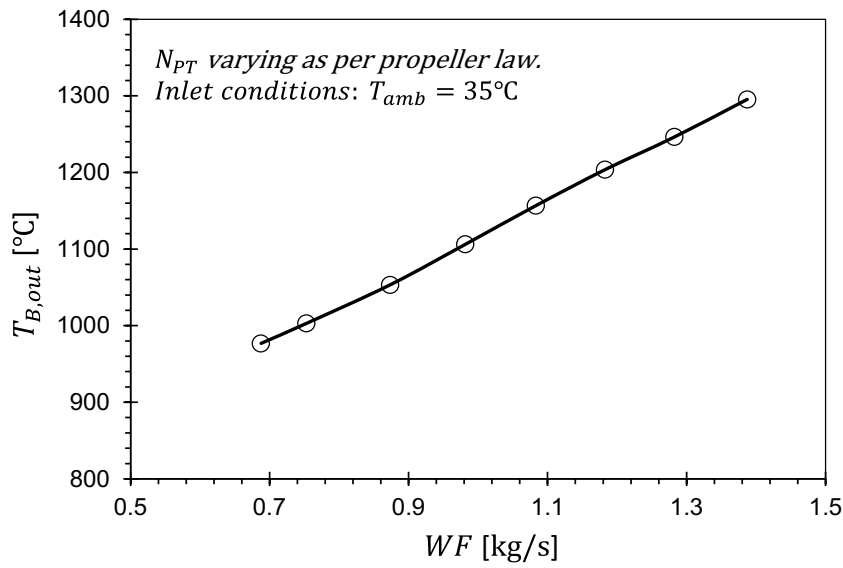


Figure 6-17 Computed variation of combustor outlet temperature ($T_{B,out}$) against fuel flow (WF) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35^\circ\text{C}$.

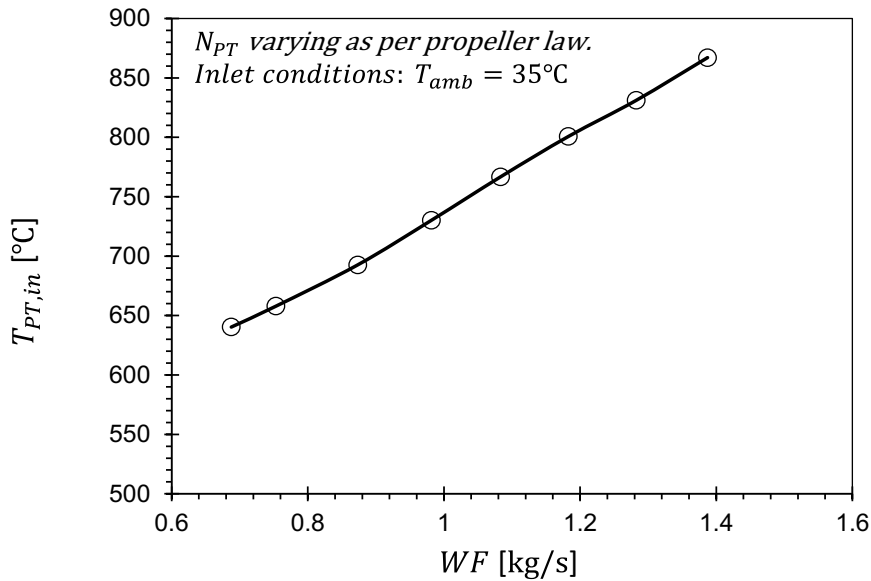


Figure 6-18 Computed variation of power turbine inlet temperature ($T_{PT,in}$) against fuel flow (WF) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35^\circ\text{C}$.

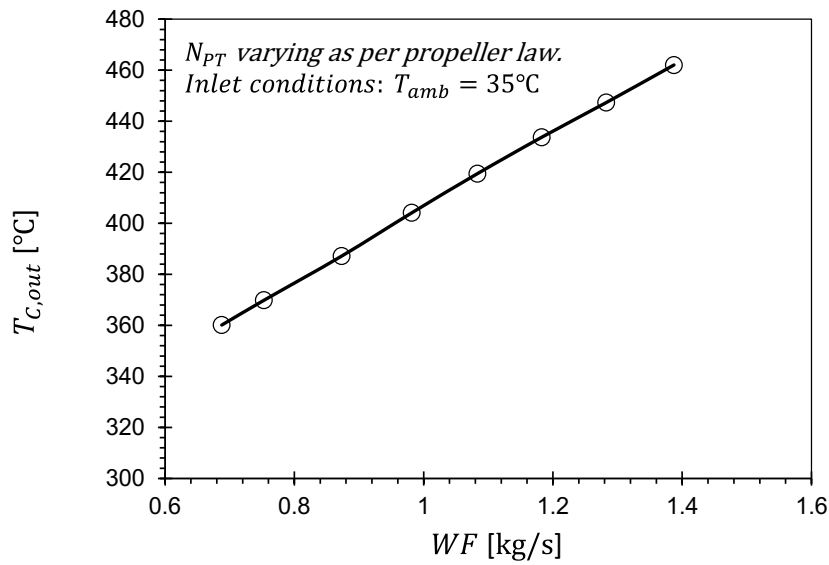


Figure 6-19 Computed variation of compressor outlet temperature ($T_{C,out}$) against fuel flow (WF) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35^\circ\text{C}$.

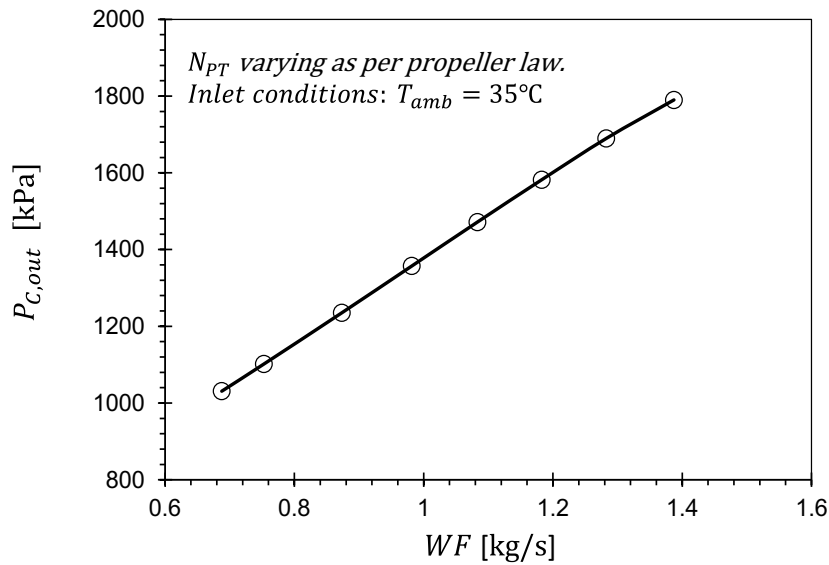


Figure 6-20 Computed variation of compressor outlet pressure ($P_{C,out}$) against fuel flow (WF) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35^\circ\text{C}$.

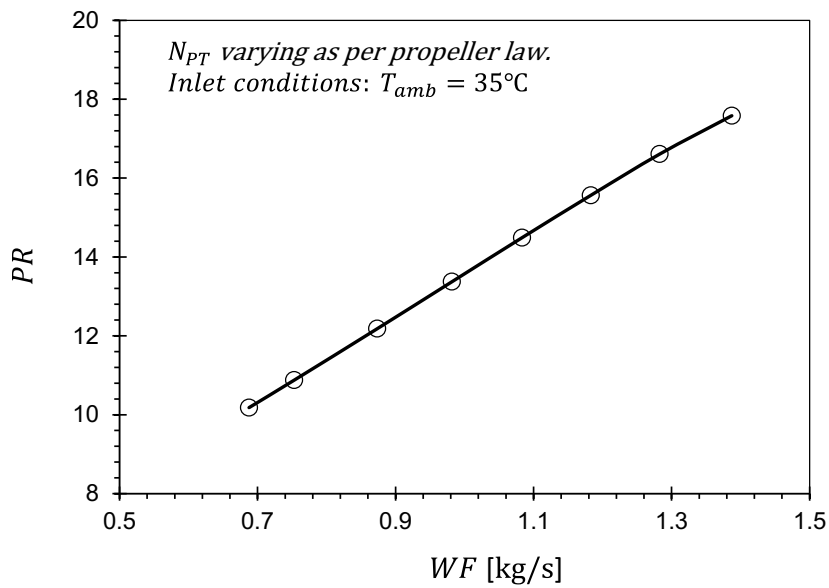


Figure 6-21 Computed variation of overall compressor pressure ratio (PR) against fuel flow (WF) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35^\circ\text{C}$.

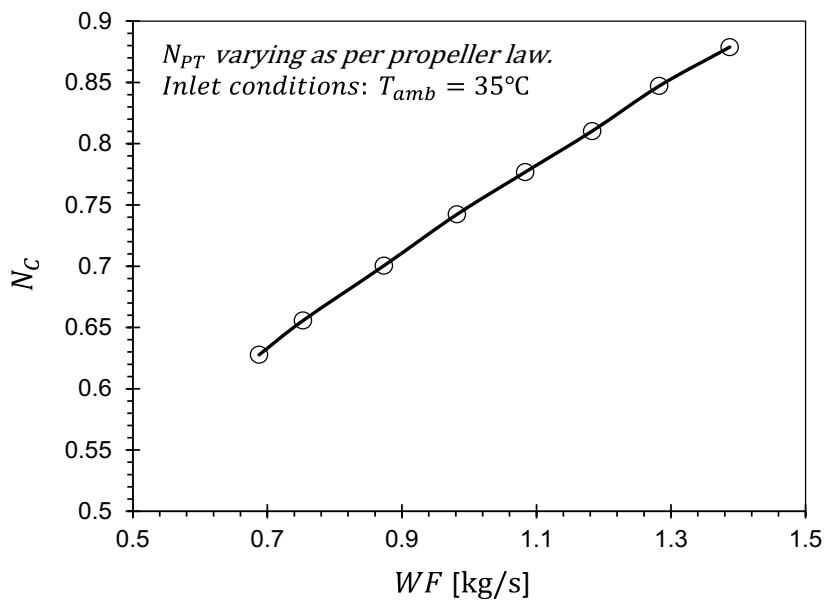


Figure 6-22 Computed variation of compressor speed ratio (N_C) against fuel flow (WF) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35^\circ\text{C}$.

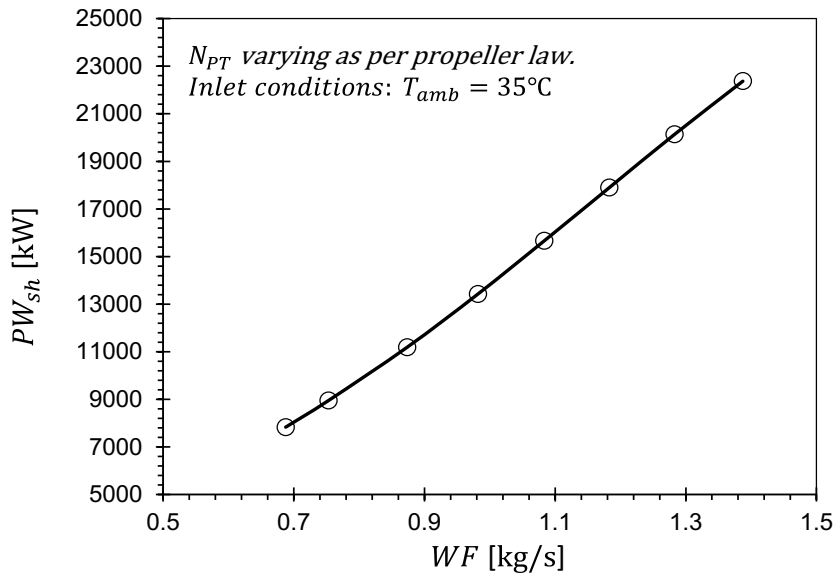


Figure 6-23 Computed variation of power turbine shaft power or engine brake power ($PW_{sh,out}$) against fuel flow (WF) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35^\circ\text{C}$.

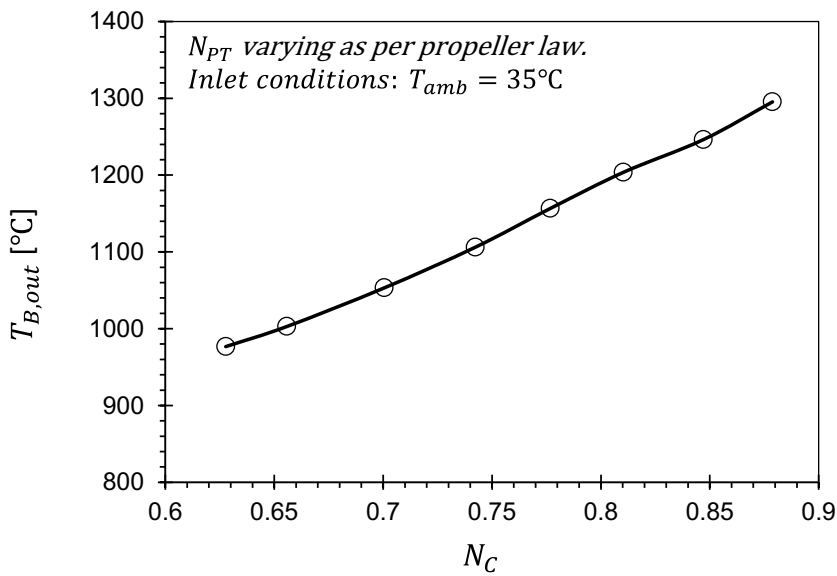


Figure 6-24 Computed variation of combustor outlet temperature ($T_{B,out}$) against compressor speed ratio (N_C) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35^\circ\text{C}$.

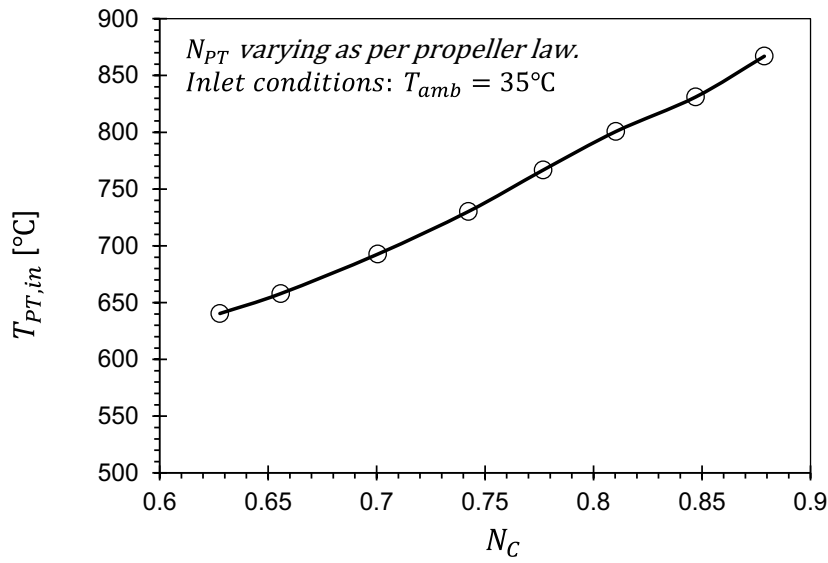


Figure 6-25 Computed variation of power turbine inlet temperature ($T_{PT,in}$) against compressor speed ratio (N_C) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35^\circ\text{C}$.

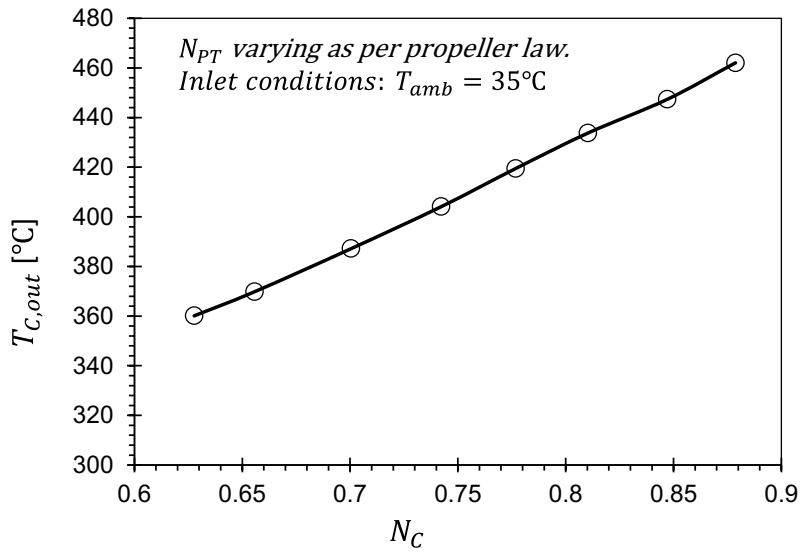


Figure 6-26 Computed variation of compressor outlet temperature ($T_{C,out}$) against compressor speed ratio (N_C) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35^\circ\text{C}$.

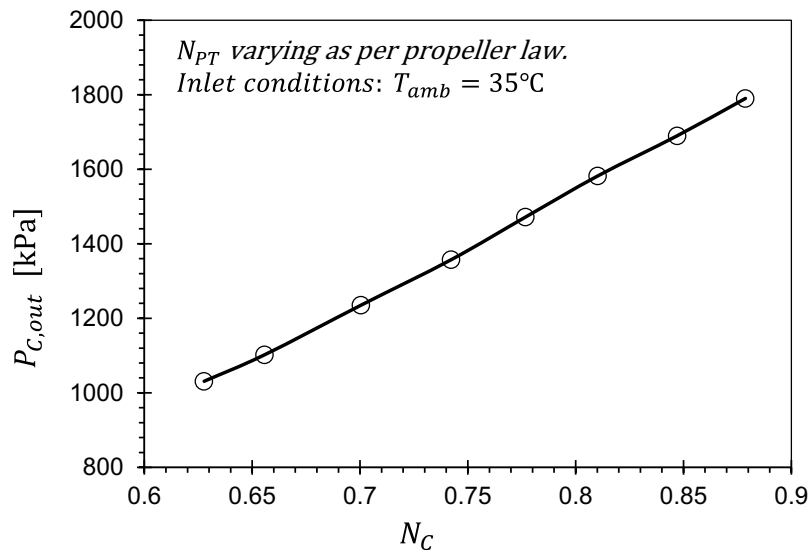


Figure 6-27 Computed variation of compressor outlet pressure ($P_{C,out}$) against compressor speed ratio (N_C) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35^\circ\text{C}$.

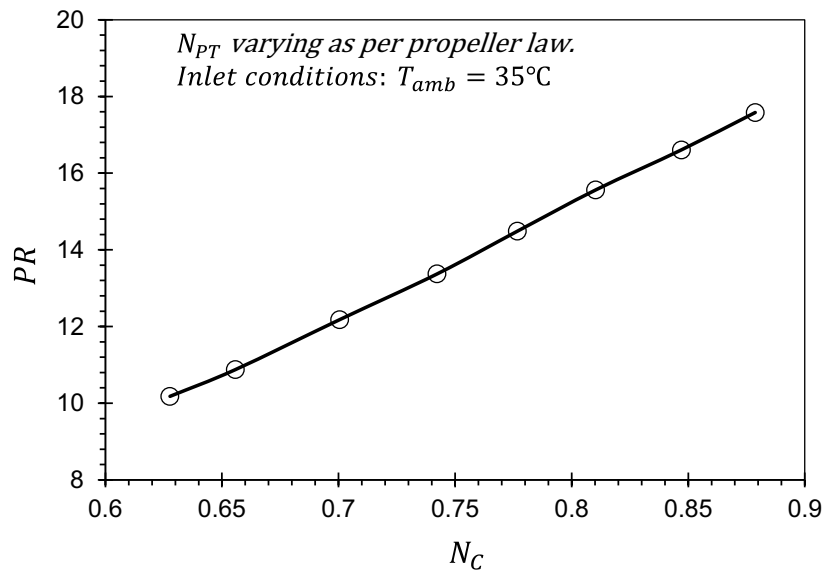


Figure 6-28 Computed variation of compressor pressure ratio (PR) against compressor speed ratio (N_C) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35^\circ\text{C}$.

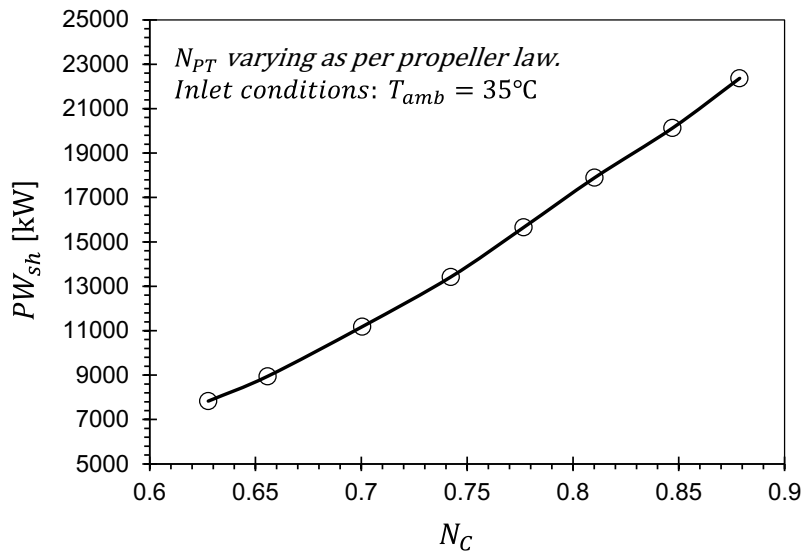


Figure 6-29 Computed variation of power turbine shaft power or engine brake power (PW_{sh}) against compressor speed ratio (N_C) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35^\circ\text{C}$.

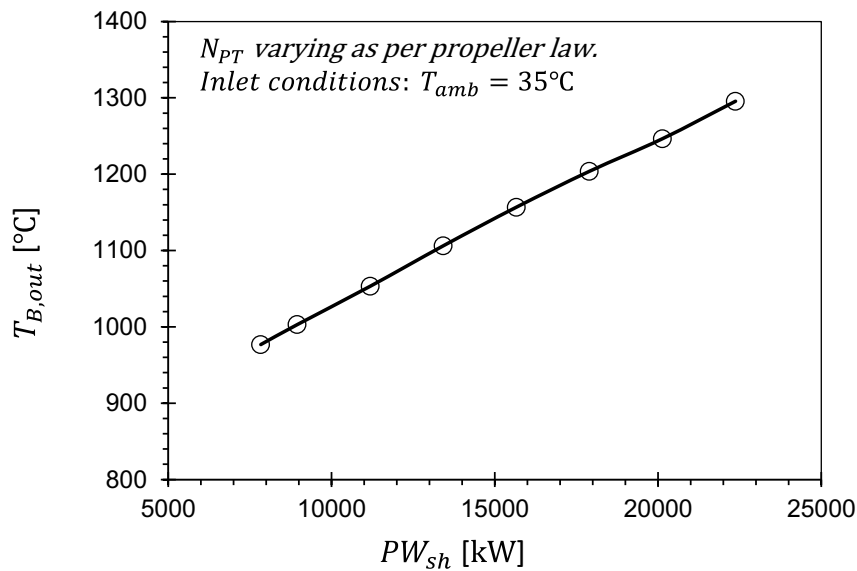


Figure 6-30 Computed variation of combustor outlet temperature ($T_{B,out}$) against engine shaft power (PW_{sh}) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35^\circ\text{C}$.

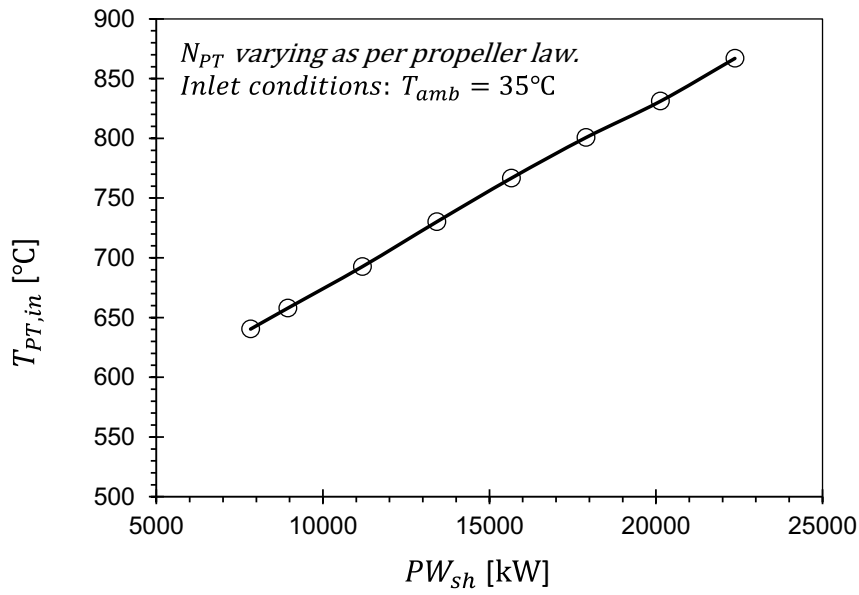


Figure 6-31 Computed variation of power turbine inlet temperature ($T_{PT,in}$) against engine shaft power (PW_{sh}) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35\text{ }^{\circ}\text{C}$.

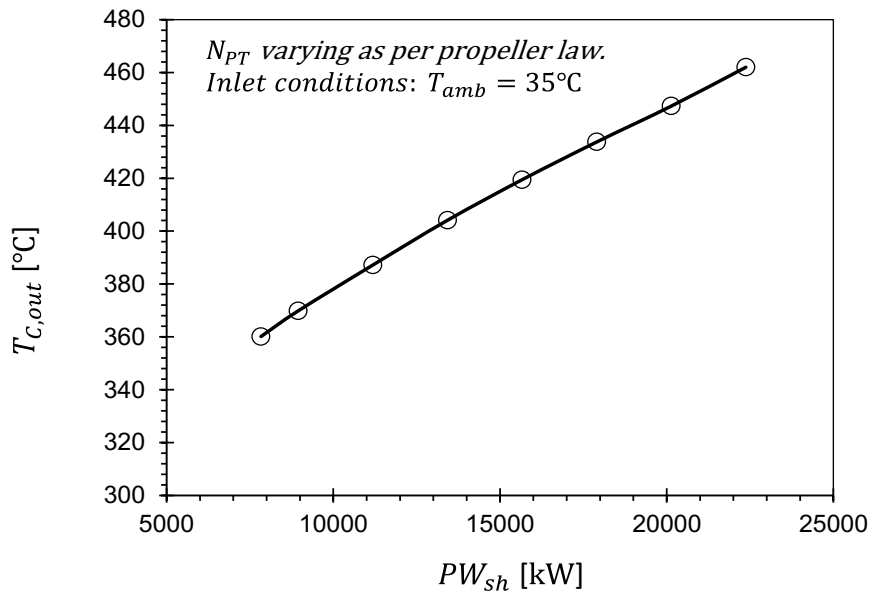


Figure 6-32 Computed variation of combustor outlet temperature ($T_{C,out}$) against engine shaft power (PW_{sh}) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35\text{ }^{\circ}\text{C}$.

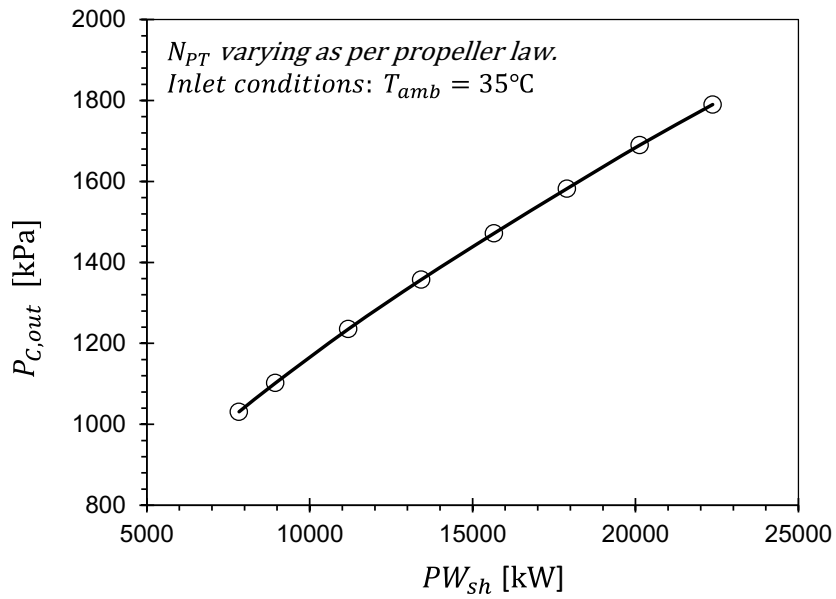


Figure 6-33 Computed variation of compressor outlet pressure ($P_{C,out}$) against engine shaft power (PW_{sh}) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35^\circ\text{C}$.

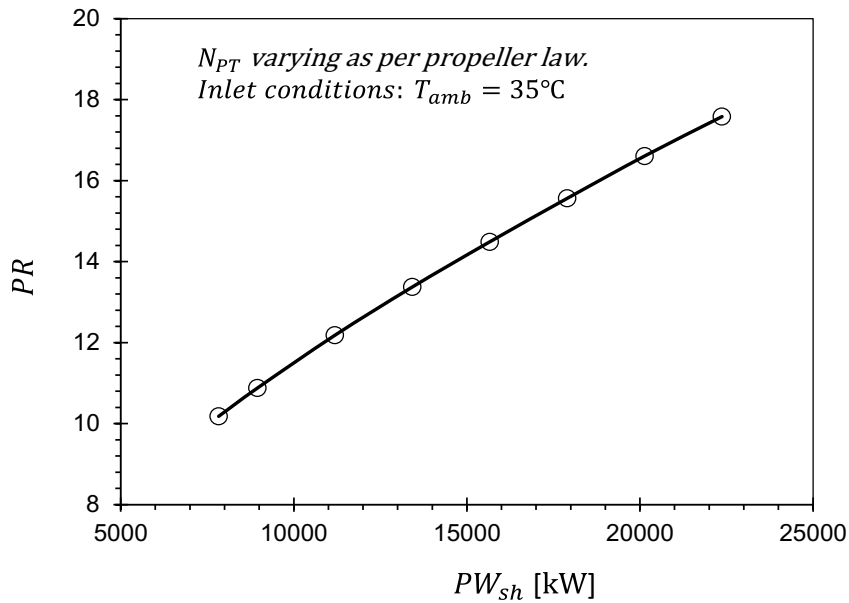


Figure 6-34 Computed variation of overall compressor pressure ratio (PR) against engine shaft power (PW_{sh}) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35^\circ\text{C}$.

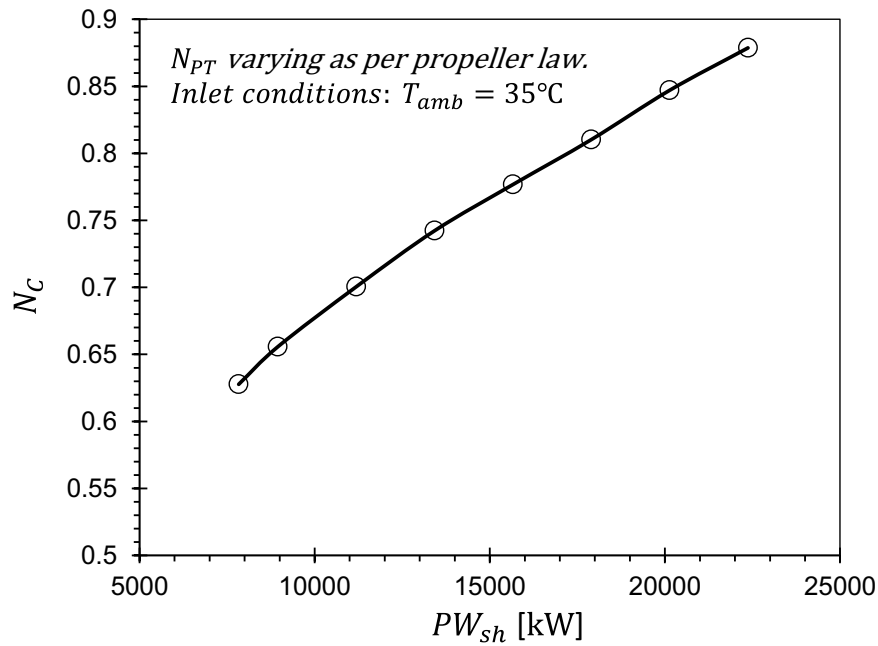


Figure 6-35 Computed variation of compressor speed ratio (N_c) against engine shaft power (PW_{sh}) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35^\circ\text{C}$.

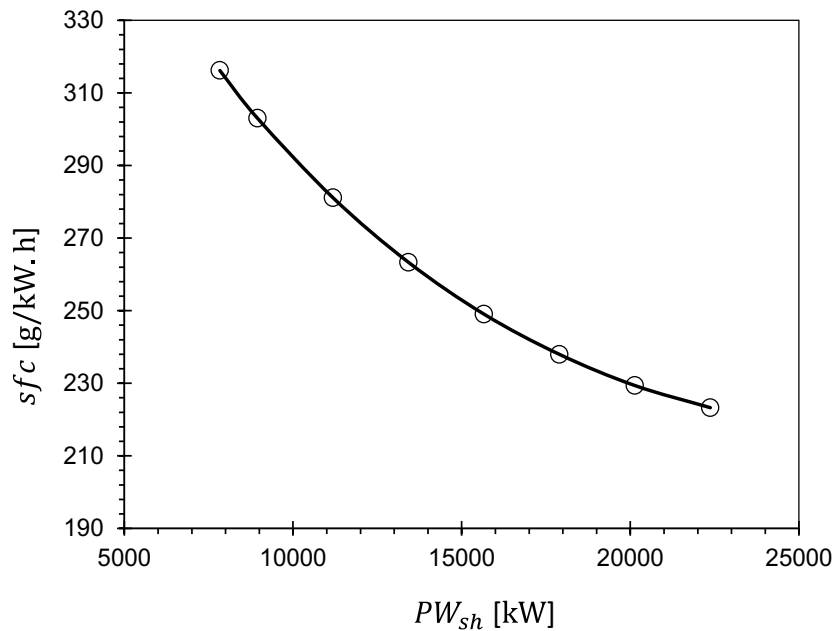


Figure 6-36 Computed variation of specific fuel consumption (sfc) against engine shaft power (PW_{sh}) for 25 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 35^\circ\text{C}$.

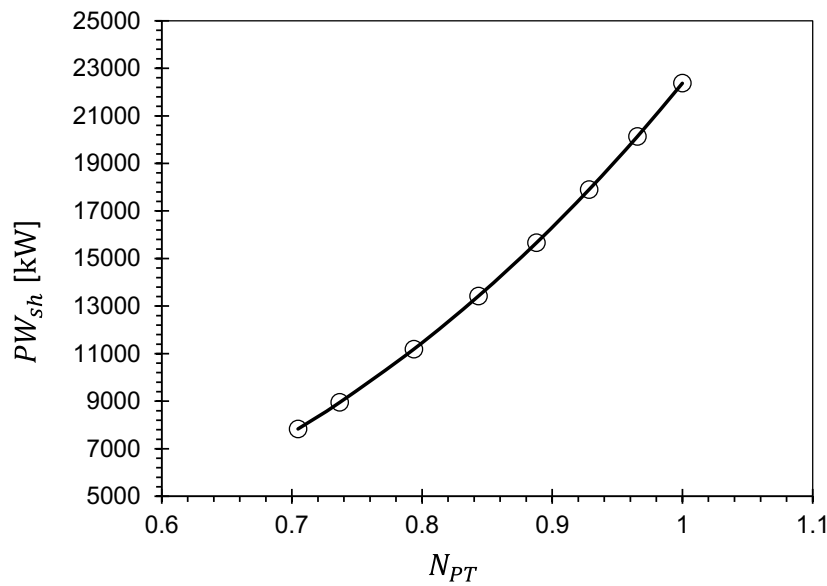


Figure 6-37 Applied propeller law expressed as the variation of engine shaft power (PW_{sh}) against power turbine speed ratio (N_{PT}) for 25 MW MGT with ambient temperature at $T_{amb} = 35$ °C.

6.2.2 Effect of Variation of Power Turbine Speed on Engine Performance

Change in the propeller loading conditions causes fluctuation in the power turbine speed of the engine even when the gas generator is maintained at the same power setting. This is an important factor required to be considered for modelling of marine gas turbines integrated with the ship propulsion plants, as this affects the performance of the marine gas turbine due to the change in the swallowing capacity of the free power turbine. To investigate this effect, the 25 MW MGT model was subjected to a constant load of 25 MW while the power turbine speed ratio was varied from 0.5 to 1. The effect of this change in power turbine speed even though the gas generator was maintained at the same power setting, has been shown against the combustor outlet temperature in Figure 6-38 and the specific fuel consumption in Figure 6-39. While this large range of variation of the power turbine speed at a steady gas generator power setting is not expected during the steady-state running of an engine, this large variation has been used here to primarily model the effects of variation of the power turbine speed.

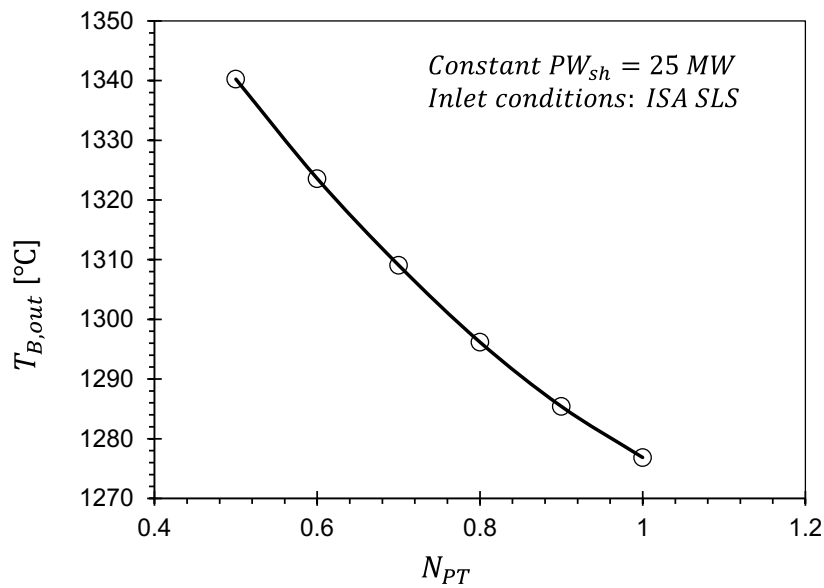


Figure 6-38 Computed variation of combustor outlet temperature ($T_{B,out}$) with variation of power turbine speed ratio (N_{PT}), when the engine shaft power is maintained constant $PW_{sh} = 25 \text{ MW}$, for 25 MW MGT at ISA SLS conditions.

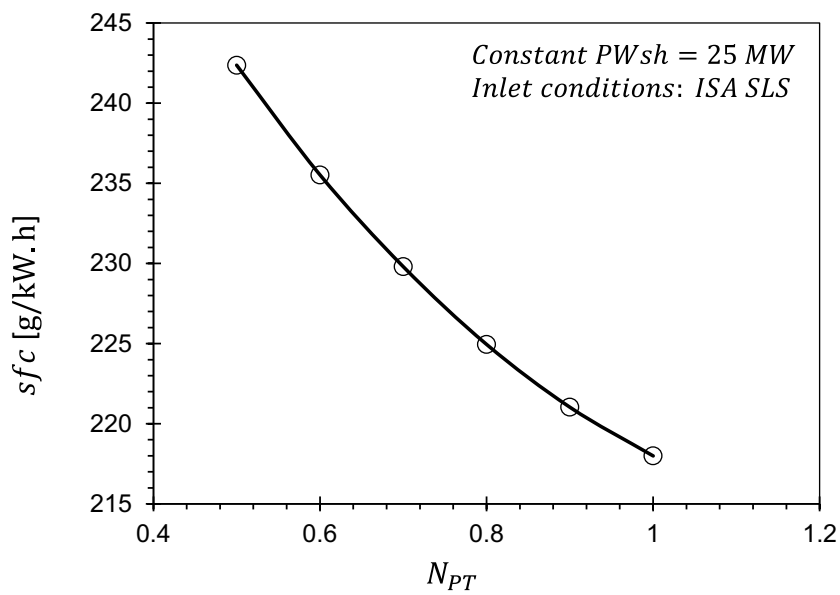


Figure 6-39 Computed variation of specific fuel combustion (sfc) with variation of power turbine speed ratio (N_{PT}), when the engine shaft power is maintained constant $PW_{sh} = 25 \text{ MW}$, for 25 MW MGT at ISA SLS conditions.

6.2.3 Effect of Variation of Ambient Air Temperature on Engine Performance

Another critical factor that affects the performance of the gas turbine is the change in ambient air temperature, due to differences in the area of operation or changing weather conditions for the ship. The effect of variation in ambient air on the parameters of the engine has been well demonstrated in previous studies like Doulgeris [58], Tsoudis [49], Bonet [50]. A critical effect that the variation in ambient air temperature causes is the maximum power rating of the engine itself. These limitations for the engine performance are often described in the suppliers' catalogues for the engines as the limiting value of the engine brake power available against the ambient air temperature, sometimes referred to as the 'tent curve'.

To investigate this effect, again the 25 MW MGT model was used. It is assumed that the engine is designed for ISA SLS conditions, at which the specified rated power of the engine is limited based on the 'mechanical limit', which in turn is based on the maximum allowable gas generator speed, and the 'material limit' of the engine is based on the maximum combustor outlet temperature. Based on the result of the investigation, as shown in Figure 6-40 the limiting brake power of the engine can be seen that with the variation of ambient air temperature. In this figure, the limiting line for ambient air temperature greater than 15 °C is based on the maximum combustor outlet temperature material limit, for which the operating points were determined by keeping combustor outlet temperature at the rated value while varying the ambient air temperature with the power turbine speed maintained at its rated value. The limiting line for ambient air temperature lower than 15 °C, is based on the mechanical limit of the engine, for which the operating points were calculated by maintaining the corrected compressor speed at its design point value while varying the ambient air temperature from 15 °C to -5 °C, with the power turbine speed maintained at its rated value. When modelling very low ambient air temperatures where icing may be possible, anti-icing measures for the engines should be considered where usually a compressor bleed arrangement is used to for heating the inlet air.

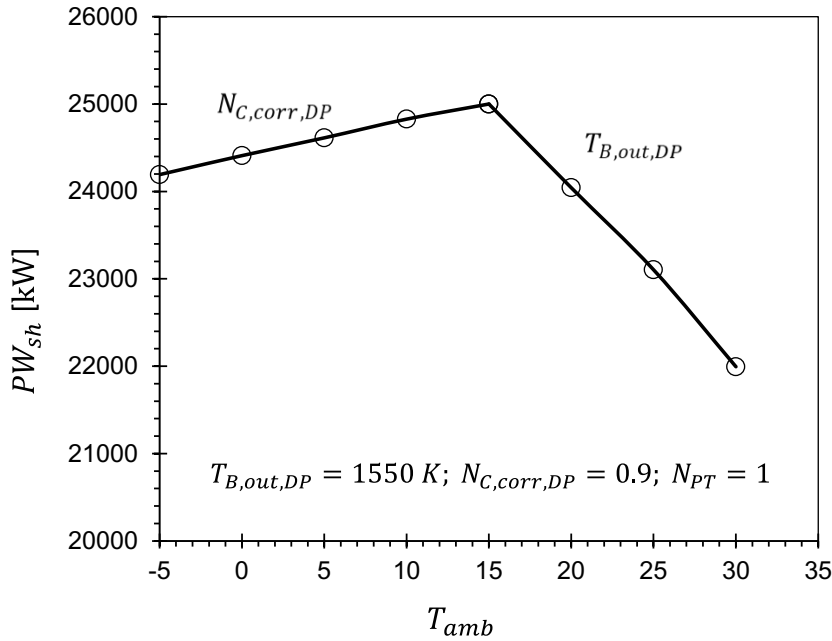


Figure 6-40 Computed limit of engine operation envelope given as maximum engine shaft power (PW_{sh}) with variation in ambient air temperature (T_{amb}), based on limits imposed by compressor speed limit ($N_{C,corr,DP}$) for $T_{amb} > 15$ °C and combustor outlet temperature ($T_{B,corr,DP}$) for $T_{amb} < 15$ °C, for 25 MW MGT.

6.3 Design of Propulsion System Architectures

Before describing the conceptual design studies taken for the notional frigate and destroyer, this section describes the brief methodology and the considerations used for the creation of the candidate combined plant architectures that populate the design space for these studies. The basic description and definitions of the configurations of combined plants often used in ship applications are given in Appendix K.

6.3.1 Engine Propeller Matching

For the present work, to undertake a conceptual design study, initially, the hull resistance calculation was undertaken independently for the defined hull parameters. This was followed by the optimization of the propeller parameters and fixing of optimal propeller speed using the procedure that has already been described earlier. Using the optimized propeller design parameters, the

approximate overall requirement of delivered power was derived for the requirements of the surge and cruising speeds. With the requirement of the delivered power known, various combinations of engines were selected and configured into candidate combined plant architectures. For each of these architectures, engine propeller matching exercises were undertaken to determine the gear ratios required for the geared transmission system or the electric motor speeds in the electric transmission systems. The process for undertaking such studies is well described in textbooks and publications like by Plumb [4], Molland [94] and Stapersma [130] etc. Some primary factors considered for each of the candidate design architectures are described in the following paragraphs.

Figure 6-41 shows the matching procedure considered for a single diesel engine driving a propeller, with a 'propeller curve' showing the power absorbed by the propeller with respect to propeller speed. When designing the propeller for clean hull and calm water, it is usual to keep the actual propeller curve to the right of the engine operating Line 1 shown in Figure 6-41, to allow for the effects of future fouling and bad weather. In the case of Line 1, if the design pitch is decreased, the line will move to Line 1a. As the ship fouls, or encounters heavy weather, the design curve Line 1 will move to the left, first to the N^3 line and then say to Line 2]. In the case of Line 2, the maximum available power at B is now not available due to the torque limit, and the maximum operating point is at C, with a consequent decrease in power and, hence, ship speed. The upper-speed limit on Line 1, is point D at about 105% maximum rpm. The basic assumption in the figure is made that $P \propto N^3$, which is considered by the engine makers as the 'Propeller Law' and they design their engines for best efficiency (e.g. fuel consumption) about this line. It should be noted, in reality, $P \propto N^x$, where x will not necessarily be 3, and it will generally lie between 2.5 and 3.5 [94]. In the present study, instead of using this approximation, the actual operating line of the propeller is generated using performance simulation and then used for the matching exercise.

For combined plant applications, an important decision that needs to be made is whether an 'AND plant' is more advantages compared to an 'OR plant'. In 'AND

plants' the power of the cruise engines is added to the power of the boost engines to achieve the full power of the propulsion plant. For instance, comparing a CODAG versus a CODOG arrangement, the primary advantage of a CODAG arrangement over CODOG is that for the given diesel and gas turbine engines, a higher power is available for propulsion. On the other hand, the advantage of a CODOG fit is that the two engines can be matched independently to the propeller so that each can develop its rated power without resorting to special measures (like twin speed gears etc.) [4].

With multiple engines driving a single propeller shaft, it is necessary to examine torque and speed characteristics when not all engines are running [4]. If no special arrangement for cruise engines is used in an 'AND' plant, the operating lines of the engines will be as shown in Figure 6-42 where the cruise engine (here diesel engine) power gets limited by the working envelope of the engine. Hence, in 'AND plants' it is required to match the cruising engine to the propeller when it operates independently and when it operates together with the boost engine. To achieve this, the application of a two-speed gearbox to the design is often the applied solution. In such a gearbox there is one reduction ratio for running on the cruise engine alone and a second ratio for when the cruise engine is driving together with the boost engine. The introduction of this two-speed gearbox adds complexity, weight and cost to the gearbox, but it enables maximum power to be realised in the cruise mode [4]. In the present work, wherever 'AND plants' are used twin speed gearboxes have been considered.

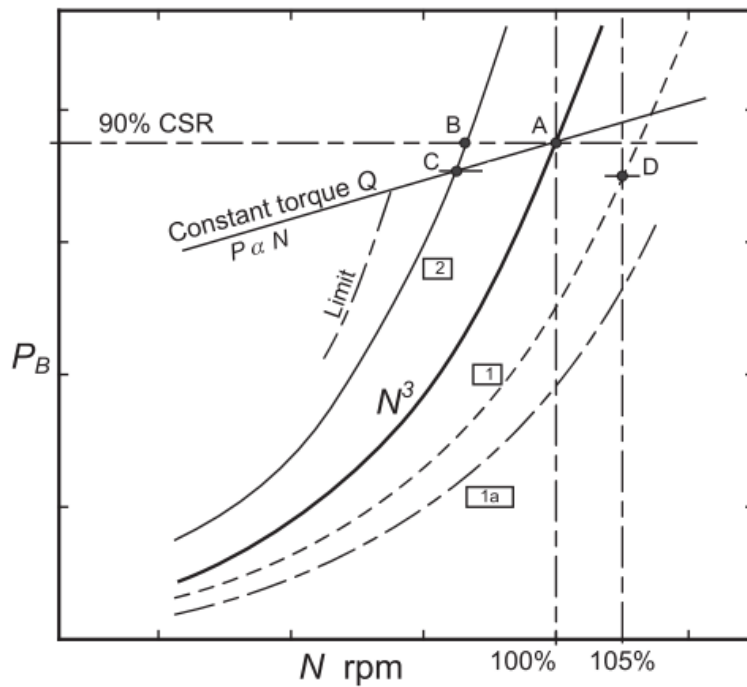


Figure 6-41 Matching of a propeller to a diesel engine [94]

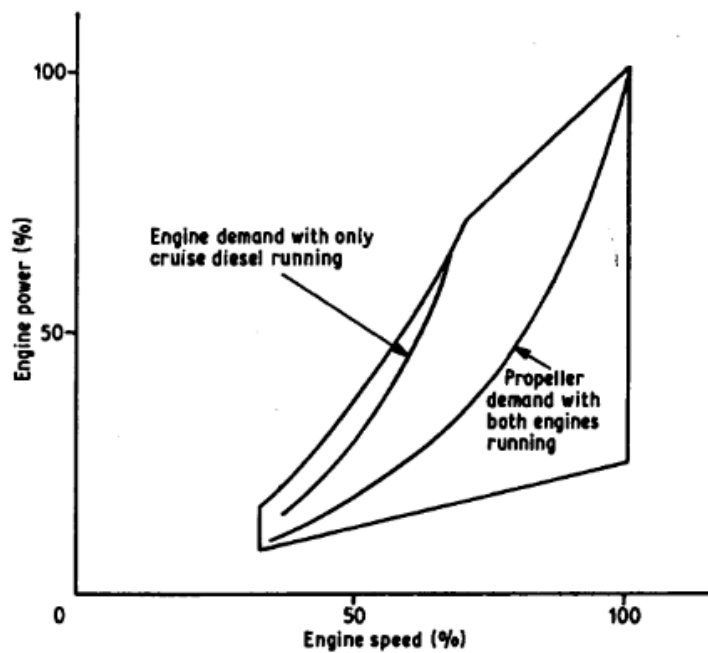


Figure 6-42 'AND' arrangement in a plant with no special arrangements for cruise engine[94]

6.3.2 Trailed Propeller Operation

While considering various drive modes of the combined propulsion plants for the present work, some modes consider running a single engine drive only a single

propeller, while the other propeller drags due to the motion of the ship. These modes referred to as the 'trailed shaft condition', are usually used to conserve the operating hours of engines.

The trailing of propeller means leads to additional, assumed to be 7.5% of the normal ship resistance, in a twin-propeller arrangement. Hence, while originally that propeller was required to overcome half of the ship resistance (two propellers operating), with a trailed propeller it has to overcome 1.075 times the original resistance [130]. This effect of added resistance can be seen in Figure 6-43 in the propeller open water diagram and Figure 6-44 for a gas turbine operating line diagram. This added effect of resistance due to the trailing propeller has been considered in the present work, and an algorithm has been implemented to detect the operation of a trailing propeller and this effect of resistance due to the drag of the trailing propeller is automatically added during the calculation.

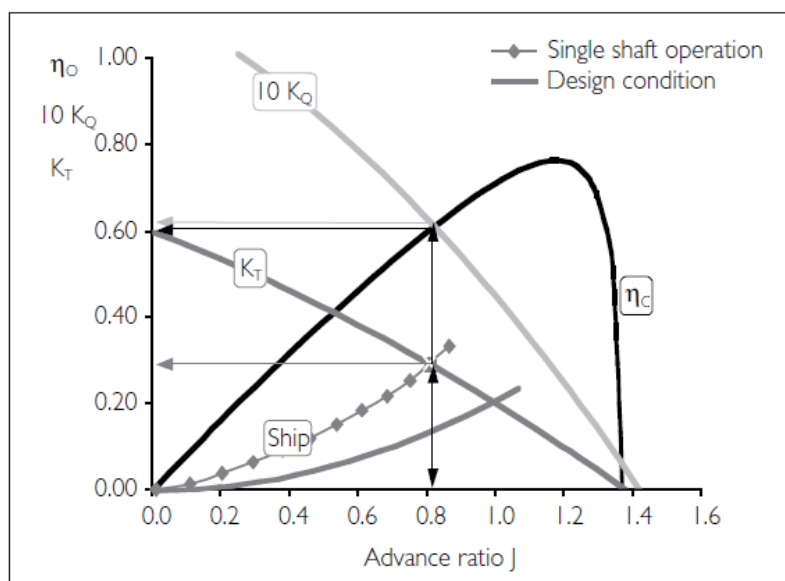


Figure 6-43 The effect of a trailing propeller (single shaft operation) on an open water diagram of a propeller [130]

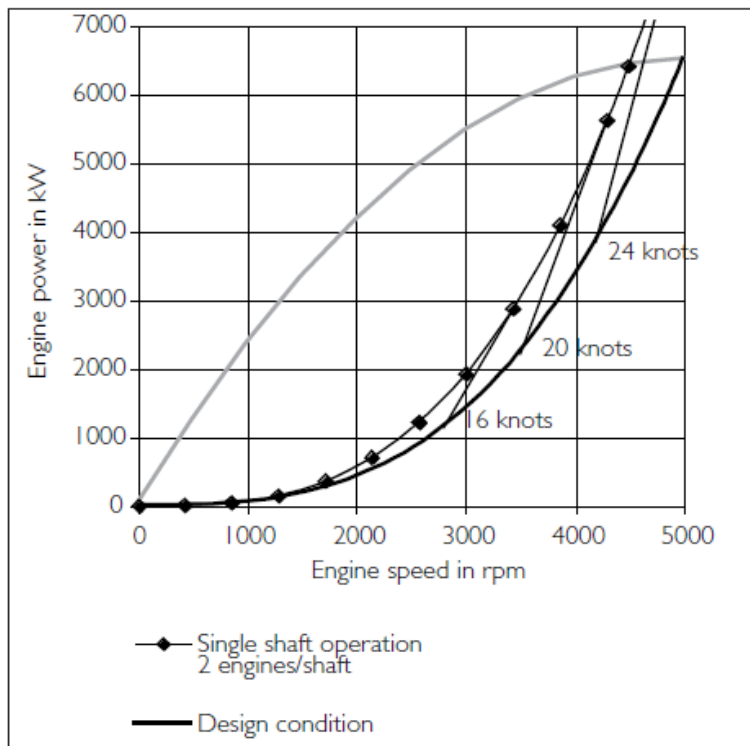


Figure 6-44 The effect of trailing propeller (single shaft operation) on operating line of gas turbine [130]

6.4 Determination of Criteria Weights for MCDM Analysis

For the present work, a common set of criteria, as described in Chapter 5, was applied for both the demonstrated conceptual design studies for the notional frigate and destroyer. The organisation of the data into the hierarchal, network structure for evaluation criteria has already been described in Chapter 5. The terminology used for the defined criteria to present the results has been shown in Table 6-2. To determine the weights of the criteria involved, the overall procedure defined in Chapter 5 has been used, and the application of this procedure is described in the further paragraphs.

First, for the performance criteria, the DANP procedure was used to determine the weights of the performance-related criteria where the criteria are considered to have significant interdependence. Thereafter, AHP was used to determine the local weights of the cost and risk objective metrics related criteria. Finally, global weights for all the criteria were calculated based on the relative weights assigned to the performance cost and risk objective metrics.

Table 6-2 Description of evaluation criteria

Objective Metric	Performance Dimension	Criteria	Criteria Abbreviation	Criteria Ref. No.
Performance	Mobility (D1)	Surge speed	P-Surg.spd.	PC11
		Cruise speed	P-Cruis.spd.	PC12
		Endurance	P-Endur.	PC13
	Operability (D2)	Op. Profile Sensitivity	P-OP.Sens.	PC21
		Operation Flexibility	P-Opn.Flex.	PC22
		Manoeuvrability	P-Manuev.	PC23
	Susceptibility (D3)	UW Noise	P-UW.Noise	PC31
		IR Signature	P-IR Sign.	PC32
		EM Signature	P-EM Sign.	PC33
	Survivability (D4)	Redundancy	P-Redund.	PC41
		Shock Resistance	P-Shock.R.	PC42
		Flooding Survivability	P-Fld.Surv.	PC43
	Maintainability (D5)	Reliability	P-Reliab.	PC51
		Availability	P-Availab.	PC52
		Repairability	P-Repair.	PC53
	Integrability (D6)	Weight	P-Weight	PC61
		Space	P-Space	PC62
		Fuel Capacity	P-Fuel.Cap.	PC63
Cost	Acquisition		C-Acq.	CC1
	Maintenance, Life Cycle		C-Maint.	CC2
	Manpower, Life Cycle		C-Man.Pow.	CC3
	Fuel, Life Cycle		C-Fuel.	CC4
	Support Infrastructure		C-Sup.Infr.	CC5
Risk	Design		R-Design	RC1
	Shipbuilding Schedule		R-Sched.	RC2
	Crew Expertise		R-Crw.Expr.	RC3
	Support Infrastructure		R-Support	RC4

6.4.1 Using DEMATEL to Determine Local Weights of Objective Metric ‘Performance’

For the Objective Metric, Performance, the degrees of relationships between the performance criteria dimensions were determined using various steps, as detailed in Appendix L. For this, the author used interactions with colleagues

working in this domain to create the scores for evaluating the Initial Direct Influence Matrix for the Performance Dimensions. Based on this the calculated Normalised Direct Influence Matrix was calculated as shown in Table 6-3. The calculated Direct Influence Matrix for Performance Dimensions is shown in Table 6-4. From the degree of relationship, 'U+W' and 'U-W' metrics were calculated as shown in Table 6-5. Based on this the Network Relationship Map (NRM) was obtained for the 'Performance Dimensions', which is shown in Figure 6-45. The NRM shows the 'degree of prominence' vs. the 'degree of effect' or 'degree of being effected'.

Table 6-3 Normalised Direct Influence Matrix for Performance Dimensions.

Dimension		D1	D2	D3	D4	D5	D6
		Mobility	Operability	Susceptibility	Survivability	Maintainability	Integrability
D1	Mobility	0.0000	0.1875	0.1250	0.0000	0.0000	0.2500
D2	Operability	0.0625	0.0000	0.0000	0.0000	0.0000	0.1250
D3	Susceptibility	0.0000	0.0000	0.0000	0.0000	0.1250	0.2500
D4	Survivability	0.0000	0.0000	0.0000	0.0000	0.1875	0.2500
D5	Maintainability	0.0625	0.0000	0.0000	0.1875	0.0000	0.1250
D6	Integrability	0.1250	0.0000	0.1250	0.0625	0.0625	0.0000

Table 6-4 Direct Influence Matrix for Performance Dimensions.

Dimension		D1	D2	D3	D4	D5	D6
		Mobility	Operability	Susceptibility	Survivability	Maintainability	Integrability
D1	Mobility	0.0589	0.1985	0.1758	0.0310	0.0495	0.3474
D2	Operability	0.0847	0.0159	0.0307	0.0131	0.0164	0.1612
D3	Susceptibility	0.0488	0.0092	0.0444	0.0490	0.1589	0.3066
D4	Survivability	0.0548	0.0103	0.0469	0.0622	0.2251	0.3204
D5	Maintainability	0.0949	0.0178	0.0395	0.2123	0.0586	0.2212
D6	Integrability	0.1478	0.0277	0.1579	0.0897	0.1063	0.1156

Table 6-5 Degree of relationship values for Performance Dimensions.

Dimension		U	V	U+V	U-V
D1	Mobility	0.8612	0.4899	1.3511	0.3713
D2	Operability	0.3220	0.2794	0.6013	0.0426
D3	Susceptibility	0.6168	0.4953	1.1121	0.1215
D4	Survivability	0.7196	0.4573	1.1768	0.2623
D5	Maintainability	0.6444	0.6147	1.2590	0.0297
D6	Integrability	0.6450	1.4724	2.1174	-0.8274

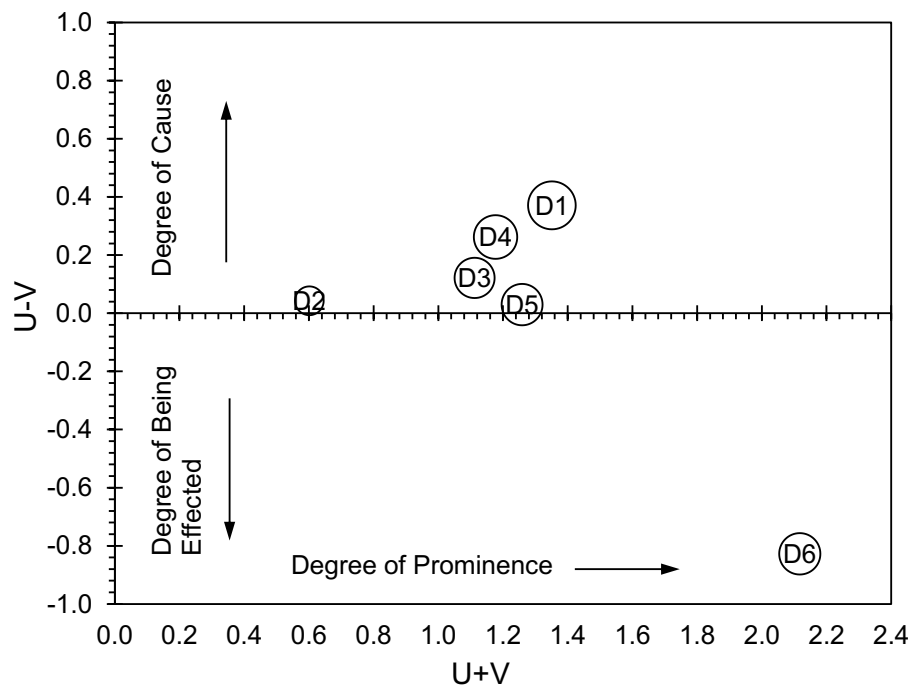


Figure 6-45 Network Relationship Map (NRM) for Performance Dimensions.

As can be observed from Figure 6-45, in terms of 'degree of prominence', the 'Performance Dimension', 'D6' or 'Integrability', is the highest while 'D2' or 'Operability', is the lowest. On the other hand, 'Performance Dimension' 'D1' or 'Mobility' provides the highest 'degree of cause', while 'D6' or 'Integrability' shows the highest 'degree of being effected'.

The Normalized Total Direct Influence Matrix calculated for the Performance Dimensions, after the removal of minor influences is shown in Table 6-6. The transpose of this table indicates the applicable relationships between the Performance Dimensions that need to be further examined.

Table 6-6 Normalized Total Direct Influence Matrix for Performance Dimensions

Dimension		D1	D2	D3	D4	D5	D6
		Mobility	Operability	Susceptibility	Survivability	Maintainability	Integrability
D1	Mobility	0.0000	0.2751	0.2436	0.0000	0.0000	0.4814
D2	Operability	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000
D3	Susceptibility	0.0000	0.0000	0.0000	0.0000	0.3414	0.6586
D4	Survivability	0.0000	0.0000	0.0000	0.0000	0.4126	0.5874
D5	Maintainability	0.0000	0.0000	0.0000	0.4897	0.0000	0.5103
D6	Integrability	0.4835	0.0000	0.5165	0.0000	0.0000	0.0000

Threshold value to remove the minor influences: 0.12

The same DEMATEL procedure, as described for Performance Dimensions in the previous steps, was repeated for the performance criteria under the respective dimensions with significant relations. The NRM, as well as Normalized Total Direct Influence Matrix, were obtained, from the comparison of the set of criteria of a 'Performance Dimension' with another. For example, based on the comparison of the criteria set of Performance Dimension criteria set D1 with that of Performance Dimension D2, the Normalised Direct Influence Matrix is shown in Table 6-7 and the calculated Normalized Total Direct Influence Matrix is given in Table 6-8. Due to the large amount of data involved, all the comparisons of the criteria set of the Performance Dimensions has not been included in this thesis, and only the finally derived values are shown in Table 6-9.

Table 6-7 Normalised Direct Influence Matrix for comparison of criteria set of Performance Dimension D1 with criteria set of Performance Dimension D2

Performance Criteria (Comparing D1 criteria with D2 criteria set)	P-OP.Sens. (PC21)	P-Opn.Flex. (PC22)	P-Manuev. (PC23)
P-Surg.spd. (PC11)	0.1667	0.3333	0.2500
P-Cruis.spd. (PC12)	0.3333	0.5000	0.1667
P-Endur. (PC13)	0.3333	0.1667	0.0000

Table 6-8 Normalized Total Direct Influence Matrix for comparison of criteria set of Performance Dimension D1 with criteria set of Performance Dimension D2

Performance Criteria (Comparing D1 criteria with D2 criteria)	P-OP.Sens. (PC21)	P-Opn.Flex. (PC22)	P-Manuev. (PC23)
P-Surg.spd. (PC11)	0.3220	0.4576	0.2203
P-Cruis.spd. (PC12)	0.3373	0.4699	0.1928
P-Endur. (PC13)	0.3902	0.4390	0.1707

After completion of the DEMATEL procedure for determining the influence matrices for the performance dimensions as well as the criteria sets belonging to the performance dimensions with significant relationships, the ANP procedure was applied. Initially, the Unweighted Supermatrix was set up as shown in Table 6-9. The Weighted Supermatrix calculated from the Unweighted Supermatrix, after application of the DEMATEL weights calculated for the performance dimensions is shown in Table 6-10. Thereafter, the Weighted Supermatrix was raised to the power of five to finally obtain the converged solution which gives the local weights for the criteria belonging to the Performance Objective Metric, as shown in Table 6-11. These computed criteria weights have been depicted graphically in Figure 6-46.

Table 6-9 Unweighted ANP Supermatrix

		D1			D2			D3			D4			D5			D6		
		PC11	PC12	PC13	PC21	PC22	PC23	PC31	PC32	PC33	PC41	PC42	PC43	PC51	PC52	PC53	PC61	PC62	PC63
D1	PC11	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1788	0.2105	0.1761
	PC12	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2914	0.3684	0.2264
	PC13	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5298	0.4211	0.5975
D2	PC21	0.3220	0.3373	0.3902	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	PC22	0.4576	0.4699	0.4390	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	PC23	0.2203	0.1928	0.1707	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
D3	PC31	0.3001	0.3999	0.3478	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.6667	0.6667	0.5556
	PC32	0.3998	0.3251	0.3478	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3333	0.3333	0.3333
	PC33	0.3000	0.2751	0.3043	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1111
D4	PC41	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5556	0.6667	0.6667	0.0000	0.0000	0.0000
	PC42	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2222	0.1667	0.1667	0.0000	0.0000	0.0000
	PC43	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2222	0.1667	0.1667	0.0000	0.0000	0.0000
D5	PC51	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3756	0.3357	0.5660	0.5385	0.5760	0.6383	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	PC52	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1629	0.2028	0.1132	0.3258	0.3280	0.2553	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	PC53	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.4615	0.4615	0.3208	0.1357	0.0960	0.1064	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
D6	PC61	0.2658	0.2414	0.0000	0.4200	0.4545	0.4545	0.4296	0.3889	0.3889	0.4414	0.4918	0.4464	0.3000	0.3000	0.2667	0.0000	0.0000	0.0000
	PC62	0.3544	0.3218	0.0000	0.4200	0.4545	0.4545	0.4148	0.4556	0.4861	0.4144	0.4098	0.4643	0.4000	0.4000	0.4667	0.0000	0.0000	0.0000
	PC63	0.3797	0.4368	1.0000	0.1600	0.0909	0.0909	0.1556	0.1556	0.1250	0.1441	0.0984	0.0893	0.3000	0.3000	0.2667	0.0000	0.0000	0.0000

Table 6-10 Weighted ANP Supermatrix with Performance Dimensions DEMATEL Weights

		D1			D2			D3			D4			D5			D6		
		PC11	PC12	PC13	PC21	PC22	PC23	PC31	PC32	PC33	PC41	PC42	PC43	PC51	PC52	PC53	PC61	PC62	PC63
D1	PC11	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0864	0.1018	0.0851
	PC12	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1409	0.1781	0.1095
	PC13	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2561	0.2036	0.2889
D2	PC21	0.0886	0.0928	0.1073	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	PC22	0.1259	0.1293	0.1208	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	PC23	0.0606	0.0530	0.0470	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
D3	PC31	0.0731	0.0974	0.0847	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3443	0.3443	0.2870
	PC32	0.0974	0.0792	0.0847	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1722	0.1722	0.1722
	PC33	0.0731	0.0670	0.0741	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0574
D4	PC41	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2721	0.3265	0.3265	0.0000	0.0000	0.0000
	PC42	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1088	0.0816	0.0816	0.0000	0.0000	0.0000
	PC43	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1088	0.0816	0.0816	0.0000	0.0000	0.0000
D5	PC51	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1282	0.1146	0.1932	0.2222	0.2377	0.2634	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	PC52	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0556	0.0692	0.0386	0.1344	0.1353	0.1053	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	PC53	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1576	0.1576	0.1095	0.0560	0.0396	0.0439	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
D6	PC61	0.1280	0.1162	0.0000	0.4200	0.4545	0.4545	0.2830	0.2561	0.2561	0.2593	0.2889	0.2622	0.1531	0.1531	0.1361	0.0000	0.0000	0.0000
	PC62	0.1706	0.1549	0.0000	0.4200	0.4545	0.4545	0.2732	0.3000	0.3202	0.2434	0.2407	0.2727	0.2041	0.2041	0.2381	0.0000	0.0000	0.0000
	PC63	0.1828	0.2102	0.4814	0.1600	0.0909	0.0909	0.1025	0.1025	0.0823	0.0847	0.0578	0.0524	0.1531	0.1531	0.1361	0.0000	0.0000	0.0000

Table 6-11 Converged Supermatrix

		D1			D2			D3			D4			D5			D6		
		PC11	PC12	PC13	PC21	PC22	PC23	PC31	PC32	PC33	PC41	PC42	PC43	PC51	PC52	PC53	PC61	PC62	PC63
D1	PC11	0.0346	0.0346	0.0346	0.0346	0.0346	0.0346	0.0346	0.0346	0.0346	0.0346	0.0346	0.0346	0.0346	0.0346	0.0346	0.0346	0.0346	0.0346
	PC12	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548	0.0548
	PC13	0.0928	0.0928	0.0928	0.0928	0.0928	0.0928	0.0928	0.0928	0.0928	0.0928	0.0928	0.0928	0.0928	0.0928	0.0928	0.0928	0.0928	0.0928
D2	PC21	0.0181	0.0181	0.0181	0.0181	0.0181	0.0181	0.0181	0.0181	0.0181	0.0181	0.0181	0.0181	0.0181	0.0181	0.0181	0.0181	0.0181	0.0181
	PC22	0.0226	0.0226	0.0226	0.0226	0.0226	0.0226	0.0226	0.0226	0.0226	0.0226	0.0226	0.0226	0.0226	0.0226	0.0226	0.0226	0.0226	0.0226
	PC23	0.0094	0.0094	0.0094	0.0094	0.0094	0.0094	0.0094	0.0094	0.0094	0.0094	0.0094	0.0094	0.0094	0.0094	0.0094	0.0094	0.0094	0.0094
D3	PC31	0.1390	0.1390	0.1390	0.1390	0.1390	0.1390	0.1390	0.1390	0.1390	0.1390	0.1390	0.1390	0.1390	0.1390	0.1390	0.1390	0.1390	0.1390
	PC32	0.0804	0.0804	0.0804	0.0804	0.0804	0.0804	0.0804	0.0804	0.0804	0.0804	0.0804	0.0804	0.0804	0.0804	0.0804	0.0804	0.0804	0.0804
	PC33	0.0194	0.0194	0.0194	0.0194	0.0194	0.0194	0.0194	0.0194	0.0194	0.0194	0.0194	0.0194	0.0194	0.0194	0.0194	0.0194	0.0194	0.0194
D4	PC41	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311	0.0311
	PC42	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095
	PC43	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095	0.0095
D5	PC51	0.0425	0.0425	0.0425	0.0425	0.0425	0.0425	0.0425	0.0425	0.0425	0.0425	0.0425	0.0425	0.0425	0.0425	0.0425	0.0425	0.0425	0.0425
	PC52	0.0205	0.0205	0.0205	0.0205	0.0205	0.0205	0.0205	0.0205	0.0205	0.0205	0.0205	0.0205	0.0205	0.0205	0.0205	0.0205	0.0205	0.0205
	PC53	0.0392	0.0392	0.0392	0.0392	0.0392	0.0392	0.0392	0.0392	0.0392	0.0392	0.0392	0.0392	0.0392	0.0392	0.0392	0.0392	0.0392	0.0392
D6	PC61	0.1261	0.1261	0.1261	0.1261	0.1261	0.1261	0.1261	0.1261	0.1261	0.1261	0.1261	0.1261	0.1261	0.1261	0.1261	0.1261	0.1261	0.1261
	PC62	0.1395	0.1395	0.1395	0.1395	0.1395	0.1395	0.1395	0.1395	0.1395	0.1395	0.1395	0.1395	0.1395	0.1395	0.1395	0.1395	0.1395	0.1395
	PC63	0.1110	0.1110	0.1110	0.1110	0.1110	0.1110	0.1110	0.1110	0.1110	0.1110	0.1110	0.1110	0.1110	0.1110	0.1110	0.1110	0.1110	0.1110

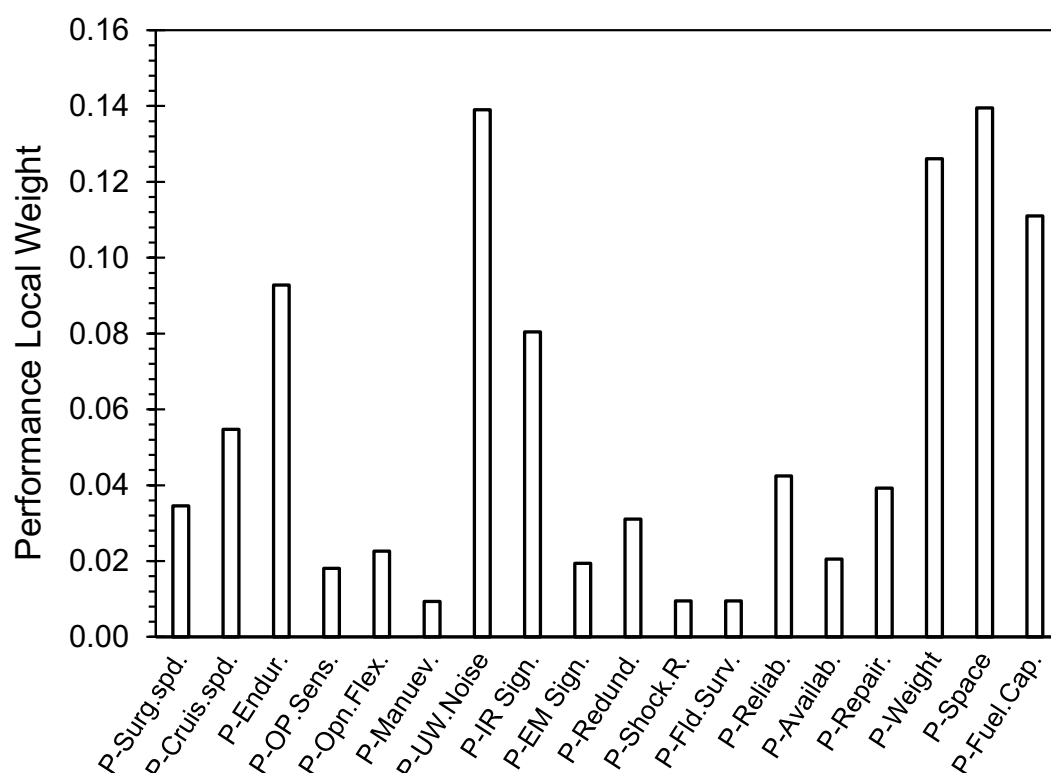


Figure 6-46 Computed local weights for the criteria set belonging to the Performance Objective Metric

6.4.2 Using AHP to Determine Local Weights of Cost and Risk Criteria

For the criteria set belonging to Objective Metric, Cost and Risk, the process of AHP was used to determine the local weights for the respective criteria sets, following the procedure detailed in Appendix M. Again, for this procedure, the author used interactions with colleagues working in this domain to undertake the pairwise comparison for the respective criteria sets. The Normalised Pair-Wise Comparison Matrices for cost and risk criteria sets is shown in Table 6-12 and Table 6-13, respectively. Consistency checks for these Comparison Matrices were also undertaken but have not been shown here for the sake of brevity. The calculated local weights of the 'Objective Metrics' of 'Cost' and 'Risk', calculated using the AHP procedure are graphically depicted in Figure 6-47.

Table 6-12 Normalized Pairwise Comparison Matrix of criteria set for Objective Metric Cost

		C-Acq.	C-Maint.	C-Man.Pow.	C-Fuel.	C-Sup.Infr.	Criteria Weight
		CC1	CC2	CC3	CC4	CC5	
C-Acq.	CC1	0.3871	0.4138	0.3529	0.4138	0.3077	0.3751
C-Maint.	CC2	0.1935	0.2069	0.2353	0.2069	0.2308	0.2147
C-Man.Pow.	CC3	0.1290	0.1034	0.1176	0.1034	0.1538	0.1215
C-Fuel.	CC4	0.1935	0.2069	0.2353	0.2069	0.2308	0.2147
C-Sup.Infr.	CC5	0.0968	0.0690	0.0588	0.0690	0.0769	0.0741

Table 6-13 Normalized Pairwise Comparison Matrix of criteria set for Objective Metric Risk

		R-Design	R-Sched.	R-Crw.Expr.	R-Support	Criteria Weight
		RC1	RC2	RC3	RC4	
R-Design	RC1	0.3750	0.3956	0.3333	0.3636	0.3669
R-Sched.	RC2	0.3125	0.3297	0.3333	0.3636	0.3348
R-Crw.Expr.	RC3	0.1250	0.1099	0.1111	0.0909	0.1092
R-Support	RC4	0.1875	0.1648	0.2222	0.1818	0.1891

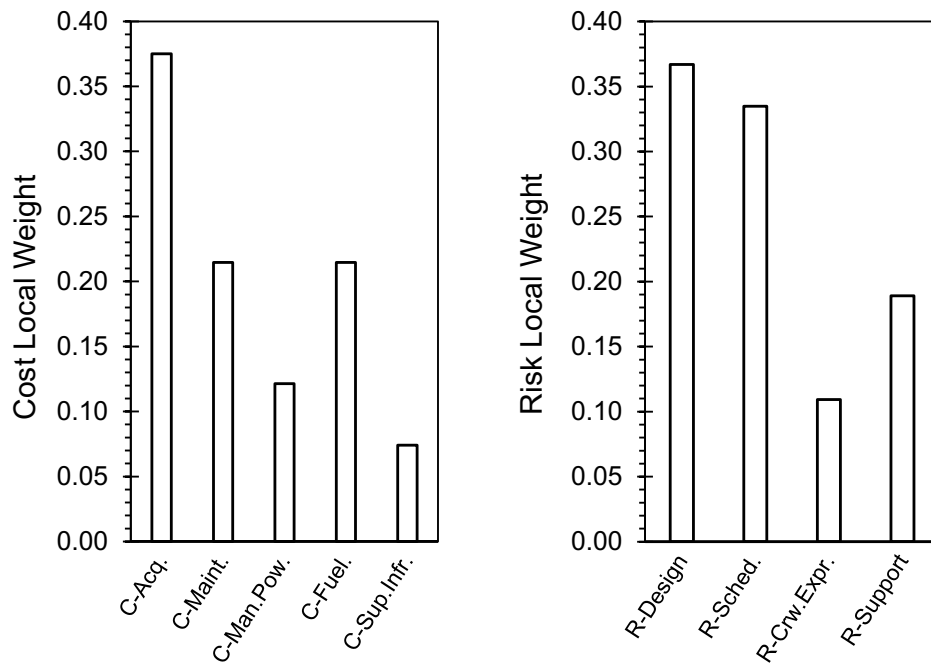


Figure 6-47 Computed local weights for the criteria set belonging to the Objective Metrics Cost and Risk

6.4.3 Calculation of Global Weights for Set of Criteria

For calculating the global weights for the criteria considered, different ‘application cases’ with overall weights attached to the ‘Objective Metrics’ of ‘Performance’ ‘Cost’ and ‘Risk’ were considered, as shown in Table 6-14. The relative weights of the ‘Objective Metrics’, were derived for these ‘application cases’ by varying the relative weights of ‘Performance’, ‘Cost’ and ‘Risk’. A comparison of the relative weights used for the ‘Objective Metrics’ of ‘Performance’, ‘Cost’ and ‘Risk’ across the various test cases is shown in Figure 6-48. In a practical application, the shipowner, designer, or builder would attach these weights based on the considerations of the role of the ship along with the perspective of the analysis. Based on each of these application cases, the overall computed global weights for the entire set of criteria have been graphically compared from Figure 6-49 to Figure 6-54.

Table 6-14 Cases considered for analysis of alternatives or candidate architectures

Case	Description
Case 1	'Performance' 'Cost' and 'Risk' equally weighted
Case 2A	'Performance' weighted moderately higher than 'Cost' and 'Risk'; 'Cost' and 'Risk' equally weighted
Case 2B	'Performance' weighted significantly higher than 'Cost' and 'Risk'; 'Cost' and 'Risk' equally weighted
Case 3	'Risk' weighted moderately higher than 'Performance' and 'Cost'; 'Performance' and 'Cost' equally weighted
Case 4	'Cost' weighted moderately higher than 'Performance' and 'Risk'; 'Performance' and 'Risk' equally weighted
Case 5	Distributed weights: 'Performance' with the highest weight, 'Risk' weighted moderately higher than 'Cost'

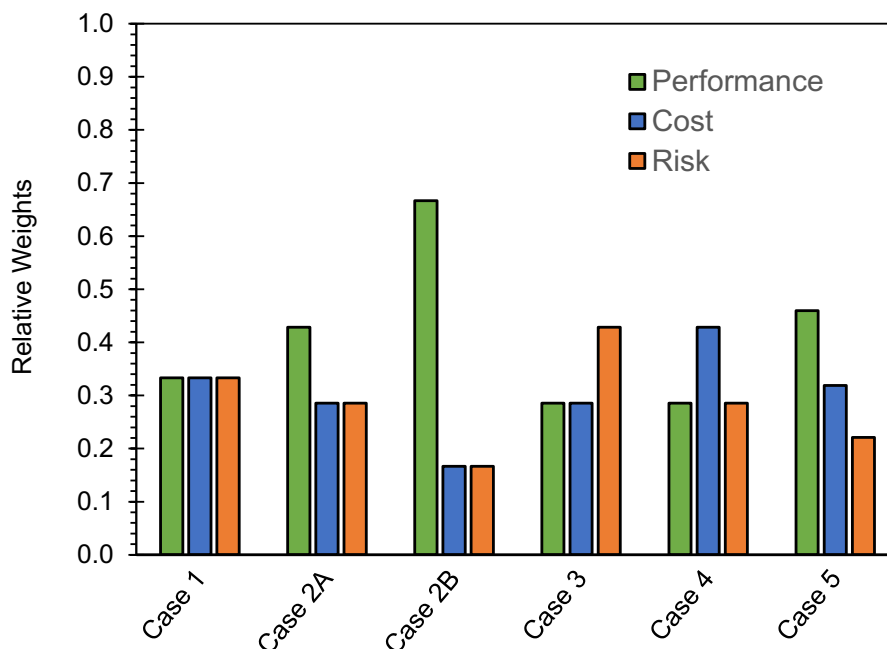


Figure 6-48 Relative weights applied for Objective Metrics of Performance, Cost and Risk across the various application cases

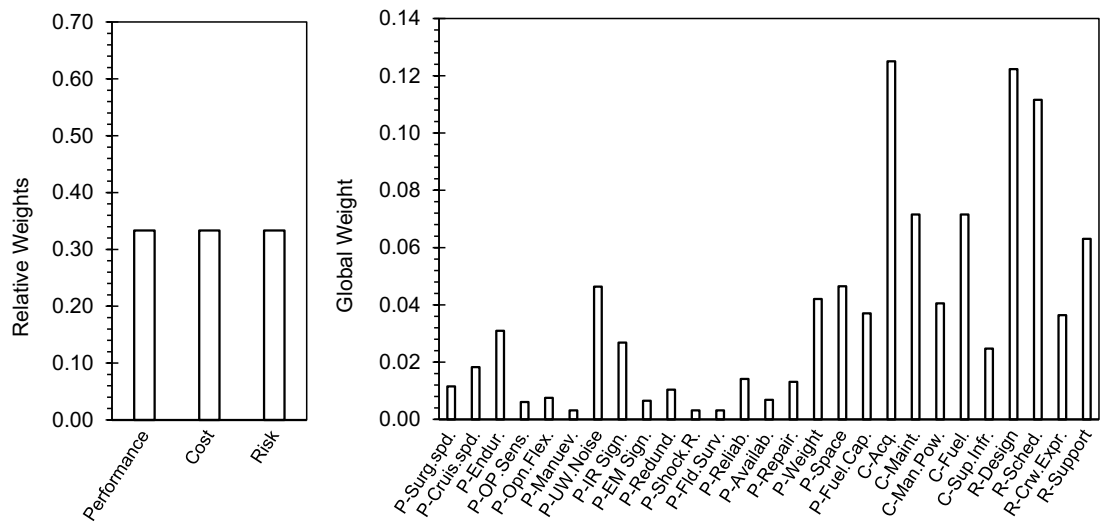


Figure 6-49 Computed global weights of the set of criteria for Application Case 1

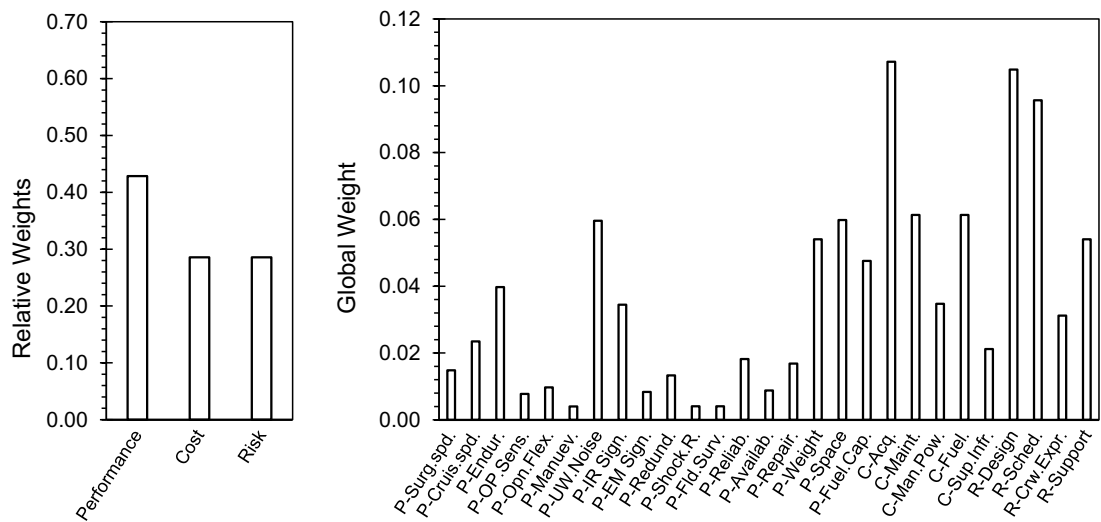


Figure 6-50 Computed global weights of set of criteria for Application Case 2A

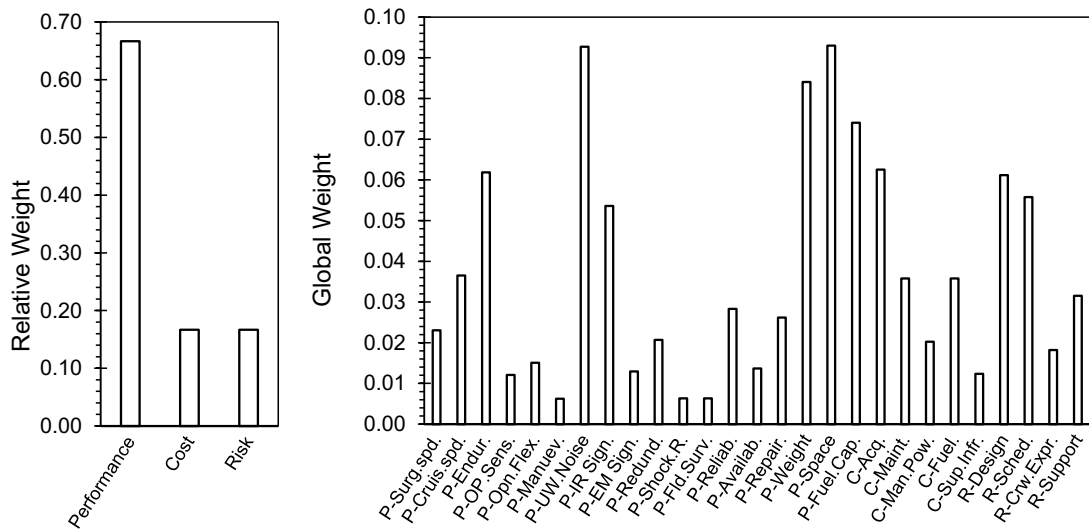


Figure 6-51 Computed global weights of set of criteria for Application Case 2B

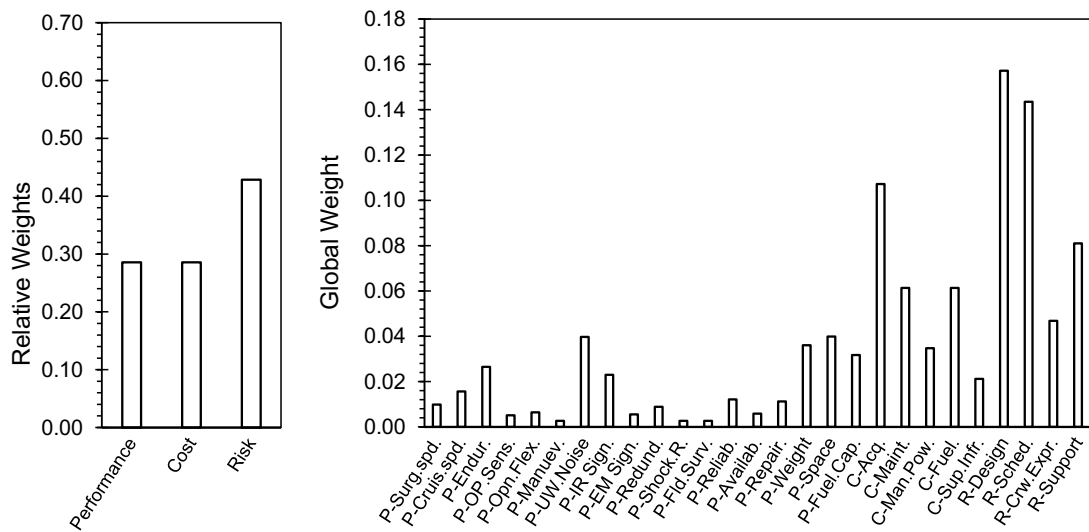


Figure 6-52 Computed global weights of set of criteria for Application Case 3

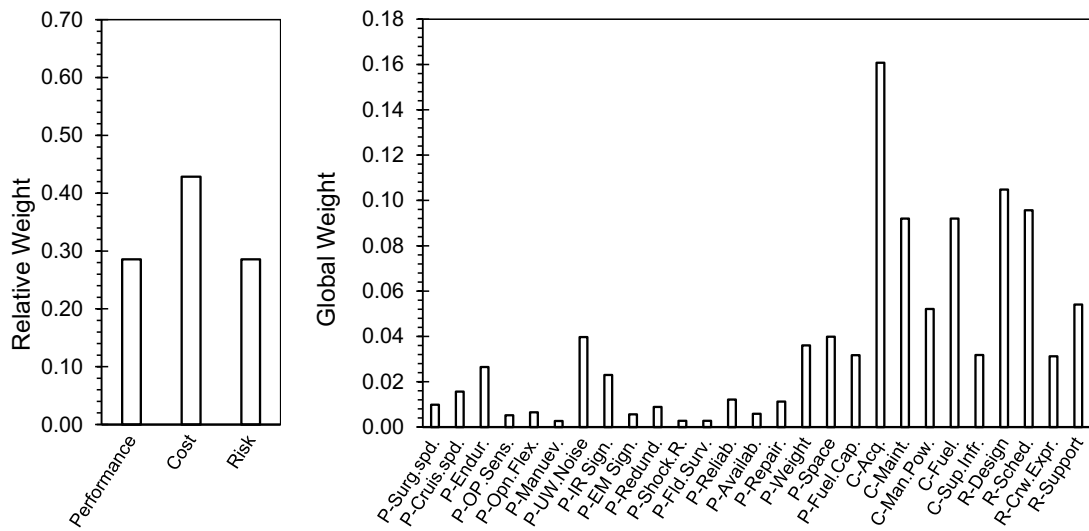


Figure 6-53 Computed global weights of set of criteria for Application Case 4

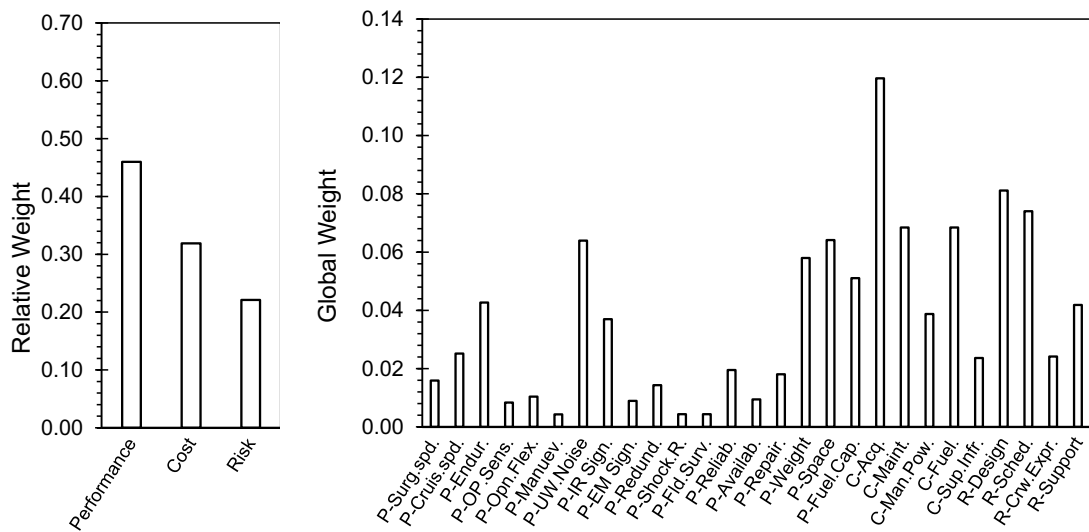


Figure 6-54 Computed global weights of set of criteria for Application Case 5

6.5 Notional Destroyer Conceptual Design Study

6.5.1 Input Data for Design

The primary speed requirements for the propulsion system design were considered as >30 knots for surge speed and >18 knots for cruise speed. The minimum endurance required for the ship at >15 knots of speed is 5000 nm. The considered operational profile of the ship derived based on the data published by Anderson [66] for such applications, is shown in Figure 6-55. The propulsor configuration considered was twin FPP or CPP. The overall average ship electrical load is considered to be 4.2 MWe. The primary parameters of the notional destroyer design considered are summarized in Table 6-15.

Table 6-15 Primary parameters of the considered notional destroyer

Parameter	Value
Displacement	9500 metric tons approx.
Length	150 m approx.
Surge speed	>30 knots
Cruise speed	>18 knots
Ship operation per year	3500 hours
Endurance	>5000 nm @ >15 knots speed
Fuel tank capacity	< 1000 metric ton
Propeller diameter	5 m approx.
Auxiliary electrical load	4.2 MWe

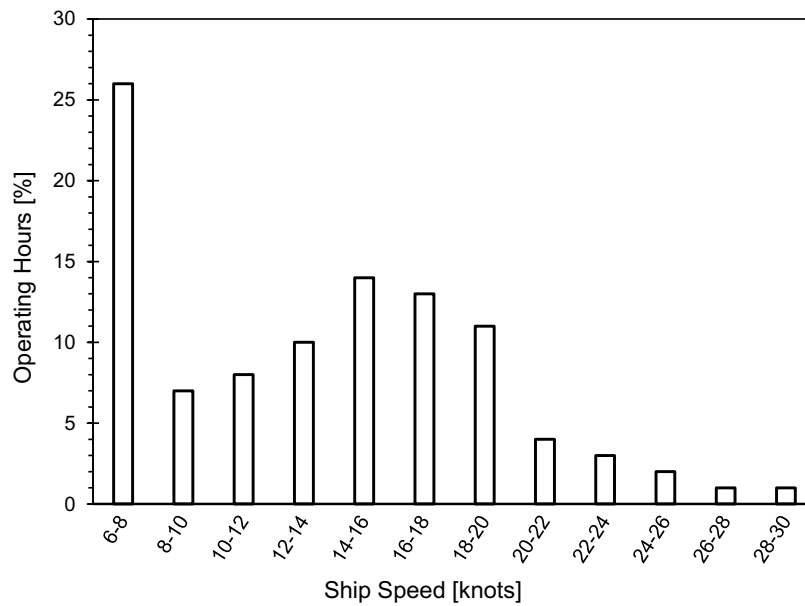


Figure 6-55 Considered operating profile for conceptual design of propulsion system for notional destroyer

6.5.2 Hull Resistance Estimation

The hull model considered for this application was based on the published data by Hlavin [127]. The primary parameters used as the input for the application of the resistance module is given in Table 6-16. The resistance curve was determined computed using Poseidon+ by the application of the F&L method. The input file used for the same is shown in Appendix Q. The computed calm water resistance from the applied model is shown in Figure 6-56, without the application of any additional margins.

Table 6-16 Primary hull parameters of the notional destroyer

Parameter	Unit	Value
Length between perpendiculars	m	154
Length on waterline	m	144.68
Beam on waterline	m	18.5
Draft Fwd	m	6.5
Draft Aft	m	7.5
Displacement	Metric Ton	9585
Coeff Midship Area	-	0.8280
Coeff Waterplane	-	0.7910
Area transverse transom immersed	m ²	12
Beam at transom	m	12
Half angle of entrance iE	degrees	10.9
Surface area of appendages	m ²	300
Air frontal area	m ²	420
Method for calculation	-	F&L

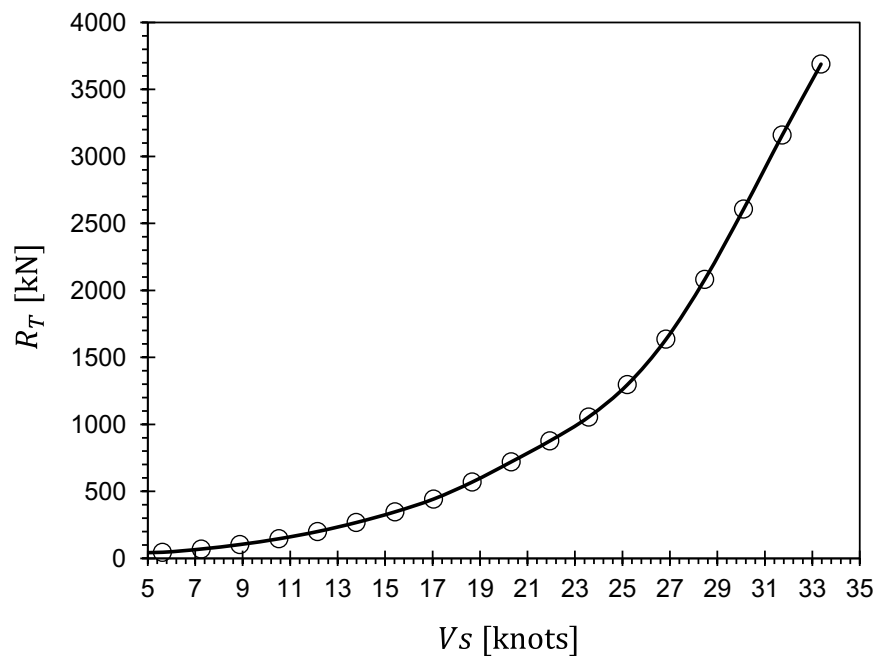


Figure 6-56 Calculated calm water resistance for the considered hull form for notional destroyer

6.5.3 Propeller Design

The propeller parameters were optimised using the input data as shown in Table 6-17. The basic parameters of the diameter and the operating point were obtained based on the work of Kravitz [131]. The B-series based optimization routine was run in Poseidon+ to obtain the final propeller parameters used as shown in Table 6-18. The open water characteristics of the optimised propeller design are shown in Figure 6-57. The characteristic of the delivered power of the propeller versus ship speed is shown in Figure 6-59. This figure also shows the effect of added resistance when a propeller is trailed. The added resistance due to the drag of the trailed propeller can be seen from the comparison of the line 'Trailing Propeller Mode' with the line '2XPropeller' which shows the hypothetical operation of a single propeller in a twin-screw arrangement if there were no added resistance due to a trailed propeller. If a 'feathering' arrangement is available on the trailed propeller, as used for some fast naval crafts, the added resistance due the trailed propeller reduces. However, for the present work such an arrangement has not been considered.

Table 6-17 Input data for propeller parameters optimization

Parameter	Unit	Value
Ship speed	knots	20
Resistance for Propeller	kN	396.96
Thrust deduction factor	-	0.076
Wake fraction	-	0.059
Propeller diameter	m	5.18
Propeller centre depth from the waterline	m	4.91
Number of blades	-	5

Table 6-18 Final parameters for the propeller design optimised for notional destroyer based on Wageningen B Series

Parameter	Unit	Value
Propeller diameter	m	5.18
P/D Design	-	0.704
EAR	-	0.5957
Number of blades	-	5

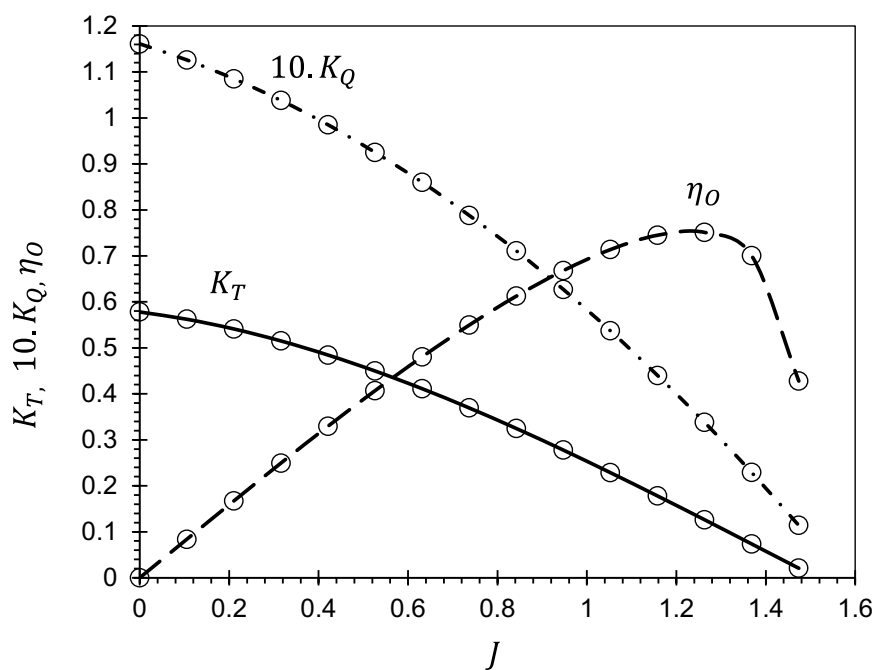


Figure 6-57 Calculated open water characteristic for the propeller design optimised based on Wageningen B Series for notional destroyer

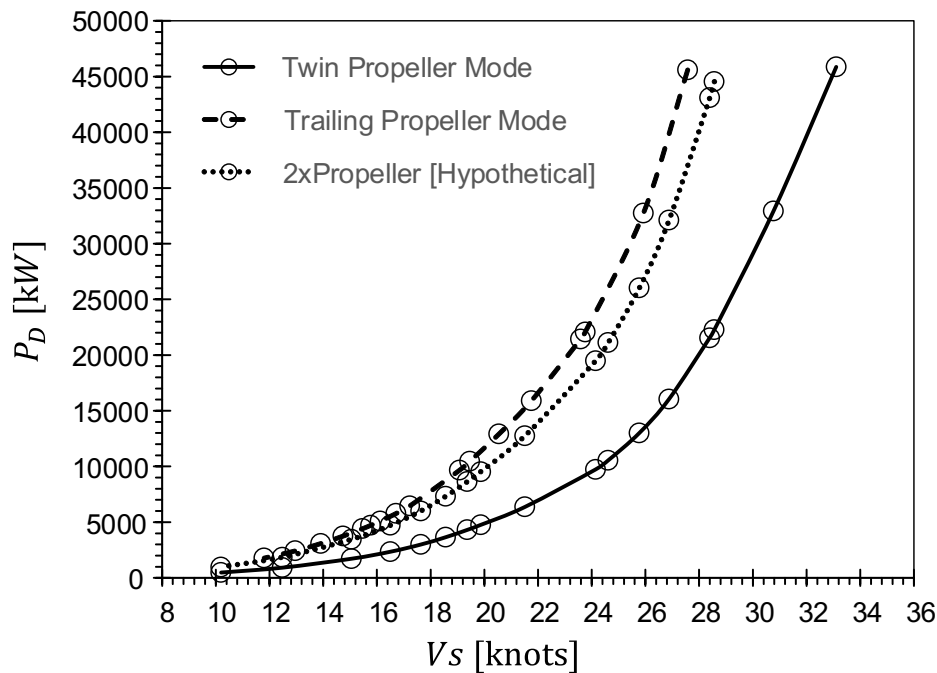


Figure 6-58 Calculated delivered power for each propeller varying with ship speed for the notional destroyer

6.5.4 Candidate Propulsion System Architectures

Based on the given design requirements, as a first step, the delivered power needed across the operating profile was calculated, as shown in Figure 6-59. Based on the already modelled hull resistance and propeller design, candidate propulsion system architectures were created. The five feasible candidate propulsion system architectures considered for the final TERA-MCDM are shown from Figure 6-60 to Figure 6-64, which are specific configurations of COGAG, CODAG, CODAG-E (Combination of Diesel engine, Gas Turbine and Electric), CODELAG and IFEP. For all designs except IFEP, a common CPP design was selected for the propulsor configurations for reversing of the propellers, while an FPP design was considered for the IFEP since the reversing of the propeller can be executed using the electric motors. Both the CPP design and FPP were considered to have the same design parameters except for the hub size.

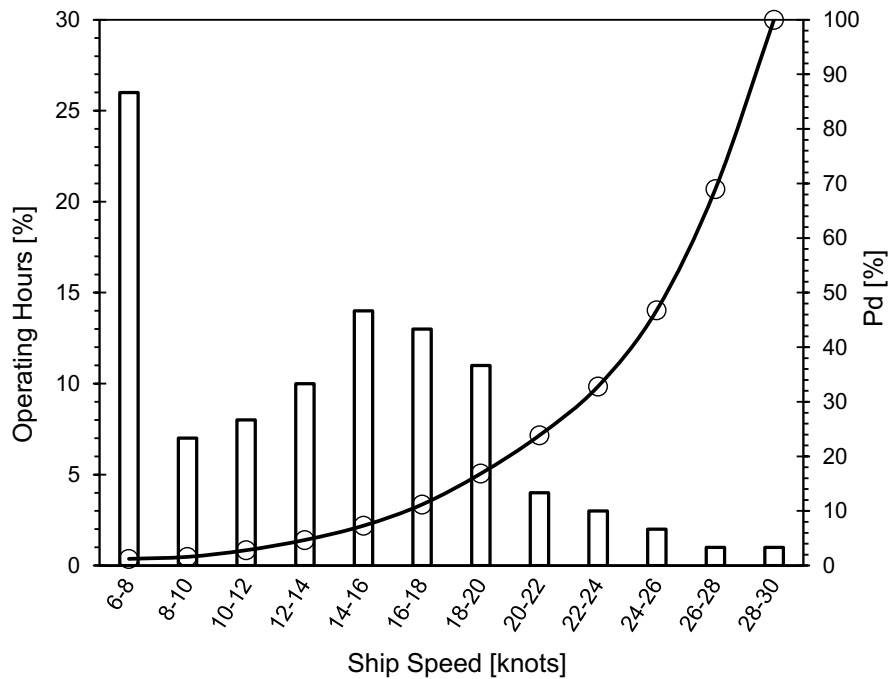


Figure 6-59 Operating profile superimposed with propeller delivered power required for notional destroyer

The COGAG architecture applied, as shown in Figure 6-60, uses two 25 MW gas turbine engines on each shaft line combining the torque from both these engines in a common reduction gearbox. In terms of the terminology used for this architecture, in some textbooks this is not considered to be a COGAG architecture as both engines are rated for equal power [3]. For the sake of simplicity, in the present work, this term is being used to refer to this architecture. This architecture has been executed on several ship designs like the US Navy DDG51, Italian Navy ‘Cavour’ etc. No ‘cross connection’ of propulsion power from one shaft line to the other is possible with this design. Hence, when only a single engine needs to be operated for very low ship speeds, one propeller would be trailing. The power generation system considered here is completely separated from the propulsion system, powered by three gas turbine-powered generator sets each rated at 3.5 MWe each. In all operating modes, two generator sets are considered to be in operation, with the third generator set being available for redundancy and transient loading conditions.

In Figure 6-61, the applied CODAG configuration is shown where each propeller is powered by a 7 MW medium-speed diesel engine as the cruise engine and 36 MW gas turbines as the boost engine. Each engine has its individual reduction gear. When the plant is operated in the combined mode, where the gas turbine and diesel engine are operated together, the torque for the gas turbine is added to the diesel engine torque using a twin speed gearing arrangement in the diesel engine gearboxes. No 'cross connection' of propulsion power from one shaft line to the other is possible in this design. The power generation system considered here is independent of the propulsion system, powered by three medium-speed diesel generator sets each rated at 2.8 MWe each. In all operating modes, two generator sets are considered to be in operation, with the third generator set being available for redundancy and transient loading conditions.

The CODAG-E configuration shown in Figure 6-62 has a very similar arrangement to the CODAG arrangement, with the primary difference being that a 1.25 MW electric motor is arranged on each shaft, for operation at very low speeds or when the ship needs to operate for low underwater radiated noise regimes. The electric motors also provide an 'electric cross connection' which avoids the need for trailing propellers at low speeds of operation.

The CODELAG arrangement, as shown in Figure 6-63, uses electric motors powered by a diesel-electric grid powered by three 6.7 MW medium-speed diesel engine generator sets. On each shaft, a 36 MW gas turbine engine is arranged as the boost engine powering the shaft line through individual reduction gears. The electric motors and the gas turbines are designed for combined operation to achieve the rated power of the plant. Due to the very large torque envelope of the electric motors, twin speed gearing is not required to combine their torque with the gas turbines. In this design, 'electric cross connection' is arranged, where a single diesel generator set or set of generator sets can power both the propellers through the electric motors connected by a common grid. The electric motors also serve as generators in Power Take-Off (PTO) mode, in a specific range of speed when powered by the gas turbines.

Figure 6-64 shows the IFEP arrangement considered, where the entire range of ship speed is achieved using large propulsion motors. These motors are powered by the electric grid system which is powered by two 36 MW gas turbine generators, two 6.7 MW medium-speed diesel engine generator sets and two 3.9 MW diesel engine generator sets. The number of engines that need to be running is determined based on the total power required by the propulsion and auxiliary load.

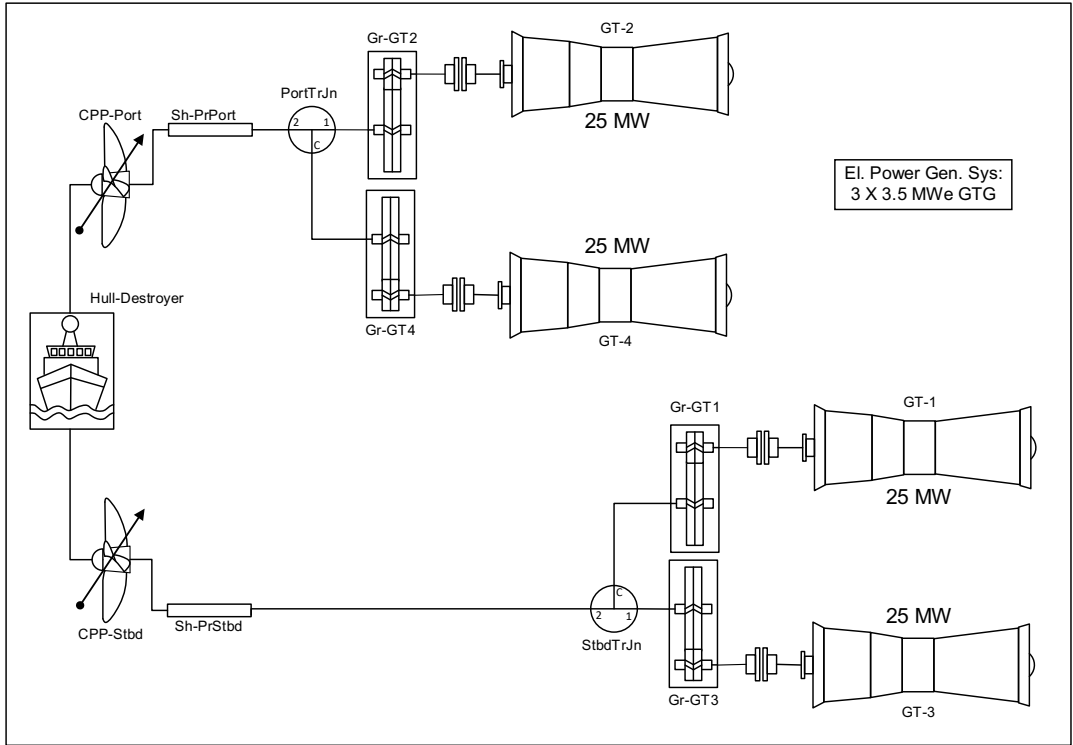


Figure 6-60 Candidate propulsion system architecture alternative A1, COGAG, for notional destroyer.

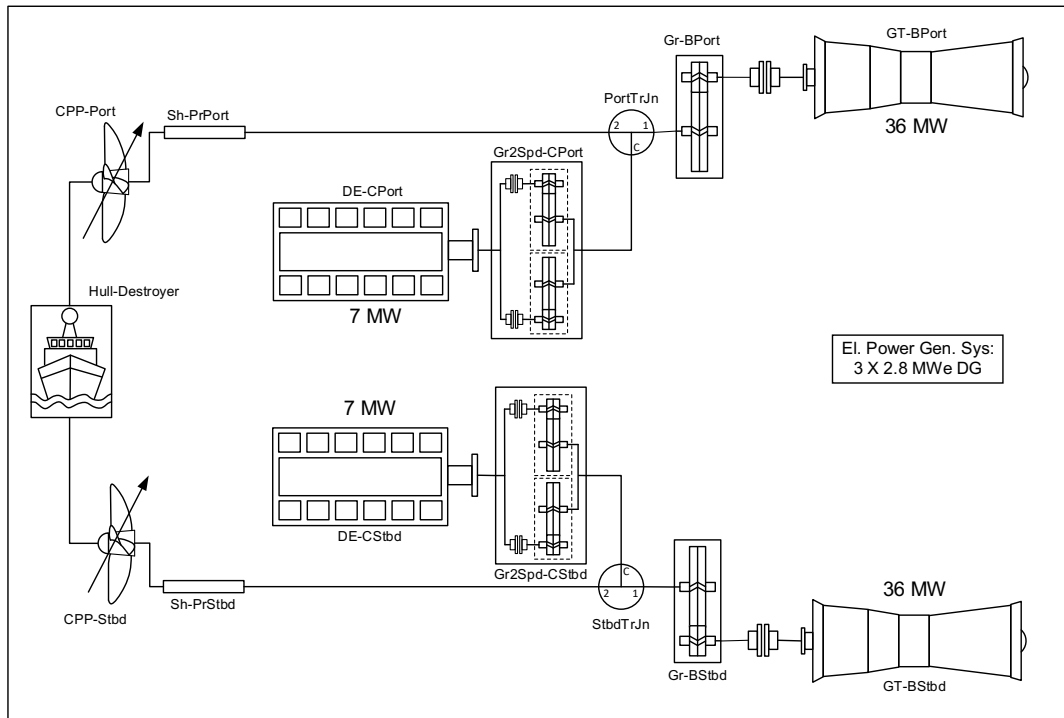


Figure 6-61 Candidate propulsion system architecture alternative A2, CODAG, for notional destroyer.

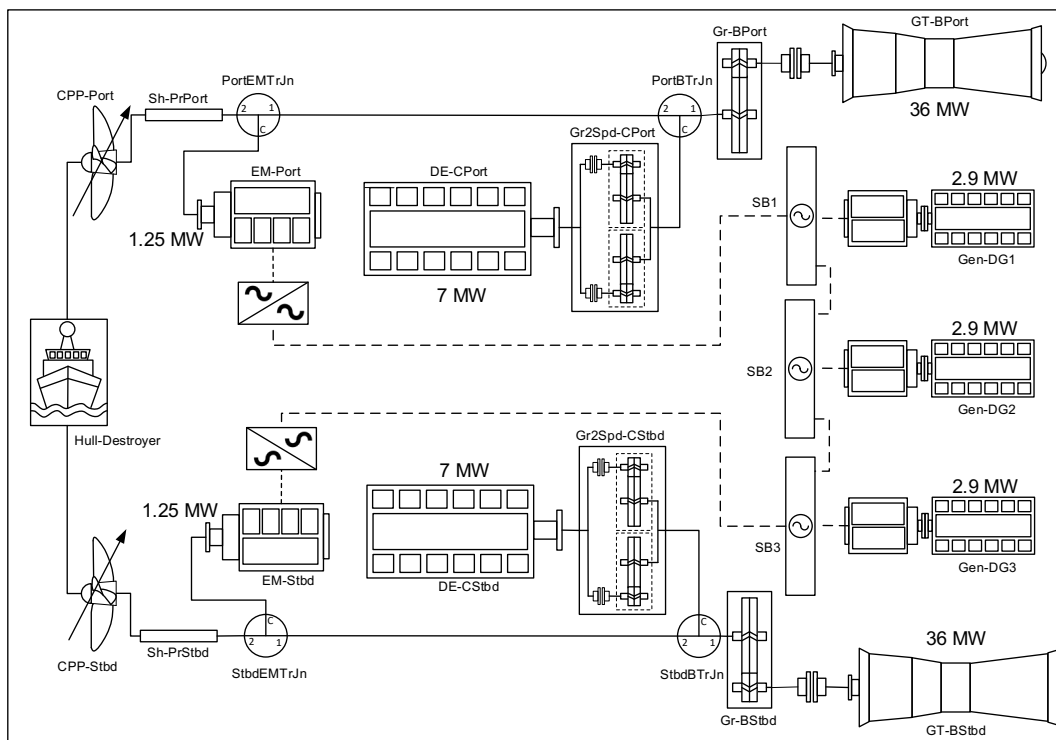


Figure 6-62 Candidate propulsion system architecture alternative A3, CODAG-E, for notional destroyer.

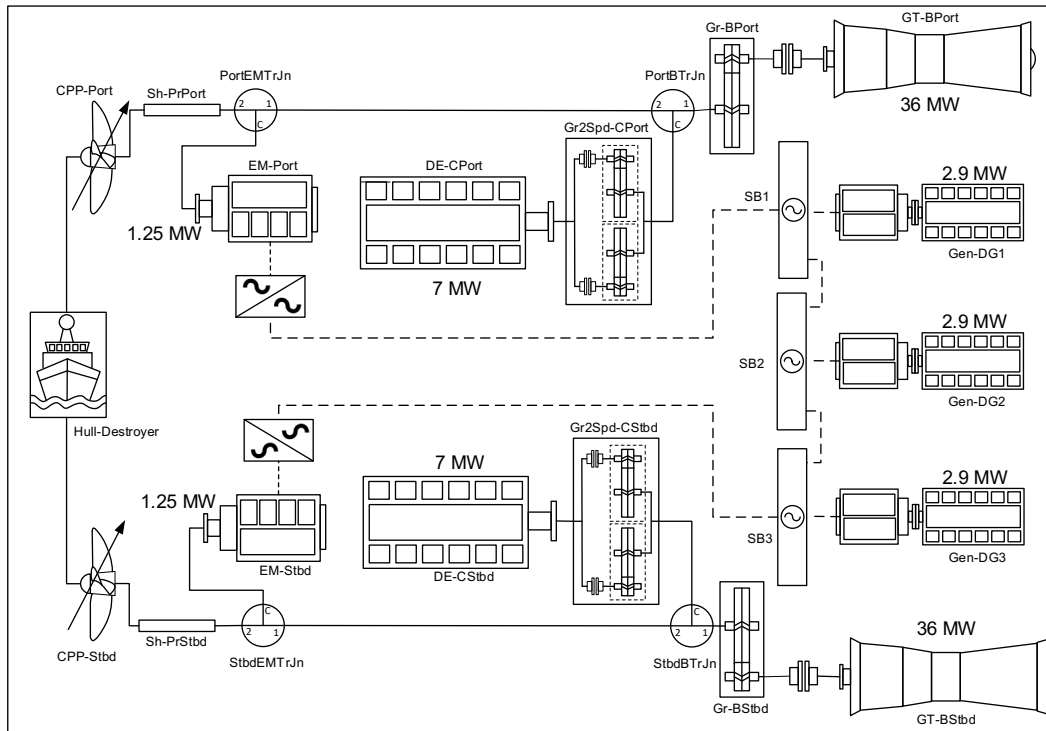


Figure 6-63 Candidate propulsion system architecture alternative A4, CODELAG, for notional destroyer.

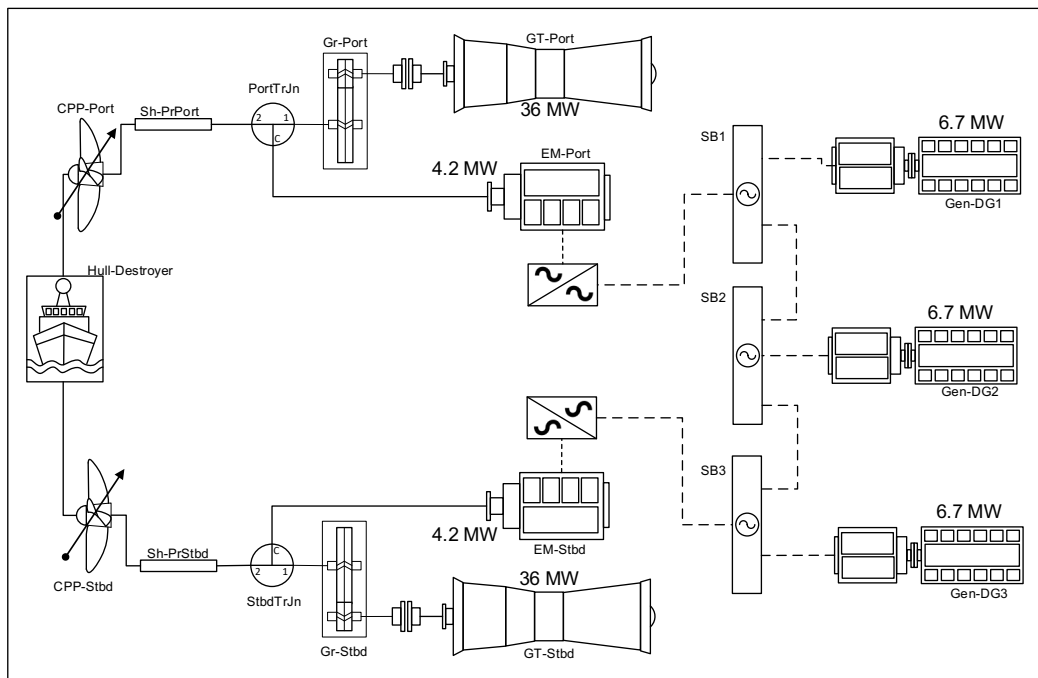


Figure 6-64 Candidate propulsion system architecture alternative A5, IFEP, for notional destroyer.

6.5.5 Performance modelling of candidate architectures

The performance modelling of the above-described candidate architectures was undertaken by using Poseidon+. The input model files were created for each of the candidate architectures, as shown in Appendix Q. Thereafter the models were used to run the propulsion and power generation system in various modes of operation to capture the performance characteristics of the system. These performance characteristics consist of engine, transmission system and propeller performance data.

The primary characteristics of the engines and transmission systems have already been discussed earlier in this thesis and are not repeated here for various operation modes for brevity. For each of the candidate architectures, basic engine-propeller matching, and feasibility analysis were undertaken using Poseidon+, based on the already described considerations of the engine operating envelopes etc. An example of the performance envelope analysis for various operating drive modes for the COGAG system is shown in Figure 6-65, where based on the nominal torque envelopes of the engines, the ship speed limits at the respective drive modes have been identified.

One of the primary characteristics of interest in such trade-off studies is the overall consumption of fuel by the ship energy system, with all the off-design efficiencies of the system considered in the simulation. These characteristics are presented here for each candidate architecture from Figure 6-66 to Figure 6-71. These operation drive modes also consider the engine envelope limitations so that only feasible operating points are considered for the analysis. The data from these characteristics was used to calculate the overall operating costs due to fuel consumption based on the defined operating profile. The comparative bar graphs for the candidate architectures with respect to maximum surge speed, cruising speed, endurance (range) based on tank capacity, required fuel tank capacity based on range requirement are shown from Figure 6-72 to Figure 6-75, respectively.

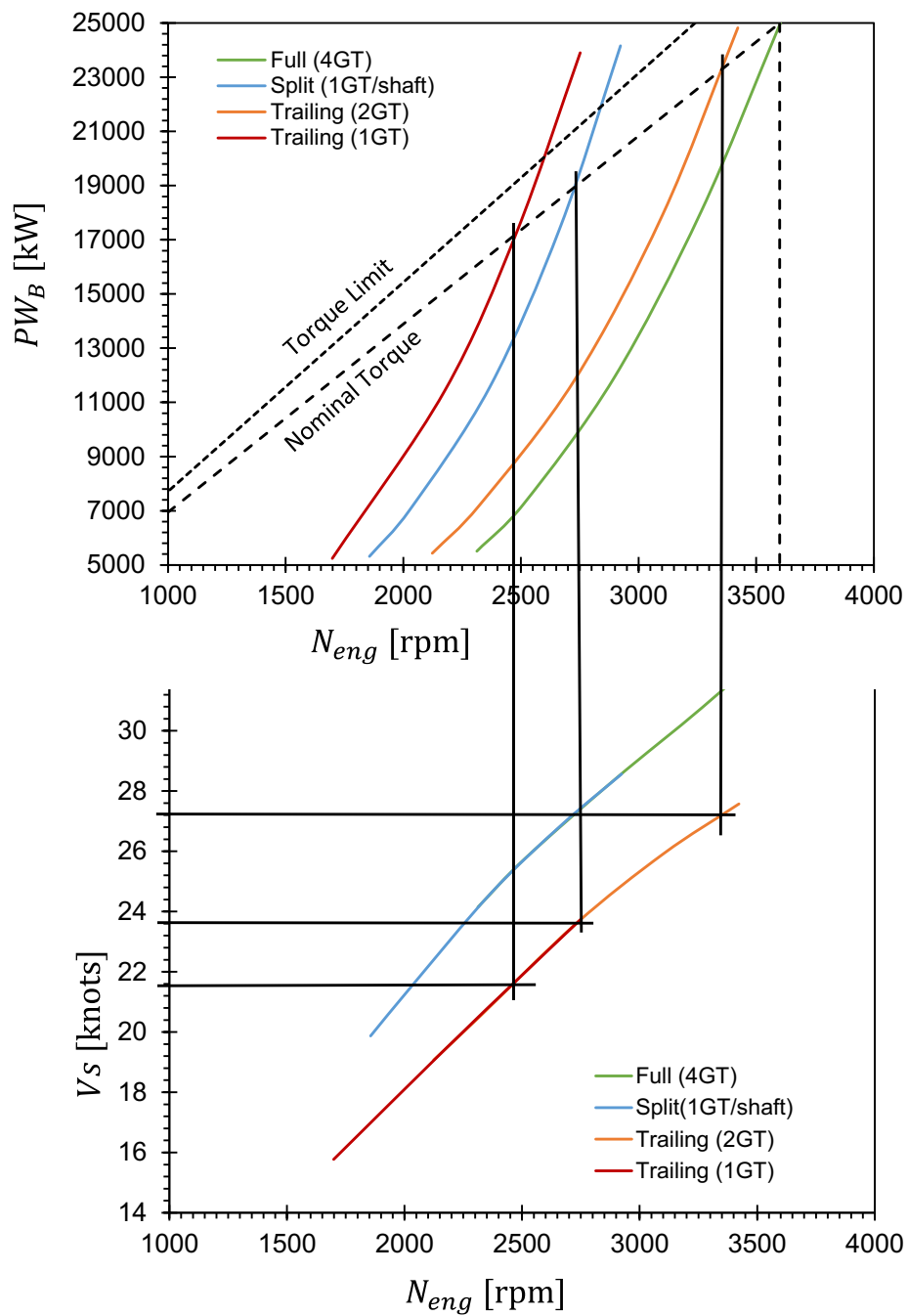


Figure 6-65 Derivation of ship speed at various operating drive modes limits based on nominal torque envelopes of the engines in the COGAG arrangement.

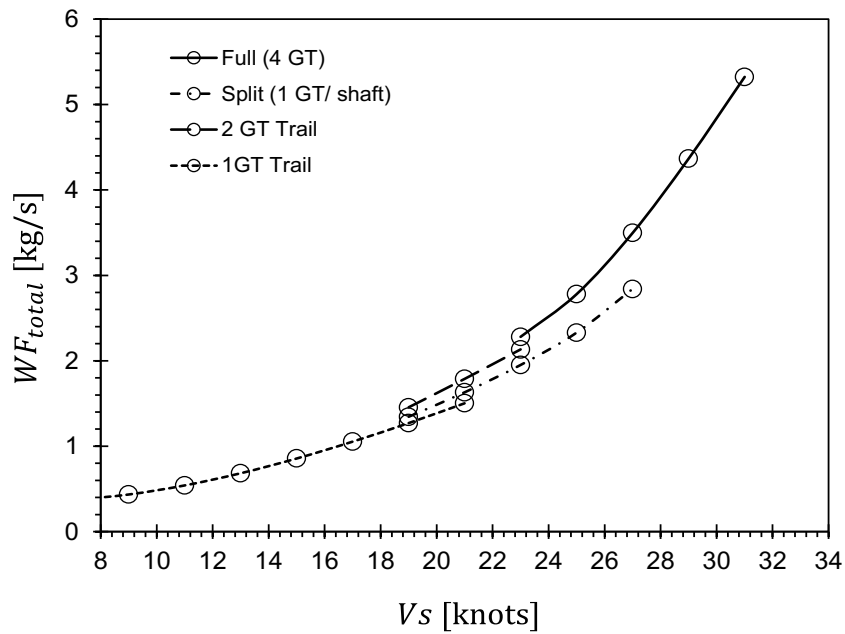


Figure 6-66 Computed overall fuel consumption curves at defined operating drive modes for the candidate architecture alternative A1 COGAG for conceptual design analysis of notional destroyer.

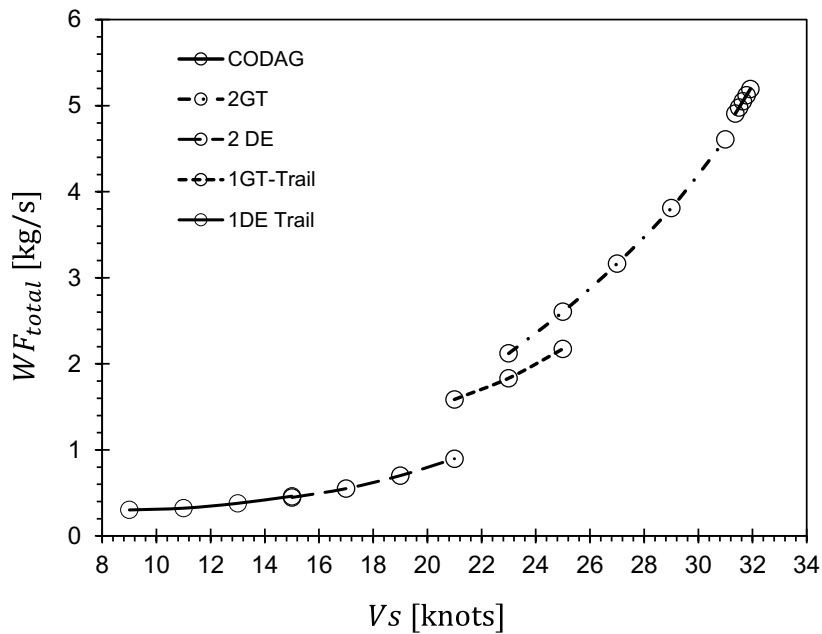


Figure 6-67 Computed overall fuel consumption curves at defined operating drive modes for the candidate architecture alternative A2 CODAG for conceptual design analysis of notional destroyer.

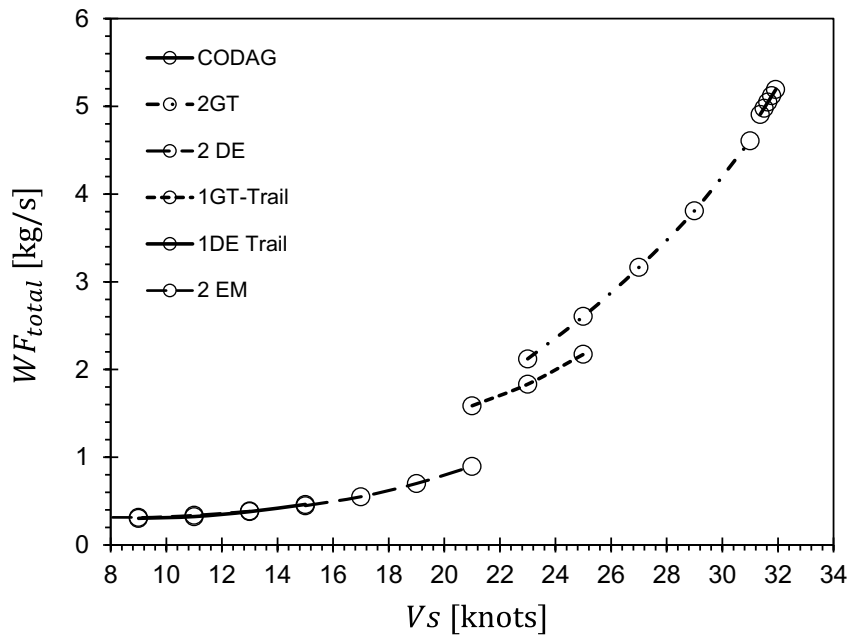


Figure 6-68 Computed overall fuel consumption curves at defined operating drive mode (full operating range) for the candidate architecture alternative A3 CODAG-E for conceptual design analysis of notional destroyer.

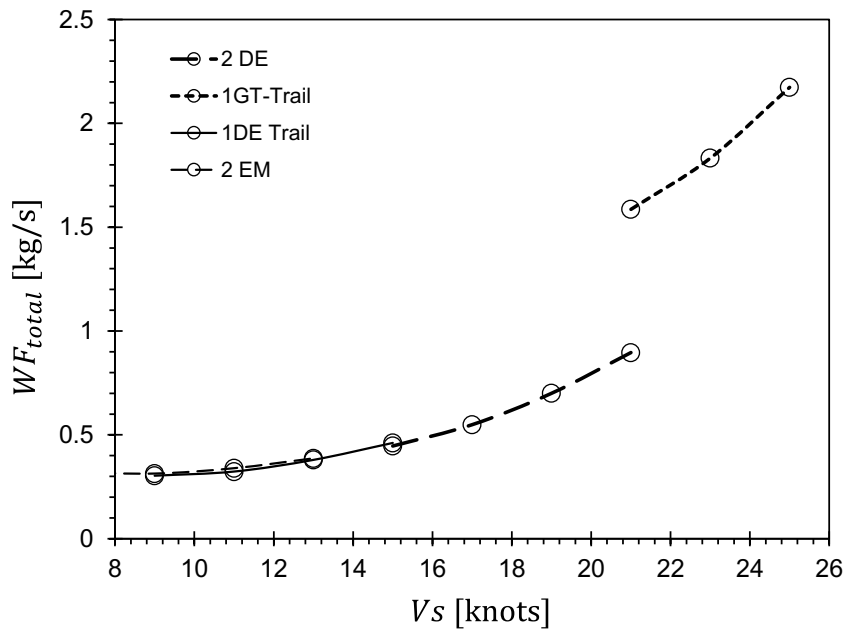


Figure 6-69 Computed overall fuel consumption curves at defined operating drive modes (low speed operating range) the candidate architecture alternative A3 CODAG-E for conceptual design analysis of notional destroyer.

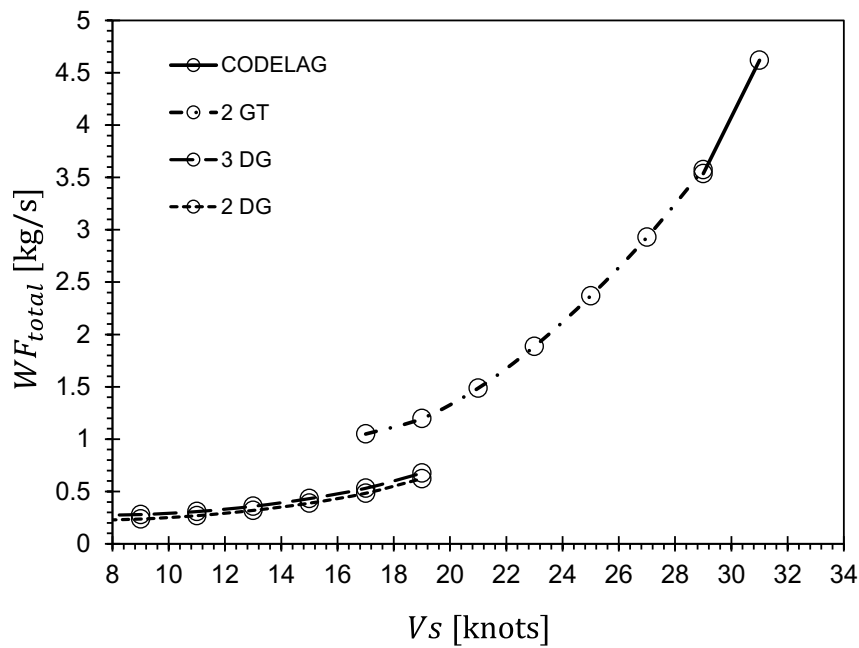


Figure 6-70 Computed overall fuel consumption curves at defined operating drive modes for the candidate architecture alternative A4 CODELAG for conceptual design analysis of notional destroyer.

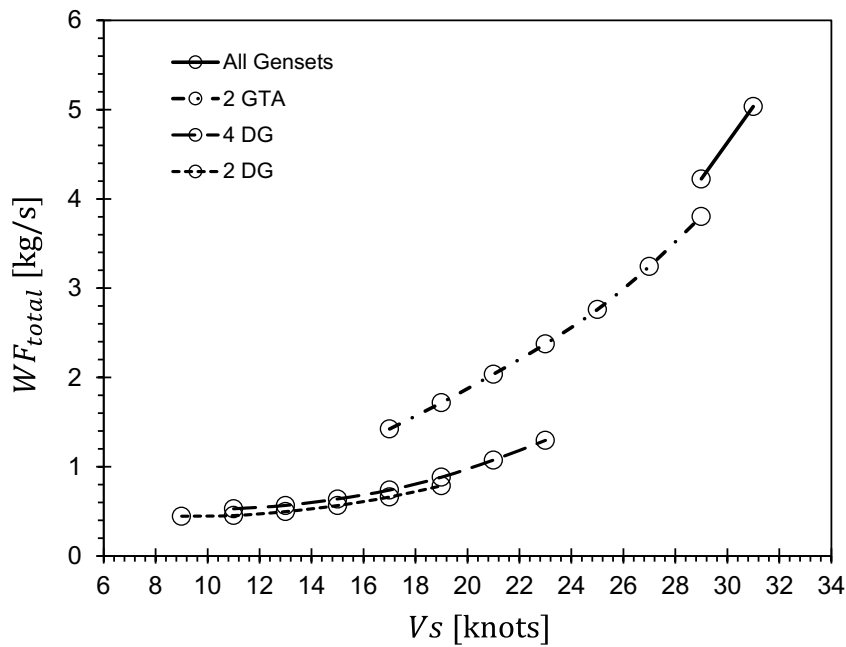


Figure 6-71 Computed overall fuel consumption curves at defined operating drive modes for the candidate architecture alternative A5 IFEP for conceptual design analysis of notional destroyer.

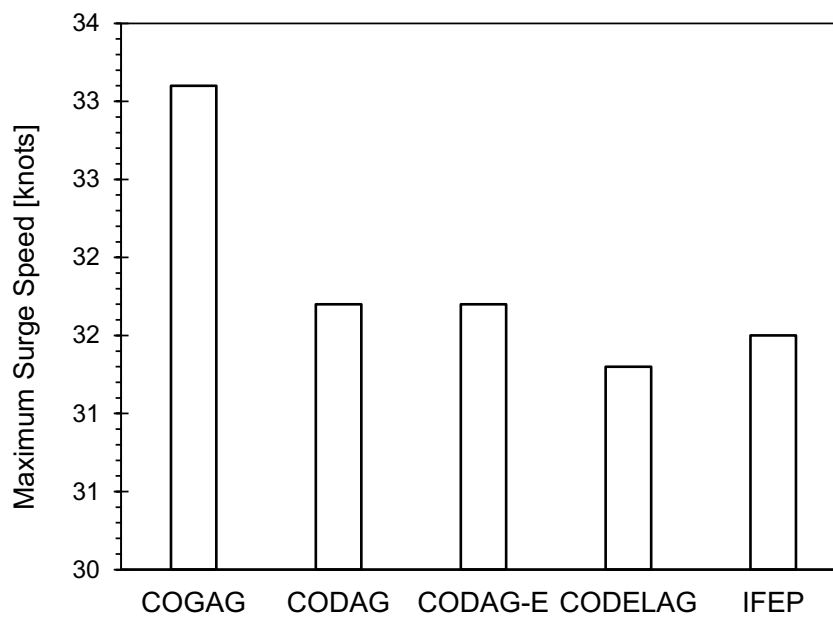


Figure 6-72 Computed maximum surge speed for candidate architecture propulsion system alternatives towards conceptual design analysis of notional destroyer.

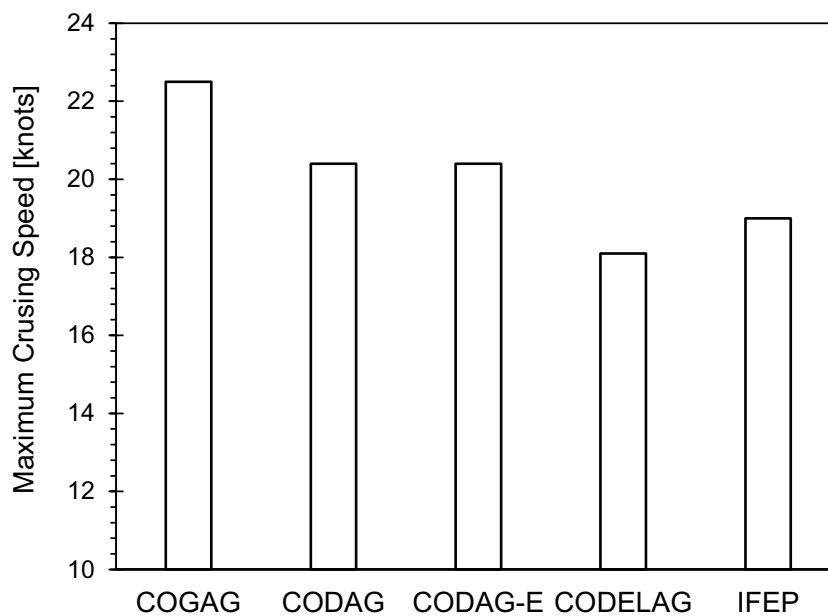


Figure 6-73 Computed maximum cruising speed for candidate architecture propulsion system alternatives towards conceptual design analysis of notional destroyer.

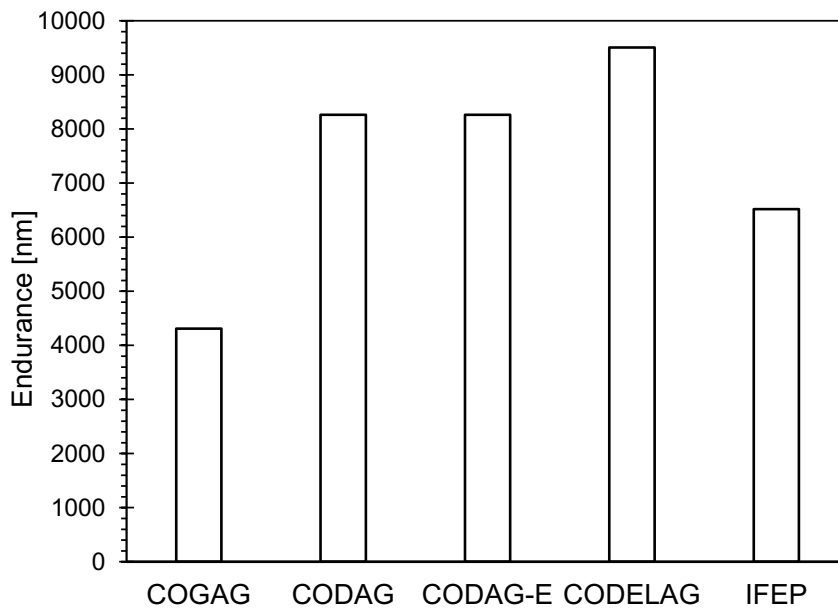


Figure 6-74 Computed endurance (range) based on tank capacity of 500 tons with ship speed of 14 knots for candidate architecture propulsion system alternatives towards conceptual design analysis of notional destroyer.

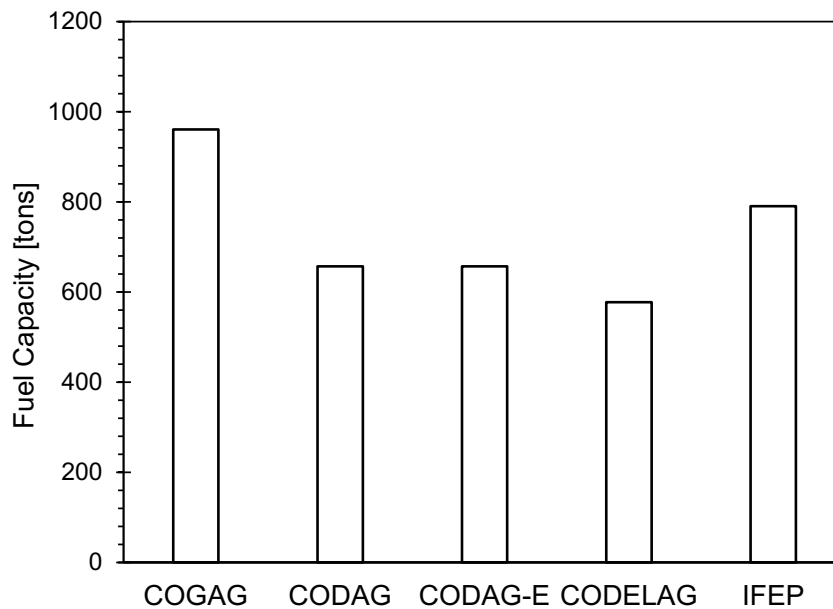


Figure 6-75 Computed required fuel tank capacity based on range requirement of 5000 nm with ship speed of 16 knots for candidate architecture propulsion system alternatives towards conceptual design analysis of notional destroyer.

6.5.6 Mass and Dimensional Estimations

The dimensioning models, as described in Appendix I, were used for calculating the overall mass and occupied deck area for each of the candidate architectures. The computed values include the propulsion equipment as well as the power generation equipment, so as to have a homogeneous comparison of the architectures where the ship electric system and propulsion system are connected (like CODLAG, CODAG-E, IFEP) with the ones where these systems are independent (like COGAG, CODAG). These dimensioning estimations include the primary equipment but not the auxiliary systems related to this main equipment as well as low voltage switchboards. Since the final architecture selection would be based on a relative analysis, this estimation was considered unnecessary for the present work. The comparative bar graphs of the various architectures in terms of mass and occupied deck area are shown in Figure 6-76 and Figure 6-77, respectively.

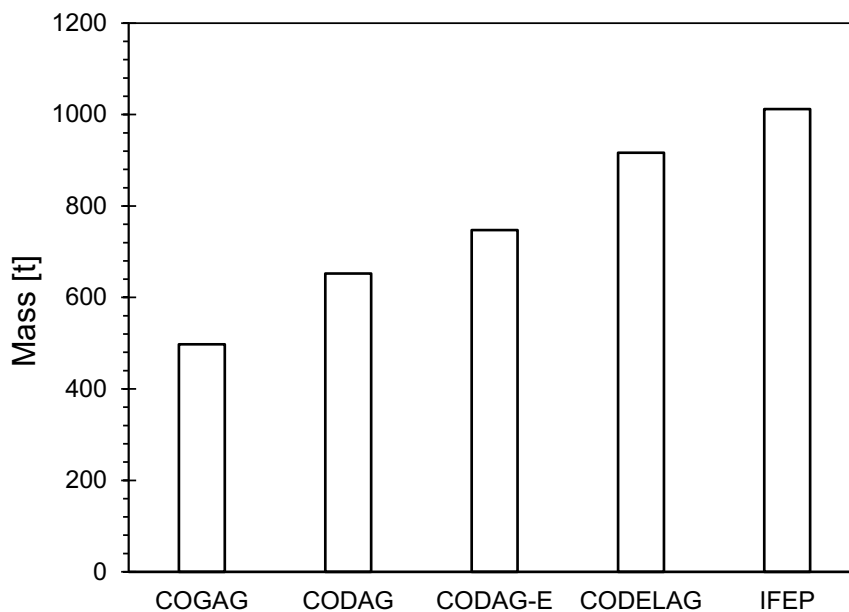


Figure 6-76 Computed mass of the main propulsion and power generation equipment for the candidate architecture alternatives for conceptual design analysis of notional destroyer.

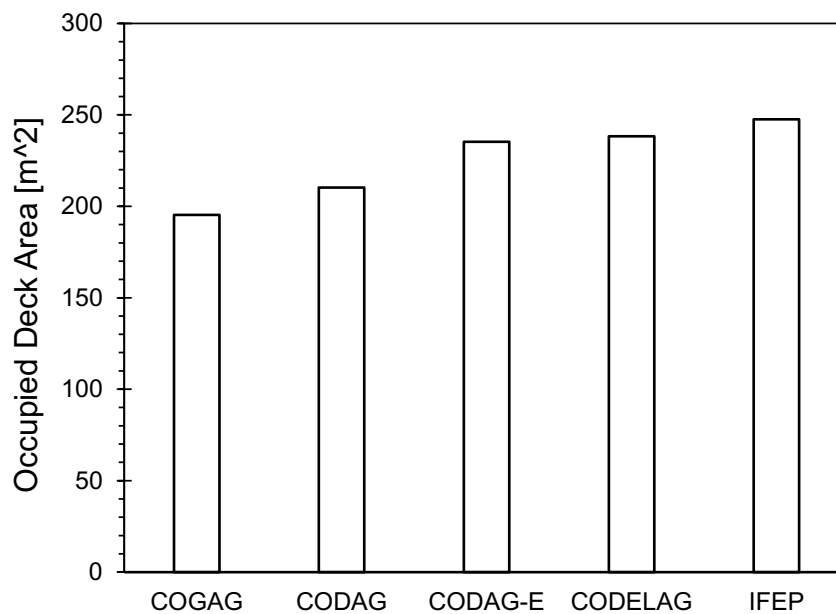


Figure 6-77 Computed occupied deck area of the main propulsion and power generation equipment for the candidate architecture alternatives for conceptual design analysis of notional destroyer.

6.5.7 Estimation of Costs

The costing models for acquisition, as described in Appendix J, were used to calculate the overall acquisition and maintenance costs for each of the candidate architectures. Again, as for dimensioning calculation, the computed values include the propulsion equipment as well as the power generation equipment, to have a homogeneous comparison of the architectures where the ship electric system and propulsion system are connected. These estimations include the primary equipment but not the auxiliary systems related to this main equipment.

The acquisition costs from the models have been adapted to the year 2021 for inflation, considered to be at an average rate of 2% per year. The maintenance costs have been calculated as follows. The overall operating hours of the propulsion equipment were first calculated based on the drive modes required to achieve certain speeds, which basically defines which equipment is running. The operating times at various speeds were calculated based on the defined operating profile, which defines the time bands for operation at various speeds,

and the overall operating hours of the ship per year. Based on the overall operating hours of the propulsion equipment, the maintenance costs were then estimated based on the defined operation-based maintenance models. Similarly, the costs of fuel over the life cycle of the ship was calculated by using the operating hours at various speed bands, the applicable operating drive mode and the corresponding overall fuel rates previously computed, and then applying the overall operating hours of the ship per year. The average cost of fuel has been derived based on US Defense Logistics Agency (DLA) Energy publication for 2020.

The comparative bar graphs of the various architectures in terms of acquisition and maintenance costs are shown in Figure 6-78 and Figure 6-79, respectively. The lifetime costs for fuel are shown in Figure 6-80. The overall distribution of considered costs over the entire life cycle is shown in Figure 6-81.

An interesting observation that can be made from this analysis is the overall influence of the operating profile and engine operating envelopes on the through life overall fuel consumption by the ship propulsion plant. While it can be seen from comparison of Figure 6-66 and Figure 6-67 that the CODAG architecture provides an overall lower fuel consumption compared to the COGAG plant, the overall lifetime fuel consumption costs for both these architectures, as seen in Figure 6-80 and Figure 6-81, are nearly the same. This can be explained by the way these plants are considered for operation in the low-speed range of 6-8 knots that dominates the considered operating profile, as shown in Figure 6-59. The COGAG plant is considered for operation in this speed range in the 'trailed shaft' mode by the operation of a single engine, which can be easily handled by gas turbines due to the large engine operating envelope. On the other hand, for the CODAG plant, the entire low speed of operation is considered to be undertaken using two diesel engines due to the rather limited engine operation envelope of the diesel engines which makes ship operations rather restrictive.

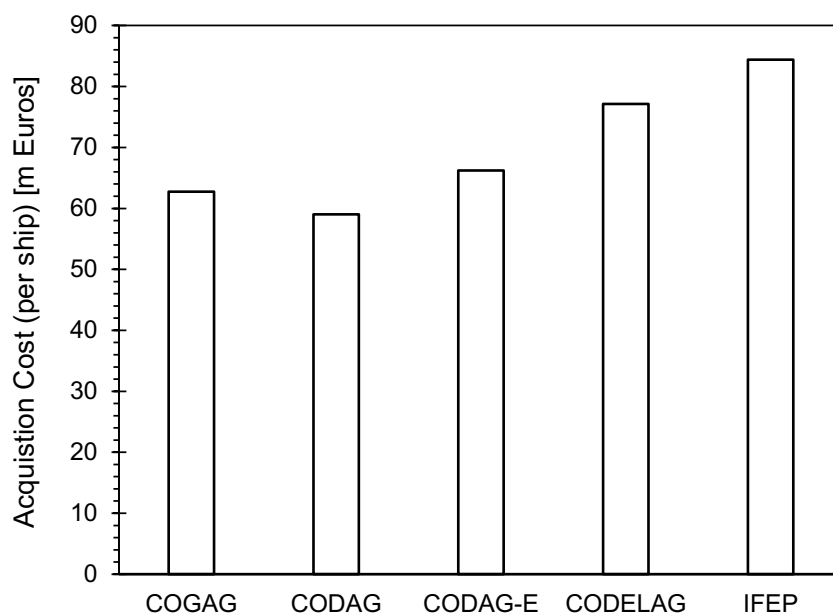


Figure 6-78 Computed acquisition cost of the main propulsion and power generation equipment for the candidate architecture alternatives for conceptual design analysis of notional destroyer.

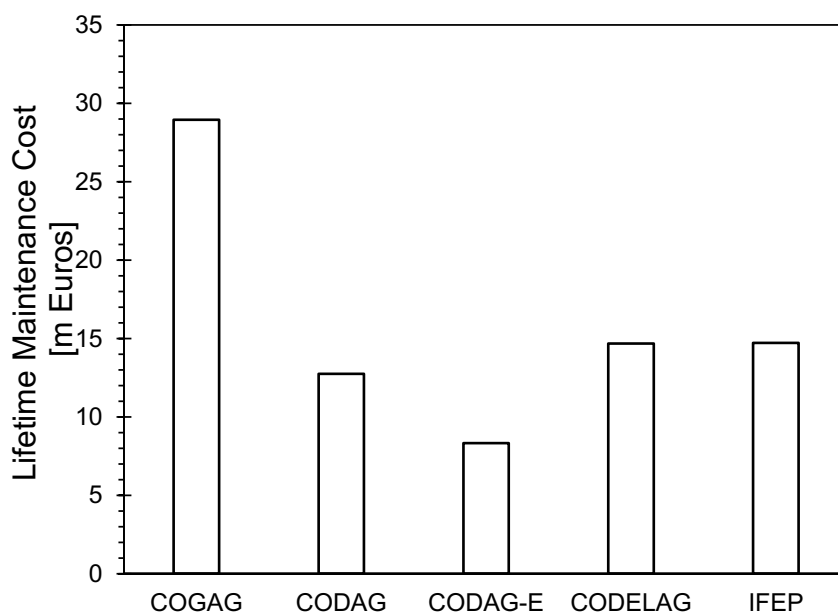


Figure 6-79 Computed lifetime maintenance cost for the main propulsion and power generation equipment for the candidate architecture alternatives for conceptual design analysis of notional destroyer.

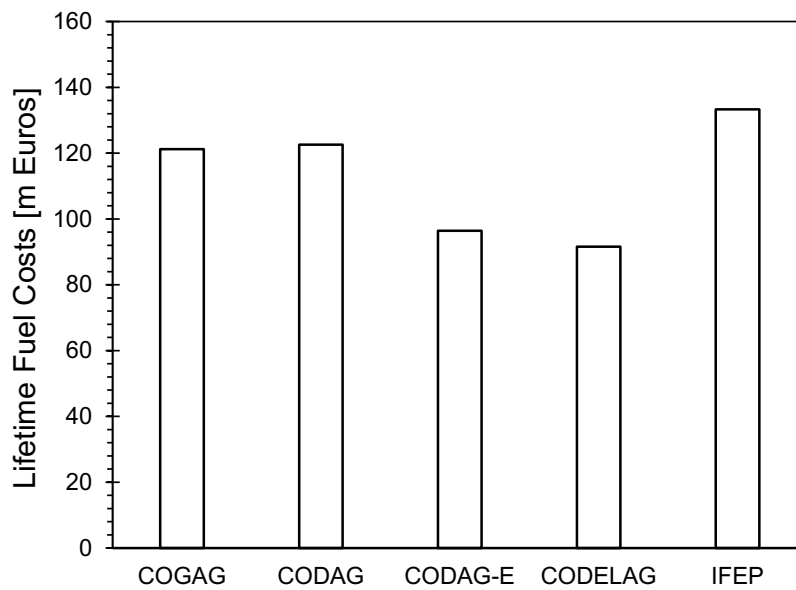


Figure 6-80 Computed lifetime fuel costs of the main propulsion and power generation equipment for the candidate architecture alternatives for conceptual design analysis of notional destroyer. Average fuel price considered 480.3 Euro per ton based on US Defense Logistics Agency (DLA) Energy publication for 2020.

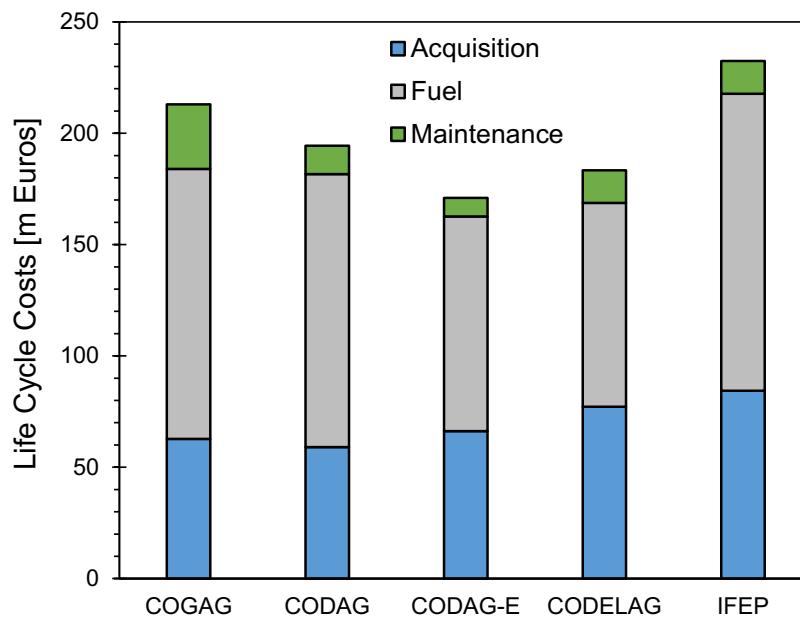


Figure 6-81 Computed occupied deck area of the main propulsion and power generation equipment for the candidate architecture alternatives for conceptual design analysis of notional destroyer.

6.5.8 Calculation of Relative Scores for Qualitative Criteria

For the evaluation of the candidate architectures against the qualitative criteria (P4-P15, C3, C5, R1-R4), the author again used discussions with experienced colleagues from the domain, to undertake an AHP based pairwise comparison method to arrive at the relative evaluation scores for the candidate architectures. The computed relative scores for the candidate architectures against the qualitative criteria are shown from Figure 6-82 to Figure 6-84.

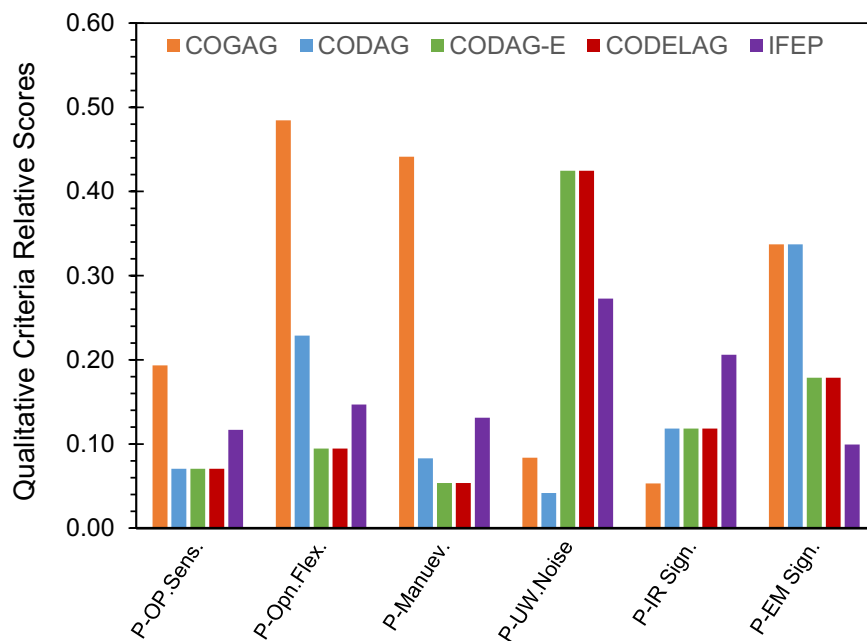


Figure 6-82 Computed relative scores of candidate architecture against qualitative criteria (P4-P9) for conceptual design analysis of notional destroyer.

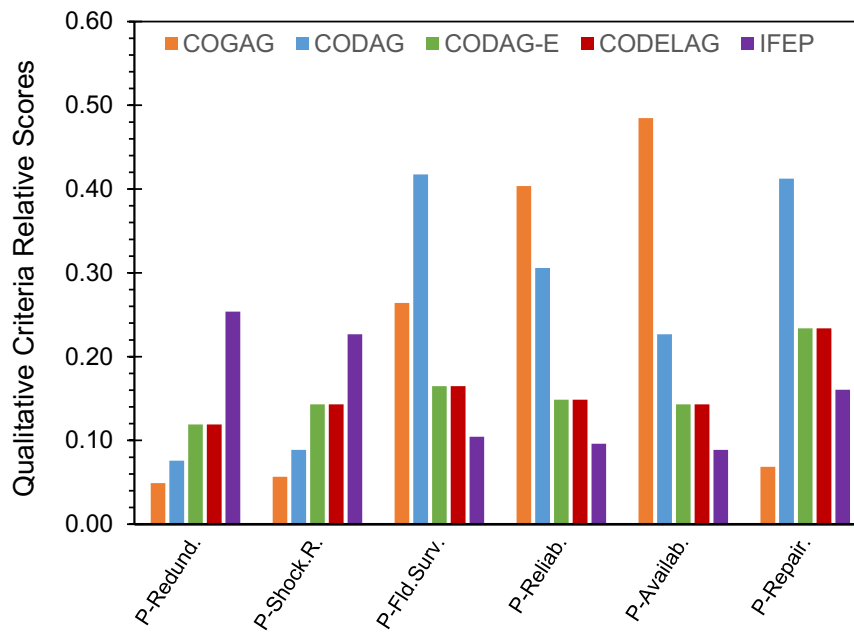


Figure 6-83 Computed relative scores of candidate architecture against qualitative criteria (P10-P15) for conceptual design analysis of notional destroyer.

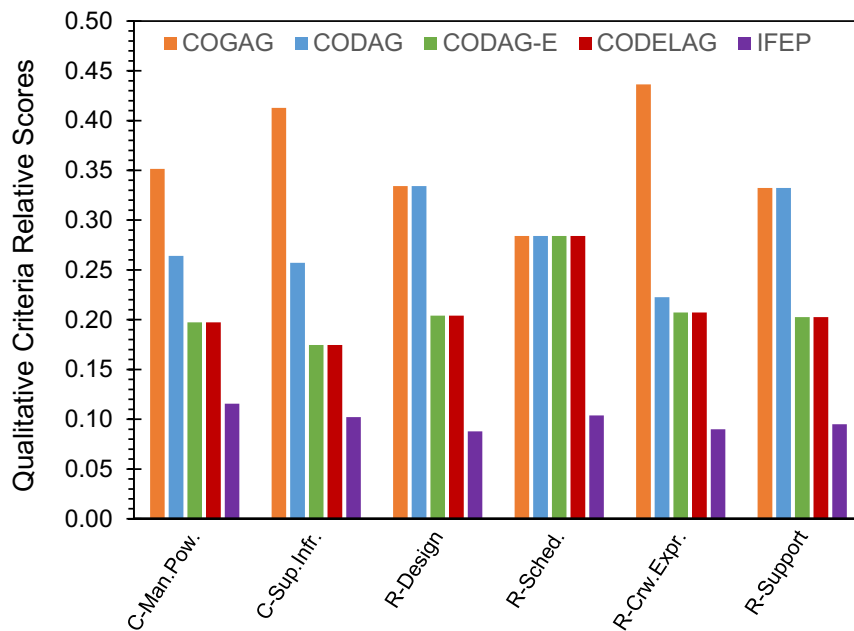


Figure 6-84 Computed relative scores of candidate architecture against qualitative criteria (C3, C5, R1-R4) for conceptual design analysis of notional destroyer.

6.5.9 Objective Comparison of Candidate Propulsion System Designs using VIKOR

To objectively undertake a techno-economic comparison of the candidate architectures, the VIKOR method, as described in Appendix N, was used to arrive at the final ranking in terms of preference based on the defined criteria. The set of metrics obtained from both the quantitative and qualitative criteria, for each of the candidate design architecture alternatives, were arranged as shown in Table 6-19. This serves as the input data for the VIKOR analysis.

The VIKOR analysis was undertaken for the application cases, as described in section 6.4.3, with the value of the 'strategy coefficient' as $v = 0.5$, to have a balance between minimizing individual differences from ideal solution (for $v < 0.5$) and satisfying most of the criteria (for $v > 0.5$). The candidate design architectures were rated by calculating the VIKOR parameters S, R, Q and the best-suited architectures were identified based on the alternative with the lowest score of Q , for all the application cases. For each application case tables for Ranks as well as ' Q ' values were calculated for the 'strategy coefficient' v varying between 0 and 1. For the sake of brevity, as an example, the tables created for Application Case 1 are shown in Table 6-20 and Table 6-21.

The results of the determined values of S, R, Q and the ranking for each of the application cases, with the balanced $v = 0.5$ 'strategy coefficient', are shown in Table 6-22. For the best-suited alternative identified, further verification for meeting the conditions of 'acceptable advantage' and 'stability in decision making'. The results of this analysis are shown in Table 6-23.

For each of the application cases, a sensitivity analysis was undertaken for variation of the ranks to the 'strategy coefficient' v by varying it between 0 and 1 at increments of 0.1 to evaluate the robustness and steadiness of the solution. Further, since the final ranks of the candidate architectures are primarily based on the VIKOR metric ' Q ', sensitivity of the metric ' Q ' to variation in the 'strategy coefficient' v was also undertaken. The results of this analysis are shown from Figure 6-85 to Figure 6-96.

Table 6-19 Combined table of qualitative and quantitative metrics for all candidate design architectures alternatives for conceptual design analysis of notional destroyer, against the complete set of design criteria.

Criteria			COGAG	CODAG	CODAG-E	CODELAG	IFEP
			A1	A2	A3	A4	A5
PC11	P-Surg.spd.	B	33.1	31.7	31.7	31.3	31.5
PC12	P-Cruis.spd.	B	22.5	20.4	20.4	18.1	19
PC13	P-Endur.	B	4311	8262	8262	9509	6520
PC21	P-OP.Sens.	B	0.193	0.071	0.071	0.071	0.117
PC22	P-Opn.Flex.	B	0.484	0.229	0.095	0.095	0.147
PC23	P-Manuev.	B	0.441	0.083	0.054	0.054	0.131
PC31	P-UW.Noise	B	0.084	0.042	0.425	0.425	0.273
PC32	P-IR Sign.	B	0.053	0.118	0.118	0.118	0.206
PC33	P-EM Sign.	B	0.337	0.337	0.179	0.179	0.099
PC41	P-Redund.	B	0.049	0.076	0.119	0.119	0.254
PC42	P-Shock.R.	B	0.057	0.089	0.143	0.143	0.227
PC43	P-Fld.Surv.	B	0.264	0.418	0.165	0.165	0.104
PC51	P-Reliab.	B	0.404	0.306	0.149	0.149	0.096
PC52	P-Availab.	B	0.485	0.227	0.143	0.143	0.089
PC53	P-Repair.	B	0.069	0.412	0.234	0.234	0.161
PC61	P-Weight	NB	497.7	652.5	747.4	916.3	1012.0
PC62	P-Space	NB	195.3	210.3	235.2	238.3	247.6
PC63	P-Fuel.Cap.	NB	960.5	656.7	656.7	577.2	790.3
CC1	C-Acq.	NB	62.74	59.03	66.22	77.14	84.39
CC2	C-Maint.	NB	28.95	12.75	8.34	14.68	14.72
CC3	C-Man.Pow.	B	0.352	0.264	0.197	0.197	0.116
CC4	C-Fuel.	NB	121.25	122.62	96.44	91.57	133.34
CC5	C-Sup.Infr.	B	0.413	0.257	0.175	0.175	0.102
RC1	R-Design	B	0.334	0.334	0.204	0.204	0.088
RC2	R-Sched.	B	0.284	0.284	0.284	0.284	0.104
RC3	R-Crw.Expr.	B	0.436	0.222	0.207	0.207	0.090
RC4	R-Support	B	0.332	0.332	0.202	0.202	0.095

B: Benefit Criteria, NB: Non-Benefit Criteria; Shaded Criteria: Quantitative Criteria

Table 6-20 Ranking determined by VIKOR method, for varying values of ν , for all candidate design architectures alternatives for conceptual design analysis of notional destroyer, for Application Case 1.

ν	COGAG	CODAG	CODAG-E	CODELAG	IFEP
	A1	A2	A3	A4	A5
0	3	1	2	4	5
0.1	2	1	3	5	4
0.2	2	1	3	5	4
0.3	2	1	3	5	4
0.4	2	1	3	5	4
0.5	2	1	3	5	4
0.6	2	1	3	5	4
0.7	2	1	3	5	4
0.8	2	1	3	5	4
0.9	2	1	4	5	3
1	2	1	4	5	3

Table 6-21 Computed VIKOR ‘Q’ values, for varying values of ν , for all candidate design architectures alternatives for conceptual design analysis of notional destroyer, for Application Case 1.

ν	COGAG	CODAG	CODAG-E	CODELAG	IFEP
	A1	A2	A3	A4	A5
0	0.2557	0.0000	0.1585	0.5027	1.0000
0.1	0.2384	0.0000	0.4845	1.0000	0.9239
0.2	0.2211	0.0000	0.4663	1.0000	0.8477
0.3	0.2038	0.0000	0.4481	1.0000	0.7716
0.4	0.1865	0.0000	0.4299	1.0000	0.6955
0.5	0.1692	0.0000	0.4118	1.0000	0.6193
0.6	0.1519	0.0000	0.3936	1.0000	0.5432
0.7	0.1346	0.0000	0.3754	1.0000	0.4671
0.8	0.1173	0.0000	0.3572	1.0000	0.3909
0.9	0.1000	0.0000	0.3390	1.0000	0.3148
1	0.0827	0.0000	0.3208	1.0000	0.2387

Table 6-22 Computed VIKOR metrics S, R, Q and determined ranks as per for all candidate design architectures alternatives for conceptual design analysis of notional destroyer, with $\nu = 0.5$.

		COGAG	CODAG	CODAG-E	CODELAG	IFEP
		A1	A2	A3	A4	A5
Case 1	S	0.30	0.26	0.44	0.83	0.39
	R	0.07	0.05	0.09	0.13	0.13
	Q	0.17	0.00	0.41	1.00	0.62
Case 2A	S	0.33	0.29	0.45	0.80	0.39
	R	0.06	0.06	0.08	0.11	0.11
	Q	0.06	0.00	0.34	1.00	0.60
Case 2B	S	0.40	0.36	0.48	0.75	0.39
	R	0.08	0.09	0.08	0.09	0.09
	Q	0.23	0.49	0.16	1.00	0.53
Case 3	S	0.26	0.23	0.43	0.85	0.34
	R	0.06	0.05	0.08	0.16	0.11
	Q	0.10	0.00	0.33	1.00	0.36
Case 4	S	0.32	0.26	0.44	0.82	0.45
	R	0.09	0.07	0.11	0.16	0.16
	Q	0.19	0.00	0.41	1.00	0.67
Case 5	S	0.36	0.31	0.46	0.79	0.43
	R	0.07	0.06	0.09	0.12	0.12
	Q	0.10	0.00	0.35	1.00	0.63

		COGAG	CODAG	CODAG-E	CODELAG	IFEP
		A1	A2	A3	A4	A5
Case 1	S	2	1	4	5	3
	R	2	1	3	4	4
	Q	2	1	3	5	4
Case 2A	S	2	1	4	5	3
	R	2	1	3	4	4
	Q	2	1	3	5	4
Case 2B	S	3	1	4	5	2
	R	2	3	1	4	4
	Q	2	3	1	5	4
Case 3	S	2	1	4	5	3
	R	2	1	3	5	4
	Q	2	1	3	5	4
Case 4	S	2	1	3	5	4
	R	2	1	3	4	4
	Q	2	1	3	5	4
Case 5	S	2	1	4	5	3
	R	2	1	3	4	4
	Q	2	1	3	5	4

Table 6-23 Selection of best suited candidate architecture and test of ‘acceptable advantage’ and ‘stability of decision’ for conceptual design analysis of notional destroyer, with $\nu = 0.5$.

	Best Suited Alternative	Acceptable Advantage (dQ)	Stability of Decision (S,R match with Q Rank)	Sensitivity to ν
Case 1	CODAG	-0.08	S & R	L
Case 2A	CODAG	-0.18	S & R	L
Case 2B	CODAG-E	-0.17	R	L
Case 3	CODAG	-0.15	S & R	L
Case 4	CODAG	-0.06	S & R	L
Case 5	CODAG	-0.15	S & R	L

$$dQ = [Q(a_Q^2) - Q(a_Q^1)] - DQ$$

Sensitivity to ν : L: Low, M: Medium H: High

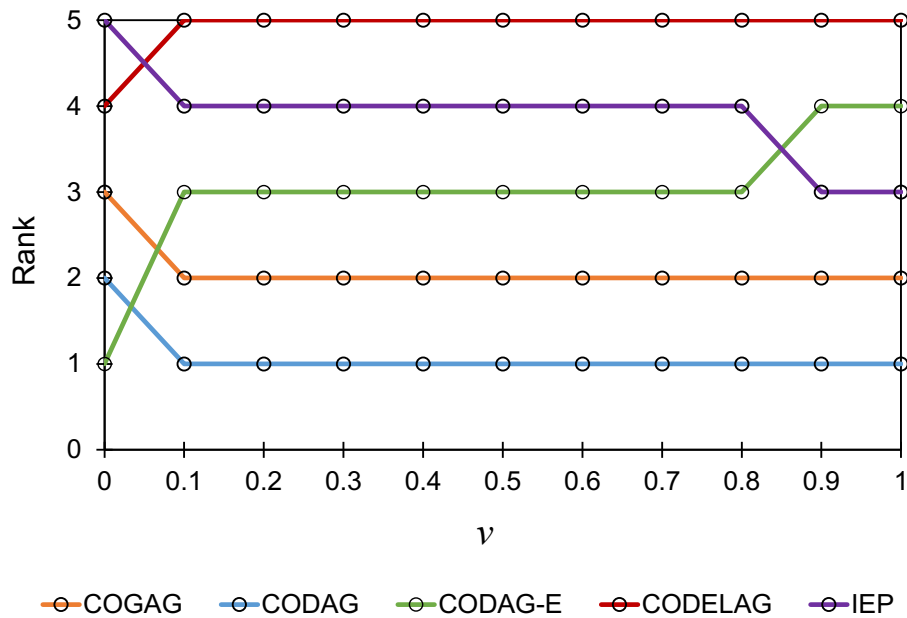


Figure 6-85 Sensitivity analysis of VIKOR ν values for Application Case 1 of conceptual design analysis of notional destroyer.

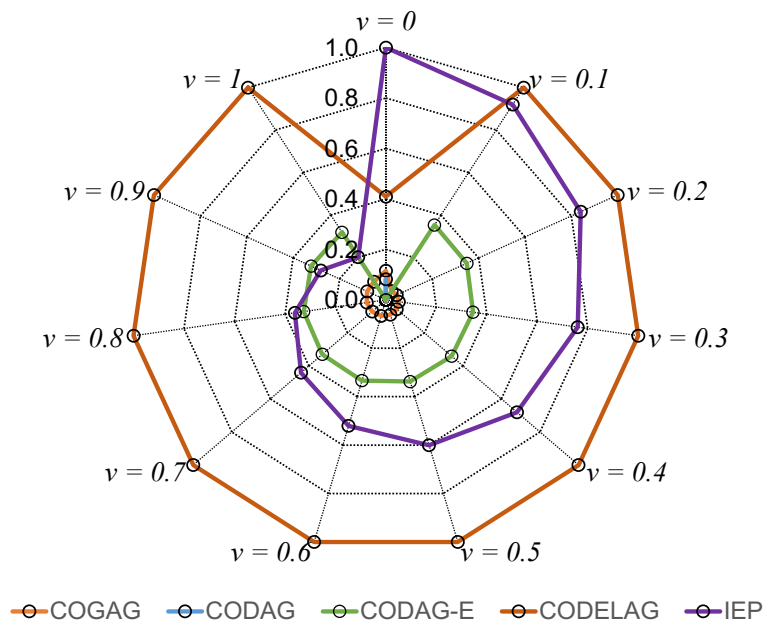


Figure 6-86 Sensitivity analysis of VIKOR ‘Q’ values for Application Case 1 of conceptual design analysis of notional destroyer.

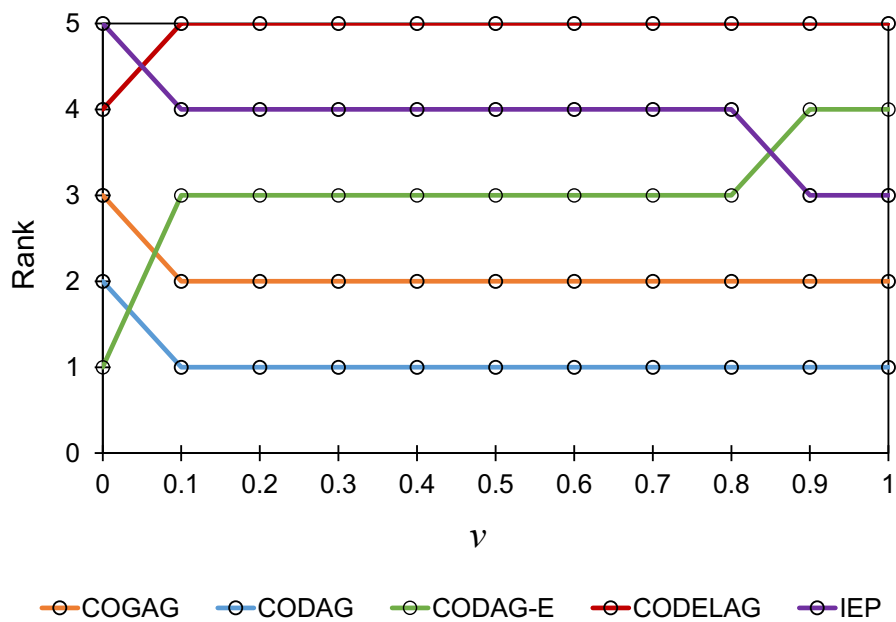


Figure 6-87 Sensitivity analysis of VIKOR v values for Application Case 2A of conceptual design analysis of notional destroyer.

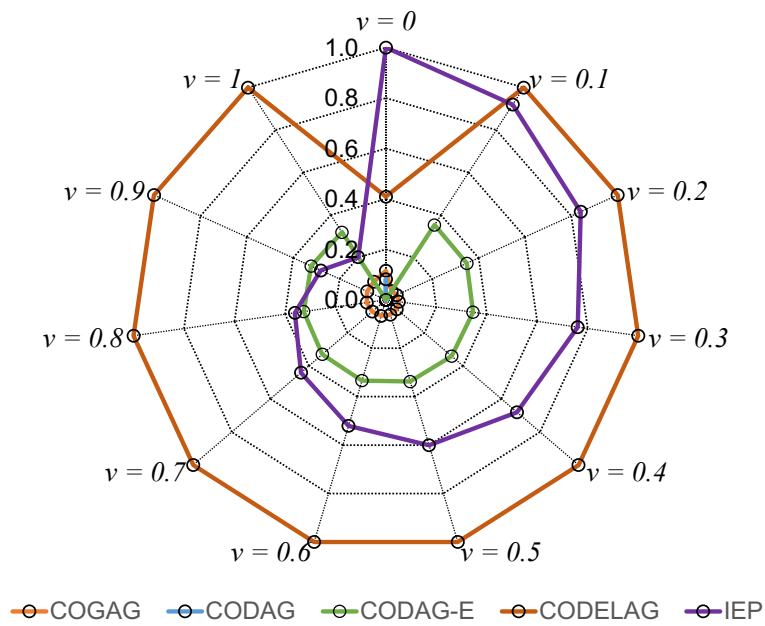


Figure 6-88 Sensitivity analysis of VIKOR 'Q' values for Application Case 2A of conceptual design analysis of notional destroyer.

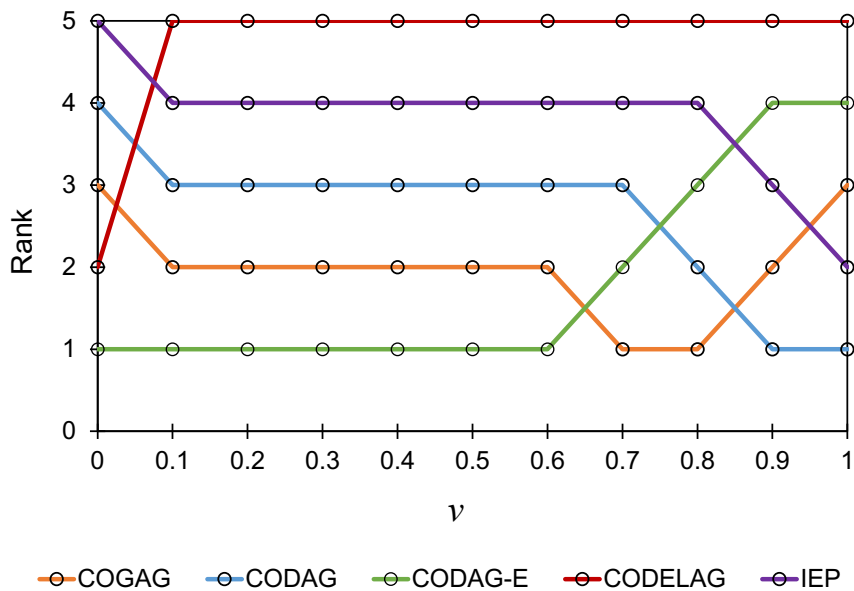


Figure 6-89 Sensitivity analysis of VIKOR v values for Application Case 2B of conceptual design analysis of notional destroyer.

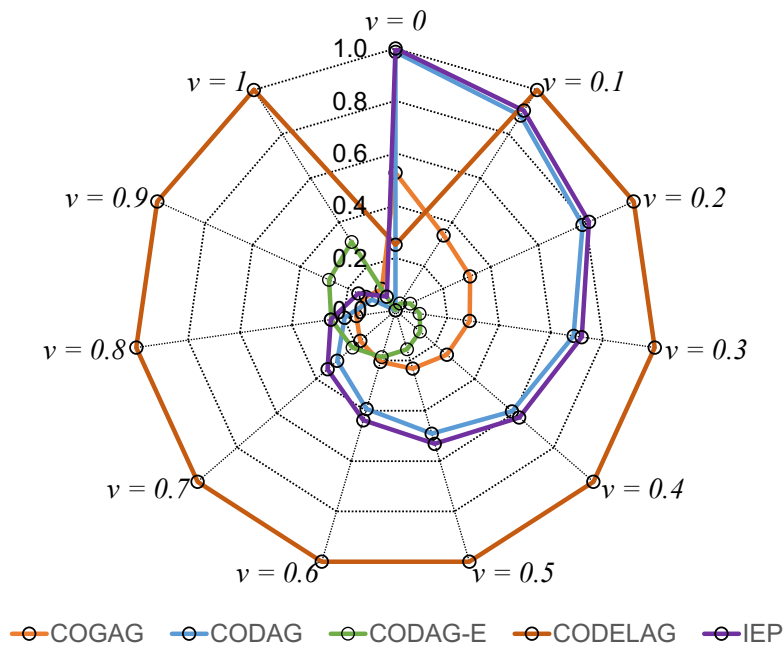


Figure 6-90 Sensitivity analysis of VIKOR ‘Q’ values for Application Case 2B of conceptual design analysis of notional destroyer.

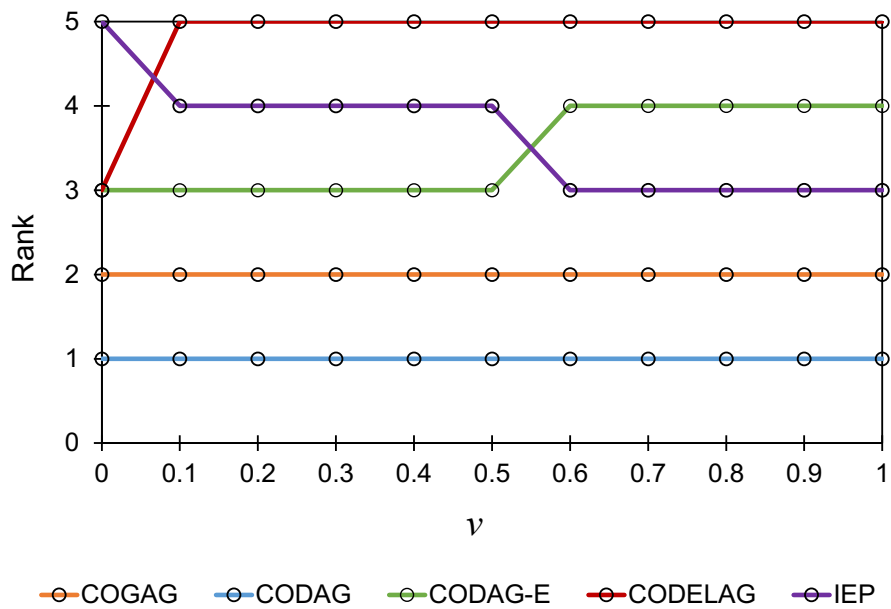


Figure 6-91 Sensitivity analysis of VIKOR v values for Application Case 3 of conceptual design analysis of notional destroyer.

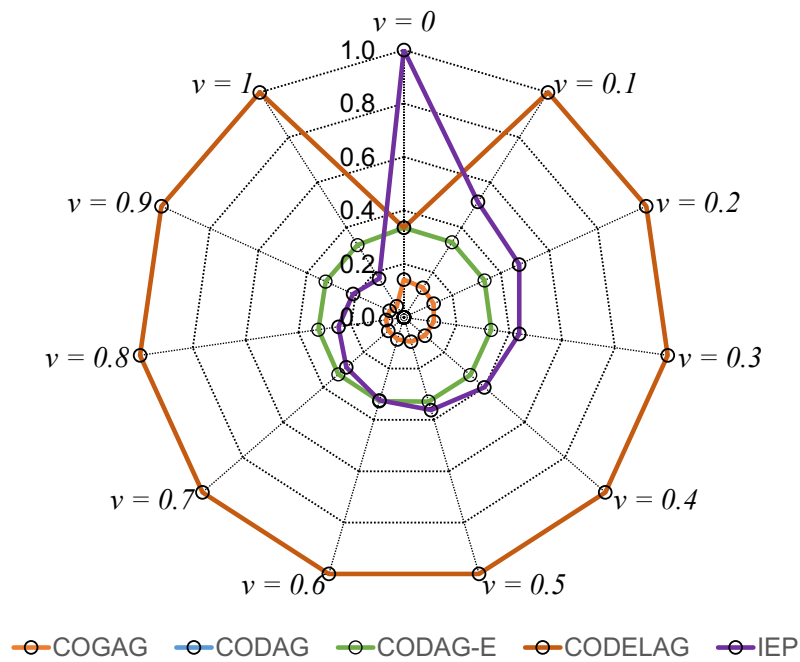


Figure 6-92 Sensitivity analysis of VIKOR 'Q' values for Application Case 3 of conceptual design analysis of notional destroyer.

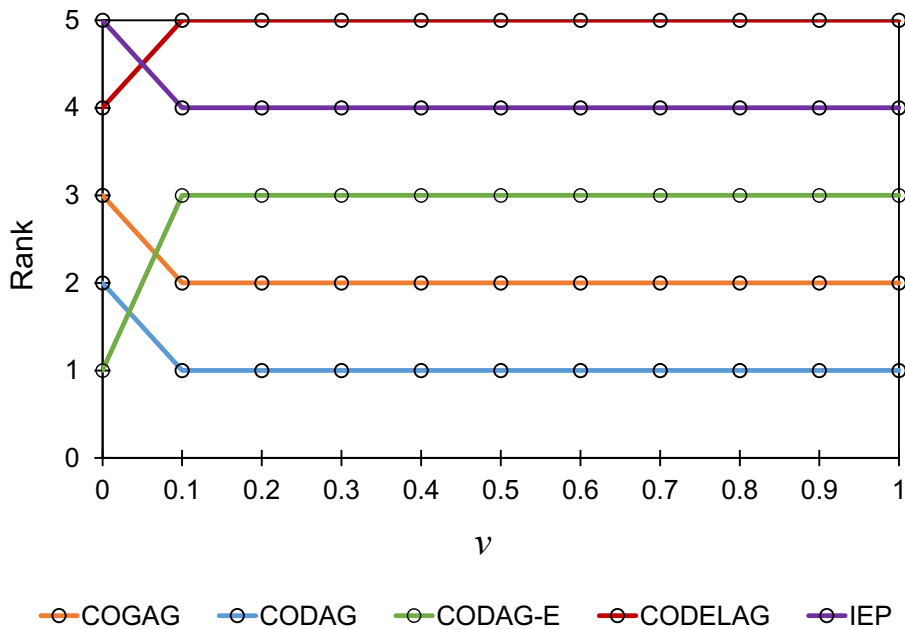


Figure 6-93 Sensitivity analysis of VIKOR v values for Application Case 4 of conceptual design analysis of notional destroyer.

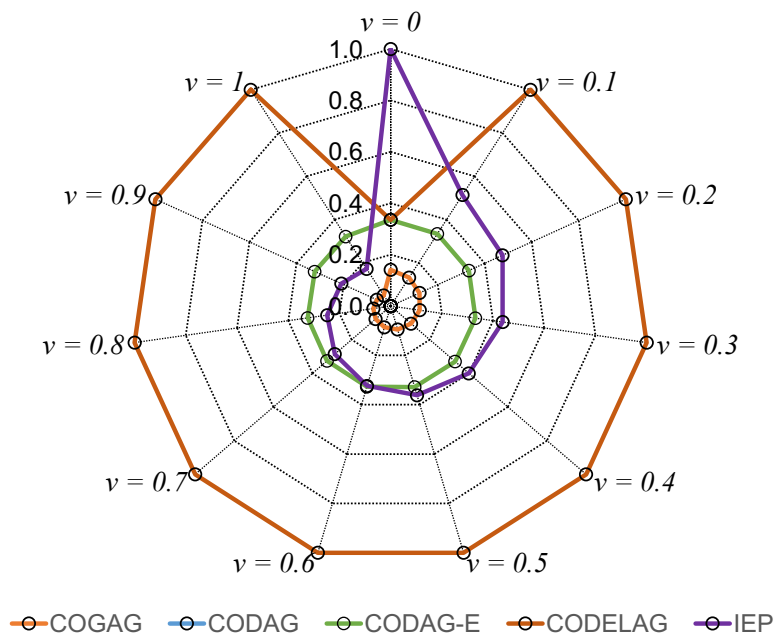


Figure 6-94 Sensitivity analysis of VIKOR 'Q' values for Application Case 4 of conceptual design analysis of notional destroyer.

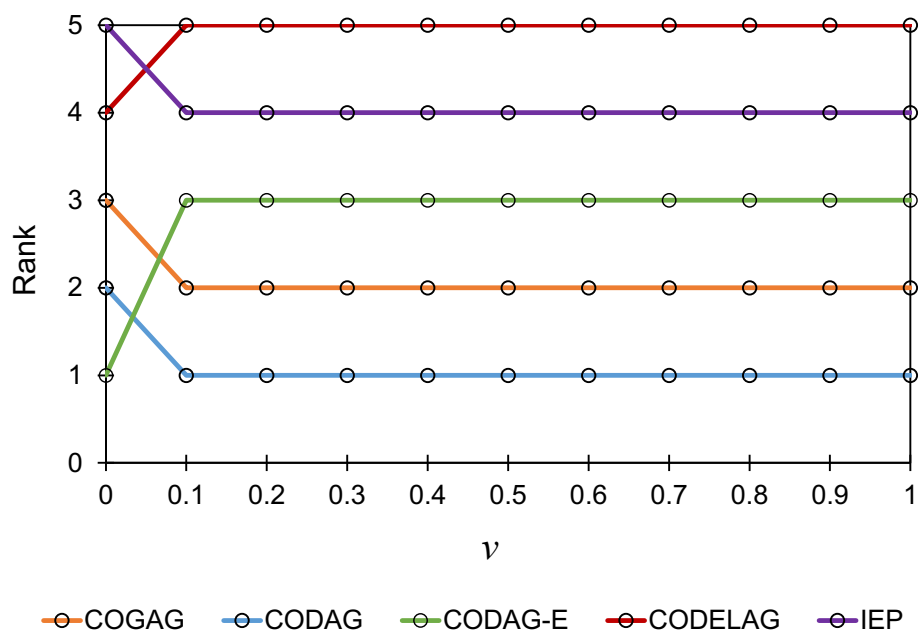


Figure 6-95 Sensitivity analysis of VIKOR v values for Application Case 5 of conceptual design analysis of notional destroyer.

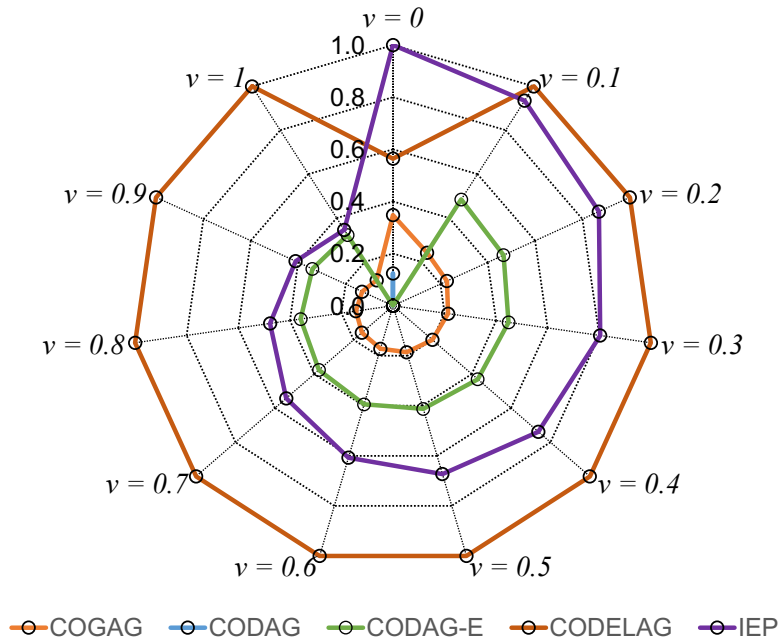


Figure 6-96 Sensitivity analysis of VIKOR ‘Q’ values for Application Case 5 of conceptual design analysis of notional destroyer.

6.5.10 Conclusions of the Propulsion System Conceptual Design Study for the Notional Destroyer

For the strategy coefficient, v , values higher than 0.5 indicate that the decision-maker is more focussed on satisfying most of the criteria, while values lower than 0.5 indicate that the decision-maker is more focussed on minimizing individual differences from the ideal solution. For the final decision making, the strategy coefficient $v = 0.5$ was primarily considered to have a ‘balanced’ decision across all the application cases, also bearing in mind the sensitivity analysis undertaken for v .

For $v = 0.5$, it can be seen from Table 6-22 that for this condition for all the application cases except Case 2B, the defined CODAG candidate architecture emerges as the architecture that is ranked first or the best-suited architecture. In Case 2B, CODAG-E emerges as the best-suited architecture. For all the application cases, COGAG emerges as the architecture ranked in second place. CODAG-E was ranked third in all cases, except Case 2B where CODAG was

ranked third. The IFEP candidate architecture was consistently ranked fourth across all the application cases.

In addition to the above analysis, it is important to also test if the preferred architecture as per the ranking from the VIKOR analysis also qualifies for the criteria for acceptable advantage and stability in decision making. The results of these tests across all the application cases are summarized in Table 6-23. It can be observed from this investigation that even though the CODAG architecture is ranked first in all the application cases except Case 2B, it does not satisfy the criteria of acceptable advantage in any of these application cases. This basically means that the degree of preference of the CODAG architecture is very close to the second-rated COGAG architecture in all the application cases except Case 2B. Hence, in these cases, the decision-makers could also select the COGAG architecture as the preferred architecture, based on certain compromises across some of the criteria. The criterion of stability of the decision-making is satisfied for both the CODAG and the COGAG architectures in all these cases. For application Case 2B even though CODAG-E emerges as the most preferred architecture based on the ranking, it does not satisfy both the criteria of criteria for acceptable advantage and stability in decision making. Hence, here too COGAG which is the second-rated architecture could be selected with certain compromises.

The sensitivity analysis undertaken with respect to the value of the strategy coefficient, ν , shows that the ranking as well as the VIKOR metric, Q , are stable in the vicinity of the selected strategy coefficient of $\nu = 0.5$. Further, the plots for the sensitivity analysis of Q also provide a good insight into the degree of acceptable advantage that one solution provides over the other across the values of the strategy coefficient. The higher the distance between the Q lines for each of the candidate architectures, the better is the degree of acceptable advantage.

The CODAG design emerges as the preferred design due to the low acquisition as well as life cycle costs and the relative simplicity of the design. The COGAG architecture provides advantages in terms of performance criteria like low mass, and occupied deck area, but has disadvantages of lowest overall plant efficiency

across the operating profile and high life cycle costs. The CODAG-E architecture provides advantages of low underwater noise and low life cycle costs, but has the disadvantages of high mass and occupied deck area. The CODELAG architecture provides relatively high plant efficiency, advantages towards some of the performance criteria, but has the disadvantages of high mass and occupied deck area. The IFEP architecture has disadvantages of high mass, occupied deck area as well as very high acquisition costs. Hence, the overall analysis undertaken using VIKOR provides fairly intuitive results.

Overall, the more traditional architectures CODAG or COGAG architecture emerge as the preferred architectures and either could be selected by the decision-makers with certain compromises. The more electric architectures were rated lower due to penalties of higher mass and occupied deck area despite some advantages they offer. From this analysis, it can be inferred that to have more electric architectures selected there have to be more specific drivers for justification of such designs than the ones that have been considered for the present analysis. On the other hand, it should also be noted that these conclusions are not general conclusions for such combined architectures, but the specific architectures considered for this analysis under the design criteria considered along with their global weights.

6.6 Notional Light Frigate Conceptual Design Study

6.6.1 Input Data for Design

The primary speed requirements for the propulsion system design were considered as >28 knots for surge speed and >18 knots for cruise speed. The minimum endurance required for the ship at speed >16 knots is 5000 nm. The considered operational profile of the ship is shown in Figure 6-97. The propulsor configuration considered was a 'twin screw' arrangement with FPP or CPP designs based on reversing requirements of the considered propulsion plant. The overall average ship auxiliary electrical load (loads other than propulsion) is considered to be 1.2 MWe. The primary parameters of the notional light frigate design considered are summarized in Table 6-24.

Table 6-24 Primary parameters of the considered notional light frigate.

Parameter	Value
Displacement	3800 metric tons approx.
Length	124 m approx.
Surge speed	>28 knots
Cruise speed	>18 knots
Ship operation per year	3200 hours
Endurance	>5000 nm @ >16 knots speed
Fuel tank capacity	< 500 metric ton
Propeller diameter	3.5 m approx.
Auxiliary electrical load	2.1 MWe

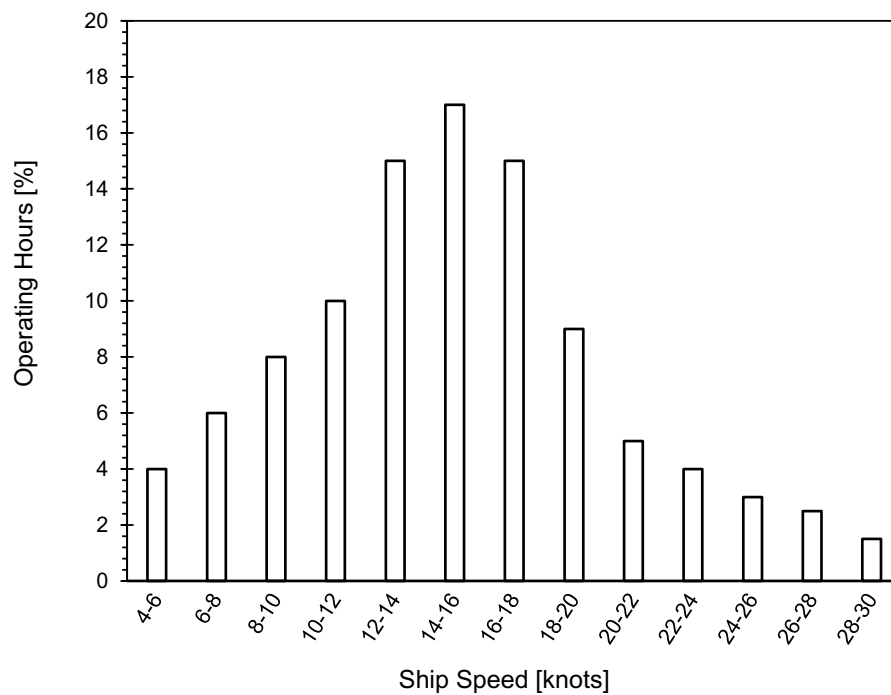


Figure 6-97 Considered operating profile for conceptual design of propulsion system for notional light frigate.

6.6.2 Hull Resistance Estimation

The primary parameters considered for the hull model, used as the input for the application of the resistance module, are given in Table 6-25. The total calm water-resistance characteristic curve was determined computed using Poseidon+. F&L method was selected for the calculation due to its suitability for high hull forms with a transom stern. The input file used for the same is shown in Appendix Q. The computed calm water resistance from the applied model is shown in Figure 6-98 without the application of any additional margins.

Table 6-25 Primary hull parameters of the notional light frigate.

Parameter	Unit	Value
Length between perpendiculars	m	123.5
Length on waterline	m	116.92
Beam on waterline	m	14.2
Draft Fwd	m	4.7
Draft Aft	m	4.7
Displacement	Metric Ton	3900
Coefficient Midship Area	-	0.82
Coefficient Waterplane	-	0.774
Area transverse transom immersed	m ²	6
Beam at transom	m	10
Half angle of entrance iE	degrees	10
Surface area of appendages	m ²	200
Air frontal area	m ²	195
Method for calculation	-	F&L

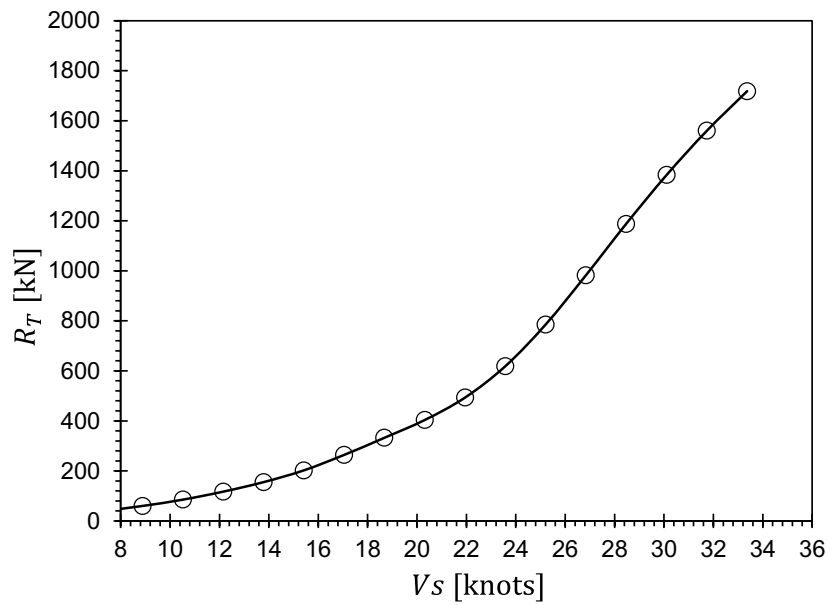


Figure 6-98 Calculated calm water resistance for the considered hull form for notional light frigate.

Table 6-26 Input data for propeller parameters optimization for the notional light frigate.

Parameter	Unit	Value
Ship speed	knots	30
Resistance for Propeller	kN	655
Thrust deduction factor	-	0.1
Wake fraction	-	0.2
Propeller diameter	m	3.52
Propeller centre depth from waterline	m	2.94
Number of blades	-	5

Table 6-27 Final parameters for the propeller design optimised for notional light frigate based on Wageningen B Series.

Parameter	Unit	Value
Propeller diameter	m	3.52
P/D Design	-	0.966
EAR	-	0.98
Number of blades	-	5

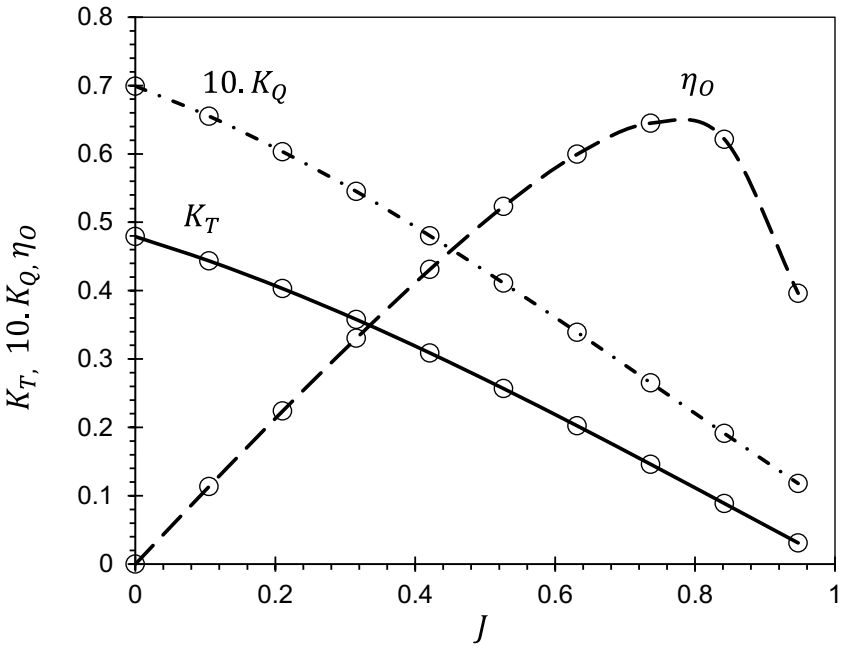


Figure 6-99 Calculated open water characteristic for the propeller design optimised for notional light frigate based on Wageningen B Series.

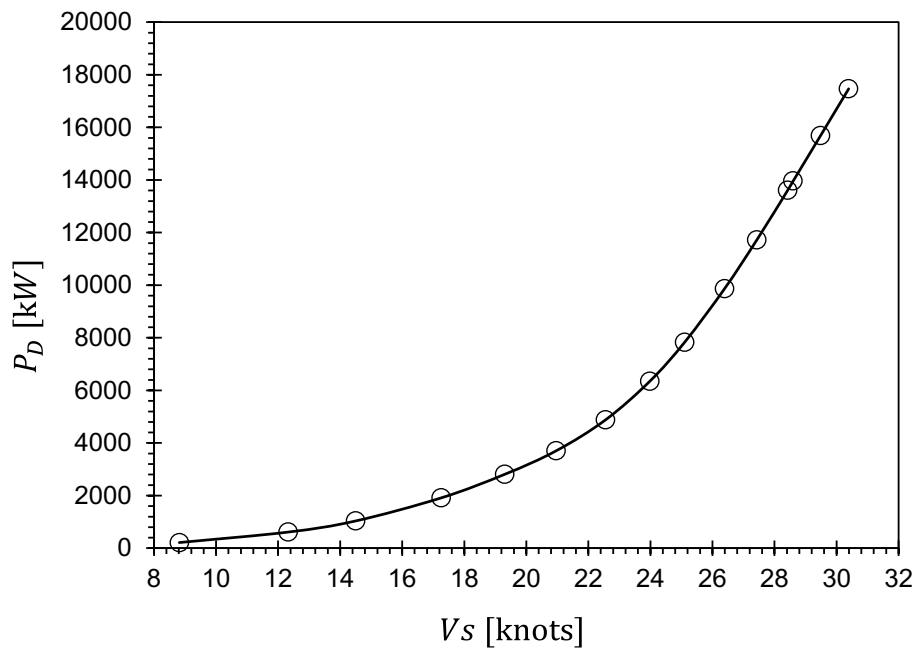


Figure 6-100 Calculated propeller delivered power (for each propeller) for ship speed for the notional light frigate in twin-propeller modes of operation.

6.6.3 Candidate Propulsion System Architectures

The given operating profile was superimposed with propeller delivered power required across the operating speed range, as shown in Figure 6-101 to determine the range of speed to be covered by specific combinations of engines. Based on this, four specific candidate propulsion system architectures were developed based on the design requirements for further MCDM analysis viz. COGAG arrangement with cruise engines connected through a 'Cross Connect Gearing' (CCG), CODAG, CODELAG and IFEP as shown from Figure 6-102 to Figure 6-105 respectively. For each of these architectures, basic engine-propeller matching and feasibility analysis were undertaken based on considerations of the engine operating envelopes etc.

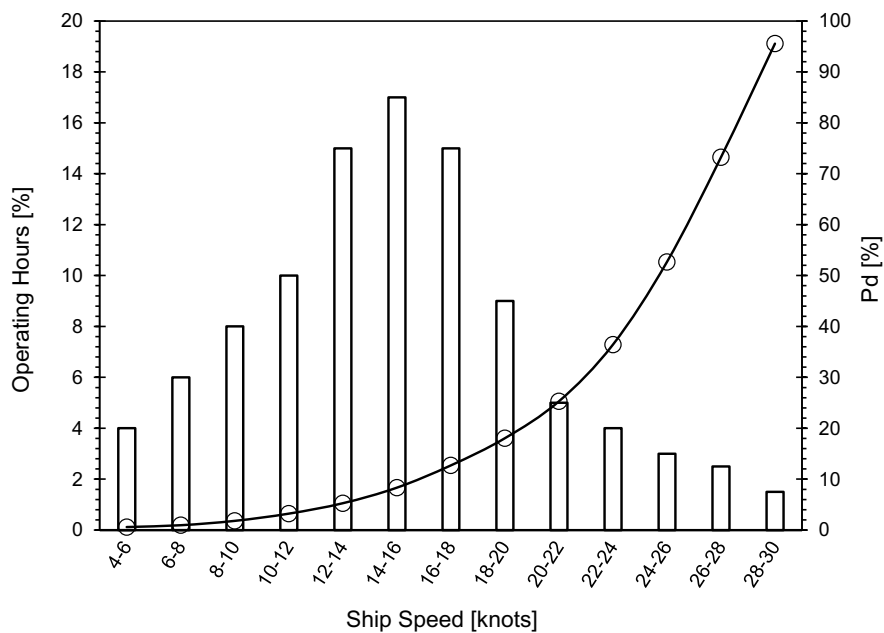


Figure 6-101 Operating profile superimposed with propeller delivered power required for the notional light frigate.

A common FPP design was selected for the propulsor configuration for COGAG, CODELAG, and IFEP designs. In the COGAG and the CODELAG arrangements, when operating on gas turbines the reversing is executed using a reversing power turbine arrangement in the gas turbines. In the IFEP arrangement and the CODELAG arrangement when operating on electric motors, the reversing is executed using the electric motors. The application of the reversing power turbine leads to the application of a simpler FPP arrangement, also allowing for a simpler propulsion control system. However, the application of a reversing power turbine arrangement leads to a relatively lower overall engine efficiency, which was considered in the respective engine models. A CPP design was selected for the CODAG architecture to enable reversing when operating with the diesel engines. Both the CPP design and FPP were considered to have the same design parameters except for the hub size.

Figure 6-102 shows the COGAG architecture applied, with each propeller is powered by a 15 MW boost gas turbine engine and a 7 MW cruise gas turbine engine with their individual reduction gearboxes. This 7MW cruise gas turbine engine is the same engine as the 7.5 MW MGT described in Appendix O.1 which

has been derated to 7MW for this application. A mechanical 'cross connect' system is arranged through CCG that enables the operation of a single 'cruise engine' to power both the propellers for increased system efficiency compared to 'trailing' a propeller while operating the ship at low speeds. The power generation system considered with this arrangement is completely separated from the propulsion system, powered by three diesel gensets each rated at 1.2 MW each. In all operating modes, two gensets are considered to be in operation, with the third genset being available for redundancy and transient loading conditions.

The applied CODAG configuration is shown in Figure 6-103, where each propeller is powered by a 15 MW boost gas turbine and a 5.5 MW cruise medium-speed diesel engine through the individual reduction gearboxes of the engines. No 'cross connection' of propulsion power from one shaft line to the other is arranged as the initial investigations, described later, proved that the benefits would be negligible compared to the added mass and complexity of a cross-connect gearing system. The power generation system considered with this arrangement is identical to the one considered for the COGAG arrangement described earlier.

Both the COGAG and CODAG architectures have been arranged with 'twin speed' gearing systems to enable the combined operation of the lower-powered 'cruise engines' together with the higher powered 'boost engines' to achieve the rated power of the propulsion plant.

The CODELAG arrangement, as shown in Figure 6-104, uses electric motors powered by a diesel-electric grid powered by four 2.7 MW medium-speed diesel engine gensets. On each shaft, a 15 MW gas turbine engine is arranged as the boost engine powering the shaft line through individual reduction gears. The electric motors and the gas turbines are designed for combined operation for achieving the rated power of the plant. Due to the large torque envelope of the electric motors, twin speed gearing is not required to combine their torque with the gas turbines. In this design, 'electric cross connection' is arranged, where a single diesel genset or set of gensets can power both the propellers through the electric motors connected by a common grid. The electric motors also serve as

generators in Power Take-Off (PTO) mode, in a specific range of speed when powered by the gas turbines. Instead of the application of two or three larger diesel engine gensets, four gensets have been used in this design to have more flexibility in managing load.

Figure 6-105 shows the IFEP arrangement considered, where the entire range of ship speed is achieved using large propulsion motors. These motors are powered by the electric grid system which is powered by a single 25 MW gas turbine gensets and a set of two 5.2 MW medium-speed diesel engine gensets. The number of engines that need to be running is determined based on the total power required by the propulsion and auxiliary shipload. To reduce the overall mass of the system to a practical value, a three genset arrangement has been applied.

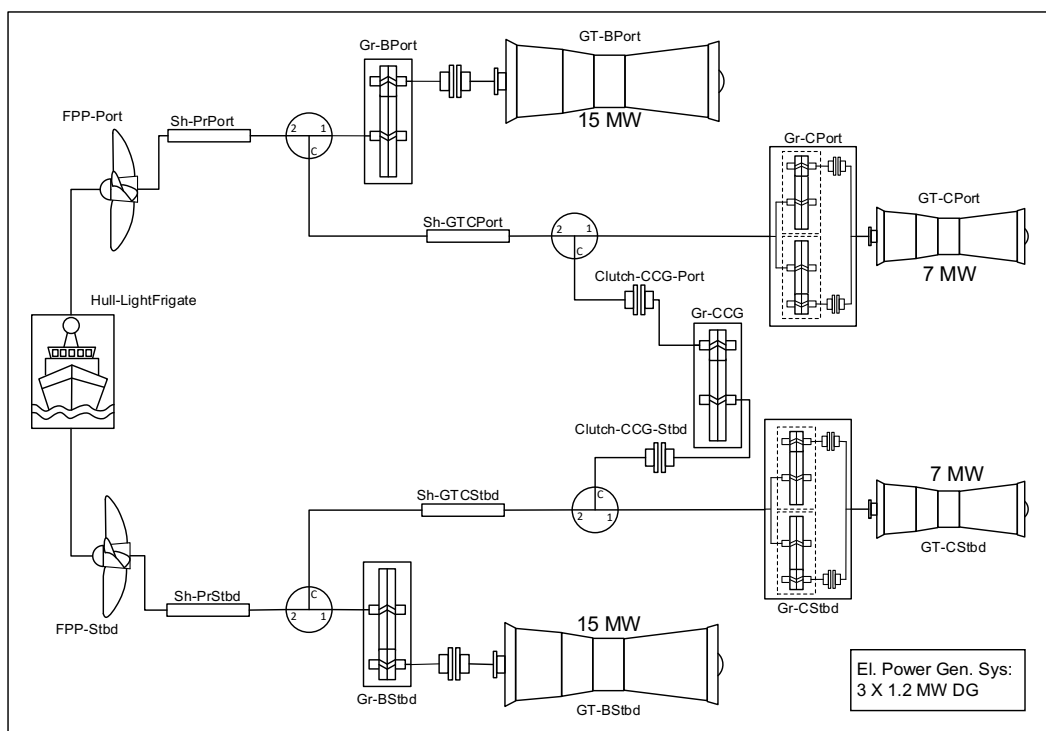


Figure 6-102 Candidate propulsion system architecture alternative A1, COGAG, for the notional light frigate.

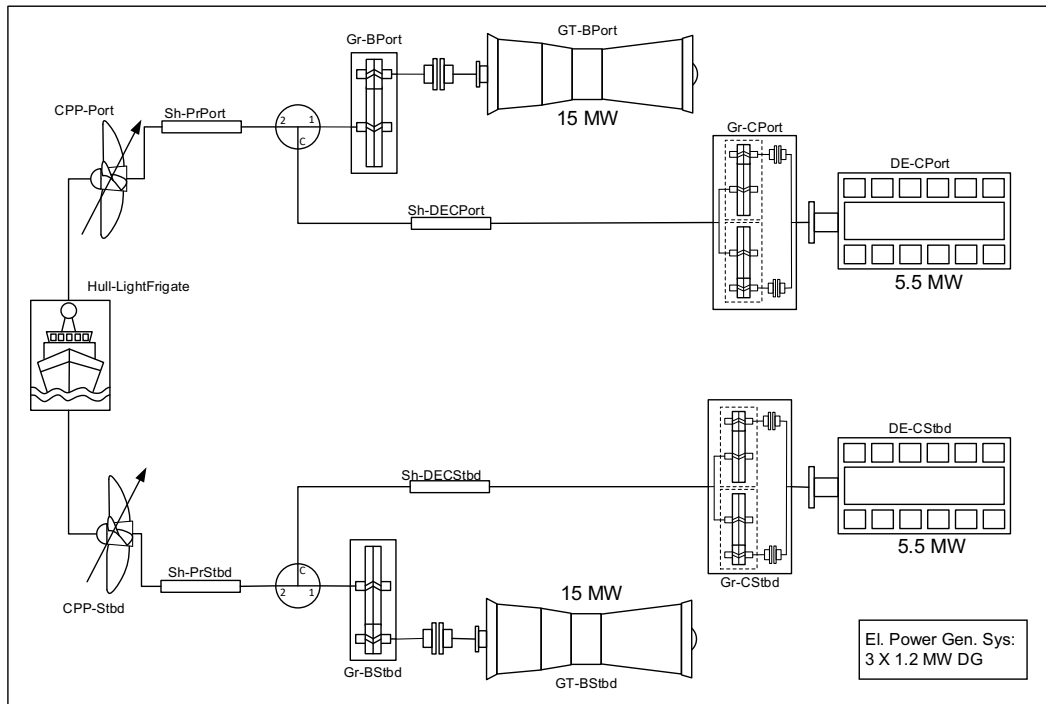


Figure 6-103 Candidate propulsion system architecture alternative A2, CODAG, for the notional light frigate.

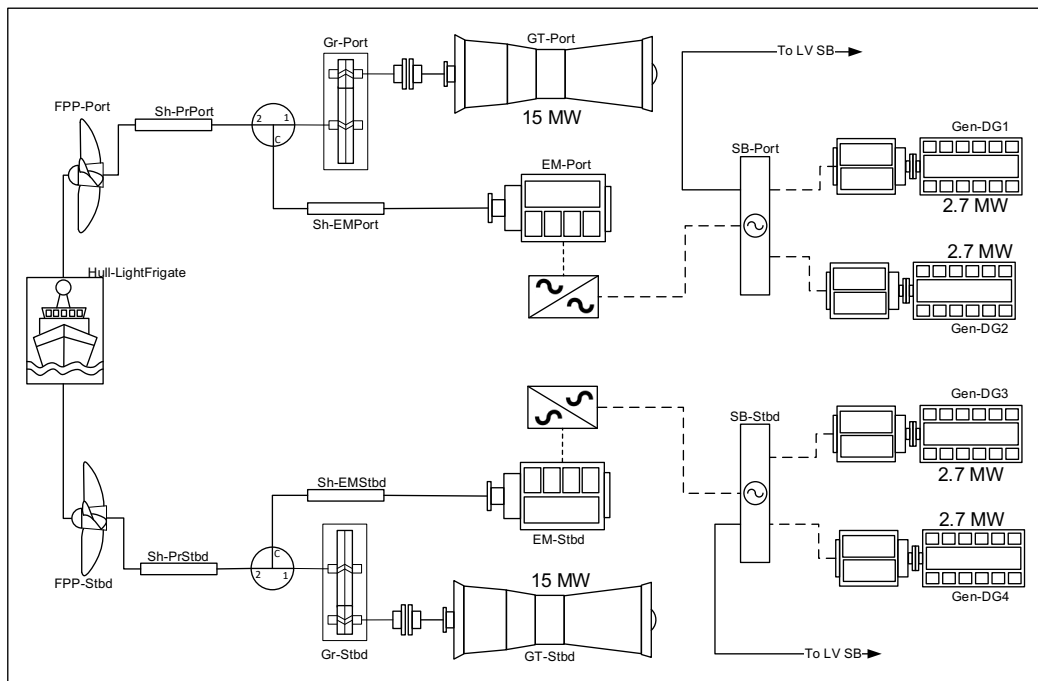


Figure 6-104 Candidate propulsion system architecture alternative A4, CODELAG, for the notional light frigate.

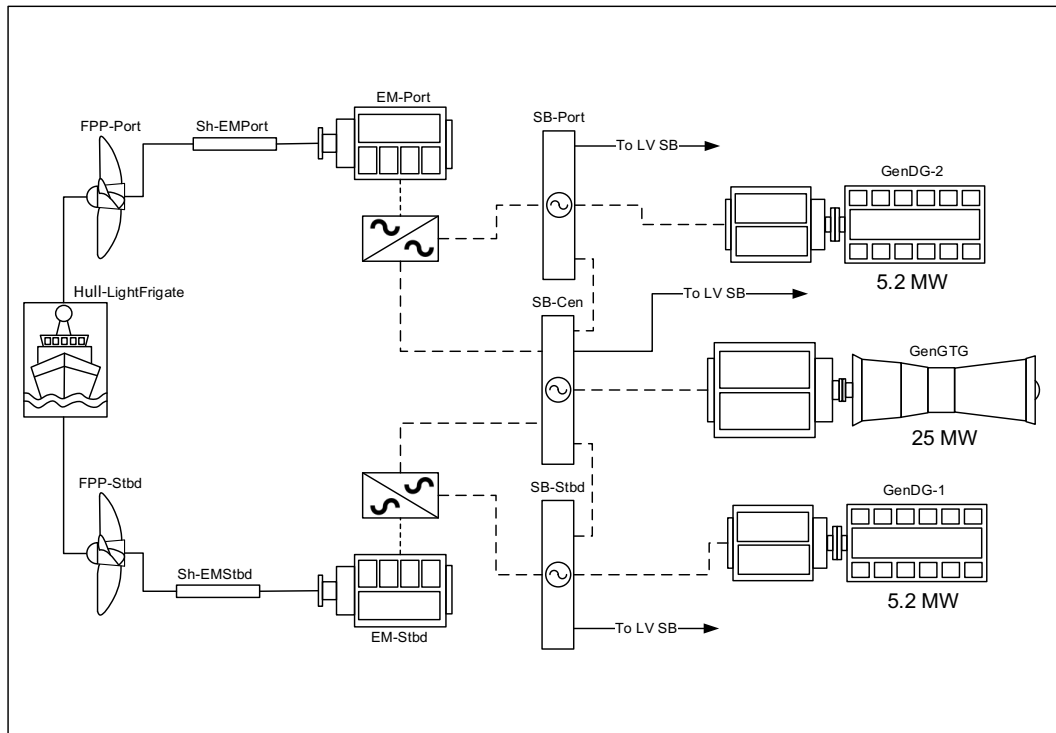


Figure 6-105 Candidate propulsion system architecture alternative A5, IFEP, for the notional light frigate.

6.6.4 Performance Modelling of Candidate Architectures

As for the analysis undertaken for the case of notional destroyer, the performance modelling of the above-described candidate architectures for the notional light frigate was undertaken by using Poseidon+. The input model files describing the models created for each of the candidate architectures are shown in Appendix Q. The primary characteristics of total fuel flow for the propulsion and power generation systems against ships speed for the candidate architectures are shown from Figure 6-106 to Figure 6-112. The comparative bar graphs for the candidate architectures with respect to maximum surge speed, cruising speed, endurance (range) based on tank capacity, required fuel tank capacity based on range requirement are shown from Figure 6-113 to Figure 6-116, respectively.

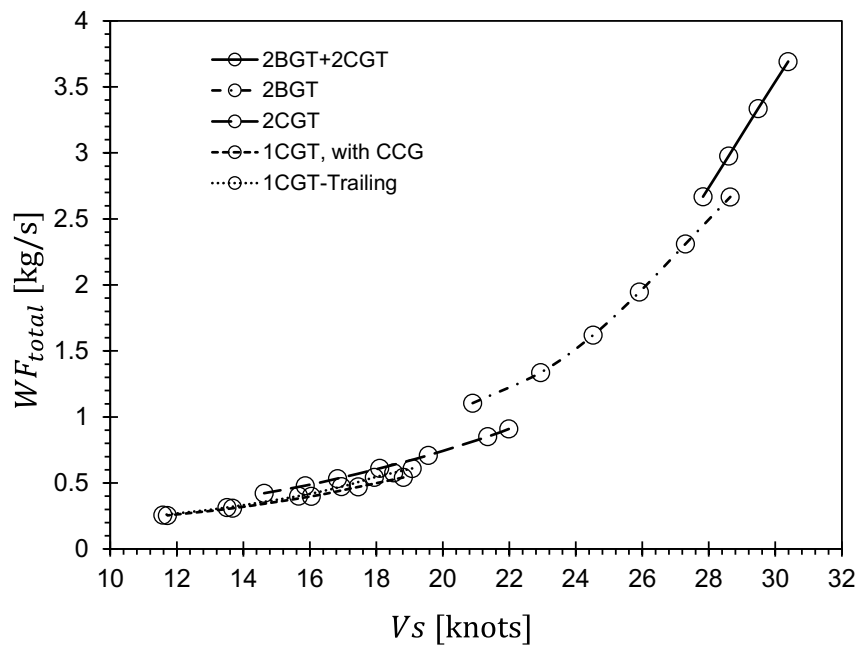


Figure 6-106 Computed overall fuel consumption curves at defined operating drive modes for the candidate architecture alternative A1 COGAG for conceptual design analysis of notional light frigate.

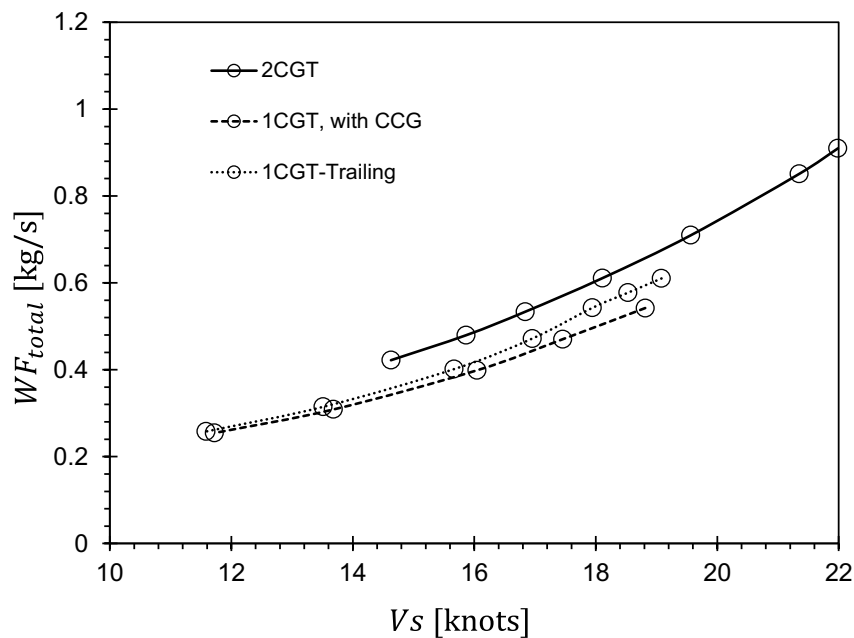


Figure 6-107 Computed overall fuel consumption curves at defined operating drive modes for the candidate architecture alternative A1 COGAG (low-speed operations) for conceptual design analysis of notional light frigate.

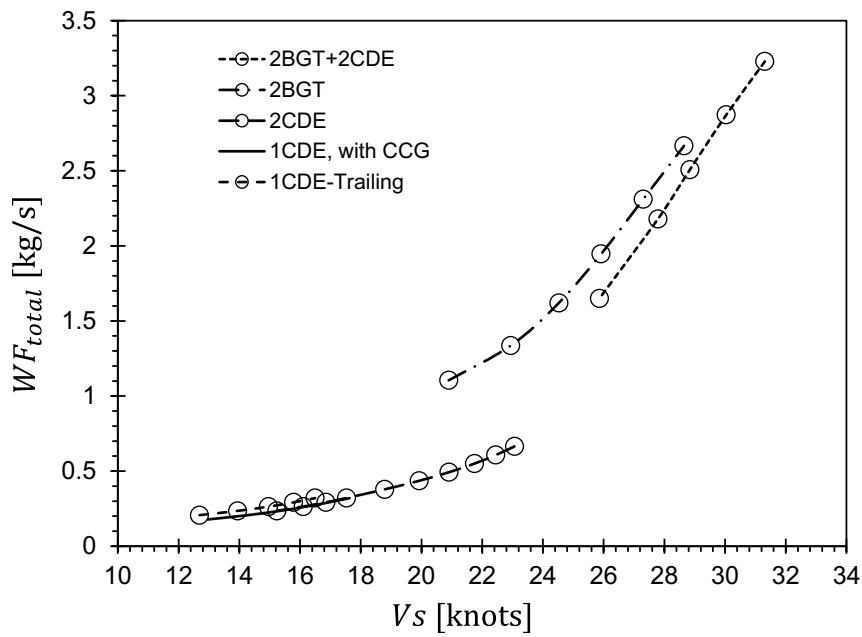


Figure 6-108 Computed overall fuel consumption curves at defined operating drive modes for the candidate architecture alternative A2 CODAG for conceptual design analysis of notional light frigate.

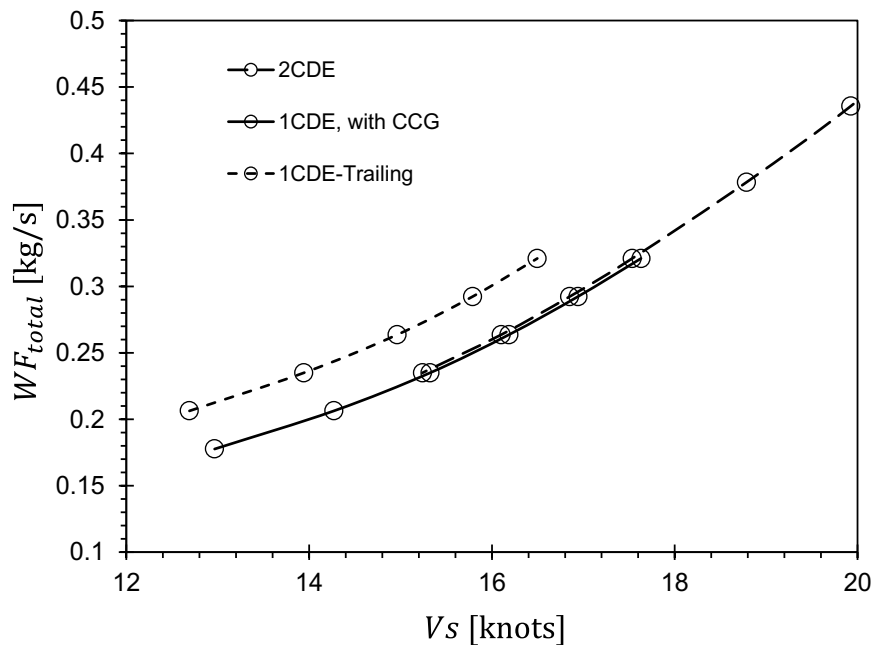


Figure 6-109 Computed overall fuel consumption curves at defined operating drive modes [overall] for the candidate architecture alternative A2 CODAG for conceptual design analysis of notional light frigate.

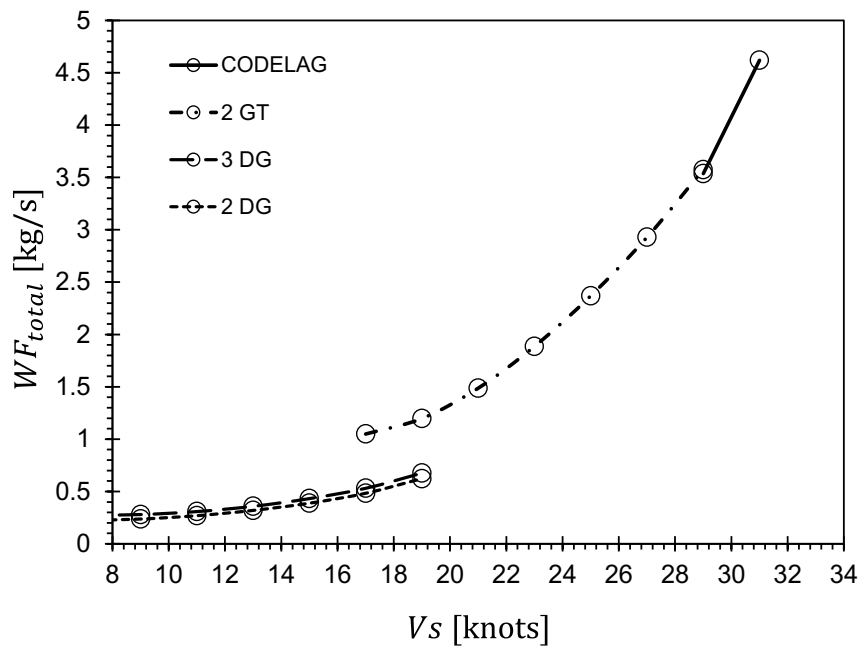


Figure 6-110 Computed overall fuel consumption curves at defined operating drive modes for [low speed range] the candidate architecture alternative A4 CODELAG for conceptual design analysis of notional light frigate.

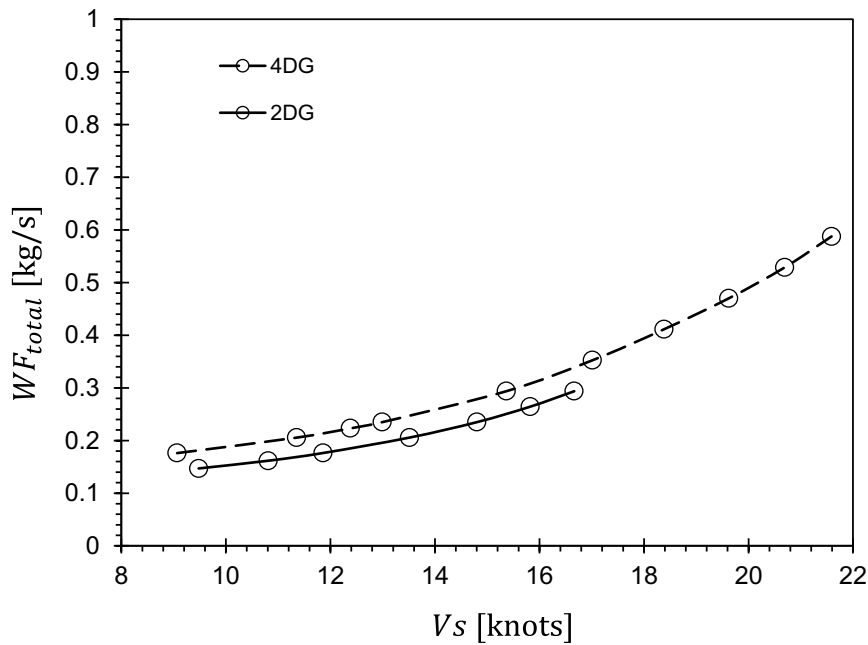


Figure 6-111 Computed overall fuel consumption curves at defined operating drive modes for the candidate architecture alternative A4 CODELAG for conceptual design analysis of notional light frigate.

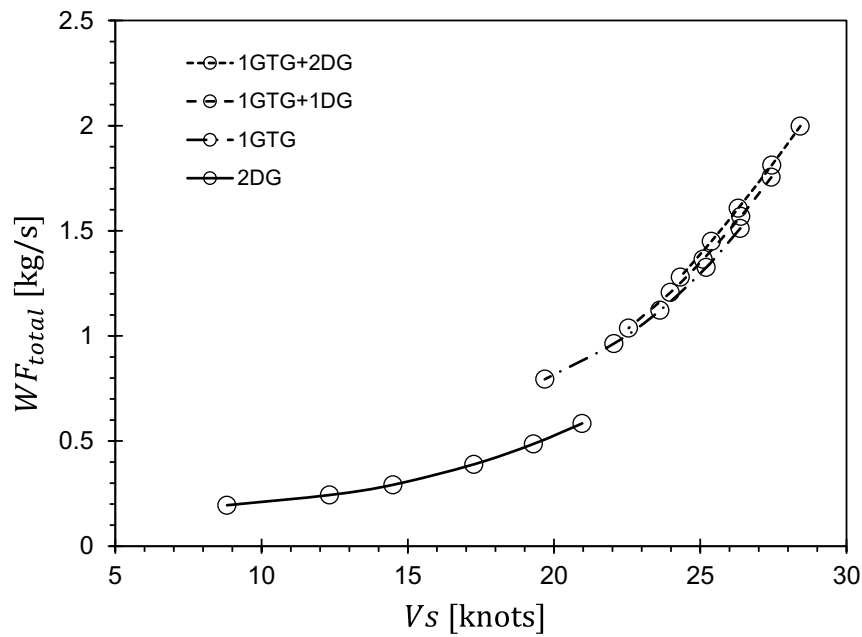


Figure 6-112 Computed overall fuel consumption curves at defined operating drive modes for the candidate architecture alternative A5 IFEP for conceptual design analysis of notional light frigate.

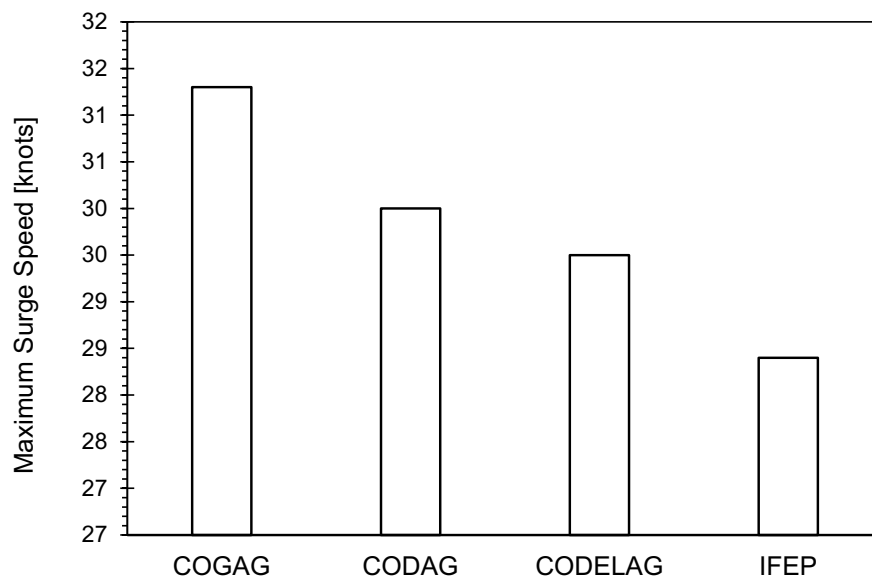


Figure 6-113 Computed maximum surge speed of propulsion system candidate architectures for conceptual design analysis of notional light frigate.

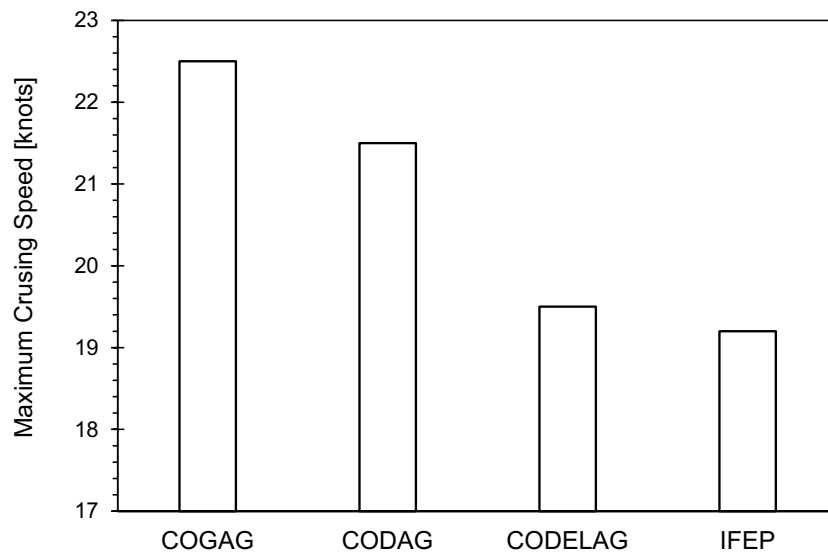


Figure 6-114 Computed maximum cruising speed of propulsion system candidate architectures for conceptual design analysis of notional light frigate.

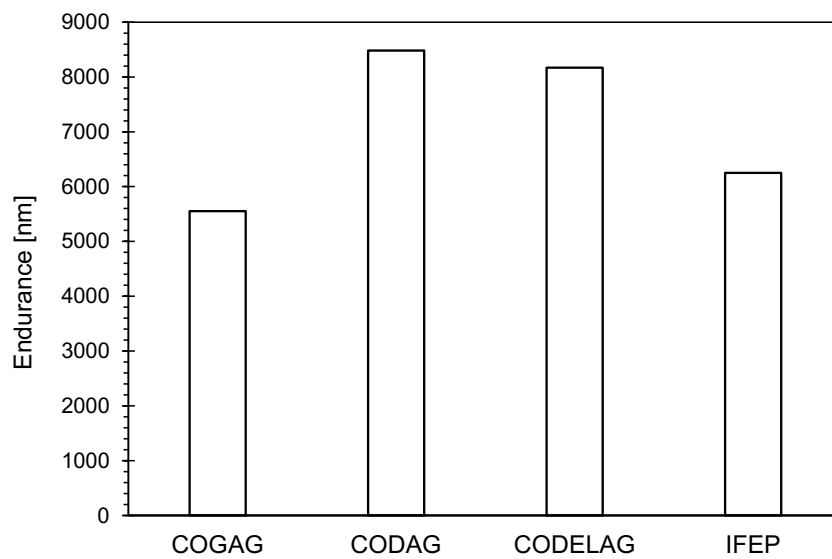


Figure 6-115 Computed endurance (range) based on tank capacity of 500 tons with ship speed of 14 knots for propulsion system candidate architectures for conceptual design analysis of notional light frigate.

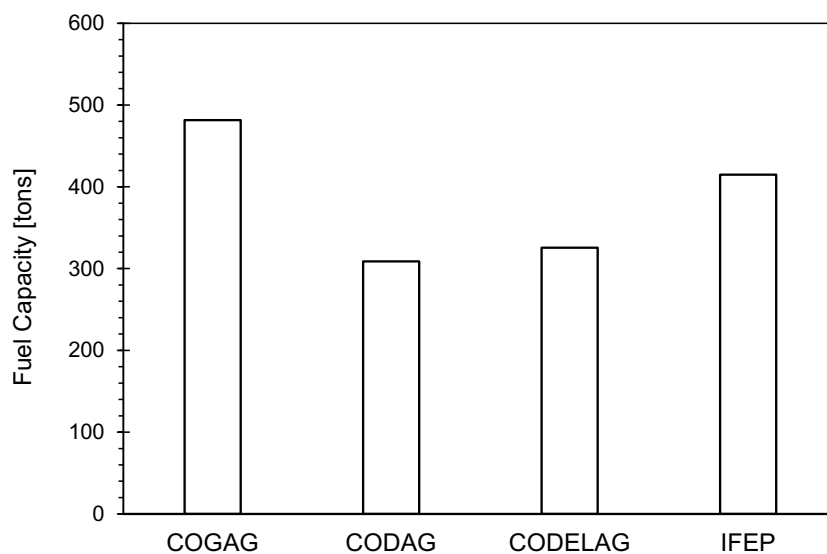


Figure 6-116 Computed required fuel tank capacity based on range requirement of 5000 nm with ship speed of 16 knots of propulsion system candidate architectures for conceptual design analysis of notional light frigate.

6.6.5 Mass and Dimensional estimations

The dimensioning models as described in Appendix I were used to calculate though overall mass and occupied deck area for each of the candidate architectures, using the same methodology and conditions as described for the case of analysis for the notional destroyer. The comparative bar graphs of the various architectures in terms of mass and occupied deck area are shown in Figure 6-117 and Figure 6-118, respectively.

6.6.6 Estimation of Costs

Using the same methodology as described for the case of analysis for notional destroyer, the costing models as described in Appendix J, adapted for the year 2021, were used to calculate the overall acquisition and maintenance costs for each of the candidate architectures. The comparative bar graphs of the various architectures in terms of acquisition and maintenance costs are shown in Figure 6-119 and Figure 6-120, respectively. The lifetime costs for fuel are shown in Figure 6-121. The overall distribution of considered costs over the entire life cycle is shown in Figure 6-122.

6.6.7 Calculation of Relative Scores for Qualitative Criteria

For the evaluation of the candidate architectures against the qualitative criteria (P4-P15, C3, C5, R1-R4), the author again used discussions with experienced colleagues from the domain, to undertake an AHP based pairwise comparison method to arrive at the relative evaluation scores for the candidate architectures. The computed relative scores for the candidate architectures against the qualitative criteria are shown from Figure 6-123 to Figure 6-125.

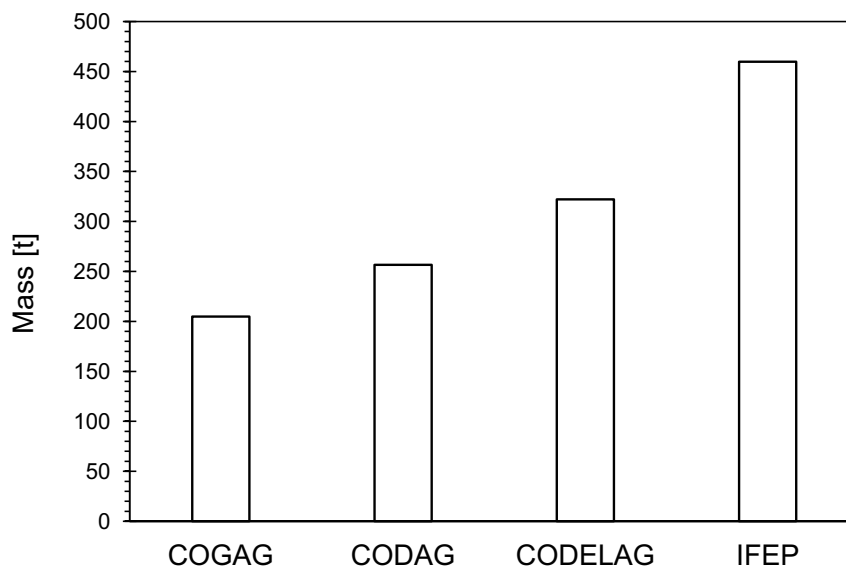


Figure 6-117 Computed mass of the main propulsion and power generation equipment for the candidate architecture alternatives for conceptual design analysis of notional light frigate

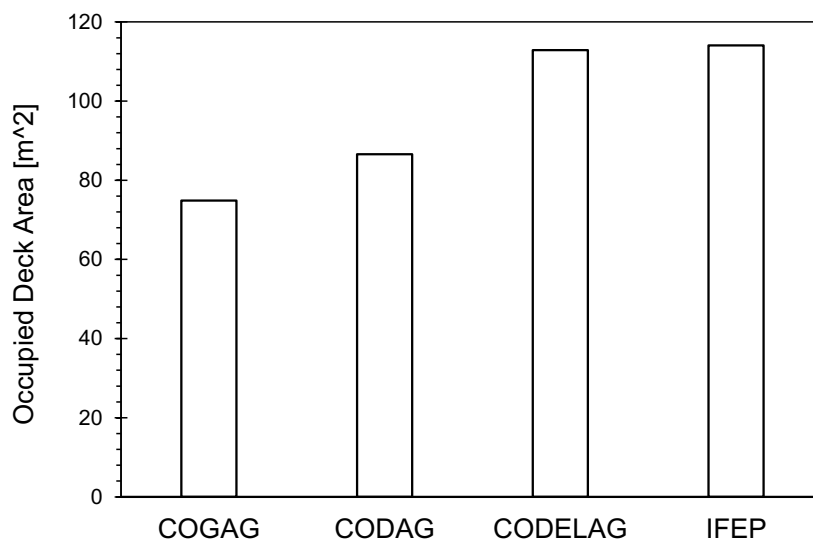


Figure 6-118 Computed occupied deck area of the main propulsion and power generation equipment for the candidate architecture alternatives for conceptual design analysis of notional light frigate

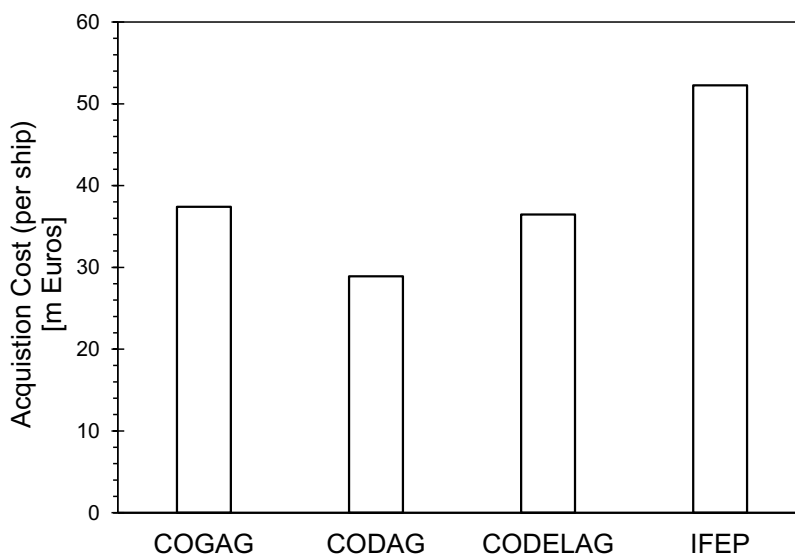


Figure 6-119 Computed acquisition cost of the main propulsion and power generation equipment for the candidate architecture alternatives for conceptual design analysis of notional light frigate

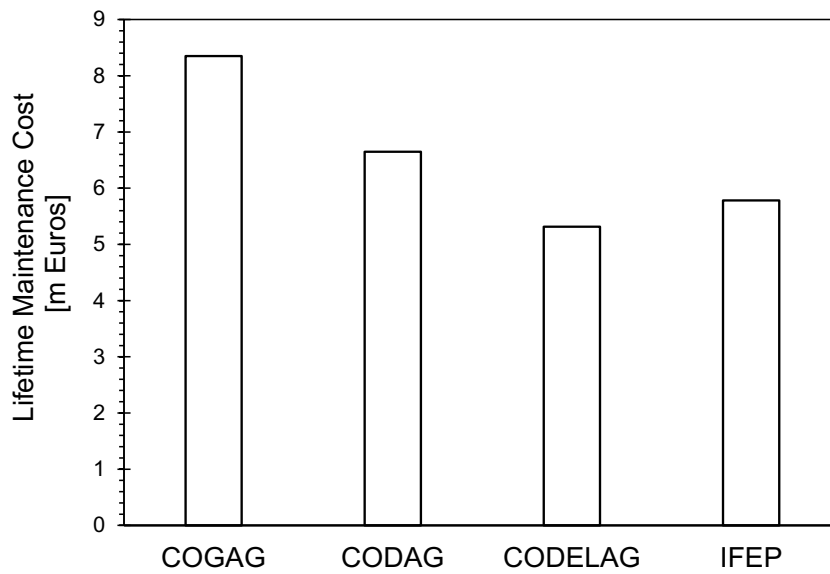


Figure 6-120 Computed lifetime maintenance cost for the main propulsion and power generation equipment for the candidate architecture alternatives for conceptual design analysis of notional light frigate

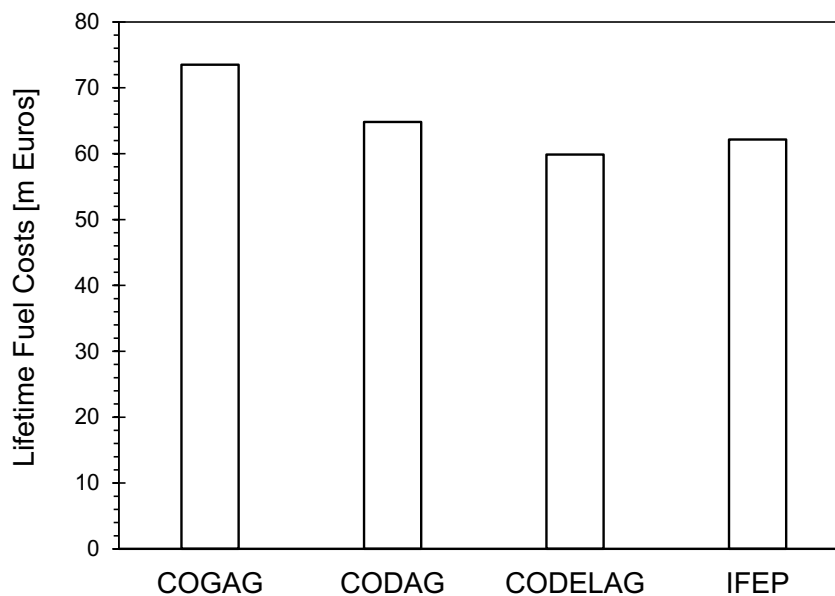


Figure 6-121 Computed lifetime fuel costs of the main propulsion and power generation equipment for the candidate architecture alternatives for conceptual design analysis of notional light frigate. Average fuel price considered 480.3 Euro per ton based on US Defense Logistics Agency (DLA) Energy publication for 2020.

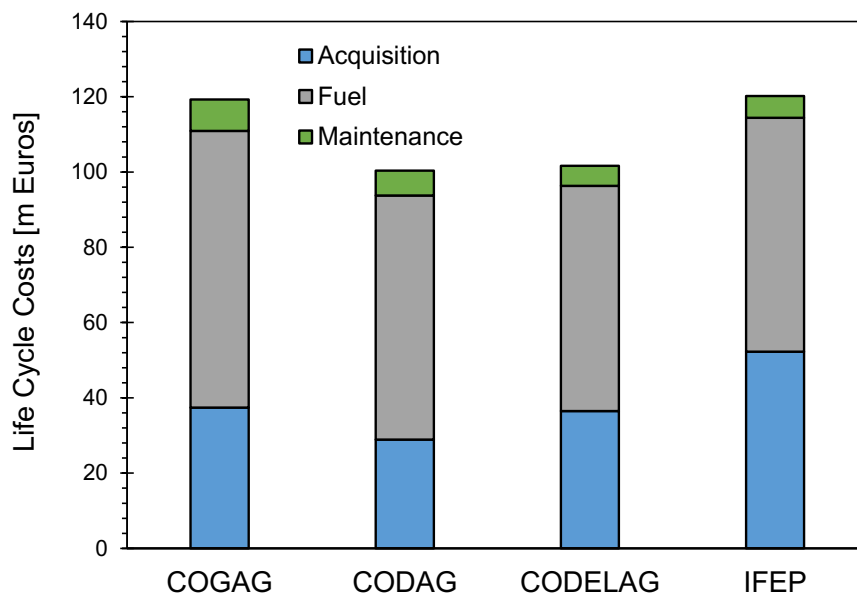


Figure 6-122 Computed life cycle costs of the main propulsion and power generation equipment for the candidate architecture alternatives for conceptual design analysis of notional light frigate

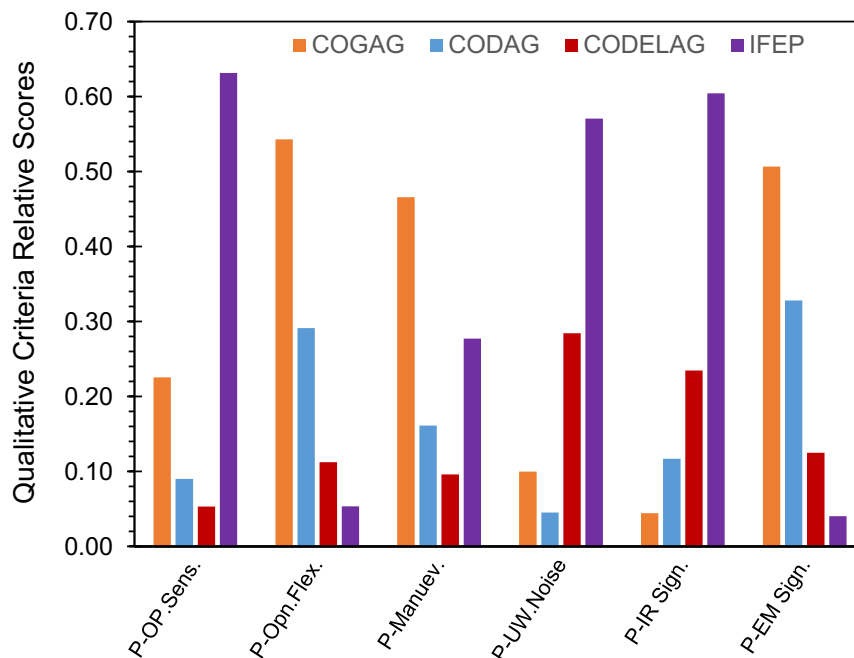


Figure 6-123 Computed relative scores of candidate architecture against qualitative criteria (P4-P9) for conceptual design analysis of notional light frigate

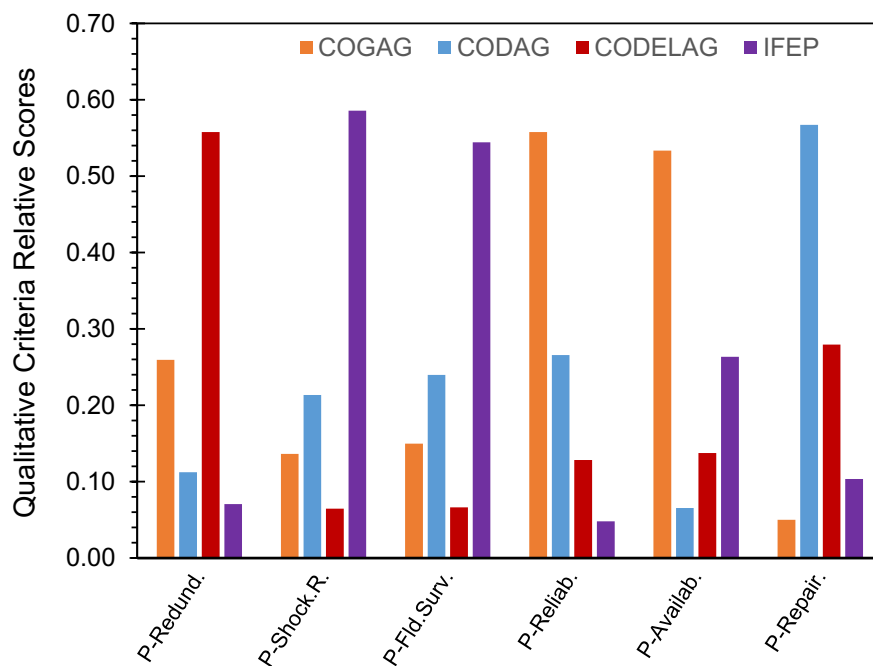


Figure 6-124 Computed relative scores of candidate architecture against qualitative criteria (P10-P15) for conceptual design analysis of notional light frigate

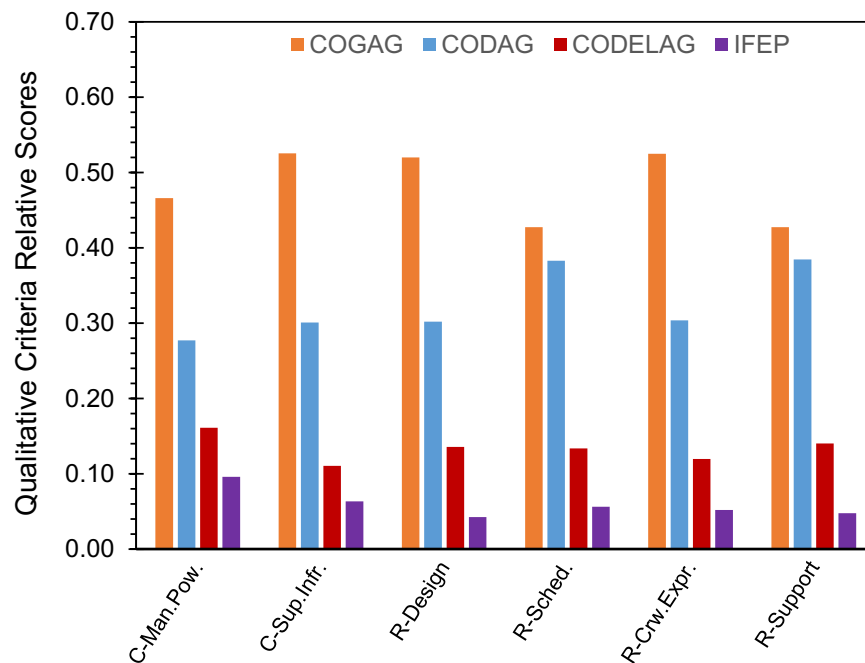


Figure 6-125 Computed relative scores of candidate architecture against qualitative criteria (C3, C5, R1-R4) for conceptual design analysis of notional light frigate

6.6.8 Objective Comparison of Candidate Propulsion System Designs using VIKOR

The techno-economic comparative analysis of the candidate architectures was undertaken the VIKOR method, as described in Appendix N, again following the same process as that described for the case of notional destroyer analysis. The set of metrics obtained against the combined set of quantitative and qualitative criteria, for each of the candidate design architecture alternatives, serving as the input data for the VIKOR analysis is shown in Table 6-28.

As for the notional destroyer analysis, the VIKOR analysis was commenced by setting the value of the 'strategy coefficient' as $v = 0.5$ and the candidate design architectures were rated by calculating the VIKOR parameters S, R, Q . The results of the determined values of S, R, Q and the ranking for each of the application cases are shown in Table 6-29.

For the best-suited alternative identified, further verification was undertaken to check if the conditions of 'acceptable advantage' and 'stability in decision making' were met. In addition, a sensitivity analysis of the ranking and values of Q to the 'strategy coefficient', was undertaken by varying the 'strategy coefficient' v between 0 and 1 at increments of 0.1 to evaluate the robustness and steadiness of the solution. The results of this analysis are shown from Figure 6-126 to Figure 6-137.

Table 6-28 Combined table of qualitative and quantitative metrics for all candidate design architectures alternatives for conceptual design analysis of notional light frigate, against the complete set of design criteria

Criteria			COGAG	CODAG	CODELAG	IFEP
			A1	A2	A3	A4
PC11	P-Surg.spd.	B	31.3	30	29.5	28.4
PC12	P-Cruis.spd.	B	22.5	21.5	19.5	19.2
PC13	P-Endur.	B	5553	8484	8172	6249
PC21	P-OP.Sens.	B	0.225	0.090	0.053	0.631
PC22	P-Opn.Flex.	B	0.543	0.291	0.112	0.054
PC23	P-Manuev.	B	0.466	0.161	0.096	0.277
PC31	P-UW.Noise	B	0.100	0.045	0.284	0.571
PC32	P-IR Sign.	B	0.044	0.117	0.235	0.604
PC33	P-EM Sign.	B	0.507	0.328	0.125	0.040
PC41	P-Redund.	B	0.259	0.112	0.558	0.071
PC42	P-Shock.R.	B	0.136	0.214	0.064	0.586
PC43	P-Fld.Surv.	B	0.150	0.240	0.066	0.544
PC51	P-Reliab.	B	0.558	0.266	0.128	0.048
PC52	P-Availab.	B	0.534	0.065	0.137	0.264
PC53	P-Repair.	B	0.050	0.567	0.279	0.104
PC61	P-Weight	NB	204.8	251.7	297.4	459.7
PC62	P-Space	NB	74.9	79.7	111.5	114.1
PC63	P-Fuel.Cap.	NB	481.6	308.8	325.4	414.9
CC1	C-Acq.	NB	37.41	28.54	35.95	52.26
CC2	C-Maint.	NB	8.35	6.65	5.32	5.78
CC3	C-Man.Pow.	B	0.466	0.277	0.161	0.096
CC4	C-Fuel.	NB	73.50	64.80	59.90	62.20
CC5	C-Sup.Infr.	B	0.525	0.301	0.110	0.063
RC1	R-Design	B	0.520	0.302	0.136	0.042
RC2	R-Sched.	B	0.427	0.383	0.134	0.056
RC3	R-Crw.Expr.	B	0.525	0.304	0.120	0.052
RC4	R-Support	B	0.427	0.385	0.140	0.048

B: Benefit Criteria, NB: Non-Benefit Criteria; Shaded Criteria: Quantitative Criteria

Table 6-29 Computed VIKOR metrics S, R, Q and determined ranks as per for all candidate design architectures alternatives for conceptual design analysis of notional light frigate, with $\nu = 0.5$

		COGAG	CODAG	CODELAG	IFEP
		A1	A2	A3	A4
Case 1	S	0.36	0.32	0.54	0.77
	R	0.07	0.06	0.10	0.13
	Q	0.15	0.00	0.56	1.00
Case 2A	S	0.38	0.33	0.55	0.75
	R	0.06	0.06	0.08	0.11
	Q	0.07	0.00	0.51	1.00
Case 2B	S	0.43	0.37	0.55	0.71
	R	0.08	0.09	0.09	0.09
	Q	0.09	0.48	0.45	1.00
Case 3	S	0.30	0.31	0.58	0.80
	R	0.06	0.07	0.13	0.16
	Q	0.00	0.06	0.62	1.00
Case 4	S	0.39	0.31	0.51	0.75
	R	0.09	0.05	0.08	0.16
	Q	0.28	0.00	0.38	1.00
Case 5	S	0.41	0.34	0.53	0.73
	R	0.06	0.07	0.07	0.11
	Q	0.09	0.03	0.27	1.00

		COGAG	CODAG	CODELAG	IFEP
		A1	A2	A3	A4
Case 1	S	2	1	3	4
	R	2	1	3	4
	Q	2	1	3	4
Case 2A	S	2	1	3	4
	R	2	1	3	4
	Q	2	1	3	4
Case 2B	S	2	1	3	4
	R	1	3	2	4
	Q	1	3	2	4
Case 3	S	1	2	3	4
	R	1	2	3	4
	Q	1	2	3	4
Case 4	S	2	1	3	4
	R	3	1	2	4
	Q	2	1	3	4
Case 5	S	2	1	3	4
	R	1	3	2	4
	Q	2	1	3	4

Table 6-30 Selection of best-suited candidate architecture and test of ‘acceptable advantage’ and ‘stability of decision’, for $\nu = 0.5$.

	Best Suited Alternative	Acceptable Advantage (dQ)	Stability of Decision (S,R match with Q Rank)	Sensitivity to ν
Case 1	CODAG	-0.18	S & R	L
Case 2A	CODAG	-0.26	S & R	L
Case 2B	COGAG	+0.03	R	L
Case 3	COGAG	-0.26	S & R	L
Case 4	CODAG	-0.05	S	L
Case 5	CODAG	-0.28	S	L

$$dQ = [Q(a_Q^2) - Q(a_Q^1)] - DQ$$

Sensitivity to ν : L: Low, M: Medium H: High

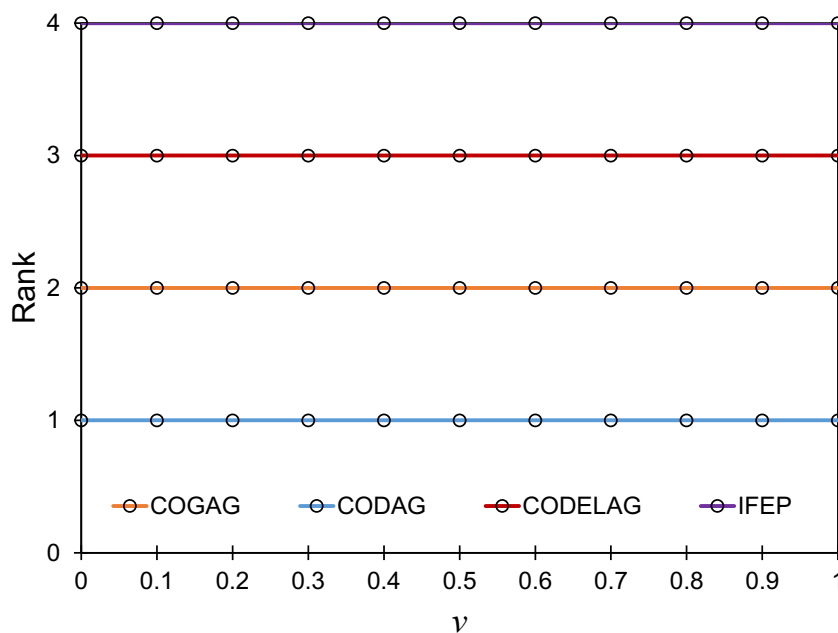


Figure 6-126 Sensitivity analysis of VIKOR ν values for Application Case 1 of conceptual design analysis of notional light frigate

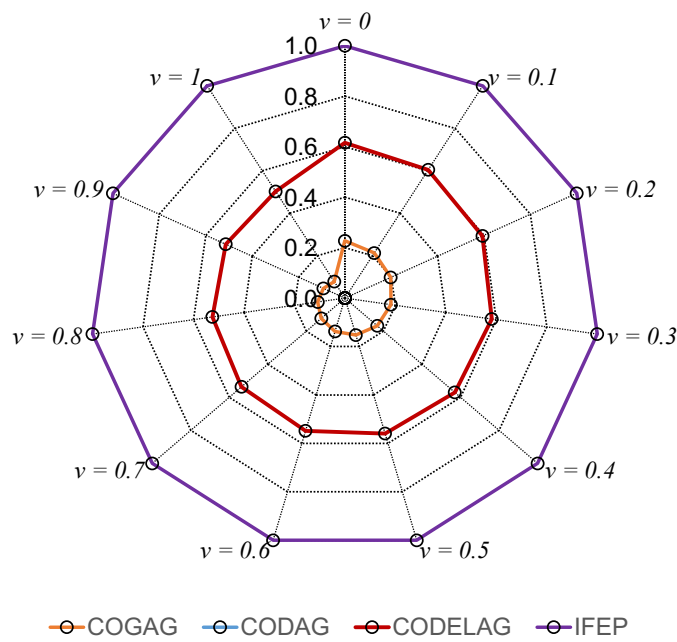


Figure 6-127 Sensitivity analysis of VIKOR 'Q' values for Application Case 1 of conceptual design analysis of notional light frigate

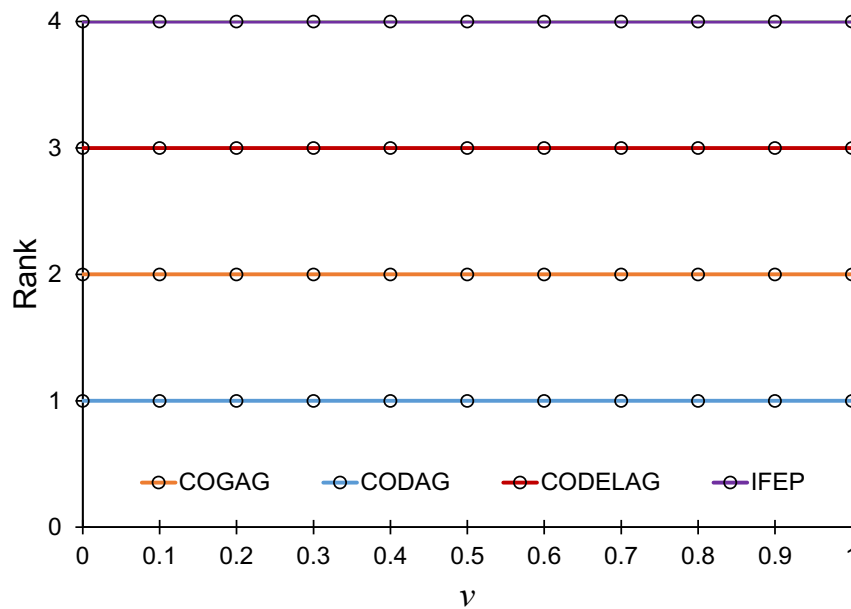


Figure 6-128 Sensitivity analysis of VIKOR v values for Application Case 2A of conceptual design analysis of notional light frigate

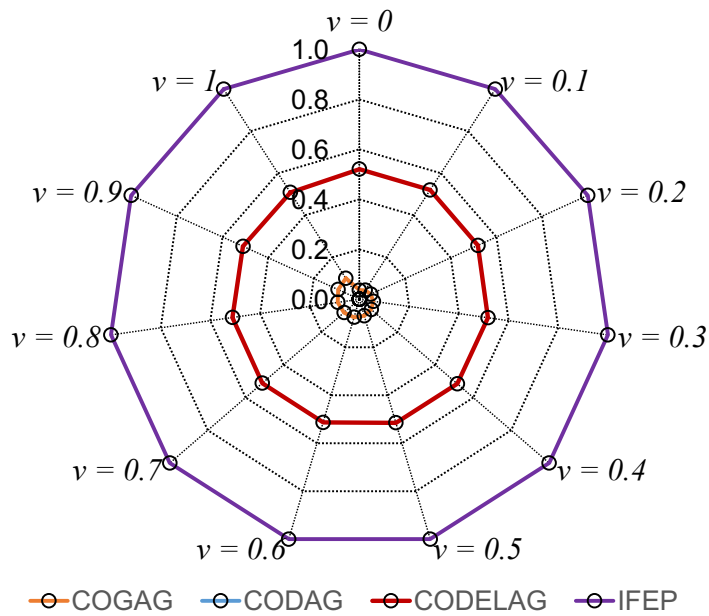


Figure 6-129 Sensitivity analysis of VIKOR 'Q' values for Application Case 2A of conceptual design analysis of notional light frigate

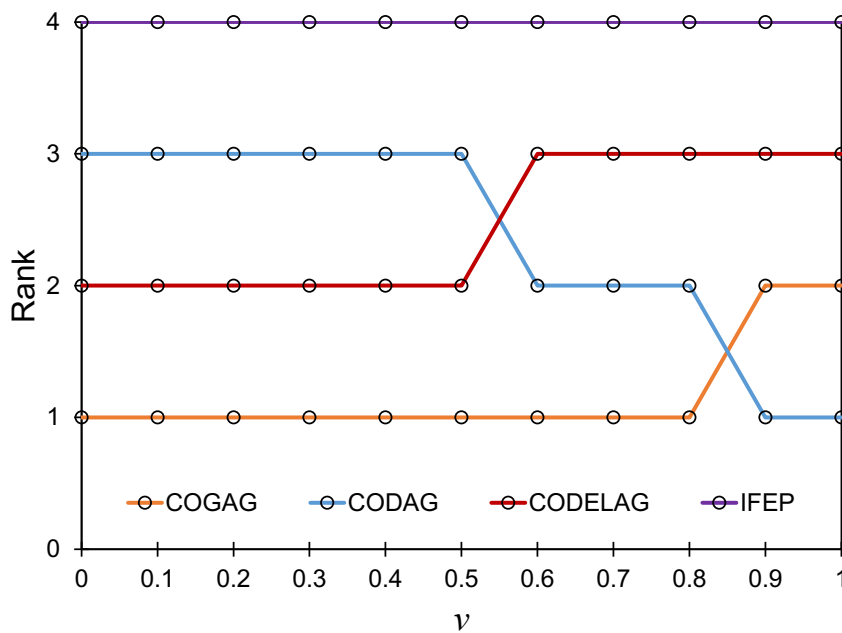


Figure 6-130 Sensitivity analysis of VIKOR v values for Application Case 2B of conceptual design analysis of notional light frigate

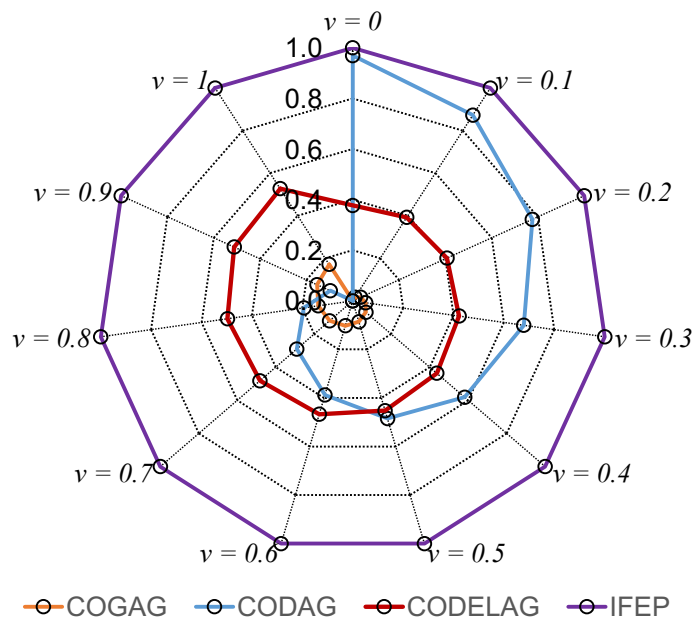


Figure 6-131 Sensitivity analysis of VIKOR 'Q' values for Application Case 2B of conceptual design analysis of notional light frigate

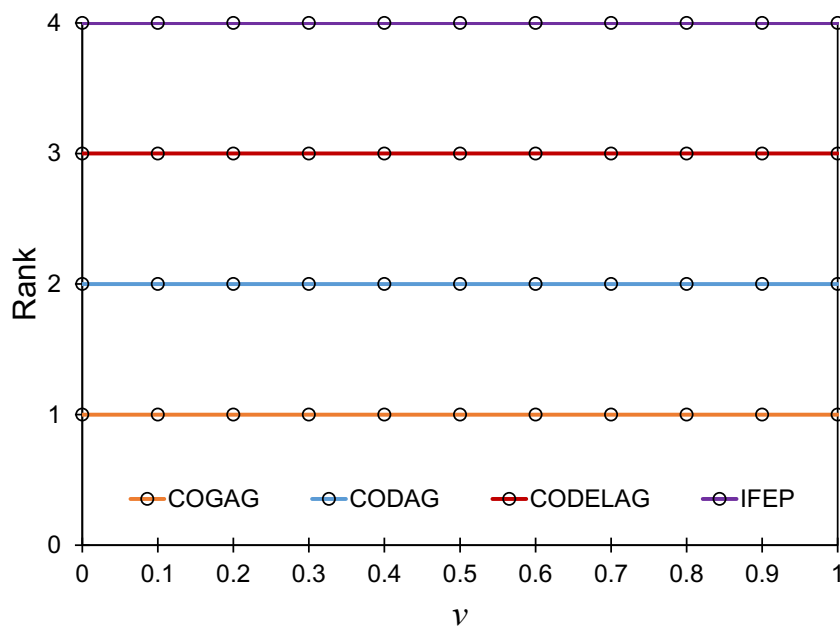


Figure 6-132 Sensitivity analysis of VIKOR v values for Application Case 3 of conceptual design analysis of notional light frigate

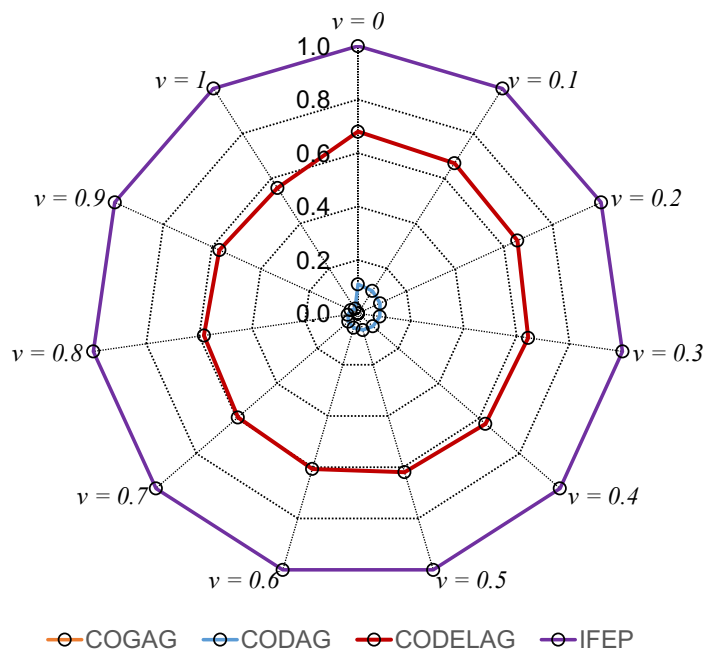


Figure 6-133 Sensitivity analysis of VIKOR 'Q' values for Application Case 3 of conceptual design analysis of notional light frigate

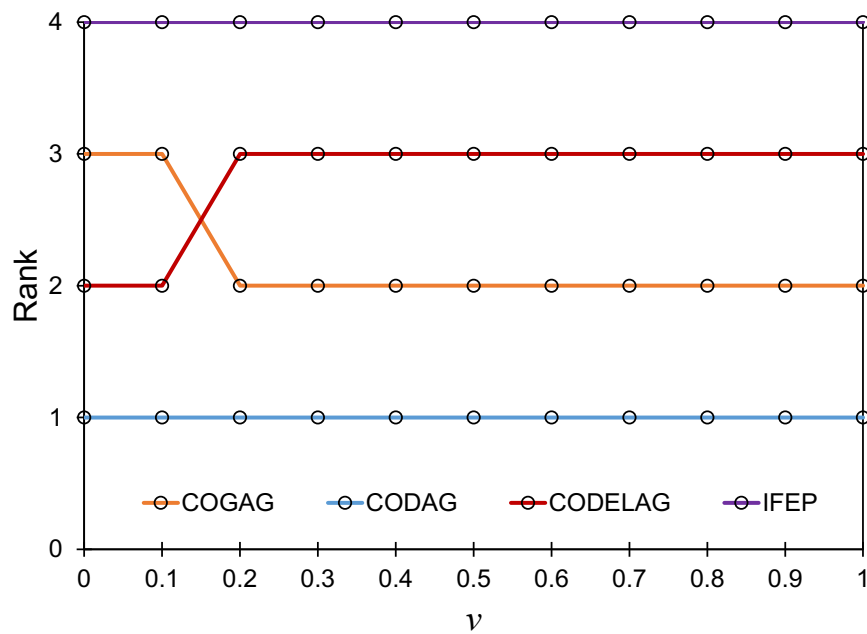


Figure 6-134 Sensitivity analysis of VIKOR v values for Application Case 4 of conceptual design analysis of notional light frigate

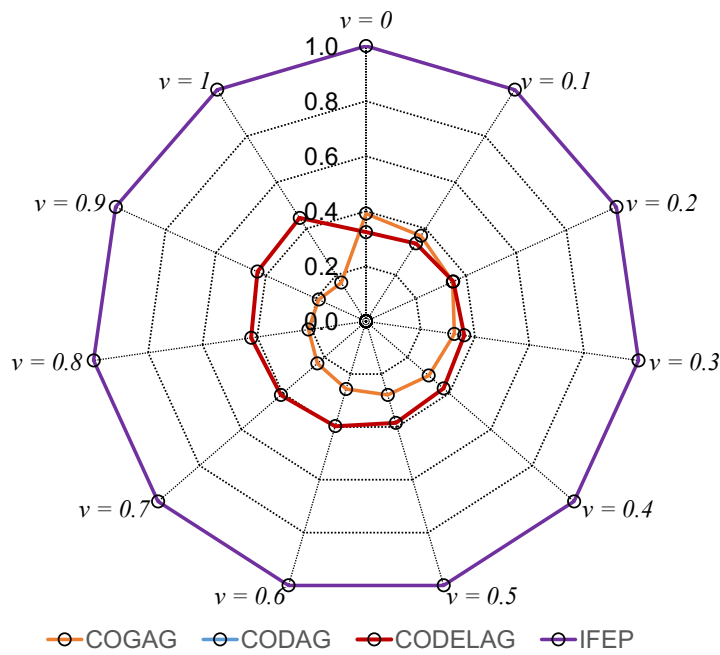


Figure 6-135 Sensitivity analysis of VIKOR 'Q' values for Application Case 4 of conceptual design analysis of notional light frigate

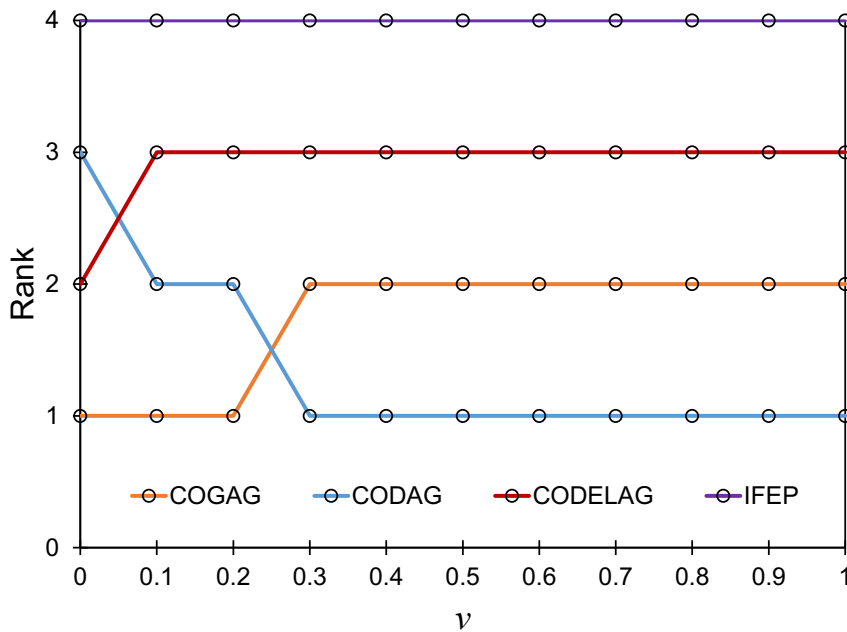


Figure 6-136 Sensitivity analysis of VIKOR v values for Application Case 5 of conceptual design analysis of notional light frigate

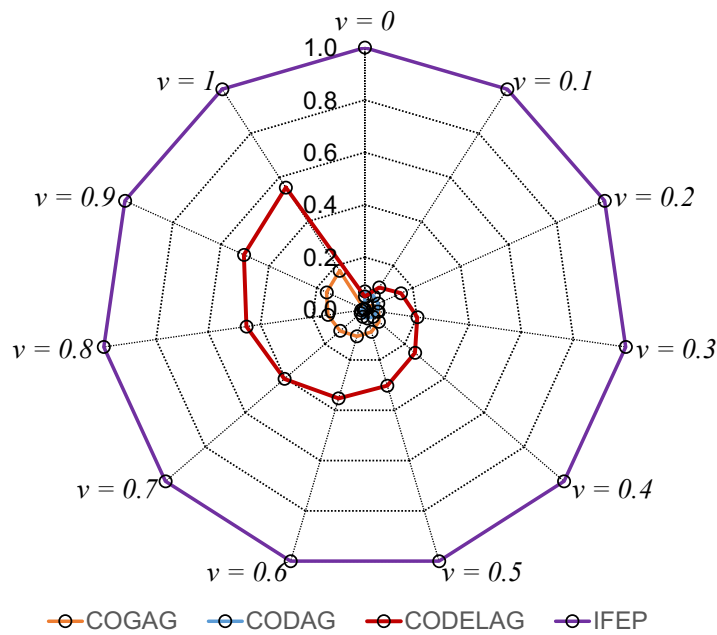


Figure 6-137 Sensitivity analysis of VIKOR ‘Q’ values for Application Case 5 of conceptual design analysis of notional light frigate.

6.6.9 Conclusions of the Propulsion System Conceptual Design Study for the Notional Light Frigate

Across all the application cases where different relative weights for ‘Objective Metrics’ of ‘Performance’ ‘Cost’ and ‘Risk’ were applied, with the ‘strategy coefficient’ set as $v = 0.5$, the following conclusions can be drawn based on the results from the VIKOR analysis.

As seen in Table 6-30, in all application cases except Cases 2B and 3, the candidate architecture CODAG is ranked as the most preferred architecture. In Cases 2B and 3, COGAG is ranked as the most preferred architecture. In all the application cases, the CODELAG candidate architecture is ranked in third place, while the IFEP candidate architecture is consistently ranked in fourth place. Hence the final primary candidates could be narrowed down to the candidate architectures CODAG and COGAG. However, it is important to also test if the preferred architecture as per the ranking from the VIKOR analysis also qualifies for the criteria for acceptable advantage and stability in decision making. The results of these tests across all the application cases are summarized in Table 6-30. It can be observed from this investigation that even though the CODAG

architecture is ranked first in most application cases, it does not satisfy the criteria of acceptable advantage in any of these application cases. This basically means that the degree of preference of the CODAG architecture is very close to the COGAG architecture in all these application cases. Hence, the decision-makers could also select the COGAG architecture, based on certain compromises across some of the criteria. The criterion of stability of the decision-making is satisfied for both the CODAG and the COGAG architectures. The sensitivity analysis undertaken with respect to the value of the strategy coefficient, v , shows that the ranking as well as the VIKOR metric, Q , are stable in the vicinity of the selected strategy coefficient of $v = 0.5$.

Like the results for the notional destroyer, the CODAG or COGAG architecture emerge as the preferred architectures and either could be selected by the decision-makers with certain compromises. Again, the more electric architectures were rated lower due to penalties of higher mass and occupied deck area. The drivers for these results are similar to the case for the destroyer. The primary difference in the results in the results of the light frigate and destroyer analysis is that for Case 2B, where higher performance is the focus, the COGAG plant was the preferred design while for the destroyer the CODAG-E architecture was the preferred design. Again, it should also be noted that these conclusions are not general conclusions for such combined architectures, but the specific architectures considered for this analysis under the design criteria considered along with their global weights.

7 CONCLUSIONS AND FUTURE WORK

7.1 Achievements

7.1.1 Model-Based Design Space Exploration for Conceptual Design

A model-based design process has been proposed for the exploration of design space towards undertaking the concept design of a propulsion system during the early design stages of a ship. The method combines the ‘quantitative’ results generated from model-based performance studies, with subject expert opinions based on ‘qualitative’ results for those aspects of designs where exact performance analysis is not possible during the early stages of ship design, to select the ‘best suited’ propulsion system architecture for an application. The novel process for undertaking the TERA analysis for the same has been demonstrated using a hybrid DANP-AHP-VIKOR based MCDM method.

7.1.2 Analysis of Degree of Relationships between Performance Criteria for Propulsion System Design

A novel approach of the derivation of weights for design criteria using a combination of hierarchal, network structure for evaluating the global weights of the design criteria for a propulsion system design, considering the mutual influence of design criteria on each other, has been demonstrated. The degree of influence between the performance criteria considered has been demonstrated using the DEMATEL method.

7.1.3 Development of an Agile Steady State 0-D Component-Based Modelling Framework for Combined Ship Propulsion Plants

A generalized ship performance modelling procedure based on a 0-D component-based approach, extended from the gas turbine modelling approach has been demonstrated. This agile modelling method is a key enabler required for executing the proposed model-based design procedure.

The development of the framework included the creation of a novel algorithm to model the multiple operating drive modes possible in a combined propulsion plant

by analysis of the direction of 'torque flow' based on the states of engines and clutches.

7.1.4 Application of Model-Based Design Space Exploration to Ship Designs

The developed model-based design space exploration approach has been demonstrated by application to two ship designs: notional destroyer and light frigate designs. The analysis included the creation of specific combined plant architectures to populate the design space, when were then been objectively compared against the defined design criteria for a ship by using a combination of performance simulation analysis using the developed modelling framework, model-based dimensioning and cost models as well as relative expert opinion-based comparisons of architectures.

7.2 Conclusions

The design process of ships, traditionally approached using the ship design spiral, is being replaced with the integrated 'systems approach' for design synthesis. However, the adhoc process for design using 'design lanes', rules of thumb etc. is still prevalent. Irrespective of the approach taken during the initial design of a ship, the propulsion system design is embedded into the process as one of the systems being addressed in the overall process. This often masks the considerations required to address all the aspects of the design of the propulsion system, especially in the context of combined propulsion plants which have added design complexity. The application of the proposed model-based design space exploration for the ship has the potential to develop designs with lower cost, risk and better-predicted performance

The application of the proposed model-based design space exploration needs agile modelling methods for steady-state performance, dimensioning and costing. Performance modelling of combined plants used for off-design analysis could provide valuable insights into the plant designs, before the decision on the final configuration, instead of focusing simulation studies on the dynamic performance of propulsion plants towards the development or tuning of the ship propulsion

control system as is the common present approach. The concept of the 0-D gas turbine modelling method in the aero industry can be effectively extended for the agile performance modelling of ship propulsion systems, as has been demonstrated in this work.

Multiple criteria decision-making (MCDM) is an effective tool operations research, concerned with designing computational and mathematical tools for supporting the subjective evaluation of performance criteria by decision-makers, and can be applied effectively for design space exploration of ship propulsion systems. When MCDM is applied, the mutual relationships between the design criteria for the ship propulsion system should be considered towards a more accurate analysis.

In the early stages of design, combining the 'quantitative' data based on models with the 'qualitative' data based on expert opinion can make a very useful tool for practically making design decisions with lower risks.

Different types of combined propulsion system architectures suit different types of hull designs, even when similar design requirements are defined. The final selection of the 'best suited' architecture is dependent on the evaluated scores of the individual designs as well as the relative weights assigned to the design criteria. The perspective from which the decision-maker is undertaking the analysis, and what is the relative importance of performance cost and risks, are important factors that influence the criteria weights.

With the analysis demonstrated for the notional frigate and destroyer, the more traditional architectures like CODAG and COGAG were the preferred designs. The more electric architectures were rated lower due to penalties of higher mass and occupied deck area despite some of the advantages they offer in the flexibility of operation and performance. From this analysis, it can be inferred that with the present technological levels, to have more electric architectures selected for such ship designs, there must be more specific drivers for justification of such designs than the ones that have been considered for the present analysis. These drivers could be requirements such as extremely high energy requirements for ship weapon systems, specific low underwater noise requirements etc. On the other hand, it should also be noted that these conclusions are not general conclusions

for such combined architectures, but the specific architectures considered for the presented analysis under considered the design criteria along with their defined and derived weights.

7.3 Impact

The proposed generalized method for undertaking the design space exploration of a ship propulsion plant has the potential to offer advantages like lower cost of design and hardware with improved overall system performance with lower risks for design, cost and time overruns. Though the proposed method has been demonstrated by application to warship propulsion architectures, the method could also easily be applied towards the concept design of propulsion plants for commercial vessels.

As the ship design process evolves and more accurate data is available, the model-based approach could be used to ascertain the validity of the data initially assumed during the early stages of design and make corrections for the future. This evolution of the performance modelling could potentially lead to having an improved process for design validation before the sea trials of a ship.

The introduces TERA based on MCDM could be extended for TERA analysis applied for investigations in other domains like aviation and power generation industries etc.

The integrated 0-D component-based plant level modelling methodology could be expanded to aero and industrial plants with the addition of the requisite models of specific components. This common modelling base could also trigger an exchange of ideas between the various disciplines.

The developed component-based modelling process is based on 'stitching' of incremental component models, which is well suited for students for undertaking research work and to enhance the capabilities of the modelling framework over time.

7.4 Future Work

Since the present work involved the creation of an overall framework to undertake the conceptual design of a system, while many aspects of the framework were developed to a high level of detail, there were others for which suitable simplifications were used to limit the overall scope of work. Some of these aspects which could be used for future work are described below.

- Dimensioning models for propulsion system equipment. Improved regression models are especially required for dimensioning of the electrical system machinery. The simple cycle gas turbines could be subdivided into categories of aero-derivative and heavy frame for better accuracy of the models.
- Maintenance cost models. Improvement of maintenance cost models, to include the considerations of conditions under which the engine are exploited, rather than averaged operating hour-based models presently used.
- MCDM methods. Experts often found it difficult to use the DEMATEL or AHP Saaty's scale for relatively rating the candidate design architectures. Application of fuzzy scales could improve the data gathered for expert opinion.
- Diesel engine modelling:
 - Extension of the gas turbine engine component-based modelling process for diesel engine modelling and simulation.
 - Addition of diesel engine related components like engine cylinders.
 - Extension of compressor and turbine modelling used in the gas turbine engines for application to diesel engine turbochargers.
- Gas turbine engine modelling:
 - Effect of water ingestion, humidity effects.
 - Application of variable geometry in compressors and turbines.
 - Additional components required for complex cycle gas turbines.
 - Ability to model compressor bleeds without the application of the splitter component.

- Addition of engine components like intercoolers, recuperators, other heat exchangers for modelling of advanced cycle gas turbines as well as applications with heat recovery.
- Propulsor
 - Extension of the propulsor model to include water jet models for integration with ship propulsion systems.
 - Addition of 4 quadrant behaviour to the implemented propeller model to model trailing or watermilling propeller behaviour.
 - Addition of more modern propeller series models to the component library.

The developed steady-state modelling framework could be extended for transient analysis so that the same models used for the analysis as presented in the present work, could be extended for dynamic simulation studies for the propulsion system.

Additional improvements could be made to the developed modelling framework, Poseidon+ by the addition of the ability to graphically create models than use the text-based modelling system currently implemented.

REFERENCES

1. Jabary W. An Enterprise Modeling Approach for the Early Ship Design. 2015.
2. Brown AJ., Thomas M. Reengineering the Naval Ship Design Process. From Research to Reality in Ship Systems Engineering Symposium', ASNE. 1998.
3. Harrington RL. Marine Engineering. Society of Naval Architects & Marine Engineers; 1992.
4. Plumb C. Warship Propulsion System Selection-Part 1. Institute of Marine Engineers; 1987.
5. Evans JH. Basic Design Concepts. Journal of the American Society for Naval Engineers. 1959; 71(4): 671–678.
6. Watson DGM. Practical Ship Design. First. Elsevier Ocean Engineering Series-Volume 1. Oxford OX5 1GB, UK: Elsevier; 1998. 1–33 p.
7. Lamb T. Ship Design and Construction. Society of Naval Architects and Marine Engineers; 2003.
8. Papanikolaou A. Ship Design Methodologies of Preliminary Design. Springer. 2014. 1–16 p.
9. S. P. C. Westwood., Spencer J., Simpson RR. Warship Propulsion System Selection. JNE. 1989; 32(1).
10. Robert MW. A Design Guide for Naval Ship Propulsion Plants. 1978; : 174.
11. Papanikolaou A., Harries S., Wilken M., Zaraphonitis G. Integrated design and multiobjective optimization approach to ship design. RINA, Royal Institution of Naval Architects - International Conference on Computer Applications in Shipbuilding 2011, Papers. 2011; 3(May 2015): 31–42.
12. Stepanchick J., Brown A. Revisiting DDGX/DDG-51 concept exploration. Naval Engineers Journal. 2007; 119(3).

13. Stratmann JP. Engineering Management of Early Stage Warship Design. 2006.
14. Batra A., Prakash R. Energy Efficient Operations of Warships: Perspective of the Indian Navy. In: Ölçer AI et al (ed.) Trends and Challenges in Maritime Energy Management. Springer International Publishing AG; 2018. pp. 83–94.
15. Stanko MT. An Evaluation of Marine Propulsion Engines for Several Navy Ships. 1993.
16. Hugel MA. An Evaluation of Propulsors for Several Navy Ships. Power Engineering. 1992;
17. Webster JS., Fireman H., Allen DA., Mackenna AJ., Hootman JC. US Navy studies on alternative fuel sources and power and propulsion methods for surface combatants and amphibious warfare ships. Naval Engineers Journal. 2007; 119(2): 35–48.
18. Gully BH. Hybrid Powertrain Performance Analysis for Naval and Commercial Ocean-Going Vessels. 2012; : 186.
19. Strock J., Brown A. Methods for naval ship concept and propulsion technology exploration in a CGX case study. Naval Engineers Journal. 2008; 120(4): 95–122.
20. Rubis CJ., Harper TR. The naval gas turbine ship propulsion dynamics and control systems research and development program. Transactions - Society of Naval Architects and Marine Engineers. 1982; 90: 321–338.
21. Rubis CJ., Harper TR. Governing Ship Propulsion Gas Turbine Engines. Transactions - Society of Naval Architects and Marine Engineers. 1986; 94: 283–308.
22. Schulten PJM. The Interaction Between Diesel Engines, Ship And Propellers During Manoeuvring. Technische Universiteit Delft. 2005. 225 p.

23. Benvenuto G., Campora U. A gas turbine modular model for ship propulsion studies. Proceedings of the 7th Symposium on High Speed Marine Vehicles, 2005 Conference, HSMV 2005. 2005. pp. 95–104.
24. Martelli M., Viviani M., Altosole M., Figari M., Vignolo S. Numerical modelling of propulsion, control and ship motions in 6 degrees of freedom. Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment. 2014; 228(4): 373–397.
25. Figari M., Altosole M. Dynamic behaviour and stability of marine propulsion systems. Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment. 2007; 221(4): 187–202.
26. Campora U., Figari M. Numerical simulation of ship propulsion transients and full-scale validation. Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment. 2003; 217(1): 41–52.
27. Altosole M., Benvenuto G., Figari M., Campora U. Real-time simulation of a COGAG naval ship propulsion system. Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment. 2009; 223(1): 47–61.
28. Martelli M., Figari M. Real-Time model-based design for CODLAG propulsion control strategies. Ocean Engineering. Elsevier Ltd; 2017; 141(December 2016): 265–276.
29. Altosole M., Dubbioso G., Figari M., Viviani M., Michetti S., Millerani Trapani A. Simulation of the dynamic behaviour of a CODLAG propulsion plant. RINA, Royal Institution of Naval Architects - Warship 2010: Advanced Technologies in Naval Design and Construction - Papers. 2010; (June): 109–115.
30. Campora U., Figari M., Martelli M., Vignolo S., Viviani M. Propulsion Plant Simulation for Fast Military Vessels. Ix Hsmv. 2011; (May): 1–7.

31. Menard LM. Prediction of Performance and Maneuvering Dynamics for Marine Vehicles Applied to DDG-1000. Archives. 2010;
32. Altosole M., Martelli M. Propulsion control strategies for ship emergency manoeuvres. Ocean Engineering. Elsevier Ltd; 2017; 137(November 2015): 99–109.
33. Vrijdag A., Stapersma D., van Terwisga T. Systematic modelling, verification, calibration and validation of a ship propulsion simulation model. Journal of Marine Engineering and Technology. 2009; 8(3): 3–20.
34. Geertsma RD., Visser K., Negenborn RR. Adaptive pitch control for ships with diesel mechanical and hybrid propulsion. Applied Energy. Elsevier; 2018; 228(June): 2490–2509.
35. Macmillan WL. Development of a modular type computer program for the calculation of gas turbine off design performance. Cranfield University; 1974.
36. Palmer JR. The Turbocode scheme for the programming of thermodynamic cycle calculations on an electronic digital computer. 1967.
37. McKinney JS. Simulation of turbofan engine, Part 1. Description of method and balancing technique. 1967.
38. Koenig RW., Fishbach LH. GENENG - A Programm for Calculating Design and Off-Design Performance for Turbojet and Turbofan Engines. NASA Technical Note. 1972.
39. Koenig RW., Fishbach LH. GENENG - A program for calculating design and off design performance for turbojet and turbofan engines: TN D-6555. 1972.
40. van den Hout F. Gas turbine performance simulation: improvements to Turbomatch scheme. 1990.
41. Sirinoglou AA. Implementation of variable geometry for gas turbine performance simulation: Turbomatch improvement. 1992.

42. Pachidis V. Gas Turbine Advanced Performance Simulation. PhD Thesis. 2006; (January): 1–384.
43. Mucino M. CCGT performance simulation and diagnostics for operations optimisation and risk management. Cranfield University; 2007.
44. Janikovic J. Gas turbine transient performance modeling for engine flight path cycle analysis. Thesis. 2010; U617280.
45. Giannakakis P. Design space exploration and performance modelling of advanced turbofan and open-rotor engines. 2013.
46. Escher PC. Pythia: An object-orientated gas path analysis computer program for general applications. 1995. p. 229. <http://dspace.lib.cranfield.ac.uk/handle/1826/3457>
47. Apostolidis A. Turbine Cooling and Heat Transfer Modelling for Gas Turbine Performance Simulation. 2015; (March): 1–179.
48. Apostolidis A., Sampath S., Laskaridis P., Singh R. Webengine - A Web-Based Gas Turbine Performance Simulation Tool. Proceedings of ASME Turbo Expo 2013 GT2013 June 3-7, 2013, San Antonio, Texas, USA. 2013. pp. 1–11.
49. Tsoudis E. Technoeconomic, environmental and risk analysis of marine gas turbine power plants. Theses 2008. 2008; MSc Thesis(July): 145.
50. Bonet MU. Techno-environmental assessment of marine gas turbines for the propulsion of merchant ships. 2011; (July): 2010–2011.
51. Bono MR. Integration of Gas Turbine Performance Model with Diesel Engine Performance Model For Marine Application. Cranfield University; 2017.
52. Mody B. Digital Simulation of Gas Turbine Steady-State and Transient Performance for Current and Advanced Marine Propulsion System. Cranfield University; 2009.

53. Woud HK., Stapersma D. Design of propulsion and electric power generation systems. London: IMarEST, Institute of Marine Engineering, Science and Technology; 2002.
54. Stapersma D., Vos P de. Dimension prediction models of ship system components based on first principles. 2015; 3(September): 15.
55. van Es GF. Designing and evaluating propulsion concepts of surface combatants. Delft University of Technology; 2011.
56. Naval Sea Systems Command. Alternative propulsion methods for surface combatants and amphibious warfare ships. 2007.
57. Woodyard D. Pounders Marine Diesel Engines and Gas Turbines Ninth Edition. Ninth. 2009.
58. Georgios C. Doulgeris. Modelling & Integration of Advanced Propulsion Systems. 2008.
59. Doulgeris G., Korakianitis T., Pilidis P., Tsoudis E. Techno-economic and environmental risk analysis for advanced marine propulsion systems. Applied Energy. Elsevier Ltd; 2012; 99: 1–12.
60. Khan RSR. TERA for Rotating Equipment Selection. 2012; (January).
61. Nalianda DK. Impact of Environmental Taxation Policies on Civil Aviation: A Techno-Economic Environmental Risk Assessment. 2012.
62. Ogaji SOT., Pilidis P., Hales R. TERA- A Tool for Aero-engine Modelling and Management. Second Word Conference on Engineering Asset Management. 2009. pp. 11–14.
63. Gayraud S. Technical and Economical Assessment for Industrial Gas Turbine Selection. 1996.
64. Whellens M., Singh R. Propulsion system optimisation for minimum Global Warming Potential. Proceedings of ICAS 2002 Congress, 2002; 1–10.

65. Bonet MU., Pilidis P., Doulgeris G. Voyage Analysis of a Marine Gas Turbine Engine Installed to Power and Propel an Ocean-Going Cruise Ship : 43.
66. Anderson LTT., Gerhard LTK., Sievenpiper LB. Operational Ship Utilization Modeling of the DDG-51 Class. 2013;
67. Mardani A., Jusoh A., Nor KMD., Khalifah Z., Zakwan N., Valipour A. Multiple criteria decision-making techniques and their applications - A review of the literature from 2000 to 2014. *Economic Research-Ekonomska Istrazivanja* . Routledge; 2015; 28(1): 516–571.
68. Saaty TL. A scaling method for priorities in hierarchical structures. *Journal of Mathematical Psychology*. 1977; 15(3): 234–281.
69. Saaty TL. *The Analytic Hierarchy Process: Planning, Priority Setting, Resources Allocation*. McGraw-Hill, New York.; 1980.
70. Ruschmeyer K., Batra A., Harth M., Wasinger P. An Approach for Concept Development and Evaluation of Propulsion Systems to Optimize the Design , Performance and Mission Effectiveness of Frigates. *SNAME Propellers & Shafting 2018 Symposium*, Norfolk, VA, USA. 2018.
71. Shamasundara MS., Arora BS., Parwekar AS. Analytic Hierarchy Process Approach for Selection of Ship Propulsion System – Case Study. *IOSR Journal of Business and Management*. 2014; 16(9): 14–19.
72. Brown A., Salcedo J. Multiple-objective optimization in naval ship design. *Naval Engineers Journal*. 2003; 115(4): 49–62.
73. Saaty TL., Sodenkamp M. The Analytic Hierarchy and Analytic Network Measurement Processes: The Measurement of Intangibles. 2010; 1(1): 91–166.
74. Kadoić N., Ređep NB., Divjak B. Decision making with the analytic network process. *Proceedings of the 14th International Symposium on Operational Research, SOR 2017*. 2017; 2017-Sept(Section 2): 180–186.

75. Rai RN., Bolia N. Optimal decision support for air power potential. *IEEE Transactions on Engineering Management*. 2014; 61(2): 310–322.
76. Uygun Ö., Kaçamak H., Kahraman ÜA. An integrated DEMATEL and Fuzzy ANP techniques for evaluation and selection of outsourcing provider for a telecommunication company. *Computers and Industrial Engineering*. 2014; 86: 137–146.
77. Chen FH., Hsu TS., Tzeng GH. A balanced scorecard approach to establish a performance evaluation and relationship model for hot spring hotels based on a hybrid MCDM model combining DEMATEL and ANP. *International Journal of Hospitality Management*. Elsevier Ltd; 2011; 30(4): 908–932.
78. Gölcük I., Baykasoglu A. An analysis of DEMATEL approaches for criteria interaction handling within ANP. *Expert Systems with Applications*. 2016; 46: 346–366.
79. Opricovic S. *Multicriteria Optimization of Civil Engineering Systems*. Faculty of Civil Engineering, Belgrade; 1998.
80. San Cristóbal JR. Multi-criteria decision-making in the selection of a renewable energy project in Spain: The VIKOR method. *Renewable Energy*. Elsevier Ltd; 2011; 36(2): 498–502.
81. Demirel H., Şener B., Yildiz B., Balin A. A real case study on the selection of suitable roll stabilizer type for motor yachts using hybrid fuzzy AHP and VIKOR methodology. *Ocean Engineering*. 2020; 217(June).
82. Chiu WY., Tzeng GH., Li HL. A new hybrid MCDM model combining DANP with VIKOR to improve e-store business. *Knowledge-Based Systems*. Elsevier B.V.; 2013; 37: 48–61.
83. NATO AVT-036. *Performance Prediction and Simulation of Gas Turbine Engine Operation (RTO TECHNICAL REPORT 44)*. 2007.

84. Pachidis VA., Nikolaidis T. Gas Turbine Performance Simulation Notes. Ver. 1.1. Cranfield University, School of Aerospace, Transport and Manufacturing (SATM) Centre for Propulsion;
85. Kurzke J. About simplifications in gas turbine performance calculations. Proceedings of the ASME Turbo Expo. 2007; 3: 493–501.
86. Gazzetta Junior H., Brighenti C., Barbosa JR., Tomita JT. Real-time gas turbine model for performance simulations. Journal of Aerospace Technology and Management. 2017; 9(3): 346–356.
87. Press WH., Flannery BP., Teukolsky SA., Vetterling WT., others. Numerical Recipes in Fortran 90 Second Edition Volume 2 of Fortran Numerical Recipes. Computing. 2007.
88. Broyden C. G. A Class of Methods for Solving Nonlinear Simultaneous Equations. Mathematics of Computation. 1965; 19(92): 577–593.
89. Press WH., Teukolsky SA., Vetterling WT., Flannery BP. Numerical Recipes in Fortran 77, second edition. 1996.
90. Walsh PP., Fletcher P. Gas Turbine Performance, 2nd Edition. Blackwell Science. 2004.
91. Bücker D., Span R., Wagner W. Thermodynamic property models for moist air and combustion gases. Journal of Engineering for Gas Turbines and Power. 2003; 125(1): 374–384.
92. Kurzke J. How To Get Component Maps for Aircraft. International Gas Turbine and Aeroengine Congress & Exhibition. 1996; : 1–7.
93. Nikolaidis T. The Turbomatch Scheme. 2015;
94. Anthony F. Molland, Stephen R. Turnock DAH. Ship Resistance and Propulsion: Practical Estimation of Ship Propulsive Power. Marine Propellers and Propulsion (Second Edition). 2011. 299–332 p.
95. Lewis E v. Principles of Naval Architecture Vol 2. Society of Naval Architects and Marine Engineers. 1988.

96. Schneekluth H., Bertram V. Ship Design for Efficiency and Economy Ship Design for Efficiency and Economy. ButterworthHeinemann. 1998. 226 p.
97. Bertram V. Practical Ship Hydrodynamics. Practical Ship Hydrodynamics. 2000;
98. Schulten P., Stapersma D. A study of the validity of a complex simulation model. Proceedings of the Institute of Marine Engineering, Science and Technology Part A: Journal of Marine Engineering and Technology. 2007; 4177(10): 67–77.
99. Moody RD. Preliminary power prediction during early design stages of a ship. 1996.
100. Holtrop J., Mennen GGJ. Statistical Power Prediction Method. International Shipbuilding Progress. 1978; 25(290): 253–256.
101. Holtrop J., Mennen GG. An Approximate Power Prediction Method. International Shipbuilding Progress. 1982. pp. 166–170. DOI:10.1007/s13398-014-0173-7.2
102. Holtrop J. A statistical re-analysis of resistance and propulsion data. International Shipbuilding Progress. 1984; 31(363).
103. Fung SC. High Speed Displacement Vessels Parametric Studies and Calm Water Resistance Predictions. 1986.
104. Fung SC. Resistance and powering prediction for transom stern hull forms during early stage ship design. SNAME Transactions. 1991; 99: 29–84.
105. Fung SC., Liebman L. Revised Speed-Dependent Powering Predictions for High-Speed Transom Stern Hull Forms. Proc. Third International Conference of Fast Sea Transportation (FAST '95). 1995. pp. 151–164.
106. Peacock D., Smith WF., Pal PK. Typographical Corrections for Three Recently published Regression based Resistance Prediction Methods. The Australian Naval Architect. 1999; 3(4).

107. Hollenbach KU. Estimating resistance and propulsion for single-screw and twin-screw ships. *Ship Technology Research*. 1998; 45(2): 72–76.
108. J S Carlton. *Marine Propellers and Propulsion*. Second. 2007.
109. van Lammeren WPA., van Manen JD., Oosterveld MWC. The Wageningen B-Screw Series. *SNAME Transactions*. 1969; : 43.
110. Oosterveld MWC., van Oossanen P. Further Computer-Analyzed Dat of the Wageningen B-Screw Series. *International Shipbuilding Progress*. 1975; 22(251): 251–262.
111. Biven R. *Interactive Optimization Programs for Initial Propeller Design*. 2009.
112. Gaafary MM. *Computerized method for Propeller design*. IMAM 2009, Istanbul, Turkey. 2009.
113. Gaafary MM., El-Kilani HS., Moustafa MM. Optimum design of B-series marine propellers. *Alexandria Engineering Journal*. Faculty of Engineering, Alexandria University; 2011; 50(1): 13–18.
114. Nelder JA., Mead R. A simplex method for function minimization. *The Computer Journal*. 1965; 7(4): 308–313.
115. Griffiths DV., Smith IM. *Numerical methods for engineers, second edition*. Numerical Methods for Engineers, Second Edition. 2006; : 1–475.
116. Sharqawy MH., Lienhard V JH., Zubair SM. Thermophysical properties of seawater: A review of existing correlations and data. *Desalination and Water Treatment*. 2010; 16(1–3): 354–380.
117. ITTC International Towing Tank Conference. *Recommended Procedures and Guidelines - Fresh Water and Seawater Properties*. ITTC – Recommended Procedures. 2011.
118. Altosole M., Figari M. Effective simple methods for numerical modelling of marine engines in ship propulsion control systems design. *Journal of Naval Architecture and Marine Engineering*. 2011; 8(2): 129–147.

119. Shi W., Grimmelius HT., Stapersma D. Analysis of ship propulsion system behaviour and the impact on fuel consumption. *International Shipbuilding Progress*. 2010. pp. 35–64.
120. Godjevac M., Drijver J., De Vries L., Stapersma D. Evaluation of losses in maritime gearboxes. *Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment*. 2016; 230(4): 623–638.
121. McCoy TJ., Amy J v. The state-of-the-art of integrated electric power and propulsion systems and technologies on ships. *IEEE Electric Ship Technologies Symposium, ESTS 2009*. IEEE; 2009; : 340–344.
122. Dalton T., Boughner A., Mako CD., Doerry N. LHD 8 - A Step Toward the All Electric Warship. *Naval Engineers Journal*. 2002; 114(3): 74–75.
123. Stevens JD., Hegner HJ., Yan J. The value of an integrated power system land based test site to the U.S. navy. *INEC 2012 - 11th International Naval Engineering Conference and Exhibition*. 2012;
124. Chen SH., Lin WT. Analyzing determinants for promoting emerging technology through intermediaries by using a DANP-based MCDA framework. *Technological Forecasting and Social Change*. Elsevier; 2018; 131(September 2017): 94–110.
125. Hsu CH., Wang FK., Tzeng GH. The best vendor selection for conducting the recycled material based on a hybrid MCDM model combining DANP with VIKOR. *Resources, Conservation and Recycling*. Elsevier B.V.; 2012; 66(2012): 95–111.
126. Opricovic S., Tzeng GH. Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. *European Journal of Operational Research*. 2004; 156(2): 445–455.
127. Hlavin J. Hydrostatic and Hydrodynamic Analysis of a Lengthened DDG-51 Destroyer Modified Repeat. 2010.

128. Bernitsas MM., Ray D. Optimal Revolution of B-Series. 1982.
129. Radojcic D. Optimal preliminary propeller design using nonlinear constrained mathematical programming technique. 1985; (October).
130. Stapersma D., Woud H. Matching propulsion engine with propulsor. *Journal of Marine Engineering and Technology*. 2005; 4(2): 25–32.
131. Kravitz E. Analysis and Experiments for Contra-Rotating Propeller. 2011.
132. S.M. Camporeale, B. Fortunato MM. A high-fidelity real-time simulation code of gas turbine dynamics for control applications. *Proceedings of ASME Turbo Expo 2002 Amsterdam, The Netherlands, 3-5 June 2002*. 2002. pp. 3–5.
133. Fung SC., Liebman L. Revised Speed-Dependent Powering Predictions for High-Speed Transom Stern Hull Forms. *FAST 95*. 1995. pp. 151–164.
134. Hodge CG., Mattick DJ. The electric warship VI. *International Maritime Technology*. 2001; 113(2): 49–63.
135. Tortarolo F. Gas Turbine For Marine Electric Propulsion. *WEGEMT Association 33rd School “Fast Ship Propulsion Plants” May 22 nd - 26th , 2000 Genova, Italy*. 2000.
136. Schuddebeurs JD., Norman PJ., Booth CD., Burt GM., McDonald JR. Emerging research issues regarding integrated-full-electric-propulsion. *41st International Universities Power Engineering Conference, UPEC 2006, Conference Proceedings*. 2006; 2(October): 669–673.

APPENDICES

Appendix A Poseidon+ Software Design

A.1 Development Language and Environment

C# was selected as the development language for Poseidon+ considering the features it offers as a modern programming language for Object-Oriented Programming (OOP). C# code is 'Compiled to an Intermediate Language' (CIL) making it independent of the target architecture and operating system. C# forms as part of the .NET framework which allows for a tightly integrated input/ output interface with or without graphics, with the main application. A brief trade-off study was undertaken for the selection of the development language before the commencement of the coding for Poseidon+. The primary drivers for the selection of C# as the development language are explained in the next paragraph.

It is planned to develop a graphical web-based user interface for Poseidon+ on the lines of 'WebEngine' in the future. A web-based user interface means that a web browser is used as the client computer software, sometimes called a 'thin client', providing the ability to update and maintain the software without the need of distributing and installing software on individual client computers. It also provides the advantage of cross-platform compatibility with multiple operating systems and hardware, with the inherent support available for web browsers. The 'WebEngine' interface for Turbomatch was also developed using C# [37]. However, since Turbomatch is developed in FORTRAN, there is a need for software 'wrappers' required to interface the two applications. C# can be effectively used to build the core application with the requisite mathematical requirements, and it can also seamlessly integrate with the web-based user interface in a selected development framework like the .NET framework. Based on these factors, C# was selected as the development language in the .NET Framework. Though C# and .NET Framework have been developed by Microsoft, they are based on open ECMA (European Computer Manufacturers Association) and ISO (International Organization for Standardization) standards, and thus the

.NET platform is also supported by the open-source ASP.NET (Active Server Pages.NET) implementations.

One of the primary requirements of a good web application framework is the separation of the data content from the presentation to the user. The data model should be open-ended so that it is usable by a variety of views, and that some controlling mechanism that interfaces the retrieved content with the appropriate presentation format. Towards this, the 'Model-View-Controller' or MVC design method is popular for .NET based applications. The MVC works on the basic principle that the 'Controller' receives a user request via the 'View', constructs the data 'Model' that fulfils this request, and selects a 'View' to present the results. The 'View' communicates with the 'Model' to update the content in the desired format. For Poseidon+, the MVC design method has been implemented, as shown in Figure A-1, using Visual Studio 2013 (VS2013) as the Integrated Development Environment (IDE). VS2013 also offers a wide array of features for development, including 'intellisense' and project management.

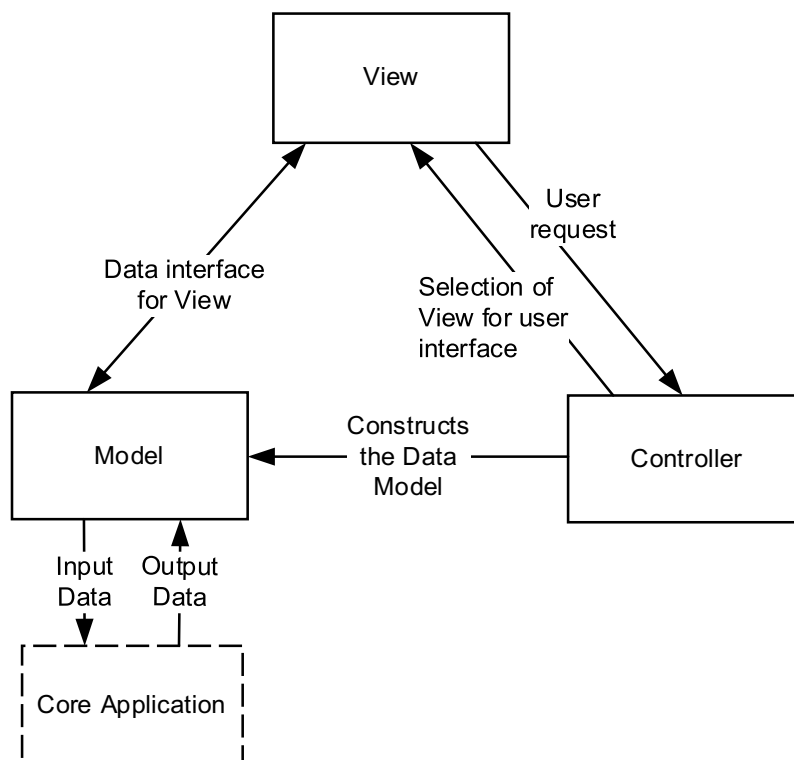


Figure A-1 'Model-View-Controller' (MVC) design implementation in Poseidon+

A.2 Overall software architecture in Poseidon+

The overall design of Poseidon+ has been developed as a collection of classes, which are instantiated and used in the paradigm of OOP. The data across various methods in the classes are transmitted in a structured format as per created classes instead of arrays, allowing for a more readable code that allows for ease of expansion when required. In general, global variables are not used to avoid errors and optimal usage of memory resources in the computing environment. The following paragraphs give a brief overview of the software architecture of Poseidon+.

The overall software architecture of Poseidon+ consists of the following software modules, which consists of their own classes and the classes their respective methods:

- Core Module
- User Interface
- MVC Controller
- Model Parser
- Output Data Handler
- Mathematical Solvers
- Optimization Functions
- Map Interpolation Functions
- Fluid (Thermodynamic) Models

A.2.1 Core Module

The 'Core Module' is designed to undertake the performance simulations calculations for gas turbine engines as well as the ship propulsion system, each executed through an individual software module. the sub-modules receive the input model data from the model parser. Both the sub-modules communicate with each other in the scenario when the propulsion system simulation involves gas turbine engine simulation. both the sub-modules use the math layer functions i.e. non-linear equation solving optimization. The core module interacts with the

system and user-defined maps through the map interpolation functions. The overall block diagram of the ‘Core Architecture’ is shown in Figure A-2.

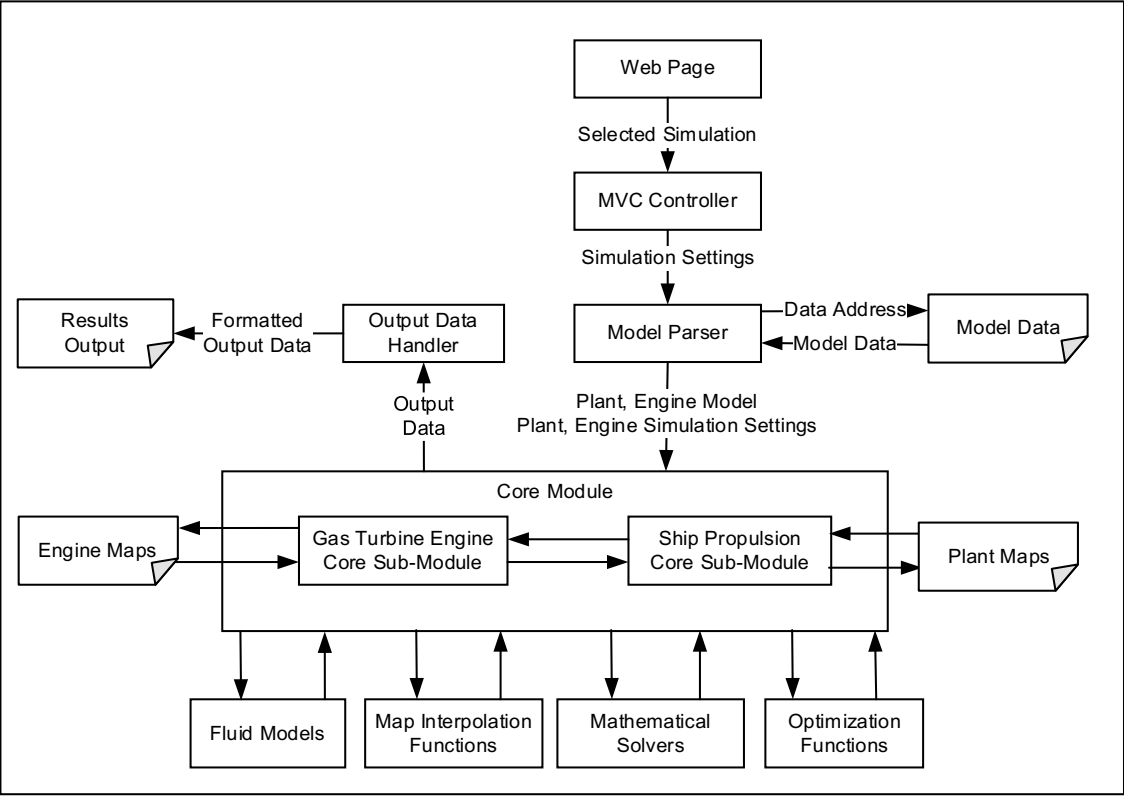


Figure A-2 Simplified overview of overall software architecture in Poseidon+.

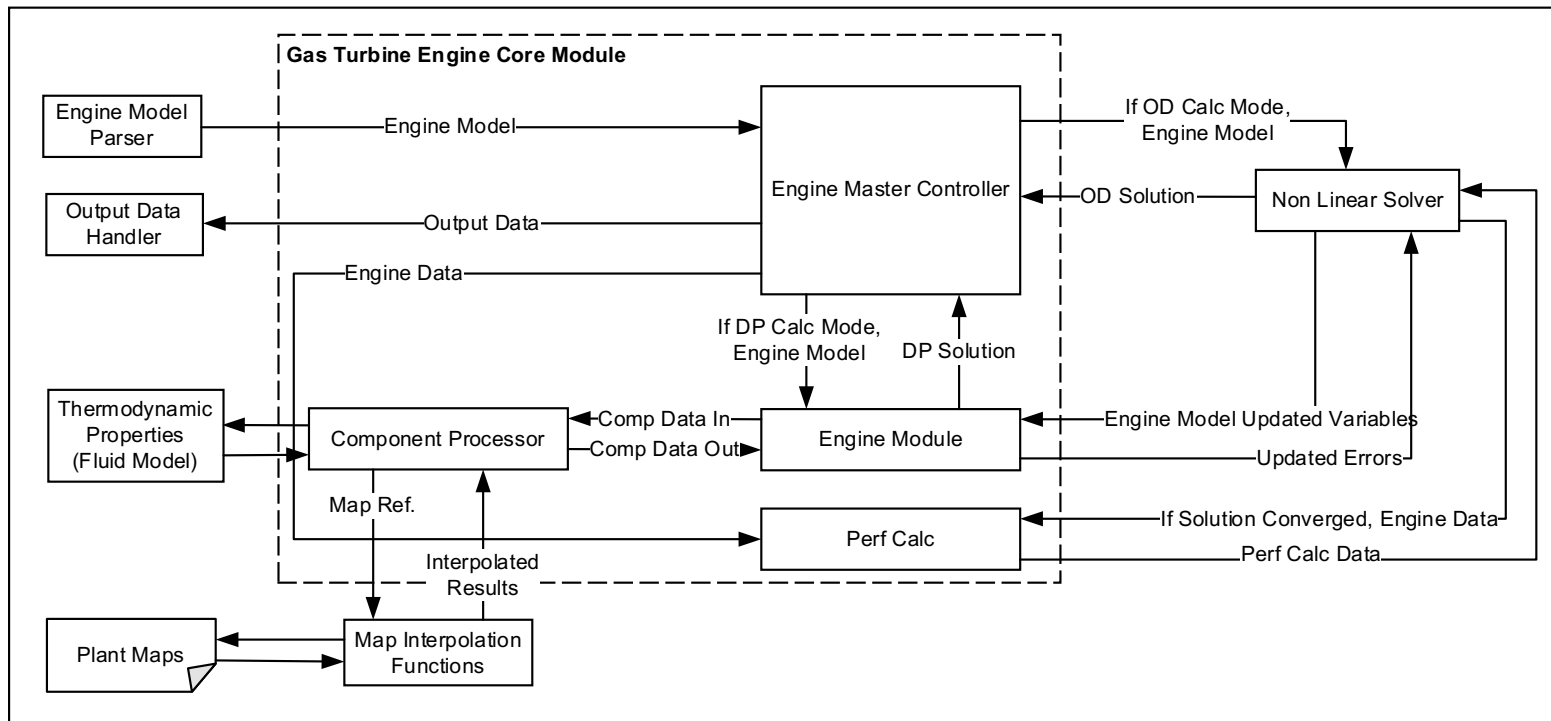


Figure A-3 Simplified overview of gas turbine engine core sub-module architecture in Poseidon+.

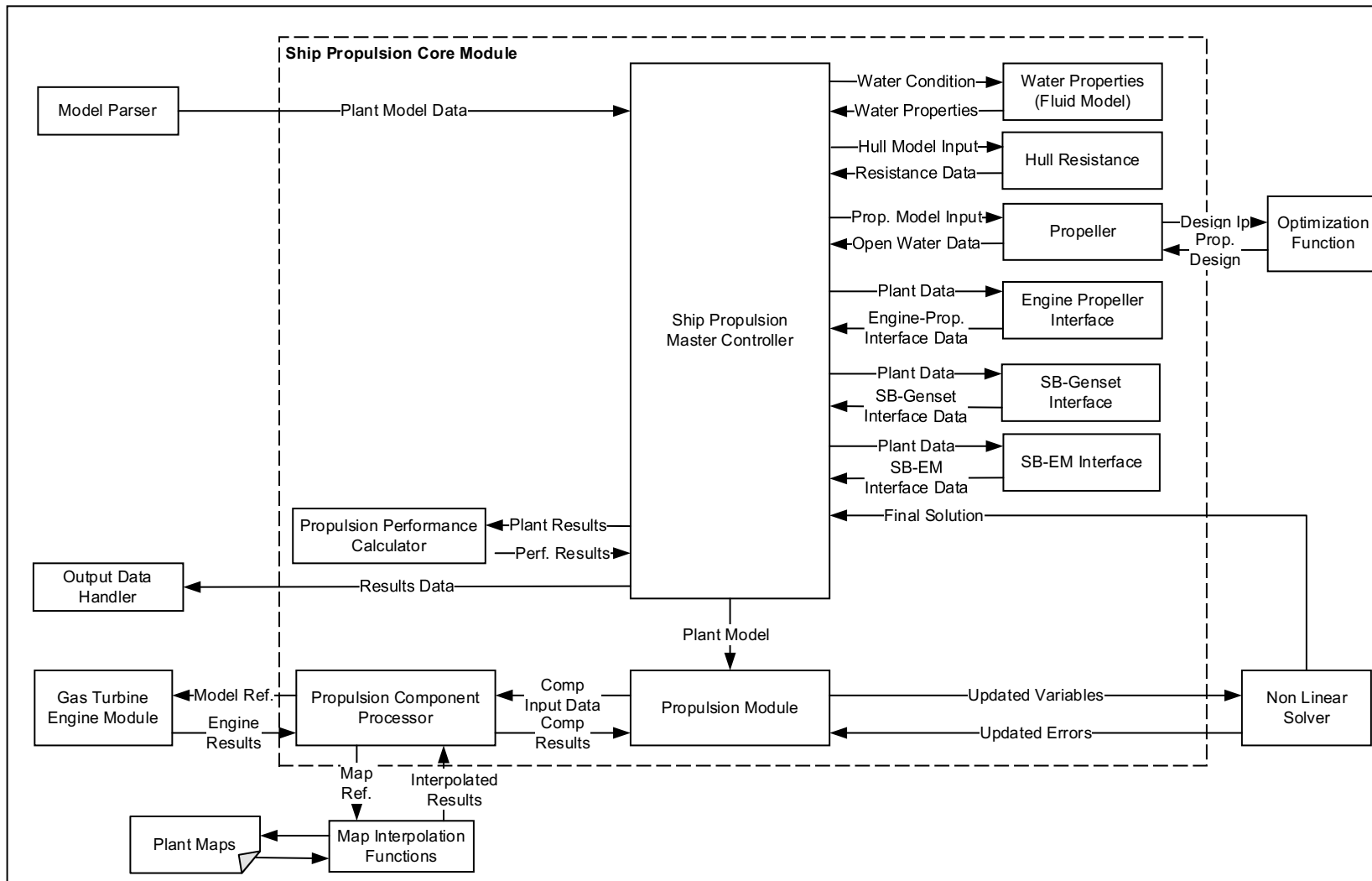


Figure A-4 Simplified overview of ship propulsion system core sub-module architecture in Poseidon+

A.2.2 Gas Turbine Engine Core Sub-module

A simplified overview of the gas turbine engine core software architecture in Poseidon+ is shown in Figure A-3. The gas turbine core submodule receives the engine model data from the model parser module. The 'Engine Master Controller' is responsible for the overall coordination and sequencing function of the sub-module. Separate sequencing routines are used for design point (DP) and off-design (OD) performance calculations. Each OD calculation involves an initial run of a design point calculation to obtain the various scaling factors required for running an OD simulation.

The 'Engine Master Controller' uses the 'Engine Module' for running both the DP and OD calculations. For the OD calculations, the solution needs to be iteratively found using the 'Engine Module' along with the nonlinear solver. For either DP or OD the 'Engine Module' uses the overall input and derived data is constructed into a structured engine model and interact with specific engine component processor modules to calculate the function plant performance for each iteration. The 'Engine Component Processer' interacts with the specific internal and user-defined component maps through the map interpolation functions. After the final solution is found, the data is output to an output file using the 'Output Data Handler'.

A.2.3 Ship Propulsion System Core Sub-module

A simplified overview of the software architecture of the ship propulsion system core sub-module in Poseidon+ is shown in Figure A-4. The ship propulsion core submodule receives the plant model data from the model parser module. The ship propulsion master controller interacts with various methods to obtain the water properties, the hull resistance data, propeller open water data, engine-propeller interface data, switchboard-genset interface data, switchboard electric motor data from the relevant methods as shown in Figure A-4. The ship propulsion master controller uses the propulsion module along with the nonlinear solver to find the ship propulsion performance simulation solution. For this, the overall input and derived data is constructed into a structured plant model which

is used by the propulsion module to interact with specific propulsion component processor modules to calculate the function plant performance for each iteration.

The propulsion component process interacts with any user-defined plant maps through the map interpolation functions. When the plant model involves a gas turbine engine, the gas turbine engine sub module is called to undertake the engine performance calculations and feedback to the propulsion system. After the final solution is found the data is output to an output file using the output data handler.

A.2.4 Fluid Properties

The fluid properties module is used to calculate the thermodynamic properties of the working gas in the gas turbine engine and properties of water used in ship propulsion system modelling, using individual methods.

The 'Thermodynamic Fluid Functions' are used to calculate the thermodynamic fluid calculations to calculate enthalpy, entropy and specific heat ratio from the given temperature and fuel-air ratio or iterative calculations of temperature from the enthalpy, entropy for the given fuel-air ratio pressure etc.

For calculating the properties of water like density, dynamic viscosity and vapour pressure based on the given temperature and salinity of water, the 'Water Properties' functions are used.

A.2.5 Model Parser

The 'Model Parser' is used to process the input data from the model file into a defined structure of an input model that is used by the 'Core Module' to undertake the performance calculations. The model parser has sub modules for reading the input data, and individual modules for processing the input data for the ship propulsion plant and gas turbine engine.

A.2.6 User Interface

The current implementation in Poseidon+ uses a web page-based interface (Figure A-5) to capture user commands for controlling the simulation or

calculations, while the details of the model are provided through a referenced text file. As described earlier in this chapter, it is planned to eventually migrate to a complete graphical user interface which would be also used for the creation of the model itself and post-processing the results into graphics. However, this would need a large amount of effort and was hence not included in the present scope of work.

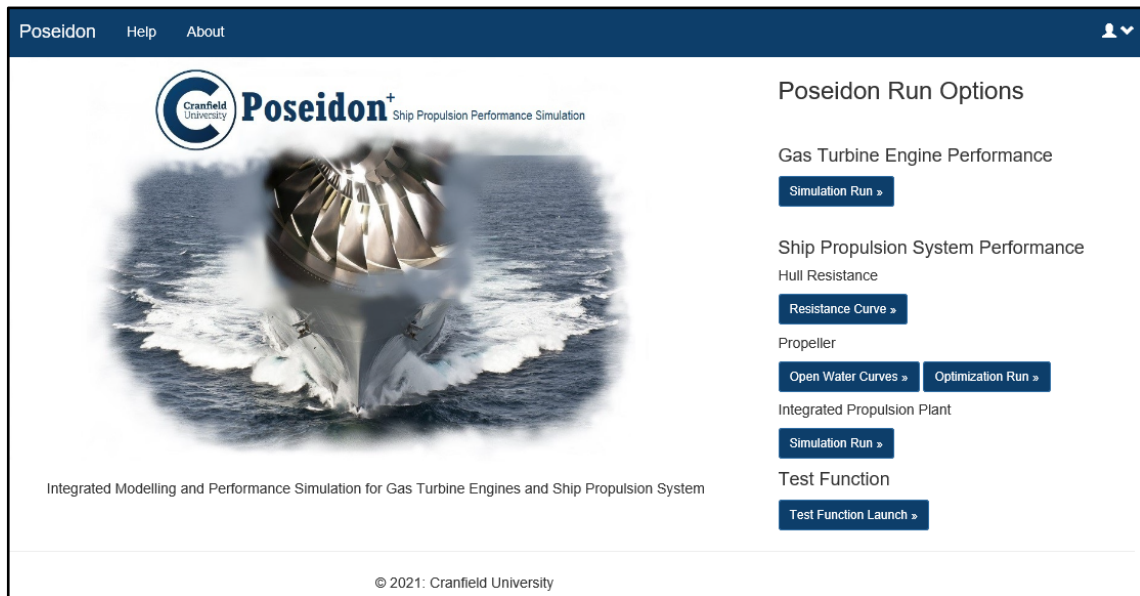


Figure A-5 Currently implemented web-based user interface for Poseidon+

A.2.7 MVC Controller

The MVC controller is used to capture the user commands from the user interface web page and call out the model parser function to initiate the simulation process. This implementation is in line with a standard MVC design implementation. While currently, the implementation of this controller is fairly simple, it would grow as the complexity of the user interface increases in the future.

A.2.8 Output Data Handler

The 'Output Data Handler' is designed to process the output data based on the mode of execution defined by the user. The current implementation of Poseidon+ allows the output data to be exported to text files for individual runs of the simulations.

In addition, Poseidon+ also includes a module to export the simulation data incrementally for each simulation run to an excel sheet. This feature is very useful to post-process and analyse the data from simulations since Poseidon+ organises the data automatically into worksheets, rather than the user having to manually undertake this exercise using text files for individual runs of the simulations.

A.2.9 Mathematical Solvers

Non-Linear Solvers

The ‘Non-Linear Solvers’ are used for iteratively solving the set of simultaneous equations for both the gas turbine engine and propulsion system simulations. In Poseidon+, the following two methods for solving nonlinear equations have been implemented:

- Newton Raphson with Backtracking
- Broyden’s Method

Polynomial Equation Root Finder

For calculation of thermodynamic properties of the gas turbine engine working fluid, polynomial equations, given in the form are often used:

$$f_n(x) = a_0 + a_1x + a_2x^2 + \cdots + a_nx^n$$

where n = the order of the polynomial and the a ’s = constant coefficients.

For root finding of such equations, includes, Mueller’s Method has been implemented in Poseidon+. The method is based on the principle of finding the root estimate by projecting a parabola through three points of the given function [115].

A.2.10 Optimization Function

The Nelder-Mead (NM) of optimization has been implemented in Poseidon+ for numeric optimization of the propeller parameters as a part of the preliminary design of the propeller. The implementation of this method is described in Chapter 4.2.

A.2.11 Map Interpolation Functions

The component maps are designed to be stored as external text files. Poseidon+ has been designed to accept standard maps as well as user-defined custom maps. standard maps. The standard maps are a library of predefined maps used for gas turbine engine performance calculations from which the user selects the applicable map for a particular model by defining it in the input model file. The user can define custom maps instead of these maps if needed by following the map formats as defined in Chapter 4.2. For ship propulsion system modelling, the user can define, custom maps to define the resistance and propeller open water characteristics, if required.

The 'Math Interpolate' functions have been designed to read, interpret, and perform interpolation for the maps defined for any model. These functions have been designed to read and interpolate for the following two types of maps with their modes of parsing: -

- 'Turbomatch style' maps for compressor and turbines are defined in Chapter 4.2.
- Standard 1D maps
- Standard 2D maps

The interpolation methods used for the maps are:

- Custom methods for interpolation of 'Turbomatch style' maps for compressor and turbines as defined in Chapter 4.2.
- 1D and 2D interpolation using linear interpolation method.
- 1D and 2D interpolation using Lagrange's method of interpolation [91].
- 1D and 2D interpolation using cubic splines [91].

.

Appendix B Symbolic Representation of Poseidon+ Model Components

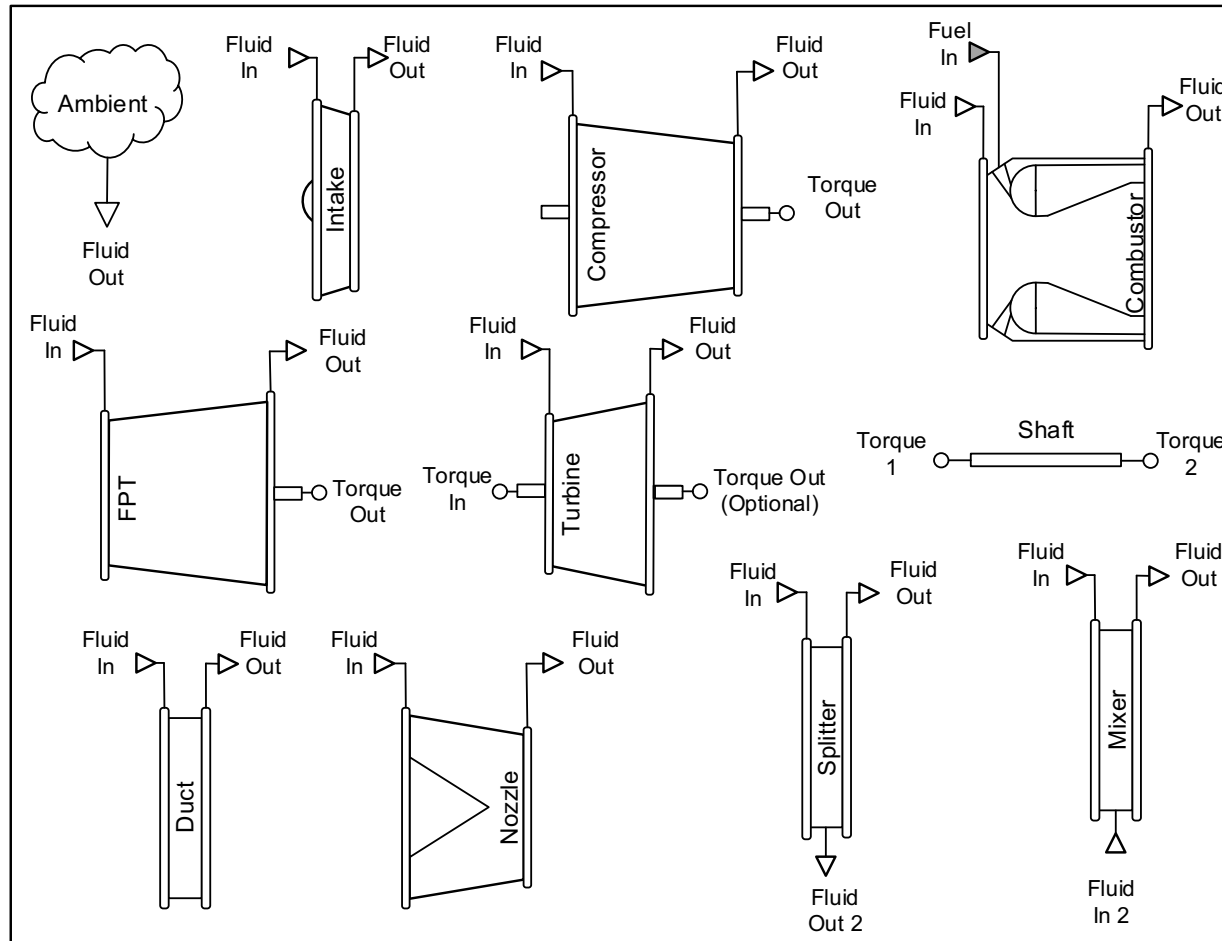


Figure B-1 Symbolic representation of Poseidon+ gas turbine model components.

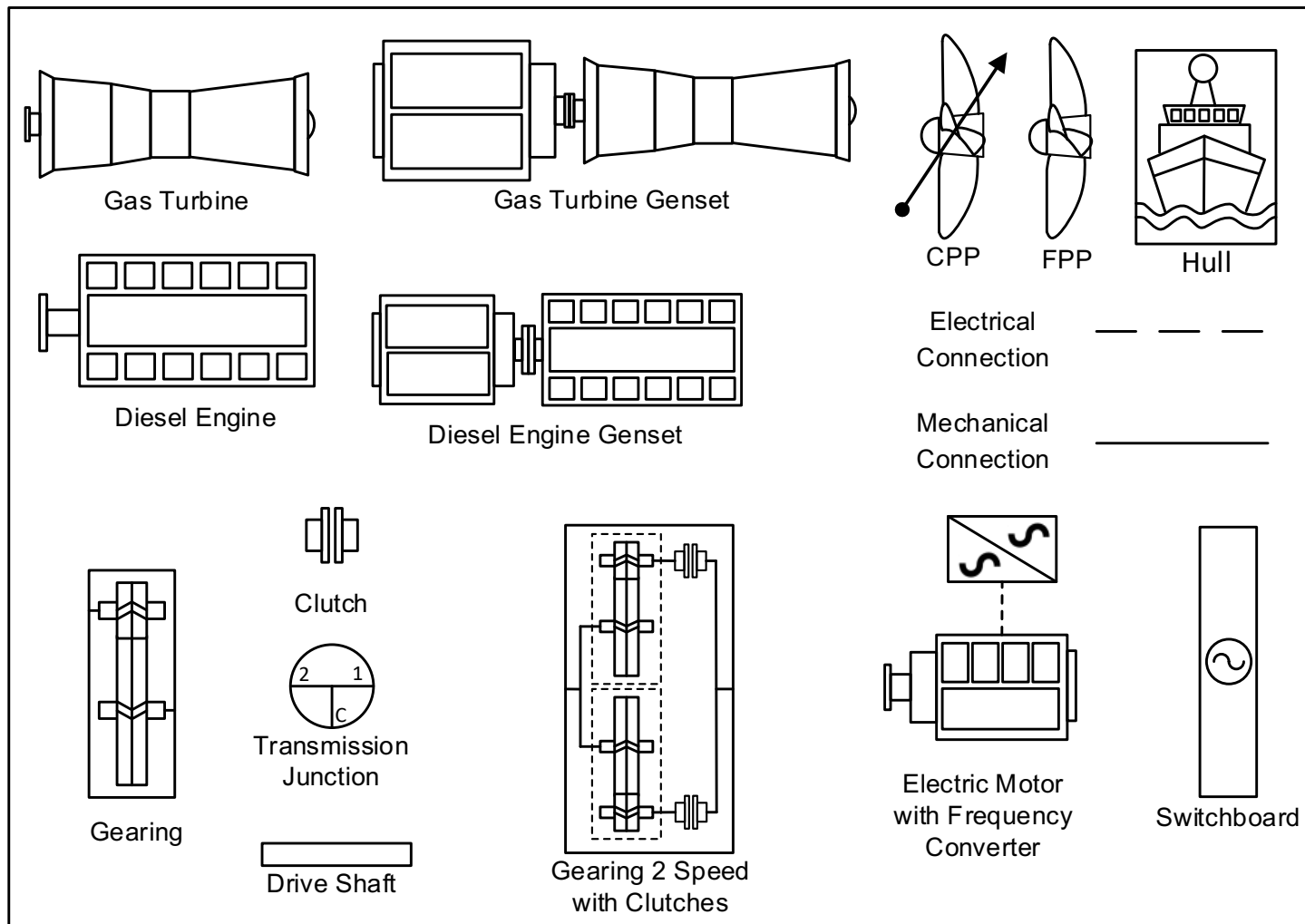


Figure B-2 Symbolic representation of Poseidon+ propulsion plant model components.

Appendix C Poseidon+ Input File Format

The input file format for Poseidon+ is based on a modern programming style interface using curly braces as the separators. This is completely different from the style of the Turbomatch input file, which is based on using line numbers and station numbers for the user inputs as shown in Figure C-1. Based on discussions with many users of Turbomatch at Cranfield University, it was decided to completely change the input file format, in order to have a more flexible format for providing model inputs.

```

////
OD SI KE VA FP
-1
-1
INTAKE S1,2      D1-6      R100
COMPRES S2,3      D7-18     R102    V7
PREMAS S3,10,4    D19-22
PREMAS S4,11,5    D69-72
BURNER S5,6      D23-30     R104    W6,6
MIXEES S6,11,7
TURBIN S7,8      D31-45     R110    V32
NOZCON S8,9,1    D46,47
PERFOR S1,0,0    D48-51,110,100,104,0,0,0,0
CODEND

DATA ITEMS ////
1 11000.          ! INTAKE: Altitude [m]
2 0.              ! Deviation from ISA temperature [K]
3 0.8            ! Mach number
4 -1             ! Pressure recovery, according to USAF
5 0.             ! Deviation from ISA pressure [atm]
6 0.             ! Relative humidity [%]

7 -1             ! COMPRESSOR I: Z = (R-R[choke])/(R[surge]-R[choke]) (if ==-1. the default value
0.85 is invoked)
8 1.             ! Relative rotational speed PCN
9 25.            ! DP Pressure ratio
10 0.85          ! isentropic efficiency
11 1.            ! Error selection
12 3.            ! Compressor Map Number
13 1.            ! Shaft number
14 1.            ! Scaling factor of Pressure Ratio - Degradation factor
15 1.            ! Scaling factor of Non-D Mass Flow - Degradation factor
16 1.            ! Scaling factor of ETAC is (Compressor isentropic efficiency) - Degradation
factor
17 0.5           ! Effective component volume [m^3]
18 0.            ! Stator angle (VSV) relative to DP

```

Figure C-1 Sample Turbomatch model input file [93]

In general, the input file format of Poseidon+ does not require the user to keep track of line numbers or any particular sequence for providing the input data. To create a model file, the user needs to use the right keywords to define the parameters or the group of parameters. The parameter groups are separated by curly braces ({ }), while the individual parameters are separated by semicolons (;). User comments are added by preceding the statement with double slashes (//).

Separate formats for the input files have been defined for the gas turbine engine and the ship propulsion plant models as shown in Figure C-2 and Figure C-3.

The Poseidon+ gas turbine engine input file, as shown in Figure C-2 is divided into two primary parts, the first part being the model definition and the second part of the file being the simulation run definition.

- The model definition consists of the basic defining parameters of the engine under the 'EngineDefinition' section, the definition of the ambient conditions under the section 'Ambient', and the various parameters of the 'EngineComponents' of the engine in the section engine components. The interconnections between the various defined components in the model file, are defined using the 'in' and 'out' ports of the components in the sections 'FluidConnections' and 'MechConnections', for defining the flow of the working fluid in the engine and the mechanical connections for torque transfer, respectively.
- The definition of the simulation run is used to define the selection of parameters for the OD simulation in the section 'SimulationODParameters' and the values of parameters required for a particular simulation run in the section 'SimulationRun'. In 'SimulationODParameters', the parameters that are to be used as the handles or the power setting parameters of the engine are identified in the section 'Handle', while the variables that are used by the nonlinear equation solver, are identified in the section 'Variables'. In 'SimulationRun', the type of simulation to be run, OD or DP, is defined using the 'RunType' parameter. The ambient conditions for the OD run are specified in the section 'Ambient' and the values of the parameters defined as the handles are defined using the parameter/s 'ODHandleValue'.

The propulsion system model input file in Poseidon+, like the gas turbine engine input file, is divided into two primary parts, the first part being of the model definition and the second part of the file being the simulation run definition.

- The model definition consists of the basic defining parameters of the propulsion plant under the 'PlantDefinition' section, the definition of the

ambient air as well as water conditions under the section 'Ambient', and the various parameters of the propulsion plant components including the hull in the section 'PlantComponents'. The interconnections between the various defined components in the model file, are defined using the 'in' and 'out' ports of the components in the sections 'PlantConnections' and 'PlantElConnections', for defining the mechanical connections for torque transfer, as well as electrical connections between the electrical system components respectively. In addition, the various combinations of engines and clutches which define a particular propulsion system 'drive mode' is defined in the section 'PlantDriveModes'. The definition of propulsion system drive modes in this manner allows referencing the simulation run conditions more consistently and concisely.

- The definition of the simulation run is used to define the selection of parameters for the section 'PlantSimulationRun'. The propulsion system drive mode for the simulation run is defined by the parameter 'DriveMode'. The ambient conditions for the OD run are specified in the section 'Ambient' and the set of values of the parameters of various components that set the overall operation point parameter setting (like fuel flow for engines, pitch setting for CPP) are defined by the parameter 'ParameterSetting' for the respective components.

It should be noted that for both the engine and propulsion system model file, the listing of components in the components section also does not need to follow any particular sequence. Similarly, parameters for each component listed in the section for components do not need to follow any defined sequence

<pre> Engine: <i>Name</i> { EngineDefinition { } Ambient { } EngineComponents { Component <i>Type: CompName</i> { Map { } } ... } FluidConnections { Connection: <i>ConnName</i>{ <i>CompName</i>(O ... } MechConnections { Connection: <i>ConnName</i>{ <i>CompName</i>(O ... } } </pre>	<pre> SimulationODParameters { Handle { ComponentType: <i>CompName</i> { } ... } Variables { ComponentType: <i>CompName</i> { } ... } } SimulationRun: <i>RunName</i> { RunType: <i>Val</i>; ODHandleValue: <i>Val</i>; Ambient { } } </pre>
--	--

Figure C-2 Input file format for a gas turbine engine model.

<pre> Plant: <i>PlantName</i> { PlantDefinition { } Ambient { } PlantComponents { Component <i>Type: CompName</i> { Map { } } ... } PlantConnections { Connection: <i>ConnName</i> { <i>CompName</i>(Out); <i>Comp</i> ... } PlantElConnections { ElConnection: <i>ConnName</i>{ <i>CompName</i>(Out); <i>Cor</i> ... } PlantDriveModes { DriveMode: <i>ModeName</i> { <i>CompName</i>(On); <i>Comp</i> } } </pre>	<pre> PlantSimulationRun: <i>SimRunName</i> { DriveMode= <i>ModeName</i>; Ambient { } PlantComponents { Component <i>Type: CompName</i> { ParameterSetting= <i>Parameter Value</i>; } } } </pre>
---	---

Figure C-3 Input file format for ship propulsion system model.

Appendix D Thermodynamic Calculation Models

The following sections describe the theoretical background, considerations for the thermodynamic calculation models and procedures implemented in Poseidon+, across the performance calculations.

D.1 Thermodynamic Property Models

The thermodynamic properties of interest that are extensively used across gas turbine calculations are specific heat at constant pressure, specific enthalpy and entropy, gas constant and ratio of specific heats. These may be defined as [90]:

- Specific heat at constant pressure c_p can be defined as the amount of energy required to raise the temperature of one kilogram of the gas by 1 deg C, at constant pressure.
- Specific enthalpy h can be defined as the energy per kilogram of gas relative to a stipulated zero datum.
- Specific entropy s . Entropy may be defined as thermal energy not available for doing work in a process. During compression or expansion, the increase in entropy is a measure of the thermal energy lost to friction, which becomes unavailable as useful work.
- Gas constant R numerically equal to the difference between c_p and specific heat at constant volume c_v .
- The ratio of specific heats, γ , is defined as the ratio of the specific heat at constant pressure c_p to that at constant volume c_v .

The performance calculations in Poseidon+, like Turbomatch, are executed using the method of fully rigorous calculations for changes in enthalpy and entropy across components are evaluated using c_p and h . The method used, based on the theoretical assumptions for the same, is described below.

All gases employed as the working fluid in gas turbine engines, except for water vapour, may be considered as perfect gases without compromising calculation accuracy. When the mass fraction of water vapour is less than 10%, which is usually the case when it results from the combination of ambient humidity and

products of combustion, then for performance calculations the gas mixture may still be considered perfect. When water vapour content exceeds 10%, the assumption of a perfect gas is no longer valid. A perfect gas has its enthalpy as only a function of temperature and not pressure and adheres to [67]:

$$Pv = RT \quad (\text{D-1})$$

which is a relation derived from the equation of state:

$$RdT = Pdv + vdP \quad (\text{D-2})$$

The thermodynamic concept of an ideal mixture of semi-perfect gases is widely used for gas turbine engine performance calculations. The mixtures of semi-perfect gases are characterized by their extensive and intensive properties. The extensive properties of a mixture are the sum of all contributions made by every component like total mass or moles of a mixture; while intensive properties are approximated by a weighted average of the properties of the components which characterize the primary thermodynamic properties. Based on the above, considerations, Poseidon+ considers the working fluid of the gas as a mixture of semi-perfect gases having the following properties:

- The specific heats of the individual components of the gas are only a function of temperature.
- The pressure of the mixture is the sum of the partial pressures of the individual gas components.

Hence, to calculate the thermodynamic properties of the working fluid, calculation of the mass fraction of each gas component is necessary, based on which the thermodynamic properties can be further calculated. This concept of a mixture of semi-perfect gases has been implemented in the Poseidon+, based on a similar implementation as in Turbomatch. The mass fraction of the components of the working fluid is calculated as follows.

The mass m of a substance is expressed in terms of moles N and molecular weight M as:

$$m = NM \quad (\text{D-3})$$

The average molecular weight of the mixture M_m with k elements is then expressed as:

$$M_m = \frac{m_m}{N_m} = \frac{\sum_{i=1}^k N_i M_i}{N_m} = \sum_{i=1}^k x_i M_i \quad (\text{D-4})$$

where x_i is the mole fraction of each component of the mixture given by:

$$x_i = \frac{N_i}{N_m} \quad (\text{D-5})$$

D.2 Calculation of Mass Fraction of Gas Components

When a hydrocarbon fuel is burnt in air, combustion products change the composition significantly. The degree of change in air composition depends both on the fuel-air ratio and fuel chemistry. The amount of fuel in the air can be expressed in a dimensionless number called the Fuel-to-Air ratio (FAR). The FAR for which all the oxygen is consumed is termed stoichiometric and the products resulting thereof are called stoichiometric combustion products. Any additional air present during the combustion process is called excess air. Theoretically, the excess air does not react during the combustion process and hence it can be considered to be unchanged as a part of the combustion products.

Gas turbine engines always operate with a large amount of excess air (100% to 250%), to maintain the flame temperature below the mechanical limits of the materials. The combustion process can be considered completed at the exit of the combustor of the gas turbine engine. Consequently, the gas mixtures can be considered to be in thermodynamic equilibrium and the unburned products can be neglected. Therefore, for gas turbines (without water or steam injection), it can be assumed that the expanding gas is composed of only two components: stoichiometric combustion products and excess air. The stoichiometric combustion products and excess air can be treated as mixtures with constant compositions. This consideration greatly reduces the number of variables

required to determine the composition of gas composition [126]. On the other hand, very complex combustion kinetics analyses are required to model incomplete combustion and to include the dissociation effects, but this is not considered necessary for most models used for gas turbine performance simulation.

Since complete combustion has been assumed, the mass balance between reactants and products is used in Poseidon+ to determine the composition of the combustion products. The actual composition of the combustion gas is determined based on the fraction of stoichiometric products as follows.

Total working medium flow W_{total} is expressed as a sum of airflow W_{air} and fuel flow WF :

$$W_{total} = W_{air} + WF \quad (D-6)$$

where airflow W_{air} is expressed as a sum of stoichiometric air low $W_{stoic\ air}$ and excess airflow $W_{excess\ air}$, as follows:

$$W_{air} = W_{stoic\ air} + W_{excess\ air} \quad (D-7)$$

The fuel-air ratio FAR is defined as:

$$FAR = \frac{WF}{W_{air}} \quad (D-8)$$

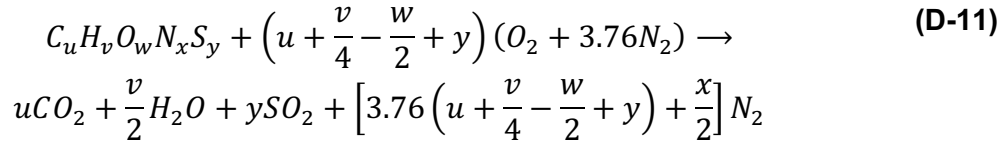
The stoichiometric fuel-air ratio FAR_{stoic} is defined as:

$$FAR_{stoic} = \frac{WF}{W_{stoic\ air}} \quad (D-9)$$

Equivalence ratio Φ is defined as:

$$\Phi = \frac{FAR}{FAR_{stoic}} \quad (D-10)$$

The following general relationship is used for hydrocarbon-based fuels to estimate the stoichiometric mole numbers of air and the main combustion products, assuming complete combustion with no dissociation:



where $C_u H_v O_w N_x S_y$ is the known composition of the fuel.

Air is found in the atmosphere as a mix of different elements including water vapour. Air containing no water vapour is called dry air. The concentration of the other elements in air such as N_2 , O_2 , Ar, Ne show no variation under different conditions, therefore, the atmospheric air is considered as a mixture of dry air and water vapour.

Hence by knowing the *FAR*, the fuel type with defined composition, the entire gas or working fluid composition can be calculated. Poseidon+ calculates the molar gas composition using *FAR* and fuel type as the input. Since the stoichiometric combustion products are solely dependent on the fuel type with defined composition, these have been predetermined in the module, based on the fuel composition.

D.3 Thermodynamic properties of the working fluids

For gas turbine performance calculations, the following basic thermodynamic relationships are used:

From the Second Law of Thermodynamics and Gibbs equation, change in entropy ds is given by:

$$ds = c_p \frac{dT}{T} - R \frac{dP}{P} \quad (D-12)$$

$$s_2 - s_1 = \int_{T_1}^{T_2} c_p \frac{dT}{T} - R \ln \frac{P_2}{P_1} \quad (D-13)$$

where specific heat capacity at constant pressure c_p is defined as:

$$c_p = \left(\frac{\partial h}{\partial T} \right)_p \quad (D-14)$$

Defining entropy function ϕ :

$$\phi = \int_{T_{ref}}^{T_2} c_p \frac{dT}{T} \quad (\text{D-15})$$

Change in entropy and enthalpy are given by:

$$s_2 - s_1 = \phi_2 - \phi_1 - R \ln \frac{P_2}{P_1} \quad (\text{D-16})$$

$$h = \int_{T_{ref}}^T c_p dT \quad (\text{D-17})$$

Knowing the pressure or temperature difference across the process the thermodynamic gas parameters can be calculated by an iterative process.

For isentropic process $ds = 0$

$$\phi_2 - \phi_1 = R \ln \frac{p_2}{p_1} \quad (\text{D-18})$$

Based on definitions:

$$R = c_p - c_v \quad (\text{D-19})$$

$$\gamma = \frac{c_p}{c_v} \quad (\text{D-20})$$

The (specific) gas constant for an individual gas R is given by:

$$R = \frac{R_u}{m} \quad (\text{D-21})$$

where R_u is the universal gas constant and m is the molecular weight of the gas.

For gas turbine engines, with a steady flow of gas, only the specific heat at constant pressure c_p , is used directly and often referred to simply as specific heat. For the gases of interest, c_p is considered as a function of only gas composition and static temperature, with the consideration as described earlier in this chapter. For calculations of c_p , total temperature can normally be used up to Mach

numbers of 0.4 with negligible loss in accuracy since dynamic temperature remains a low proportion of the total.

Changes in enthalpy, rather than absolute values, are important for gas turbine performance calculations. Total or static enthalpy may be calculated, depending on which of the respective temperatures is used. Total enthalpy, like total temperature, is most common in performance calculations. Changes in entropy, rather than absolute values are of interest. The ideal work would be required or produced if entropy did not change, i.e., if the process were isentropic. Isentropic efficiency, defined as the appropriate ratio of actual and ideal work, is used to account for the effects of entropy.

The ratio of specific heats γ is considered to be a function of gas composition and static temperature. However, the total temperature may be used when the Mach number is less than 0.4.

The thermodynamic properties of the gas c_p , h and R are considered to be intensive properties of a mixture and are thus calculated using a weighted average of the properties of the components of the mixture. The weighting factor is either the mass fraction or mole fraction of each component x_i , calculated by dividing the component mass or the number of moles over the mixture total mass or moles. Thus, c_p , h for the working fluid can be calculated as:

$$h_m = \sum_{i=1}^k x_i h_i \quad (\text{D-22})$$

$$c_{p,m} = \sum_{i=1}^k x_i c_{p,i} \quad (\text{D-23})$$

The thermodynamic properties of the individual elements are evaluated as a function of temperature using defined polynomial laws. There are many sets of polynomials for the calculation of properties of the common elements in air and combustion products. Poseidon+ uses the set of equations developed by Bucker et.al. [118] to characterize the thermodynamic properties of interest for the main components of combustion gases. These equations have been developed

specifically for gas turbine engine applications, with a high degree of accuracy for gas mixtures at temperatures from 200 to 3300 K. The thermodynamic properties for the mixtures are calculated as per the equations [118]:

$$c_{p,m} = \sum_{i=1}^{10} a_{m,i} \left(\frac{T}{T_0} \right)^{b_i} \quad (\text{D-24})$$

$$h_m = a_{m,I} + \sum_{i=1}^{10} a_{m,i} \frac{T_0}{b_i + 1} \left(\frac{T}{T_0} \right)^{b_i+1} \quad (\text{D-25})$$

$$s_m = a_{m,II} - R_u \ln \left(\frac{P}{P_0} \right) + \Delta^{mix} s^o + a_{m,I} \ln \left(\frac{T}{T_0} \right) + \sum_{i=2}^{10} \frac{a_{m,i}}{b_i} \left(\frac{T}{T_0} \right)^{b_i} \quad (\text{D-26})$$

where:

$a_{m,i}$: coefficients for the mixture, calculated for $i = \text{I, II, 1, 2, ...}, 10$ according to:

$$a_{m,i} = \sum_{k=1}^8 x_k a_{k,i} \quad (\text{D-27})$$

where:

$a_{k,i}$ are substance-specific coefficients $a_{k,i}$ given in Table D-1

k denotes the component of the mixture,

x_k is the mole fraction (mole/ concentration in mol/g).

b_i : exponents, not substance-specific and given in Table D-2.

The definitions of the constants, reference temperature T_0 , reference pressure P_0 and the universal gas constant R_u used in the above equations are:

$$T_0 = 273.15 \text{ K}$$

$$P_0 = 101.325 \text{ kPa}$$

$$R_u = 8.314472 \text{ J/mol/K}$$

Table D-1 Values of substance-specific coefficients $a_{k,i}$.

i	Nitrogen	Oxygen	Argon	Neon
I	4.305300363×10^8	5.295253592×10^7	-5.677745067×10^3	-5.677745067×10^3
II	-4.085709350×10^6	-7.353805669×10^5		
1	2.475830346×10^6	6.408242565×10^5	2.078618000×10^1	2.078618000×10^1
2	-2.815239891×10^4	-1.599937045×10^3		
3	1.116401165×10^5	9.984801256×10^3		
4	-8.147644187×10^5	-1.280873444×10^5		
5	2.185120405×10^6	4.186599156×10^5		
6	-2.978031305×10^6	-6.720142804×10^5		
7	-1.308008001×10^6	-3.799977202×10^5		
8	4.305948510×10^5	1.378691801×10^5		
9	-8.082302563×10^4	-2.806954185×10^4		
10	6.622545214×10^3	2.459943097×10^3		
i	Water	Carbon Dioxide	Carbon Monoxide	Sulfur Dioxide
I	-7.574888563×10^8	2.042361458×10^8	4.306836224×10^8	-3.845730250×10^8
II	7.373724814×10^6	-1.912121053×10^6	-4.203685809×10^6	3.543224735×10^6
1	-4.747782033×10^6	1.103695150×10^6	2.670755728×10^6	-2.076653674×10^6
2	4.799919289×10^4	-1.365096910×10^4	-2.715629936×10^4	2.589571253×10^4
3	-1.931588954×10^5	5.357704944×10^4	1.096509012×10^5	-1.012523438×10^5
4	1.460728340×10^6	-3.816063864×10^5	-8.303525865×10^5	7.161863952×10^5
5	-4.000075762×10^6	1.008950325×10^6	2.269213594×10^6	-1.889754780×10^6
6	5.576209858×10^6	-1.352938737×10^6	-3.151865706×10^6	2.535020356×10^6
7	2.570488297×10^6	-5.701809626×10^5	-1.438126165×10^6	1.082842148×10^6
8	-8.670521019×10^5	1.828513133×10^5	4.824833432×10^5	-3.524395911×10^5
9	1.666429390×10^5	-3.329618224×10^4	-9.227524508×10^4	6.552035769×10^4
10	-1.396634620×10^4	2.635366727×10^3	7.701550175×10^3	-5.325634796×10^3

Table D-2 Values of exponent b_i .

i	b_i
1	0.00
2	-1.50
3	-1.25
4	-0.75
5	-0.50
6	-0.25
7	0.25
8	0.50
9	0.75
10	1.00

D.4 Additional Thermodynamic Relations Used

Stagnation properties:

$$T = T_S + \frac{V^2}{2c_p} \quad (\text{D-28})$$

$$H = H_S + \frac{V^2}{2} \quad (\text{D-29})$$

‘Corrected form’ of non-dimensional parameters:

Corrected speed:

$$CN = \frac{(N/N_{DP})}{\sqrt{\theta}} \quad (\text{D-30})$$

Corrected mass flow:

$$CMF = \frac{W\sqrt{\theta}}{\delta} \quad (\text{D-31})$$

where θ and δ are defined as:

$$\theta = \frac{T_{in}}{T_{std}}$$

$$\delta = \frac{P_{in}}{P_{std}}$$

with the following constants:

$$T_{std} = 288.149 \text{ K}$$

$$P_{std} = 101.325 \text{ kPa}$$

Appendix E Gas Turbine Component Models

E.1 Ambient Air Model

The ambient air model is designed to calculate the air temperature and pressure based on user-specified altitude, as needed primarily needed for aero applications. For ship propulsion system applications, the user can define the deviation in a temperature and pressure from the standard (ISA SLS) conditions.

Model Input:

For ship propulsion: Deviation from ISA temperature and pressure dT_{ISA} , dP_{ISA}

For flight calculations: Flight altitude Alt in m, defined as user input.

Calculations (common for DP and OD Calculations):

Based on Alt , TS_{amb} and PS_{amb} are calculated.

For $Alt < 11000$

$$TS_{ISA} = 288.15 - 0.0065 Alt \quad (E-1)$$

$$PS_{ISA} = 101.325 \left(\frac{288.15}{TS_{amb}} \right)^{-5.25588} \quad (E-2)$$

For $11000 \leq Alt < 24994$

$$TS_{ISA} = 216.65 \quad (E-3)$$

$$PS_{ISA} = \frac{22.63253}{e^{0.000157689 (Alt - 10998.1)}} \quad (E-4)$$

For $24994 \leq Alt < 30000$

$$TS_{ISA} = 216.65 - 0.0065 Alt \quad (E-5)$$

$$PS_{ISA} = 2.5237 \left(\frac{216.65}{TS_{amb}} \right)^{11.8} \quad (E-6)$$

Users can also define the deviation from ISA temperature and pressure

Based on dT_{ISA} , dP_{ISA} using which the TS_{amb} and PS_{amb} are calculated as:

$$TS_{amb} = TS_{ISA} + dT_{ISA} \quad (E-7)$$

$$PS_{amb} = PS_{ISA} + dP_{ISA} \quad (E-8)$$

It can be seen that for ship calculations, $Alt = 0$, giving:

$$T_{ISA} = 288.15$$

$$PS_{ISA} = 101.325$$

E.2 Intake

Intakes or Inlets are designed to guide required airflow into the front face of the engine with minimum loss and distortion. The intake drag and pressure losses are modelled to calculate accurate average total pressures for the compressor inlet face. Intake interfaces with the ambient air model component to read TS_{amb} , PS_{amb} as TS_{in} , PS_{in} respectively. Different ambient blocks may be specified for DP and OD calculations.

Model Design Input Data:

Ram Recovery Factor (for flight) or Pressure Loss (for ship): dP_{intake}

Flight Mach Number M_0 . Not used for ship calculations

Calculations (common for DP and OD Calculations):

$$R_a = f_{TD,R}(FAR = 0) \quad (E-9)$$

$$c_{p_a} = f_{TD,cp}(TS_{amb}, FAR = 0) \quad (E-10)$$

$$\gamma_a = \frac{c_{p_a}}{c_{p_a} - R_a} \quad (E-11)$$

$$V_{in} = M_0 \sqrt{\gamma_a R_a TS_{amb}} \quad (E-12)$$

$$HS_a = f_{TD,H}(TS_{amb}, FAR = 0) \quad (E-13)$$

$$H_{in} = HS_a + \frac{V_{in}^2}{2} \quad (\text{E-14})$$

T_{in} is calculated iteratively from H_{in} , starting with a guessed $T_{in,guess}$ and H_{in} .

P_{in} is calculated from the relation:

$$\phi_{T_{in}} - \phi_{TS_{amb}} = R_a \ln \frac{P_{in}}{PS_{amb}} \quad (\text{E-15})$$

For flight applications, if the user does not define Ram Recovery Factor, it is calculated as per MIL-E-5008B based on given M_0 as follows:

For $M_0 < 1$

$$dP_{intake} = 1 \quad (\text{E-16})$$

For $1 < M_0 \leq 5$

$$dP_{intake} = 1 - 0.075 (M_0 - 1)^{1.35} \quad (\text{E-17})$$

For $M_0 < 1$

$$dP_{intake} = \frac{800}{M_0^4 + 935} \quad (\text{E-18})$$

P_{out} is calculated as:

$$P_{out} = P_{in} dP_{intake} \quad (\text{E-19})$$

T_{out} remains unchanged:

$$T_{out} = T_{in} \quad (\text{E-20})$$

Momentum Drag XR is calculated as (only needed for flight applications):

$$XR = W_{in} V_{in} \quad (\text{E-21})$$

E.3 Compressor

The compressor model utilizes compressor performance maps for the calculation of off-design performance parameters. The design point run is used to calculate the scaling factors for the compressor maps which are then utilised during off-design runs. Air bleeds from the compressor used in the engine for turbine cooling etc. are modelled separately by using a combination of splitters and mixers. hence there are no separate quotes on the compressor for bleeds.

Model Design Input Data:

Operating Point Definition, Speed Ratio: $N_{c,DP}$

where N_c is defined as:

$$N_c = \frac{n_c}{n_{c,nom}} \quad (\text{E-22})$$

where:

n_c : actual compressor speed

$n_{c,nom}$: nominal compressor speed

Operating Point Definition, Surge Margin: $Z_{c,DP}$

where $Z_{c,DP}$ is defined as:

$$Z_c = \frac{PR_c - PR_{cmin}}{PR_{cmax} - PR_{cmin}} \quad (\text{E-23})$$

where PR_c is defined as:

$$PR_c = \frac{p_{out}}{p_{in}} \quad (\text{E-24})$$

Calculations:

DP Calculations:

Corrected speed ratio and inlet mass flow for the compressor are calculated as:

$$N_{cDP,corr} = \frac{N_{cDP}}{\sqrt{\theta_{DP}}} \quad (\text{E-25})$$

$$W_{cin,DP,corr} = \frac{W_{cin,DP} \cdot \sqrt{\theta_{DP}}}{\delta_{DP}} \quad (\text{E-26})$$

At the DP, defined N_{cDP}, Z_{cDP} is used to calculate

$PR_{cmap,DP}, W_{cmap,DP}, \eta_{cmap,DP}$ from the specified map by the user, using the function:

$$PR_{cmap,DP}, W_{cmap,DP}, \eta_{cmap,DP} = f_{interpTM,C} (N_{cDP,corr}, Z_{cDP}) \quad (\text{E-27})$$

where *interpTM*: interpolation function for TM style map

Using the map outputs, the DP scaling factors for the compressor map are calculated as:

$$SF_{N_c} = \frac{N_{cDP}}{N_{cDP,corr}} \quad (\text{E-28})$$

$$SF_{PR_c} = \frac{PR_{cDP} - 1}{PR_{cmap,DP} - 1} \quad (\text{E-29})$$

$$SF_{\eta_c} = \frac{\eta_{cDP}}{\eta_{cmap,DP}} \quad (\text{E-30})$$

$$SF_{W_c} = \frac{W_{cin,DP,corr}}{W_{cmap,DP}} \quad (\text{E-31})$$

The model design values are updated into the variables for further thermodynamic calculations, as:

$$PR_c = PR_{cDP} \quad (\text{E-32})$$

$$\eta_c = \eta_{cDP} \quad (\text{E-33})$$

$$W_{c,out} = W_{c,in} \quad (\text{E-34})$$

OD Calculations:

Corrected speed ratio and inlet mass flow for the compressor are calculated as:

$$N_{c_{OD,corr}} = \frac{N_{c,OD}}{\sqrt{\theta_{OD}}} \quad (\text{E-35})$$

$$W_{c_{in,OD,corr}} = \frac{W_{c_{in,OD}} \cdot \sqrt{\theta_{OD}}}{\delta_{OD}} \quad (\text{E-36})$$

To input the speed ratio in the map, a scaling factor is applied to the corrected speed ratio:

$$N_{c_{OD,corr,sc}} = N_{c_{OD,corr}} SF_{N_c} \quad (\text{E-37})$$

where the suffix *sc* stands for scaled value.

Using the defined compressor map, $PR_{c_{map,OD}}$, $W_{c_{map,OD}}$, $\eta_{c_{map,OD}}$ are calculated from the map using $N_{c_{OD,corr,sc}}$, $Z_{c,OD}$ as:

$$PR_{c_{map,OD}}, W_{c_{map,OD}}, \eta_{c_{map,OD}} = f_{interpTM,C} (N_{c_{OD,corr,sc}}, Z_{c,OD}) \quad (\text{E-38})$$

Application of scaling factors on the map out gives:

$$PR_c = 1 + SF_{PR_c} (PR_{c_{map,OD}} - 1) \quad (\text{E-39})$$

$$W_{c_{map,OD,sc}} = W_{c_{map,OD}} SF_{W_c} \quad (\text{E-40})$$

Since map output is in terms of corrected form, the mass flow at compressor outlet is calculated as:

$$W_{c_{out}} = \frac{W_{c_{map,OD,sc}} \cdot \delta_{OD}}{\sqrt{\theta_{OD}}} \quad (\text{E-41})$$

Application of scaling factors on map out for efficiency gives:

$$\eta_c = \eta_{c_{map,OD}} SF_{\eta_c} \quad (\text{E-42})$$

Error term for OD calculations is calculated as:

$$Err_{c1} = \frac{W_{c_{out}} - W_{c_{in}}}{W_{c_{in}}} \quad (\text{E-43})$$

where $W_{c_{in}}$ is the station vector input for mass flow.

Common thermodynamic calculations:

Further calculations undertaken are as follows:

$$p_{out} = p_{in} PR_c \quad (\text{E-44})$$

$$H_{in} = f_{TD,H}(T_{in}, FAR = 0) \quad (\text{E-45})$$

$T_{out,isen}$ is calculated iteratively for p_{in}, p_{out}, T_{in} .

$$H_{out,isen} = f_{TD,H}(T_{out,isen}, FAR = 0) \quad (\text{E-46})$$

$$dH_{isen} = H_{out,isen} - H_{in} \quad (\text{E-47})$$

$$dH = \frac{dH_{isen}}{\eta_c} \quad (\text{E-48})$$

where dH is defined as:

$$dH = H_{out} - H_{in} \quad (\text{E-49})$$

$$PW_c = W dH \quad (\text{E-50})$$

where $W = W_{out} = W_{in}$

$$H_{out} = dH + H_{in} \quad (\text{E-51})$$

T_{out} is calculated using the function:

$$T_{out} = f_{TD,T}(H_{out}, dp) \text{ with initial guess} = T_{out,isen}$$

E.4 Combustor (Burner)

The combustor is typically used between the compressor and turbine components, as the primary heat addition component. The combustor is modelled to represent the energy rise and pressure drop across it, based on the

operating conditions. The combustion is considered as a heat addition at quasi-constant pressure (since there are pressure losses). To model the changes of burning efficiencies according to the combustor inlet conditions, combustor efficiency is calculated based on a generic combustor map.

Model Design Input Data:

Combustion chamber pressure loss dPR_{DP} , defined as:

$$dPR_{DP} = \left(\frac{P_{in} - P_{out}}{P_{in}} \right)_{DP} = \left(\frac{dP}{P_{in}} \right)_{DP} \quad (\text{E-52})$$

Combustion efficiency, given by: $\eta_{b,DP}$

Calculations:

DP Calculation:

Pressure Loss Constant CB is defined as:

$$\left(\frac{dP}{P_{in}} \right)_{DP} = CB \cdot \left(\frac{W_{in} \sqrt{T_{in}}}{P_{in}} \right)_{DP}^2 \quad (\text{E-53})$$

For DP conditions, pressure loss across the combustor, dP is calculated using CB , as:

$$dP = CB \left(\frac{W_{in}^2 T_{in}}{P_{in}} \right) \quad (\text{E-54})$$

$$P_{out} = P_{in} - dP \quad (\text{E-55})$$

The combustor map is used to calculate the scaling factor for η_b :

$$\eta_{b,map} = f_{interp,2D} \left(\frac{P_{in}}{P_{ref}}, T_{out} - T_{in,map_b} \right) \quad (\text{E-56})$$

$$SF_{\eta_b} = \frac{\eta_{b,DP}}{\eta_{b,map}} \quad (\text{E-57})$$

OD Calculations:

η_b is calculated as:

$$\eta_{b,map} = f_{interp,2D} \left(\frac{P_{in}}{P_{ref}}, T_{out} - T_{in,map_b} \right) \quad (E-58)$$

$$\eta_b = \eta_{b,map} SF_{\eta_b} \quad (E-59)$$

W_{out} is calculated as:

$$W_{out} = W_{in} + WF_{in} \quad (E-60)$$

FAR is defined as:

$$FAR = \frac{WF_{in}}{W_{in}} = \frac{WF_{in}}{W_{out} - WF_{in}} \quad (E-61)$$

$$W_{out} = (1 + FAR) W_{in} \quad (E-62)$$

To calculate FAR , the relationship required is derived as:

From the energy balance equation:

$$W_{out} H_{out} - W_{in} H_{in} = \eta_b WF_{in} LHV + WF_{in} H_f \quad (E-63)$$

Using the definition of FAR to replace W_{out}, W_{in}, WF_{in} terms in the above equation:

$$(1 + FAR)H_{out} = H_{in} + FAR \eta_b LHV + H_f \quad (E-64)$$

Rearranging terms to calculate h_{out} :

$$H_{out} = \frac{H_{in} + FAR \eta_b LHV + H_f}{(1 + FAR)} \quad (E-65)$$

Rearranging terms to calculate FAR :

$$FAR = \frac{H_{out} - H_{in}}{\eta_b LHV + H_f - H_{out}} \quad (E-66)$$

$$H_{in} = f_{TD,h}(T_{in}, FAR = 0) \quad (E-67)$$

For OD simulation either T_{out} or FAR would be a known quantity. For each of these scenarios, calculations proceed as:

If $COT (T_{out})$ is given:

$$H_{out} = f_{TD,h}(T_{out}, FAR = 0) \quad (\text{E-68})$$

$$FAR = \frac{H_{out} - H_{in}}{\eta_b LHV + H_f - H_{out}} \quad (\text{E-69})$$

If FAR is given:

The solution is found iteratively using Muller's Method by guessing $T_{out,guess}$ and using the same method as above to calculate FAR_{guess} and comparing with the given FAR for convergence.

E.5 Turbine and Free Power Turbine

Turbine modelling is executed in a very similar way to compressor modelling. As mentioned earlier, the modelling of turbine cooling is undertaken separately using the splitter and mixer components. Hence there is no port for turbine cooling is included in the turbine model. As far as the user interface is concerned, the turbine and free power turbine are considered as separate engine model components. However, since the calculations required in both these component models are very similar, a common calculation procedure is used for both these components.

Model Design Input Data:

Operating Point, Speed Ratio: $N_{t,DP}$

where:

$$N_t = \frac{n_t}{n_{t,nom}} \quad (\text{E-70})$$

where:

n_t : actual turbine speed

$n_{t,nom}$: nominal turbine speed

Operating Point, turbine enthalpy ratio point: $Z_{t,DP}$

where $Z_{t,DP}$ is defined as:

$$Z_t = \frac{dH/T_t}{dH/T_{t,max}} \quad (\text{E-71})$$

where dH/T_t is defined as the enthalpy ratio for the turbine as:

$$dH/T_t = \frac{H_{in} - H_{out}}{T_{in}} \quad (\text{E-72})$$

Calculations:

DP Calculations:

The corrected speed ratio, $N_{t,DP,corr}$ and corrected flow $W_{t,in,DP,corr}$ at DP is calculated as:

$$N_{t,DP,corr} = \frac{N_{t,DP}}{\sqrt{\theta_{t,DP}}} \quad (\text{E-73})$$

$$W_{t,in,DP,corr} = \frac{W_{t,in,DP} \cdot \sqrt{\theta_{t,DP}}}{\delta_{t,DP}} \quad (\text{E-74})$$

At the DP, defined $N_{t,DP}$, $Z_{t,DP}$ is used to calculate $dH/T_{t,map,DP}$, $W_{t,map,DP}$, $\eta_{t,map,DP}$ from the specified map by the user, given by:

$$dH/T_{t,map,DP}, W_{t,map,DP}, \eta_{t,map,DP} = f_{interpTM,t} \left(N_{t,DP,corr}, Z_{t,DP} \right) \quad (\text{E-75})$$

where *interpTM*: interpolation function for TM style map.

The scaling factors are calculated as:

$$SF_{N_t} = \frac{N_{t,DP}}{N_{t,DP,corr}} \quad (\text{E-76})$$

$$SF_{dH/T_t} = \frac{dH/T_{t_{DP}}}{dH/T_{t_{map,DP}}} \quad (\text{E-77})$$

$$SF_{\eta_t} = \frac{\eta_{t_{DP}}}{\eta_{t_{map,DP}}} \quad (\text{E-78})$$

$$SF_{W_t} = \frac{W_{t_{in,DP,corr}}}{W_{t_{map,DP}}} \quad (\text{E-79})$$

The model design data is assigned to the respective variables for further thermodynamic calculations as:

$$PR_c = PR_{c_{DP}} \quad (\text{E-80})$$

$$\eta_t = \eta_{t_{DP}} \quad (\text{E-81})$$

$$W_{t_{out}} = W_{t_{in}} \quad (\text{E-82})$$

$$FAR_{t_{out}} = FAR_{t_{in}} \quad (\text{E-83})$$

OD Calculations:

The corrected speed ratio, $N_{t_{OD,corr}}$ and corrected flow $W_{t_{in,OD,corr}}$ at OD point is calculated as:

$$N_{t_{OD,corr}} = \frac{N_{t_{OD}}}{\sqrt{\theta_{t,OD}}} \quad (\text{E-84})$$

$$W_{t_{in,OD,corr}} = \frac{W_{t_{in,OD}} \cdot \sqrt{\theta_{t,OD}}}{\delta_{t,OD}} \quad (\text{E-85})$$

To input the speed ratio in the map, a scaling factor is applied to $N_{t_{OD,corr}}$ as:

$$N_{t_{OD,corr,sc}} = N_{t_{OD,corr}} SF_{N_t} \quad (\text{E-86})$$

$dH/T_{t_{map,OD}}$, $W_{t_{map,OD}}$, $\eta_{t_{map,OD}}$ with $N_{t_{OD,corr,sc}}$, Z_t are calculated using the defined turbine map as:

$$dH/T_{t_{map,OD}}, W_{t_{map,OD}}, \eta_{t_{map,OD}} = f_{interpTM,t} (N_{t_{OD,corr,sc}}, Z_t) \quad (E-87)$$

$$dH/T_{t_{map,OD,sc}} = dH/T_{t_{map,OD}} SF_{dH/T_t} \quad (E-88)$$

$$W_{t_{map,OD,sc}} = W_{t_{map,OD}} SF_{W_t} \quad (E-89)$$

Since map output is in terms of corrected form, the turbine inlet flow is calculated as:

$$W_{t_{in}} = \frac{W_{t_{map,OD,sc}} \delta_{t,OD}}{\sqrt{\theta_{t,OD}}} \quad (E-90)$$

Turbine efficiency is calculated as:

$$\eta_t = \eta_{t_{map,OD}} SF_{\eta_t} \quad (E-91)$$

Common Thermodynamic Calculations:

Total turbine power based on map is calculated as:

$$PW_{t_{map}} = dH/T_{t_{map,OD,sc}} T_{in} \quad (E-92)$$

$$H_{in} = f_{TD,H}(T_{in}, FAR) \quad (E-93)$$

Based on how the turbine component is modelled, two cases can arise:

Case 1: p_{out} is given, PW_t , T_{out} to be calculated

$H_{out,isen}$ is calculated iteratively for p_{out} as:

$$dH_{isen} = H_{out,isen} - H_{in} \quad (E-94)$$

$$dH = \frac{dH_{isen}}{\eta_t} \quad (E-95)$$

where dH is defined as:

$$dH = H_{out} - H_{in} \quad (E-96)$$

$$PW_t = W dH \quad (E-97)$$

where $W = W_{out} = W_{in}$

H_{out} is calculated as:

$$H_{out} = dH + H_{in} \quad (\text{E-98})$$

T_{out} is calculated as:

$$T_{out} = f_{TD,T}(H_{out}, dp) \text{ with initial guess} = T_{out,isen}$$

Output power from turbine shaft is calculated as:

$$PW_{t,OP} = PW_t - PW_c - PW_{aux} \quad (\text{E-99})$$

where PW_{aux} are any additional auxiliary loads on the turbine shaft (input to the model).

Case 2: $PW_{t,OP}$ is given, PW_t , p_{out} , T_{out} to be calculated:

Turbine power PW_t is calculated as:

$$PW_t = PW_{t,OP} + PW_c + PW_{aux} \quad (\text{E-100})$$

H_{out} is calculated using the definition of PW_t :

$$H_{out} = H_{in} - \frac{PW_t}{W_t} \quad (\text{E-101})$$

where $W_t = W_{out} = W_{in}$

$H_{out,isen}$ is calculated as:

$$dH_{isen} = \frac{dH}{\eta_t} \quad (\text{E-102})$$

$$H_{out,isen} = H_{in} - dH_{isen}$$

$T_{out,isen}$, p_{out} is calculated iteratively for $H_{out,isen}$, FAR , p_{in} .

T_{out} is calculated iteratively for H_{out} , FAR .

OD Error functions are calculated as:

$$Err_{1,t} = \frac{W_{t_{in,OD,corr}} - W_{t_{map,OD,sc}}}{W_{t_{in,OD,corr}}} \quad (E-103)$$

$$Err_{2,t} = \frac{PW_{t_{map}} - PW_t}{PW_{t_{map}}} \quad (E-104)$$

E.6 Nozzle

The exhaust nozzle component contains the exit throttling area (throat) of the engine. It meters flow and sets the turbine back-pressure, thereby controlling turbine work. It is one of the primary metering areas in the engine, regulating the cycle. The characteristic for a nozzle is very similar to that for a turbine and is usually plotted as a non-dimensional mass flow against nozzle pressure ratio, as shown in Figure E-1. It can be seen that the nozzle non-dimensional mass flow rises with the pressure ratio up to a certain point (critical nozzle pressure ratio) and then remains constant as soon as choking conditions are reached. Up to the critical pressure ratio, the nozzle exit static pressure is equal to the ambient pressure and beyond this point, the nozzle exit static pressure becomes greater than the ambient pressure. As soon as the critical nozzle pressure ratio is reached, the Mach number becomes equal to one (choking conditions) and the nozzle exit velocity becomes equal to the sonic velocity [60].

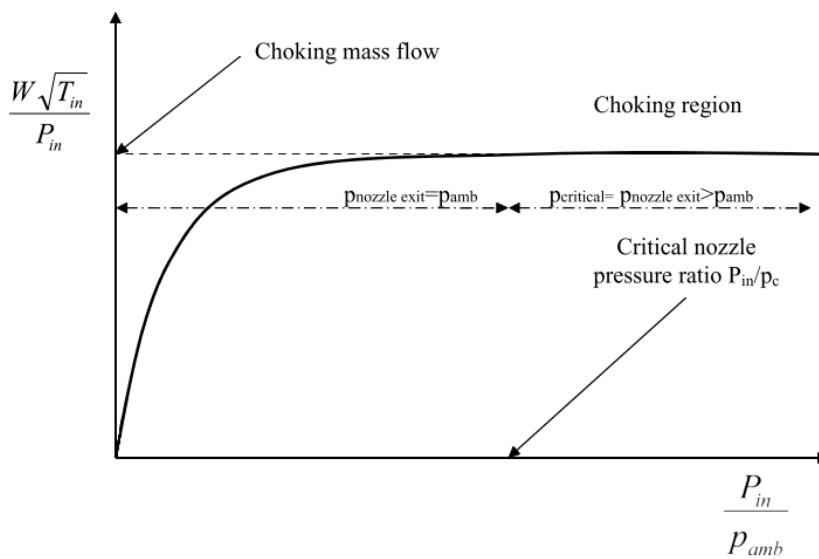


Figure E-1 Typical convergent nozzle characteristic [60]

It is important to note that the nozzle is not a component in marine gas turbines, with its functionality being performed by the power turbine. However, for modelling purposes in Poseidon+, the nozzle is added in the engine models to maintain a common method of modelling with aero engines. The nozzle, in this scenario, should be thought of as an extension to the power turbine in the model to which it is connected providing the turbine backpressure. The area of the nozzle is obtained from the DP calculations and remains fixed in OD calculations.

Model Design Input Data:

No specific parameters are required.

Calculations

DP calculation

At DP: Exit Area A is calculated:

$$R = f_{TD,R}(FAR) \quad (\text{E-105})$$

$$H_{in} = f_{TD,H}(T_{in}, FAR) \quad (\text{E-106})$$

Sonic velocity V_{sonic} is calculated, for the given conditions:

TS_{sonic} is calculated iteratively, starting with a guessed TS_{sonic}

$$c_{p_{sonic}} = f_{TD,H}(TS_{sonic}, FAR) \quad (\text{E-107})$$

$$\gamma_{sonic} = \frac{c_{p_{sonic}}}{c_{p_{sonic}} - R} \quad (\text{E-108})$$

$$V_{sonic} = \sqrt{\gamma_{sonic} R TS_{sonic}} \quad (\text{E-109})$$

$$HS_{sonic,vel} = H_{in} - \frac{V_{sonic}^2}{2} \quad (\text{E-110})$$

$$HS_{sonic,TS} = f_{TD,H}(TS_{sonic}, FAR) \quad (\text{E-111})$$

$HS_{sonic,vel}$ and $HS_{sonic,TS}$ are compared to check for convergence.

Exit velocity $V_{out,ck}$ for $TS_{out,ck}$ is calculated as:

$TS_{out,ck}$ is calculated iteratively, starting with a guessed $TS_{out,ck}$ and using known T_{in} , p_{in} .

$$HS = f_{TD,H}(TS_{out,ck}, FAR) \quad (E-112)$$

$$dH = H_{in} - HS \quad (E-113)$$

$$V_{out,ck} = \sqrt{2 dH} \quad (E-114)$$

If $V_{TS_{out}} \geq V_{sonic}$, flow is choked, and hence:

$$V_{out} = V_{sonic} \quad (E-115)$$

$$TS_{out} = TS_{sonic} \quad (E-116)$$

PS_{out} is calculated iteratively using TS_{out} , T_{in} , p_{in}

$$M_{out} = 1 \quad (E-117)$$

If $V_{out} < V_{sonic}$, flow is unchoked, and hence:

$$V_{out} = V_{out,ck} \quad (E-118)$$

$$TS_{out} = TS_{out,ck} \quad (E-119)$$

$$PS_{out} = PS_{atm} \quad (E-120)$$

M_{out} is calculated as:

$$c_{p_{TS_{out}}} = f_{TD,H}(TS_{out}, FAR) \quad (E-121)$$

$$\gamma_{out} = \frac{c_{p_{TS_{out}}}}{c_{p_{TS_{out}}} - R} \quad (E-122)$$

The velocity of sound at TS_{out} is calculated as:

$$Va_{TS_{out}} = \sqrt{\gamma_{out} R TS_{out}} \quad (E-123)$$

Mach number:

$$M_{out} = \frac{V_{out}}{Va_{TS_{out}}} \quad (\text{E-124})$$

Exit Area A is calculated as:

$$\rho = \frac{PS_{out}}{R TS_{out}} \quad (\text{E-125})$$

$$A = \frac{W_{in}}{\rho V_{out}} \quad (\text{E-126})$$

Unchanged parameters are updated as:

$$P_{out} = P_{in} \quad (\text{E-127})$$

$$T_{out} = T_{in} \quad (\text{E-128})$$

$$W_{out} = W_{in} \quad (\text{E-129})$$

OD Calculation:

Exit Area A is taken from DP.

R and H_{in} as calculated as:

$$R = f_{TD,R}(FAR) \quad (\text{E-130})$$

$$H_{in} = f_{TD,H}(T_{in}, FAR) \quad (\text{E-131})$$

TS_{sonic} is calculated, for the given conditions, similar to DP calculations. V_{sonic} , γ_{sonic} are also calculated by the same function.

Critical Exit Area A_c is calculated as:

$$P_{in,c} = PS_{atm} \left(\frac{T_{in}}{TS_{sonic}} \right)^{\frac{\gamma_{sonic}}{\gamma_{sonic}-1}} \quad (\text{E-132})$$

$$\rho_c = \frac{PS_{atm}}{R TS_{sonic}} \quad (\text{E-133})$$

$$A_c = \frac{W_{in}}{\rho_c V_{sonic}} \quad (\text{E-134})$$

If Exit Area $\leq$ Critical Exit Area $A \leq A_c$, flow is choked, and hence:

$$V_{out} = V_{sonic} \quad (\text{E-135})$$

$$TS_{out} = TS_{sonic} \quad (\text{E-136})$$

$$PS_{out} = PS_{atm} \frac{A_c}{A} \quad (\text{E-137})$$

$$P_{in,OD} = PS_{out} \left(\frac{T_{in}}{TS_{out}} \right)^{\frac{\gamma_{sonic}}{\gamma_{sonic}-1} \frac{A_c}{A}} \quad (\text{E-138})$$

$$M_{out} = 1 \quad (\text{E-139})$$

If Exit Area $>$ Critical Exit Area ($A > A_c$), flow is unchoked, and hence:

TS_{out} is calculated iteratively using T_{in} , PS_{atm} , W_{in} , A_c , V_{out} , γ are also calculated by the same function.

$$P_{in,OD} = PS_{atm} \left(\frac{T_{in}}{TS_{out}} \right)^{\frac{\gamma}{\gamma-1}} \quad (\text{E-140})$$

$$PS_{out} = PS_{atm} \quad (\text{E-141})$$

Further thermodynamic parameters are calculated as:

$$M_{out} = \frac{V_{out}}{V_{sonic}} \quad (\text{E-142})$$

Nozzle Pressure Ratio PR_n is calculated as:

$$P_{out} = P_{in} \quad (\text{E-143})$$

$$T_{out} = T_{in} \quad (\text{E-144})$$

$$W_{out} = W_{in} \quad (\text{E-145})$$

$$PR_n = \frac{P_{out}}{PS_{atm}} \quad (\text{E-146})$$

Nozzle coefficient C_n is calculated from the nozzle map using:

$$C_n = f_{interp2D,n}(1, PR_n) \quad (\text{E-147})$$

Nozzle thrust F_n is calculated using

$$F_n = C_n W_{out} V_{out} + (PS_{out} - PS_{atm})A \quad (\text{E-148})$$

Nozzle OD error is defined as:

$$Err_n = \frac{P_{in,OD} - P_{in}}{P_{in,OD}} \quad (\text{E-149})$$

E.7 Splitter

The splitter component is used to model the splitting of fluid flows from components. The model requires simple tracking of flow (and pressure, if needed) of the main flow and the 'split flow', by 'Fluid Out' and 'Fluid Out2' ports respectively. The compressed air extracted for turbine cooling is modelled using a splitter. In aero engines, the flow from a fan into the core engine and the bypass stream can also be modelled using a splitter.

Model Design Input Data:

Flow fraction: dW

Flow offset: cW

Pressure fraction: dP

Pressure offset: cP

Calculations (common for DP and OD cases):

The flow outputs to the flow outlet ports are calculated as:

$$W_{out,1} = W_{in} dW + cW \quad (\text{E-150})$$

$$W_{out,2} = W_{in} - W_{out,1} \quad (\text{E-151})$$

If pressure change parameters are defined, the pressure of the outlet flow is calculated as:

$$P_{out,1} = P_{in} dP + cP \quad (\text{E-152})$$

$$P_{out,2} = P_{in} - P_{out,1} \quad (\text{E-153})$$

If no pressure change is specified (usually the case), the pressure of the outlet flow is calculated as:

$$P_{out,1} = P_{in} \quad (\text{E-154})$$

$$P_{out,2} = P_{in} \quad (\text{E-155})$$

Other parameters that remain unchanged are updated as:

$$T_{out,1} = T_{in} \quad (\text{E-156})$$

$$T_{out,2} = T_{in} \quad (\text{E-157})$$

$$FAR_{out,1} = FAR_{in} \quad (\text{E-158})$$

$$FAR_{out,2} = FAR_{in} \quad (\text{E-159})$$

E.8 Mixer

The mixer implemented currently in Poseidon+ is modelled as a simple mixing model (not complete mixing), considering a large flow mixing with the small flow without pressure changes of the mixing steams. This is a safe assumption for flows used to model bleed air from compressors used for turbine cooling.

Model Design Input Data:

Flow fraction, given by: dW

Flow offset, given by: cW

Pressure, fraction given by: dP

Pressure, offset given by: cP

Calculations (common for DP and OD cases):

The flow of the mixed stream is calculated as:

$$W_{out} = W_{in,1} + W_{in,2} \quad (\text{E-160})$$

where the subscript $in,1$ denotes the flow at port 'Fluid In' and the subscript $in,2$ denotes the flow at port 'Fluid In 2' as shown in the used symbol.

The final pressure of the mixed stream is based on the pressure of the larger stream, calculated as:

$$\text{If } W_{in,1} \geq W_{in,2}$$

$$P_{out} = P_{in,1} \quad (\text{E-161})$$

$$\text{If } W_{in,1} < W_{in,2}$$

$$P_{out} = P_{in,2} \quad (\text{E-162})$$

FAR for the mixed stream FAR_{out} is calculated as:

Airflow at the outlet, without fuel is given by:

$$W_{air,out} = \frac{W_{in,1}}{1 + FAR_{in,1}} + \frac{W_{in,2}}{1 + FAR_{in,2}} \quad (\text{E-163})$$

FAR_{out} is calculated as:

$$FAR_{out} = \frac{W_{out} - W_{air,out}}{W_{air,out}} \quad (\text{E-164})$$

T_{out} for the mixed stream is calculated as:

$$H_{in,1} = f_{TD,H}(T_{in,1}, FAR_{in,1}) \quad (\text{E-165})$$

$$H_{in,2} = f_{TD,H}(T_{in,2}, FAR_{in,2}) \quad (\text{E-166})$$

$$H_{out} = \frac{H_{in,1} W_{in,1} + H_{in,2} W_{in,2}}{W_{out}} \quad (\text{E-167})$$

T_{out} is calculated iteratively starting with a $T_{out,guess}$ and using the calculated H_{out} and FAR_{out} .

E.9 Ducts

The connecting ducts in the engine are modelled using this component. The duct is modelled as a pressure loss causing component modelled, which is modelled in a similar way as for pressure loss in a combustor.

Model Design Input Data:

Duct pressure loss $dPR_{d,DP}$, defined as:

$$dPR_{d,DP} = \left(\frac{P_{in} - P_{out}}{P_{in}} \right)_{DP} = \left(\frac{dP}{P_{in}} \right)_{DP} \quad (\text{E-168})$$

where the subscript d stands for duct.

Calculations:

DP Calculation:

Press Loss Constant CD is calculated using the definition:

$$\left(\frac{dP}{P_{in}} \right)_{DP} = CD \cdot \left(\frac{W_{in} \sqrt{T_{in}}}{P_{in}} \right)_{DP}^2 \quad (\text{E-169})$$

Press Loss Constant CD is updated as a ‘scaling factor’ (though technically it is not), for application in OD calculations:

P_{out} is calculated as:

$$P_{out} = P_{in} - dP \quad (\text{E-170})$$

Other parameters that remain unchanged are updated as:

$$T_{out} = T_{in} \quad (\text{E-171})$$

$$W_{out} = W_{in} \quad (\text{E-172})$$

$$FAR_{out} = FAR_{in} \quad (\text{E-173})$$

OD Calculation:

dP is calculated using CD obtained from DP calculations:

$$dP = CD \left(\frac{W_{in}^2 T_{in}}{P_{in}} \right) \quad (\text{E-174})$$

P_{out} is calculated as:

$$P_{out} = P_{in} - dP \quad (\text{E-175})$$

Other parameters that remain unchanged are updated as:

$$T_{out} = T_{in} \quad (\text{E-176})$$

$$W_{out} = W_{in} \quad (\text{E-177})$$

$$FAR_{out} = FAR_{in} \quad (\text{E-178})$$

E.10 Shaft

The shaft is a simple component that is used to make the connections between the mechanical or torque ports of components like compressor, turbine, free power turbine. Since presently Poseidon+ only has steady-state modelling implemented, the shaft element has limited functionality serving as a connection element, but when its functionality is extended to transient modelling, additional calculations would be necessary for determining angular acceleration etc.

Appendix F Hull Resistance Model

F.1 Model Input Data in Poseidon+

The hull resistance model component in Poseidon+ is designed to calculate the predicted resistance based on the defined basic hull parameters as per the user-selected method. If the user so desires the resistance data along with the propulsive coefficients can be fed as a map to Poseidon+ in the form of an external file. While utilising the three methods for deriving resistance, it is important that the range of parameters for the applicability of these methods is considered. This data is included in Appendix F.8 for reference.

Model Design Input Data:

General Inputs (non-method-specific)

Method of resistance calculation: H&M, F&L or Hollenbach.

Length between perpendiculars	L_{pp}	Water Area Coefficient:	C_{WP}
Length on waterline	L	Wetted Surface Area*:	S
Beam:	B	Half angle of entrance*:	i_E
Draft Fwd	T_F	Area transverse transom immersed:	A_T
Draft Aft	T_A	Wetted Surface Area of Appendages:	S_{APP}
Displacement volumetric in metric ton:	∇	Appendage resistance factor:	$(1 + k_2)_{eq}$
Midship Area Coefficient:	C_M	Air frontal area:	A_p
Coefficient of air drag	C_D		

Appendage resistance factor ($1 + k_2$): applied as follows:

Rudder behind skeg	1.5-2.0
Rudder behind stern	1.3-1.5
Rudder behind stern	2.8
Shaft brackets	3.0
Skeg	1.5-2.0
Strut bossings	3.0
Hull bossings	2.0
Shafts	2.0-4.0
Stabilizers fins	2.8
Dome	2.7
Bilge keels	1.4

Additional inputs specific to H&M Method

Longitudinal position of centre of buoyance forward of 0.5 L in %	lcb	Stern Coefficient:	C_{stern}
Coefficient for bow thruster openings. (0.003 .. 0.012)	C_{BTO}	Bow thruster tunnel diameter:	d
Transverse sectional area of the bulb at the position where the still water surface intersects the stern:	A_{BT}	Height of centre of transverse bulb area from keel plane:	h_B

C_{stern} is selected by the user based on the guideline:

for V-shaped sections	-10
for normal sections	0
for U shaped sections	10

Additional inputs specific to F&L Method

Beam at transom: B_T

Additional inputs specific to Hollenbach Method

Length over surface:	L_{OS}	Propeller diameter	D_p or D
Draft Config		=design draft, 2=ballast draft, 3=with bulbous bow, 4= without bulbous bow	
Number of rudders: (1..2)	N_{Rud}	Number of bossings: (0..2)	N_{Boss}
Number of brackets: (0..2)	N_{Brac}	Number of side thrusters (0..4)	N_{The}

Additional definitions used:

Block Coefficient	C_B	Prismatic Coefficient (based on waterline length L)	C_P
Ship speed	V or V_S	Density of air	ρ_{air}
Density of water	ρ_w or ρ		

F.2 Derived Hull Parameters

The derived hull parameters as calculated as follows [100,101]:

Form factor of the hull, for H&M method

$$1 + k_1 = c_{13} \left\{ \frac{0.93 + c_{12} (B/L_R)^{0.92497} \cdot (0.95 - C_P)^{-0.521448}}{(1 - C_P + 0.0225 lcb)^{0.6906}} \right\} \quad (\text{F-1})$$

where:

L_R reflects the length of the run, given by:

$$L_R = L \{1 - C_P + 0.06 C_P lcb / (4 C_P - 1)\} \quad (\text{F-2})$$

c_{13} : coefficient to account for the shape of the afterbody, given by:

$$c_{13} = 1 + 0.003 \cdot C_{stern} \quad (\text{F-3})$$

Coefficient c_{12} is calculated as:

$$\text{for } T/L > 0.05$$

$$c_{12} = (T/L)^{0.2228446} \quad (\text{F-4})$$

for $0.02 < T/L < 0.05$

$$c_{12} = 48.20(T/L - 0.02)^{2.078} + 0.479948 \quad (\text{F-5})$$

for $T/L < 0.02$

$$c_{12} = 0.479948 \quad (\text{F-6})$$

Wetted Surface Area

Wetted surface area S is calculated using the published equation in [76]:

$$S = L(2T + B)\sqrt{C_M} (0.453 + 0.4425 C_B - 0.2862 C_M - 0.003467 B/T + 0.3696 C_{WP}) + 2.38 A_{BT}/C_B \quad (\text{F-7})$$

Half angle of entrance

Half angle of entrance i_E is defined as the angle of the waterline at the bow with reference to the centre plane, neglecting the local shape of the hull, in degrees ranging from 1 to 90 degrees. If the user does not enter the value, the value is calculated based on [76], as:

$$i_E = 1 + 89 \exp \left\{ \begin{array}{l} -(L/B)^{0.80856} (1 - C_{WP})^{0.30484} \\ (1 - C_P - 0.0225 lcb)^{0.6367} \\ (L_R/B)^{0.34574} (100 \nabla/L^3)^{0.16302} \end{array} \right\} \quad (\text{F-8})$$

F.3 Model correlation allowance coefficient

Correlation allowance coefficient C_A is given by [76]:

$$C_A = 0.006 (L + 100)^{-0.16} - 0.00205 + 0.003 \sqrt{L/7.5} C_B^4 c_2 (0.04 - c_4) \quad (\text{F-9})$$

where c_4 is given by:

for $T_F/L \leq 0.04$

$$c_4 = T_f/L \quad (\text{F-10})$$

for $T_F/L > 0.04$

$$c_4 = 0.04 \quad (\text{F-11})$$

If hull roughness is greater than the standard $k_s > 150 \mu m$ (mean apparent amplitude), ITTC-1978 formation is used to calculate the increase in C_A , ΔC_A as:

$$\Delta C_A = (0.105 k_s^{1/3} - 0.005579)/L^{1/3} \quad (\text{F-12})$$

F.4 Appendage Resistance Factor

Appendage Resistance Factor $(1 + k_2)_{eq}$ is given by:

$$(1 + k_2)_{eq} = \frac{\Sigma(1 + k_2)S_{APP}}{\Sigma S_{APP}} \quad (\text{F-13})$$

where $(1 + k_2)$ is given a value by the user based on:

rudder behind skeg	1.5-2.0
rudder behind stern	1.3-1.5
rudder behind stern	2.8
shaft brackets	3.0
skeg	1.5-2.0
strut bossings	3.0
hull bossings	2.0
shafts	2.0-4.0
stabilizers fins	2.8
dome	2.7
bilge keels	1.4

F.5 Residual Resistance: H&M Method

The implementation is based on the publication in 1984 by Holtrop and Mennen [77].

$$R_R = R_W + R_B + R_{TR} \quad (\text{F-14})$$

where:

R_W : Wave Making Resistance

R_B : Resistance due to Bulbous Bow,

R_{TR} : Resistance based on Transom.

F.5.1 Wave Making Resistance

Wave Making Resistance R_W is given by:

$$R_W = c_1 c_2 c_5 \nabla \rho g \exp \{m_1 F_n^d + m_2 \cos (\lambda F_n^{-2})\} \quad (\text{F-15})$$

where:

c_1 is calculated as:

$$c_1 = 2223105 c_7^{3.78613} (T/B)^{1.07961} (90 - i_E)^{-1.37565} \quad (\text{F-16})$$

where c_7 is calculated as:

for $B/L < 0.11$

$$c_7 = 0.229577 (B/L)^{0.33333} \quad (\text{F-17})$$

for $0.11 < B/L < 0.25$

$$c_7 = B/L \quad (\text{F-18})$$

for $B/L > 0.25$

$$c_7 = 0.5 - 0.0625L/B \text{ when} \quad (\text{F-19})$$

c_2 accounts for the reduction of wave resistance due to bulbous bow, calculated as:

$$c_2 = \exp (-1.89\sqrt{c_3}) \quad (\text{F-20})$$

c_5 accounts for the influence of transom stern on wave resistance, calculated as:

$$c_5 = 1 - 0.8 A_T / (B.T.C_M) \quad (\text{F-21})$$

λ is calculated as:

for $L/B < 12$

$$\lambda = 1.446 C_p - 0.03 L/B \quad (\text{F-22})$$

for $L/B > 12$

$$\lambda = 1.446 C_p - 0.36 \quad (\text{F-23})$$

m_1 is calculated as:

$$m_1 = 0.0140407 L/T - 1.75254 \nabla^{1/3}/L - 4.79323 B/L - c_{16} \quad (\text{F-24})$$

where c_{16} is calculated as:

for $C_p < 0.80$

$$c_{16} = 8.07981 C_p - 13.8673 C_p^2 + 6.984388 C_p^3 \quad (\text{F-25})$$

for $C_p > 0.80$

$$c_{16} = 1.73014 - 0.7067 C_p \quad (\text{F-26})$$

m_2 is calculated as:

$$m_2 = c_{15} C_p^2 \exp(-0.1 F_n^{-2}) \quad (\text{F-27})$$

where c_{15} is calculated as:

for $L^3/\nabla < 512$

$$c_{15} = -1.69385 \quad (\text{F-28})$$

for $512 < L^3/\nabla < 1727$

$$c_{15} = -1.69385 + (L/\nabla^{1/3} - 8)/2.36 \quad (\text{F-29})$$

for $L^3/\nabla > 1727$

$$c_{15} = 0 \quad (\text{F-30})$$

where F_n : Froude number,

d is a constant given by:

$$d = -0.9 \quad (\text{F-31})$$

c_3 determines the influence of the bulbous bow, calculated as:

$$c_3 = 0.56 A_{BT}^{1.5} / \{BT(0.31 \sqrt{A_{BT}} + T_F - h_B)\} \quad (\text{F-32})$$

F.5.2 Resistance due to bulbous bow

Resistance due to bulbous bow is given by:

$$R_B = 0.11 \exp(-3 P_B^{-2}) F_{ni}^3 A_{BT}^{1.5} \rho g / (1 + F_{ni}^2) \quad (\text{F-33})$$

where:

P_B is the coefficient for the emergence of the bow, given by:

$$P_B = 0.56 \sqrt{A_{BT}} / (T_F - 1.5 h_B) \quad (\text{F-34})$$

F_{ni} is the Froude number based on the immersion, given by:

$$F_{ni} = V / \sqrt{g (T_F - h_B - 0.25 \sqrt{A_{BT}}) + 0.15 V^2} \quad (\text{F-35})$$

F.5.3 Resistance due to immersed transom

Resistance (pressure resistance) due to immersed transom is given by:

$$R_{TR} = 0.5 \rho V^2 A_T c_6 \quad (\text{F-36})$$

where c_6 is based on the Froude number based on the immersed transom, given by:

for $F_{nT} < 5$

$$c_6 = 0.2 (1 - 0.2 F_{nT}) \quad (\text{F-37})$$

for $F_{nT} \geq 5$

$$c_6 = 0 \quad (\text{F-38})$$

where F_{nT} is given by:

$$F_{nT} = V / \sqrt{2 g A_T / (B + B C_{WP})} \quad (\text{F-39})$$

where C_{WP} is the coefficient of water plane.

F.6 Residual Resistance: Fung & Leibman Method

Residuary resistance coefficient C_R is given by:

$$C_R = \exp \left\{ \sum_{i=0}^{69} \left[B_i \prod_{j=1}^9 (X_j^{c_{ij}}) \right] \right\} \quad (\text{F-40})$$

where:

B_i : coefficients of regression terms, given in the Table F-1.

c_{ij} : exponents of regression terms.

X_j are regression terms, given as:

$$X_1 = F_n^d \quad (\text{F-41})$$

$$X_2 = \cos(\lambda F_n^e) \exp \left(\frac{a}{F_n^2} \right) \quad (\text{F-42})$$

where Model Scale Ratio λ is defined as the ratio of the length of the full-scale ship in comparison to the length of the model, is given by:

$$\lambda = a_1 C_P + 0.034977 a_2 C_P \Delta_{LT} (L_{wl,ft}/100)^3 \quad (\text{F-43})$$

$$X_3 = \left\{ 0.034977 \left[\frac{\Delta_{LT}}{\left(\frac{L_{wl,ft}}{100} \right)^3} \right] \right\}^{0.5} \quad (\text{F-44})$$

$$X_4 = A_T / A_M \quad (\text{F-45})$$

$$X_5 = C_P^2 \quad (\text{F-46})$$

$$X_6 = B_T/B \quad (\text{F-47})$$

$$X_7 = B/T \quad (\text{F-48})$$

$$X_8 = \ln(90 - i_E) \quad (\text{F-49})$$

$$X_9 = C_M \quad (\text{F-50})$$

where:

Δ_{LT} : Displacement in Long Tons

$L_{wl,ft}$: Length on waterline in feet

A_T : Projected transom area

A_m : Section area at station of maximum area

B_T : Transom Breadth

B : Beam at station of maximum area

i_E : Half Entrance Angle

C_P : Prismatic Coefficient

C_M : Midship's Coefficient

F_n : Froude number

Constants:

$$a = -0.2000$$

$$a_1 = 0.7500$$

$$a_2 = 0.0350$$

$$d = -0.7000$$

$$e = -1.9300$$

Coefficients: as per Table F-1

Table F-1 Coefficients for F&L Method

	B_i	X1	X2	X3	X4	X5	X6	X7	X8	X9
0	-0.0768852	0	0	0	0	0	0	0	0	0
1	-5.3817900	1	0	0	0	0	0	0	0	0
2	-7.3172000	0	1	0	0	0	0	0	0	0
3	4.0212100	0	0	1	0	0	0	0	0	0
4	-3.0154100	0	0	0	1	0	0	0	0	0
5	-3.3034700	0	0	0	0	0	1	0	0	0
6	-0.3560160	0	0	0	0	0	0	1	0	0
7	-0.7864200	0	0	0	0	0	0	0	1	0
8	0.5219150	2	0	0	0	0	0	0	0	0
9	3.6728900	1	1	0	0	0	0	0	0	0
10	-0.5265970	1	0	1	0	0	0	0	0	0
11	3.6657800	1	0	0	1	0	0	0	0	0
12	2.9864900	1	0	0	0	1	0	0	0	0
13	2.9831400	1	0	0	0	0	1	0	0	0
14	0.3224910	1	0	0	0	0	0	1	0	0
15	1.3066300	1	0	0	0	0	0	0	0	1
16	2.1950800	0	2	0	0	0	0	0	0	0
17	6.3962400	0	1	0	1	0	0	0	0	0

	B_i	X1	X2	X3	X4	X5	X6	X7	X8	X9
35	-0.6353710	2	0	0	1	0	0	0	0	0
36	-0.2575700	2	0	0	0	0	1	0	0	0
37	-0.0217107	2	0	0	0	0	0	1	0	0
38	0.5663620	1	2	0	0	0	0	0	0	0
39	-0.4384070	1	1	1	0	0	0	0	0	0
40	-2.1790300	1	1	0	1	0	0	0	0	0
41	-0.1157800	1	1	0	0	0	0	1	0	0
42	0.1795660	1	0	2	0	0	0	0	0	0
43	-0.4294660	1	0	1	1	0	0	0	0	0
44	-0.2797660	1	0	1	0	0	1	0	0	0
45	0.0317788	1	0	1	0	0	0	1	0	0
46	-0.3435530	1	0	1	0	0	0	0	0	1
47	-2.2750200	1	0	0	2	0	0	0	0	0
48	3.6338800	1	0	0	1	0	1	0	0	0
49	-0.1088050	1	0	0	1	0	0	1	0	0
50	-2.5626000	1	0	0	0	1	1	0	0	0
51	-0.1188630	1	0	0	0	0	1	1	0	0
52	-0.1846400	1	0	0	0	0	0	1	0	1

	B_i	X1	X2	X3	X4	X5	X6	X7	X8	X9
18	3.3582200	0	1	0	0	1	0	0	0	0
19	0.3036790	0	1	0	0	0	0	1	0	0
20	-1.4792000	0	1	0	0	0	0	0	0	1
21	-0.9375770	0	0	2	0	0	0	0	0	0
22	0.8657370	0	0	1	1	0	0	0	0	0
23	-0.5543990	0	0	1	0	1	0	0	0	0
24	0.5885840	0	0	1	0	0	1	0	0	0
25	-0.1395060	0	0	1	0	0	0	1	0	0
26	0.6936350	0	0	1	0	0	0	0	0	1
27	-7.4962600	0	0	0	1	0	1	0	0	0
28	-0.6192280	0	0	0	1	0	0	1	0	0
29	2.0395900	0	0	0	0	1	1	0	0	0
30	0.3454600	0	0	0	0	1	0	1	0	0
31	-5.4932300	0	0	0	0	1	0	0	0	1
32	0.2514840	0	0	0	0	0	1	1	0	0
33	-0.9467220	0	0	0	0	0	1	0	0	1
34	0.6660340	0	0	0	0	0	0	0	0	2

	B_i	X1	X2	X3	X4	X5	X6	X7	X8	X9
53	-0.2616470	0	2	1	0	0	0	0	0	0
54	-3.8195800	0	2	0	0	1	0	0	0	0
55	0.1225660	0	1	2	0	0	0	0	0	0
56	-0.2800950	0	1	1	0	0	1	0	0	0
57	-0.0338132	0	1	1	0	0	0	1	0	0
58	0.3287260	0	1	1	0	0	0	0	0	1
59	-5.6044500	0	1	0	1	1	0	0	0	0
60	0.4034580	0	1	0	0	0	2	0	0	0
61	0.7806980	0	1	0	0	0	1	0	0	1
62	0.3615190	0	0	2	1	0	0	0	0	0
63	0.0332259	0	0	2	0	0	0	1	0	0
64	-0.9738470	0	0	1	2	0	0	0	0	0
65	-0.1611350	0	0	1	1	0	0	1	0	0
66	4.1889600	0	0	0	2	1	0	0	0	0
67	0.7622500	0	0	0	2	0	0	1	0	0
68	1.5920600	0	0	0	1	0	2	0	0	0
69	0.7761980	0	0	0	1	0	0	1	0	1

F.7 Residual Resistance: Hollenbach Method

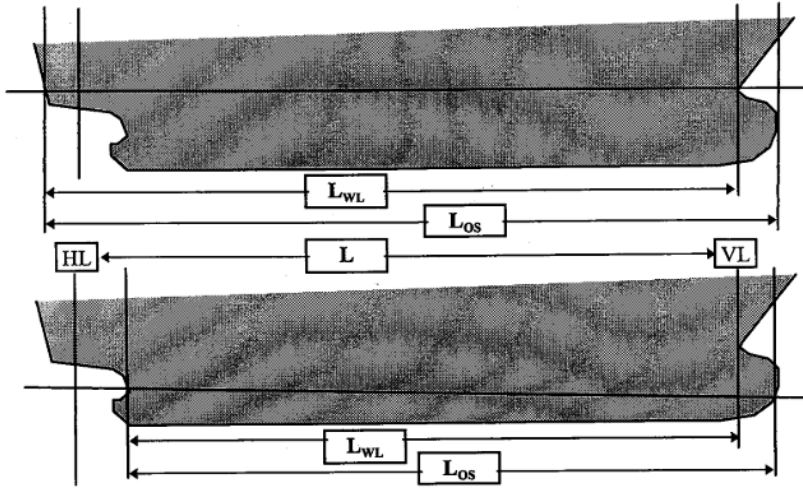


Figure F-1 Definition of lengths L , L_{wl} , L_{os} [106].

For the calculation to proceed the following definitions of length are defined:

$L = L_{pp}$ Length between perpendiculars

L_{wl} : Length over waterline

L_{os} : Length over surface, defined as shown in Figure F-1, defined as:

- for the design draught, the length between the aft end of the design waterline and the most forward point of the ship below the design waterline, for example, the fore-end of a bulbous bow.
- for the ballast draught, the length between the aft end and the forward end of the hull at the ballast waterline, for example, the fore-end of a bulbous bow would be taken into account but a rudder is not taken into account.

The Froude number in the following formulae is based on the length L_{fn} :

$$L_{fn} = \begin{cases} L_{os} & \text{for } L_{os}/L < 1 \\ L + 2/3(L_{os} - L) & \text{for } 1 \leq L_{os}/L < 1.1 \\ 1.0667 L & \text{for } 1.1 \leq L_{os}/L \end{cases} \quad (\text{F-51})$$

The residual resistance is given by:

$$R_R = 0.5 \rho C_R V^2 (B T) \quad (\text{F-52})$$

It should be noted that $(B T)$ is being used in this equation instead of wetted surface area S .

The coefficient C_R is expressed for 'mean' and 'minimum' values as follows, calculated by using the respective coefficients for 'mean' and 'minimum' from the Table F-2:

$$\begin{aligned} C_R = C_{R, \text{Standard}} \cdot C_{R, \text{Fnkrit}} \cdot k_L \cdot (T/B)^{a1} \cdot (B/L)^{a2} \\ \cdot \left(\frac{L_{os}}{L_{wl}} \right)^{a3} \cdot (L_{wl}/L)^{a4} \cdot (D_P/T_A)^{a6} \cdot \left(1 + \frac{(T_A - T_F)}{L} \right)^{a5} \\ \cdot (1 + N_{\text{Rud}})^{a7} \cdot (1 + N_{\text{Brac}})^{a8} \\ \cdot (1 + N_{\text{Boss}})^{a9} \cdot (1 + N_{\text{Thr}})^{a10} \end{aligned} \quad (\text{F-53})$$

where:

T_A draft at AP

T_F draft at FP

D_P : Propeller diameter

N_{Rud} : Number of rudders (1..2)

N_{Brac} : Number of brackets (0..2)

N_{Boss} : Number of bossings (0..2)

N_{Thr} : Number of side thrusters (0..4)

and $C_{R, \text{Standard}}$, $C_{R, \text{Fnkrit}}$, k_L are calculated as:

$$\begin{aligned} C_{R, \text{Standard}} = b_{11} + b_{12}F_n + b_{13}F_n^2 + C_B (b_{21} + b_{22}F_n + b_{23}F_n^2) \\ + C_B^2 (b_{31} + b_{32}F_n + b_{33}F_n^2) \end{aligned} \quad (\text{F-54})$$

$$C_{R, \text{Fnkrit}} = \max[1.0, (F_n/F_{n, \text{krit}})^{c1}] \quad (\text{F-55})$$

$$F_{n, \text{krit}} = d_1 + d_2 C_B + d_3 C_B^2 \quad (\text{F-56})$$

$$k_L = e_1 L^{e_2} \quad (\text{F-57})$$

The above formulae are valid for Froude number intervals as follows:

$$F_{n,min} = \min(f_1, f_1 + f_2 \cdot (f_3 - C_B)) \quad (\text{F-58})$$

$$F_{n,max} = g_1 + g_2 C_B + g_3 C_B^2 \quad (\text{F-59})$$

The maximum total resistance is given by:

$$R_{T,max} = h_1 \cdot R_{T, \text{mean}} \quad (\text{F-60})$$

where the values for the coefficients/ variables $a_{1..6}$; $b_{11...33}$; c_1 ; $d_{1..3}$; $e_{1..3}$; $f_{1..3}$; $g_{1..3}$; h_1 are obtained from Table F-2.

Table F-2 Hollenbach resistance coefficients [94].

	Mean			Minimum	
	Single-screw		Twin-screw	Single-screw	
	Design draught	Ballast draught		Design draught	Twin-screw
a_1	-0.3382	-0.7139	-0.2748	-0.3382	-0.2748
a_2	0.8086	0.2558	0.5747	0.8086	0.5747
a_3	-6.0258	1.1606	-6.7610	-6.0258	-6.7610
a_4	-3.5632	0.4534	-4.3834	-3.5632	-4.3834
a_5	9.4405	11.222	8.8158	0	0
a_6	0.0146	0.4524	-0.1418	0	0
a_7	0	0	-0.1258	0	0
a_8	0	0	0.0481	0	0
a_9	0	0	0.1699	0	0
a_{10}	0	0	0.0728	0	0
b_{11}	-0.57424	-1.50162	-5.34750	-0.91424	3.27279
b_{12}	13.3893	12.9678	55.6532	13.38930	-44.1138
b_{13}	90.5960	-36.7985	-114.905	90.59600	171.692
b_{21}	4.6614	5.55536	19.2714	4.6614	-11.5012
b_{22}	-39.721	-45.8815	-192.388	-39.7210	166.559
b_{23}	-351.483	121.820	388.333	-351.483	-644.456
b_{31}	-1.14215	-4.33571	-14.35710	-1.14215	12.4626
b_{32}	-12.3296	36.0782	142.73800	-12.3296	-179.505
b_{33}	459.254	-85.3741	-254.76200	459.25400	680.921
c_1	Fr/Fr_{krit}	$10C_B(Fr/Fr_{krit} - 1)$	Fr/Fr_{krit}	-	-
d_1	0.854	0.032	0.8970	-	-
d_2	-1.228	0.803	-1.4570	-	-
d_3	0.497	-0.739	0.7670	-	-
e_1	2.1701	1.9994	1.8319	-	-
e_2	-0.1602	-0.1446	-0.1237	-	-
f_1	0.17	0.15	0.16	0.17	0.14
f_2	0.20	0.10	0.24	0.20	0
f_3	0.60	0.50	0.60	0.60	0
g_1	0.642	0.42	0.50	0.614	0.952
g_2	-0.635	-0.20	0.66	-0.717	-1.406
g_3	0.150	0	0.50	0.261	0.643
h_1	1.204	1.194	1.206	-	-
Ship length $L(m)$	42.0–205.0	50.2–224.8	30.6–206.8	42.0–205.0	30.6–206.8
$L/\nabla^{1/3}$	4.49–6.01	5.45–7.05	4.41–7.27	4.49–6.01	4.41–7.27
C_B	0.60–0.83	0.56–0.79	0.51–0.78	0.60–0.83	0.51–0.78
L/B	4.71–7.11	4.95–6.62	3.96–7.13	4.71–7.11	3.96–7.13
B/T	1.99–4.00	2.97–6.12	2.31–6.11	1.99–4.00	2.31–6.11
L_{OS}/L_{WL}	1.00–1.05	1.00–1.05	1.00–1.05	1.00–1.05	1.00–1.05
L_{WL}/L	1.00–1.06	0.95–1.00	1.0–1.07	1.00–1.06	1.00–1.07
D_P/T	0.43–0.84	0.66–1.05	0.50–0.86	0.43–0.84	0.50–0.86

Note: Table of coefficients in the original paper, there was a sign error in coefficient a_3 ballast which should be +1.1606, not -1.1606 [94], hence this table has been used.

F.8 Application Range for Resistance Calculation Models

Table F-3 H&M Method: Range of Application [98,106].

Ship Type	F_n	C_p		L/B		B/T	
	max.	min.	max.	min.	max.	min.	max.
Tankers, bulk carriers (ocean)	0.24	0.73	0.85	5.1	7.1	2.4	3.2
Trawlers, coasters, tugs	0.38	0.55	0.65	3.9	6.3	2.1	3.0
Container ships, destroyers	0.45	0.55	0.67	6.0	9.5	3.0	4.0
Cargo liners	0.30	0.56	0.75	5.3	8.0	2.4	4.0
Ro-Ro's, car ferries	0.35	0.55	0.67	5.3	8.0	3.2	4.0

Table F-4 F&L method: Range of Application [132].

	Minimum	Maximum
F_n	0.15	0.90
DLR	16.239	359.180
iE	2.600	31.730
L/B	2.520	17.935
B/T	1.696	10.204
C_p	0.526	0.774
C_m	0.556	0.994
C_{wp}	0.662	0.841
TA	0	0.740
TB	0	1.000
TT	0	0.770

Table F-5 Hollenbach method: Range of Application [106].

	'mean'			'minimum'	
	single-screw		twin-screw	single-screw	twin-screw
	design draft	ballast draft		design draft	
ship length L [m]	42.0...205.0	50.2...224.8	30.6...206.8	42.0...205.0	30.6...206.8
$L/\nabla^{1/3}$	4.49...6.01	5.45...7.05	4.41...7.27	4.49...6.01	4.41...7.27
C_B	0.60...0.83	0.56...0.79	0.51...0.78	0.60...0.83	0.51...0.78
L/B	4.71...7.11	4.95...6.62	3.96...7.13	4.71...7.11	3.96...7.13
B/T	1.99...4.00	2.97...6.12	2.31...6.11	1.99...4.00	2.31...6.11
L_{os}/L_{wl}	1.00...1.05	1.00...1.05	1.00...1.05	1.00...1.05	1.00...1.05
L_{wl}/L	1.00...1.06	0.95...1.00	1.00...1.07	1.00...1.06	1.00...1.07
D_P/T	0.43...0.84	0.66...1.05	0.50...0.86	0.43...0.84	0.50...0.86

F.9 Propulsive coefficients calculation

The propulsive coefficients are calculated, applicable for twin-screw ships, as follows [100,101]:

Wake fraction w is calculated as:

$$w = 0.3095 C_B + 10 C_V C_B - 0.23 D/\sqrt{B T} \quad (\text{F-61})$$

where C_V : viscous resistance coefficient, given by:

$$C_V = (1 + k)C_F + C_A \quad (\text{F-62})$$

Thrust deduction t is calculated as:

$$t = 0.325 C_B - 0.1885 D/\sqrt{B T} \quad (\text{F-63})$$

Relative rotative efficiency η_R is calculated as:

$$\eta_R = 0.9737 + 0.111 (C_P - 0.0225 lcb) - 0.06325 P/D \quad (\text{F-64})$$

Appendix G Propeller Model

G.1 Wageningen B- Series Propeller Coefficients

Coefficients for the K_T and K_Q polynomials representing the Wageningen B-propeller series for a Reynolds number of 2×10^6 [108]

Table G-1 Coefficients for the K_T and K_Q polynomials representing the Wageningen B-propeller series for a Reynolds number of 2×10^6 [108].

Thrust (K_T)						Torque (K_Q)					
n	$C_{s,J,u,v}$	$s(J)$	$t(P/D)$	$u(A_E/A_O)$	$v(Z)$	n	$C_{s,J,u,v}$	$s(J)$	$t(P/D)$	$u(A_E/A_O)$	$v(Z)$
1	+0.00880496	0	0	0	0	1	+0.00379368	0	0	0	0
2	-0.204554	1	0	0	0	2	+0.00886523	2	0	0	0
3	+0.166351	0	1	0	0	3	-0.032241	1	1	0	0
4	+0.158114	0	2	0	0	4	+0.00344778	0	2	0	0
5	-0.147581	2	0	1	0	5	-0.0408811	0	1	1	0
6	-0.481497	1	1	1	0	6	-0.108009	1	1	1	0
7	+0.415437	0	2	1	0	7	-0.0885381	2	1	1	0
8	+0.0144043	0	0	0	1	8	+0.188561	0	2	1	0
9	-0.0530054	2	0	0	1	9	-0.00370871	1	0	0	1
10	+0.0143481	0	1	0	1	10	+0.00513696	0	1	0	1
11	+0.0606826	1	1	0	1	11	+0.0209449	1	1	0	1
12	-0.0125894	0	0	1	1	12	+0.00474319	2	1	0	1
13	+0.0109689	1	0	1	1	13	-0.00723408	2	0	1	1
14	-0.133698	0	3	0	0	14	+0.00438388	1	1	1	1
15	+0.00638407	0	6	0	0	15	-0.0269403	0	2	1	1
16	-0.00132718	2	6	0	0	16	+0.0558082	3	0	1	0
17	+0.168496	3	0	1	0	17	+0.0161886	0	3	1	0
18	-0.0507214	0	0	2	0	18	+0.00318086	1	3	1	0
19	+0.0854559	2	0	2	0	19	+0.015896	0	0	2	0
20	-0.0504475	3	0	2	0	20	+0.0471729	1	0	2	0
21	+0.010465	1	6	2	0	21	+0.0196283	3	0	2	0
22	-0.00648272	2	6	2	0	22	-0.0502782	0	1	2	0
23	-0.00841728	0	3	0	1	23	-0.030055	3	1	2	0
24	+0.0168424	1	3	0	1	24	+0.0417122	2	2	2	0
25	-0.00102296	3	3	0	1	25	-0.0397722	0	3	2	0
26	-0.0317791	0	3	1	1	26	-0.00350024	0	6	2	0
27	+0.018604	1	0	2	1	27	-0.0106854	3	0	0	1
28	-0.00410798	0	2	2	1	28	+0.00110903	3	3	0	1
29	-0.000606848	0	0	0	2	29	-0.000313912	0	6	0	1
30	-0.0049819	1	0	0	2	30	+0.0035985	3	0	1	1
31	+0.0025983	2	0	0	2	31	-0.00142121	0	6	1	1
32	-0.000560528	3	0	0	2	32	-0.00383637	1	0	2	1
33	-0.00163652	1	2	0	2	33	+0.0126803	0	2	2	1
34	-0.000328787	1	6	0	2	34	-0.00318278	2	3	2	1
35	+0.000116502	2	6	0	2	35	+0.00334268	0	6	2	1
36	+0.000690904	0	0	1	2	36	-0.00183491	1	1	0	2
37	+0.00421749	0	3	1	2	37	+0.000112451	3	2	0	2
38	+0.0000565229	3	6	1	2	38	-0.0000297228	3	6	0	2
39	-0.00146564	0	3	2	2	39	+0.000269551	1	0	1	2
						40	+0.00083265	2	0	1	2
						41	+0.00155334	0	2	1	2
						42	+0.000302683	0	6	1	2
						43	-0.0001843	0	0	2	2
						44	-0.000425399	0	3	2	2
						45	+0.0000869243	3	3	2	2
						46	-0.0004659	0	6	2	2
						47	+0.0000554194	1	6	2	2

G.2 Wageningen B- Series Reynolds Number Corrections

Corrections applied for Wageningen B- Series Propeller characteristics for Reynolds numbers within the range 2×10^6 to 2×10^9 [84]:

$$\begin{Bmatrix} K_T(Re) \\ K_Q(Re) \end{Bmatrix} = \begin{Bmatrix} K_T(Re = 2 \times 10^6) \\ K_Q(Re = 2 \times 10^6) \end{Bmatrix} + \begin{Bmatrix} \Delta K_T(Re) \\ \Delta K_Q(Re) \end{Bmatrix} \quad (\text{G-1})$$

where:

$$\begin{aligned} \Delta K_T = & 0.000353485 \\ & -0.00333758(A_E/A_O)J^2 \\ & -0.00478125(A_E/A_O)(P/D)J \\ & +0.000257792(\log Re - 0.301)^2 \cdot (A_E/A_O)J^2 \\ & +0.0000643192(\log Re - 0.301)(P/D)^6J^2 \\ & -0.0000110636(\log Re - 0.301)^2(P/D)^6J^2 \\ & -0.0000276305(\log Re - 0.301)^2Z(A_E/A_O)J^2 \\ & +0.0000954(\log Re - 0.301)Z(A_E/A_O)(P/D)J \\ & +0.0000032049(\log Re - 0.301)Z^2(A_E/A_O) \\ & \times (P/D)^3J \end{aligned} \quad (\text{G-2})$$

$$\begin{aligned} \Delta K_Q = & -0.000591412 \\ & +0.00696898(P/D) \\ & -0.0000666654Z(P/D)^6 \\ & +0.0160818(A_E/A_O)^2 \\ & -0.000938091(\log Re - 0.301)(P/D) \\ & -0.00059593(\log Re - 0.301)(P/D)^2 \\ & +0.0000782099(\log Re - 0.301)^2(P/D)^2 \\ & +0.0000052199(\log Re - 0.301)Z(A_E/A_O)J^2 \\ & -0.00000088528(\log Re - 0.301)^2Z(A_E/A_O) \\ & \times (P/D)J \\ & +0.0000230171(\log Re - 0.301)Z(P/D)^6 \\ & -0.00000184341(\log Re - 0.301)^2Z(P/D)^6 \\ & -0.00400252(\log Re - 0.301)(A_E/A_O)^2 \\ & +0.000220915(\log Re - 0.301)^2(A_E/A_O)^2 \end{aligned} \quad (\text{G-3})$$

where the Reynolds number Re is given by:

$$Re = \frac{\rho n_p D^2}{\mu} \quad (\text{G-4})$$

where μ : dynamic coefficient of viscosity of the water

G.3 Wageningen B- Series Extent of Parameters

Table G-2 Extent of B-Series propeller parameters.

<i>Z</i>	2	3	4	5	6	7
(A_E/A_o) lower bound	0.30	0,35	0,40	0,45	0,50	0,55
(A_E/A_o) upper bound	0.38	0.80	1.00	1.05	0.8	0.85
P/D lower bound	0.5	0.5	0.5	0.5	0.6	0.6
P/D upper bound	1.4	1.4	1.4	1.4	1.4	1.4
Blade thickness ratio (t/D)	0.055	0.050	0.045	0.040	0.035	0.035
Boss diameter ratio (d/D)	0.180	0.180	0.167	0.167	0.167	0.180
Pitch reduction at blade root	0	0	20%	0	0	0
Blade rake angle (φ)	15	15	15	15	15	5

Appendix H Water Properties Model

H.1 Model Input Data in Poseidon+

Water Type: seawater or freshwater, seawater assumed by default.

dS_p : Deviation from standard water temperature, in deg C , where $t_{C,std} = 15$ deg C

dt_C : Deviation from standard salinity, in 'Practical Salinity scale

where $S_{p,std} = 35$ g/kg

H.2 Temperature and salinity of water

The temperature and salinity of water are calculated as:

$$t_C = t_{C,std} - dt_C \quad (\text{H-1})$$

$$S_P = S_{P,std} - dS_P \quad (\text{H-2})$$

H.3 Density

Freshwater

$$\begin{aligned} \rho_w = & 999.842594 + 6.793952 \times 10^{-2} t_C - 9.09529 \times 10^{-3} t_C^2 \\ & + 1.001685 \times 10^{-4} t_C^3 - 1.120083 \times 10^{-6} t_C^4 \\ & + 6.536336 \times 10^{-9} t_C^5 \end{aligned} \quad (\text{H-3})$$

Seawater

$$\rho_{sw} = \rho_w + AS_P + BS_P^{3/2} + CS_P^2 \quad (\text{H-4})$$

where:

$$\begin{aligned} A = & 0.824493 - 4.0899 \times 10^{-3} t_C + 7.6438 \times 10^{-5} t_C^2 - 8.2467 \times 10^{-7} t_C^3 \\ & + 5.3875 \times 10^{-9} t_C^4 \end{aligned} \quad (\text{H-5})$$

$$B = -5.72466 \times 10^{-3} + 1.0227 \times 10^{-4} t_C - 1.6546 \times 10^{-6} t_C^2 \quad (\text{H-6})$$

$$C = 4.8314 \times 10^{-4} \quad (\text{H-7})$$

Model validity range:

$$-2 < t_c < 40^\circ\text{C}; 0 < S_p < 42 \text{ g/kg}$$

H.4 Dynamic Viscosity

Freshwater

$$\ln(\mu_w) = -10.7019 + \frac{604.129}{139.18 + t_c} \quad (\text{H-8})$$

Seawater

$$\mu_{sw} = \mu_w(1 + AS_p + BS_p^2) \quad (\text{H-9})$$

where:

$$A = 1.474 \times 10^{-3} + 1.5 \times 10^{-5}t_c - 3.927 \times 10^{-8}t_c^2 \quad (\text{H-10})$$

$$B = 1.073 \times 10^{-5} - 8.5 \times 10^{-8}t_c + 2.230 \times 10^{-10}t_c^2 \quad (\text{H-11})$$

Model validity range:

$$10 < t_c < 180^\circ\text{C}; 0 < S_p < 150\text{g/kg}$$

H.5 Kinematic Viscosity

Calculated as:

$$\mu / \rho \quad (\text{H-12})$$

H.6 Vapour Pressure

Freshwater

$$\ln(p_{v,w}) = a_1/T + a_2 + a_3T + a_4T^2 + a_5T^3 + a_6\ln(T) \quad (\text{H-13})$$

where:

$$a_1 = -5800$$

$$a_2 = 1.391$$

$$a_3 = -4.846 \times 10^{-2}$$

$$a_4 = 4.176 \times 10^{-5}$$

$$a_5 = -1.445 \times 10^{-8}$$

$$a_6 = 6.545$$

Note: $p_{v,w}$ in Pa;

Model validity range:

$$273.15 \leq T \leq 473.15\text{K}$$

Seawater

$$p_{v,sw} = p_{v,w} + AS_p + BS_p^{3/2} \quad (\text{H-14})$$

where:

$$A = -2.3311 \times 10^{-3} - 1.4799 \times 10^{-4}t_c - 7.520 \times 10^{-6}t_c^2 - 5.5185 \times 10^{-8}t_c^3 \quad (\text{H-15})$$

$$B = -1.1320 \times 10^{-5} - 8.7086 \times 10^{-6}t_c + 7.4936 \times 10^{-7}t_c^2 - 2.6327 \times 10^{-8}t_c^3 \quad (\text{H-16})$$

Note: $p_{v,sw}$ and $p_{v,w}$ in (mm Hg).

Model validity range:

$$0 < t_c < 40^\circ\text{C};$$

$$0 < S_p < 40 \text{ g/kg}$$

Appendix I Propulsion Equipment Dimension and Mass Estimation Models

I.1 Prime Movers

I.1.1 Gas Turbines

The majority of the marine gas turbines engines used for shipboard applications are aero-derivative engines from General Electric and Rolls Royce. While specifically designed gas turbines for marine applications are also available from Zorya-Mashproekt, these have not been considered for the regression analysis, as these have rather limited application. van Es [98] has used a database from manufacturers and previous work undertaken on 59 gas turbines including non-marine gas turbines. The final expressions were created using 13 gas turbines, of which 12 were simple cycle engines while one was an Inter-Cooled Regenerative cycle (ICR) engine. The dimensions and mass include the complete gas turbine module, which means that the expressions include the engine with its base frame and enclosure.

The length L_{GT} and width W_{GT} of the gas turbine module (for both simple cycle and ICR cycle designs), in m , is given solely as a function of the rated brake power PW_B of the engine given in MW , as:

$$L_{GT} = (3.2535 \cdot PW_B^{-0.715}) \cdot PW_B \quad (I-1)$$

$$W_{GT} = (1.4945 \cdot PW_B^{-0.820}) \cdot PW_B \quad (I-2)$$

The height of the gas turbine module, in m , is calculated separately for the simple cycle engine, $H_{GT,SC}$, and ICR cycle $H_{GT,ICR}$, given solely as a function of the rated brake power PW_B of the engine given in MW , as:

$$H_{GT,SC} = (2.3332 \cdot PW_B^{-0.903}) \cdot PW_B \quad (I-3)$$

$$H_{GT,ICR} = (3.4998 \cdot PW_B^{-0.903}) \cdot PW_B \quad (I-4)$$

The mass of the gas turbine module, in *ton*, is calculated respectively for the simple cycle engine, $m_{GT,SC}$, and ICR cycle $m_{GT,ICR}$, solely as a function of the rated brake power PW_B of the engine given in *MW*, as:

$$m_{GT,SC} = (5.9713 \cdot PW_B^{-0.591}) \cdot PW_B \quad (I-5)$$

$$m_{GT,ICR} = (11.9426 \cdot PW_B^{-0.591}) \cdot PW_B \quad (I-6)$$

where the subscript *SC* is used to denote simple cycle engines and *ICR* is used to denote ICR cycle, engines.

I.1.2 Diesel Engines

For the regression-based dimensioning model of the diesel engines, van Es [98] used existing extensive databases of engines divided into three groups:

- High-speed engines ($> 1000 \text{ rpm}$), containing 54 engines V-engines
- Medium-speed engines ($300 - 1000 \text{ rpm}$), containing 116 engines, subdivided into Inline and V-engines.
- Low-speed engines ($< 300 \text{ rpm}$), containing 296 engines.

For the present work, only medium-speed diesel engines were used in the case studies, due to their higher efficiencies compared to high-speed engines. Low-speed engines are considered impractical for the applications considered due to their very large dimensions and mass. Hence only the models used for medium-speed engines (distinguished by subscript *MS*) from van Es [98], for both Inline (distinguished by subscript *inline*) and V-engines (distinguished by subscript *vee*) have been presented here.

The length $L_{DE,MS,inline}$ and $L_{DE,MS,vee}$ for Inline and V-engines respectively, in *m*, is given solely as a function of the rated brake power PW_B of the engine given in *MW*, as:

$$L_{DE,MS,inline} = (2.9474 \cdot PW_B^{-0.508}) \cdot PW_B \quad (I-7)$$

$$L_{DE,MS,vee} = (1.9363 \cdot PW_B^{-0.344}) \cdot PW_B \quad (I-8)$$

The width $W_{DE,MS,inline}$ and $W_{DE,MS,vee}$ for Inline and V-engines respectively, in m , is given solely as a function of the rated brake power PW_B of the engine given in MW , as:

$$W_{DE,MS,inline} = (1.7680 \cdot PW_B^{-0.719}) \cdot PW_B \quad (I-9)$$

$$W_{DE,MS,vee} = (1.2567 \cdot PW_B^{-0.582}) \cdot PW_B \quad (I-10)$$

The height $H_{DE,MS}$, in m , is given by a common expression for Inline and V-engines, solely as a function of the rated brake power PW_B of the engine given in MW , as:

$$H_{DE,MS} = (1.7016 \cdot PW_B^{-0.537}) \cdot PW_B \quad (I-11)$$

The mass $m_{DE,MS,inline}$ and $m_{DE,MS,vee}$ in ton , for Inline and V-engines respectively, calculated solely as a function of the rated brake power PW_B of the engine given in MW , is given as:

$$m_{DE,MS,inline}, m_{DE,MS,vee} = (1281.2 \cdot PW_B^{-0.7606}) \cdot PW_B \quad (I-12)$$

I.2 Geared Transmission Systems

For the dimensioning models of the gearboxes, van Es [55] used a series of single-stage horizontally offset SISO type Commercial Off the Shelf (COTS) boxes and a limited number of horizontally offset gearboxes used for combined plants for CODOG, CODAD and CODLOD applications to develop the dimensioning model. The present work is based on these models, with an extension for the cases of cross-connect gears and twin speed gearboxes required in the AND type combined systems.

For the purpose of dimensioning, gearboxes have been classified into the following categories (with the subscripts used to distinguish the categories):

- Single Input: SI
- Twin or Dual Input, DI

- Cross-connect gear (CCG) without 'splitter' (only input and output connections, but no splitting of torque to different transmission paths):
CCG, trs
- CCG with 'splitter' (CCG splitting of torque to different transmission paths):
CCG, spl
- Twin or Dual Speed: *DS*

Overall, the main design parameters of a gearbox that determine the size of the gear wheels, weight and costs are the offset distance, the reduction ratio and the input power. The dimensions for the gearboxes are considered to be a function of the input power P_{in} in *kW* and the output speed in *rpm*, of the gearbox. To calculate the dimensions, the power to input speed ratio, *PNR*, is calculated for each of the defined categories of the gearboxes as:

- Single Input:

$$PNR = \frac{PW_{in}}{N_{out}} \quad (I-13)$$

- Twin or Dual Input:

For the two inputs, *PNR* is calculated for both the input shafts and the higher value of the two is selected as the final *PNR* for dimensioning calculations, as:

$$PNR_{DI,R1} = \frac{PW_{in1}}{N_{out}} \quad (I-14)$$

$$PNR_{DI,R2} = \frac{PW_{in2}}{N_{out}} \quad (I-15)$$

$$PNR = (PNR_{DI,R1}, PNR_{DI,R2})_{max} \quad (I-16)$$

- CCG with 'splitter':

$$PNR = \frac{PW_{in}}{N_{out}} \quad (I-17)$$

- Cross-connect gear (CCG) without 'splitter':

$$PNR = \frac{PW_{in}}{N_{out}}/3 \quad (I-18)$$

- Twin or Dual Speed:

$$PNR = 1.5 \left(\frac{PW_{in}}{N_{out1}}, \frac{PW_{in}}{N_{out2}} \right)_{max} \quad (I-19)$$

The length L_{GB} of the gearbox, in m , is calculated as a function of the calculated PNR by the relationship:

$$L_{GB} = 0.54 \cdot PNR^{0.37} \quad (I-20)$$

The height H_{GB} of the gearbox, in m , is calculated as a function of the calculated PNR by the relationship:

$$H_{GB} = 0.98 \cdot PNR^{0.27} \quad (I-21)$$

The width $W_{GB,SI}$, $W_{GB,DS}$ for Single Input and Twin or Dual Speed type gearboxes, in m , is calculated respectively as a function of the calculated PNR by the relationship:

$$W_{GB,SI}, W_{GB,DS} = 0.84 PNR^{0.27} \quad (I-22)$$

The width $W_{GB,DI}$ for Twin or Dual Input type gearboxes, in m , is calculated respectively as a function of the calculated PNR by the relationship:

$$W_{GB,DI} = 0.84 \cdot (PNR_{DI,R1}^{0.27} + PNR_{DI,R2}^{0.27}) \quad (I-23)$$

The width $W_{GB,CC}$ for both types of defined cross-connect type gearboxes, in m , is calculated as a function of the calculated PNR by the relationship:

$$W_{GB,CC} = 0.84 \cdot (2 PNR_{CC}^{0.27}) \quad (I-24)$$

The mass $m_{GB,SI}$ for Single Input type gearboxes, in ton , is calculated as a function of the calculated PNR by the relationship:

$$m_{GB,SI} = 0.3 PNR \quad (I-25)$$

The mass $m_{GB,DI}$, $m_{GB,CC}$ for Dual Input and both types of cross-connect type gearboxes, in *ton*, is calculated respectively as a function of the calculated *PNR* by the relationship:

$$m_{GB,DI} , m_{GB,CC} = 0.6 PNR \quad (I-26)$$

The mass $m_{GB,DS}$ for Twin or Dual Speed type gearboxes, in *ton*, is calculated as a function of the calculated *PNR* by the relationship:

$$m_{GB,DS} = 0.4 PNR \quad (I-27)$$

I.3 Electrical Systems

I.3.1 Electric Machines

Estimating dimensions of an electrical machine is a difficult task, due to a large number of configurations possible such as single or double wounded windings; single or double armature; transverse, radial or axial flux; characteristics of materials used etc. Hence, derived auxiliary parameters are used to develop the dimension and mass estimation models. The equations used for estimating the dimensions and mass for the electric machines in the present work from van Es [98] are given in the following text. While there are a large number of types of electric machines, only conventional and ‘advanced’ AC machines have been used in the present work, and hence the following data is limited to these machine types. ‘Advanced’ AC machines being referred to here is on the basis of description by Hodge et.al. for higher power density motors used for propulsion [133].

The auxiliary parameters used in the equations for dimensions are defined as follows, with an overview of the dimensions and volumes used shown in Figure I-1.

TRV: Torque per Rotor Volume, , in Nm/m^3 , given as:

$$TRV = \frac{Q_{EM}}{V_{rotor}}$$

where Q_{EM} is the electric machine torque, in Nm

s : Split ratio is the rotor/stator diameter ratio, given as:

$$s = \sqrt{\frac{V_{rotor}}{V_{stator}}}$$

L/D : length to the diameter of the stator.

CVF Cooling Volume Factor, given as:

$$CVF = \frac{V_{install}}{V_{stator}}$$

where $V_{install}$ is the total installation volume of the machine.

MF : mass factor, to convert installed volume to mass.

The guideline for selection these parameters for conventional and advanced AC machines, as used in the present work is:

	Conv.AC	Adv. AC
TRV	70	200
s	0.45	0.5
L/D	1.6	1.2
CVF	2.5	1.7
MF	1.20	2.65

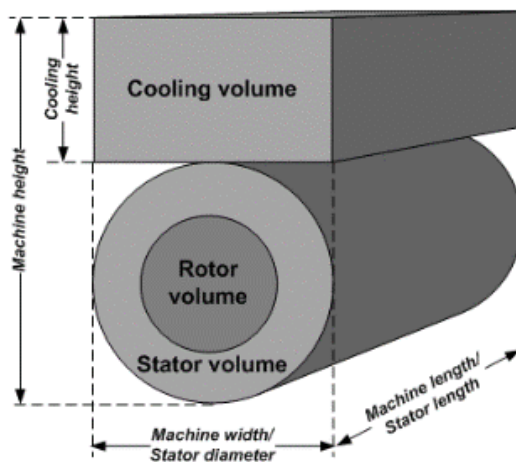


Figure I-1 Overview of volumes and dimensions in the dimensioning model [98]

The width W_{EM} , of the electric machine in m , is given by:

$$W_{EM} = D_{stator} = \left(\frac{Q_{EM}}{TRV \cdot s^2 \cdot \frac{\pi}{4} \cdot L/D} \right)^{\frac{1}{3}} \quad (I-28)$$

The length L_{EM} , of the electric machine in m , is given by:

$$L_{EM} = L_{stator} = L/D \cdot \left(\frac{Q_{EM}}{TRV \cdot s^2 \cdot \frac{\pi}{4} \cdot L/D} \right)^{\frac{1}{3}} \quad (I-29)$$

The height H_{EM} , of the electric machine in m , is given by:

$$H_{EM} = \left(\frac{Q_{EM}}{TRV \cdot s^2} \right)^{\frac{1}{3}} \cdot CVF \cdot (L/D)^{-\frac{1}{3}} \cdot \left(\frac{\pi}{4} \right)^{\frac{2}{3}} \quad (I-30)$$

Installation volume of the electrical machine, $V_{install}$, is calculated as (in m^3):

$$V_{install} = L_{EM} W_{EM} H_{EM} \quad (I-31)$$

The mass m_{EM} of the electric motor, in ton , is calculated as:

$$m_{EM} = MF \cdot V_{install} \quad (I-32)$$

I.3.2 Gas Turbine Generators Sets (Gensets) (GTG)

In the work of van Es, the dimensions of the gas turbine gensets have been derived directly from the individual dimensions of the gas turbine and the alternator as the electric machine. However, the results when compared with limited publications on the subject like from Tortarolo [110] and catalogue data etc., were found to have significant deviations, primarily on the alternator. Hence additional factors have been derived and applied to the alternator calculations as shown in the following paragraphs.

Alternator for GT (GTA)

For the calculations, the conventional electric machine denoted in the subscripts as EM_{conv} has been used as the basis.

The length L_{GTA} , of the GTA in m , is given by:

$$L_{GTA} = 1.5 L_{EM,conv} \quad (I-33)$$

The width W_{GTA} , of the GTA in m , is given by:

$$W_{GTA} = 1.7 W_{EM,conv} \quad (I-34)$$

The height H_{GTA} , of the GTA in m , is given by:

$$H_{GTA} = 1.1 H_{EM,conv} \quad (I-35)$$

Using the derived dimensions, $V_{install,GTA}$ is calculated as:

$$V_{install,GTA} = L_{GTA} W_{GTA} H_{GTA} \quad (I-36)$$

The mass m_{EM} of the electric motor, in ton , is calculated as:

$$m_{GTA} = MF \cdot V_{install,GTA} \quad (I-37)$$

Overall Dimensions for Gas Turbine Genset (GTG)

The overall dimensions and mass for the GTG are calculated from the individual dimensions of the GT and GTA as follows.

The length L_{GTG} , of the GTG in m , is given by:

$$L_{GTG} = 1.03(L_{GT} + L_{GTA}) \quad (I-38)$$

The width W_{GTG} , of the GTG in m , is given by:

$$W_{GTG} = W_{GT} \text{ or } W_{GTA}, \text{ whichever is greater} \quad (I-39)$$

The height H_{GTG} , of the GTG in m , is given by:

$$H_{GTG} = H_{GT} \text{ or } H_{GTA}, \text{ whichever is greater} \quad (I-40)$$

The mass m_{GTA} of the GTG, in ton , is calculated as:

$$m_{GTA} = m_{GT} + m_{GTA} \quad (I-41)$$

I.3.3 Diesel Engine Generators Sets (Gensets) (DG)

The overall dimensions and mass for the DG are calculated from the individual dimensions of the diesel engine (shown by subscript DE) and the alternator (shown by subscript DA) as follows.

The length L_{DG} , of the DG in m , is given by:

$$L_{DG} = 1.1(L_{DE} + L_{DA}) \quad (I-42)$$

The width W_{DG} , of the DG in m , is given by:

$$W_{DG} = W_{DA} \quad (I-43)$$

The height H_{DG} , of the DG in m , is given by:

$$H_{DG} = H_{DA} \quad (I-44)$$

The mass m_{DG} of the DG, in ton , is calculated as:

$$m_{DG} = m_{DE} + m_{DA} \quad (I-45)$$

I.3.4 Frequency Converter (FC)

For AC motor control many types of frequency converters are available ranging from synchro-converters, cyclo-converter to Pulse Width Modulation (PWM) converters, of which PWM are most commonly used onboard. Hence on PWM converters have been used in the present work and the following relationships apply only to PWM converters. PWM converters can have various types of switching elements like transistors, IGBT, IGCT or GTO thyristors of which IGBT, IGCT /GTO are more commonly used. van Es [98] has used an existing database as the basis and corrected it with data on FC designs used on certain warships.

The apparent power S in MVA is calculated as:

$$S = UI \quad (I-46)$$

Using the apparent power S , the volume $V_{FC,IGBT}$, $V_{FC,GTO/IGCT}$ for the IGBT, IGCT /GTO type FC, respectively, is defined as:

$$V_{FC,IGBT} = 2 S + 7.5 \quad (I-47)$$

$$V_{FC,GTO/IGCT} = 0.7 S + 7.5 \quad (I-48)$$

The width W_{FC} , of the IGBT, IGCT /GTO type FC in m , is given by:

$$W_{FC,IGBT} = \frac{2 S + 7.5}{2.3 (0.09 S + 0.7)} \quad (I-49)$$

$$W_{FC,GTO/IGCT} = \frac{0.7 S + 7.5}{2.3 (0.06 S + 0.7)} \quad (I-50)$$

The depth D_{FC} , of the IGBT, IGCT /GTO type FC in m , is given by:

$$D_{FC,IGBT} = 0.09 S + 0.7 \quad (I-51)$$

$$D_{FC,GTO/IGCT} = 0.06 S + 0.7 \quad (I-52)$$

The height H_{FC} , of the FC in m , is given by:

$$H_{FC} = 2.3 \quad (I-53)$$

The mass m_{FC} , of the FC in ton , is given by:

$$m_{FC} = 1500 + 750 S \quad (I-54)$$

The mass includes the mass of the cabinets with bedplates and shock mounting, semiconductors, and cooling equipment.

I.3.5 Switchboard

Switchboards (SB) are generally but up using a number of standard modules dimensions of which depend on the manufacturer. The number of modules used is dependent on the number of incoming and outgoing fields (n_f). For the dimensioning models of the switchboards boxes, van Es [98] used an existing database and some switchboards used for naval applications. Sperate sets of relationships have been used for medium and low voltage switchboards.

Medium Voltage SB

Using the total numbers of incoming and outgoing fields $n_f = n_{f,in} + n_{f,out}$, the dimensions of the medium voltage SB, denoted by the subscript MV , are given by the following relationships:

The length $L_{SB,MV}$ of the SB in m , is given by:

$$L_{SB,MV} = 0.65 n_f \quad (\text{I-55})$$

The width $W_{SB,MV}$ of the SB in m , is given by:

$$W_{SB,MV} = 1.70 \quad (\text{I-56})$$

The height $H_{SB,MV}$ of the SB in m , is given by:

$$H_{SB,MV} = 2.60 \quad (\text{I-57})$$

The mass $m_{SB,MV}$ of the SB in $tons$, is given by:

$$m_{SB,MV} = n_{f,in} \quad (\text{I-58})$$

van Es [98] further provides guidance on estimating the number of fields, if the user does not have this information, as follows:

- 2 incoming generator fields per switchboard,
- 1 bus coupler field per switchboard,
- 1 outgoing field per bowthruster per switchboard,
- 1 or 2 outgoing fields per electrical propulsion motor per switchboard depending on the power,
- 2 outgoing fields to the distribution transformers,
- 1 spare outgoing field
- If needed, 1 field for high voltage shore connection.

Low Voltage (LV) SB

The length $L_{SB,LV}$ of the SB in m , is given by:

$$L_{SB,LV} = 0.65 \cdot \left(n_{f,in} + \frac{1}{4} \cdot n_{f,out} \right) \quad (\text{I-59})$$

The width $W_{SB,LV}$ of the SB in m , is given by:

$$W_{SB,LV} = 1 \quad (\text{I-60})$$

The height $H_{SB,LV}$ of the SB in m , is given by:

$$H_{SB,LV} = 2.20 \quad (\text{I-61})$$

The mass $m_{SB,LV}$ of the SB in m , is given by:

$$m_{SB,LV} = 500 \cdot n_{f,in} + 450 \cdot \frac{1}{4} \cdot n_{f,out} \quad (\text{I-62})$$

If the number of fields is not known an assumption must be made.

van Es [98] further provides guidance on a rough estimation of fields for low voltage SB as:

- 2 incoming fields from diesel generators or high voltage switchboards,
- 1 bus coupler field,
- 1 shore connection,
- 1 emergency generator,
- The number of outgoing fields can be estimated by dividing the electrical load of the ship by the voltage and dividing that number by an average field current.

I.4 Propellers

The selection process used for primary design characteristics of the propellers has been described in detail in section 4.3. Here the relationship for estimating the mass of the propeller is described.

The weight of a propeller depends on multiple parameters like the propeller diameter, number of blades, propeller type (CPP or FPP), manufacturer, blade thickness, material etc. The type of propeller is a large weight-driver because for

a CPP the hub contributes a large part of the propeller weight. The material NiAlBr is commonly used for the types of propulsion systems, as has been considered in the present work.

The following relationship was used as proposed by van Es [98], using data available for naval applications to provide the following relationship for the mass of the propeller in *ton* , solely based on propeller diameter D (valid for diameters between 3 *m* and 6 *m*) and the type of propeller:

$$m_{FPP} = 337.35 D^{2.28}/1000 \quad \textbf{(I-63)}$$

$$m_{CPP} = 39.209 D^{3.87}/1000 \quad \textbf{(I-64)}$$

Appendix J Propulsion Equipment Acquisition and Maintenance Cost Models

J.1 Prime Movers

J.1.1 Gas Turbines

The acquisition cost $CA_{GT,SC}$ of a simple cycle gas turbine in $k\text{€}$, derived for this work based on known data, based on brake power of the engine, PW_B in MW , is calculated as:

$$CA_{GT,SC} = 347.94 PW_B + 1.6711 \quad (\text{J-1})$$

The maintenance cost $CM_{GT,SC}$ of a simple cycle gas turbine in €/h , based on van Es [98], is calculated as:

$$CM_{GT,SC} = 6.50 \cdot PW_B \quad (\text{J-2})$$

J.1.2 Diesel Engines

The acquisition cost $CA_{DE,MS}$ of a medium-speed diesel in $k\text{€}$, derived for this work based on known data, based on brake power of the engine, PW_B in MW , is calculated as:

$$CA_{DE,MS} = (557.36 + 96.16 \cdot \ln PW_B) PW_B \quad (\text{J-3})$$

The maintenance cost $CM_{DE,MS}$ of a medium-speed diesel in €/h , based on van Es [98], is calculated as:

$$CM_{DE,MS} = 11.74 \cdot PW_B \quad (\text{J-4})$$

J.2 Geared Transmission System

The acquisition cost CA_{GB} of a gearbox in $k\text{€}$, based on van Es [98], based on input power to the gearbox, PW_B in MW , and gear ratio, i_{gr} , where applicable is calculated for the various types of gearboxes as:

- Single Input

$$CA_{GB,SI} = 2.17 \cdot i_{gr} + 0.135 \cdot i_{gr} \cdot PW_B \quad (\text{J-5})$$

- Twin or Dual Input, CCG with ‘splitter’:

$$CA_{GB,DI}, CA_{GB,CC,spl} = 82 \cdot PW_B \quad (\text{J-6})$$

- Cross-connect gear (CCG) without ‘splitter’:

$$CA_{GB,CC,trs} = 57.4 PW_B \quad (\text{J-7})$$

- Twin or Dual Speed:

$$CA_{GB,DS} = 1.9 (2.17 \cdot i_{gr} + 0.135 \cdot i_{gr} \cdot PW_B) \quad (\text{J-8})$$

where input power to the gearbox PW_B , and gear ratio i_{gr} with twin inputs is considered as:

$$PW_B = (PW_{B,in1}, PW_{B,in2})_{max} \quad (\text{J-9})$$

$$i_{gr} = (i_{gr1}, i_{gr2})_{max}$$

J.3 Electrical Systems

J.3.1 Electric Machines

The acquisition cost $CA_{DE,MS}$ of an electrical machine in $k\text{€}$, derived for this work based on van Es [98] with a derived correction factor $CF_{CA,EM}$, as a function of brake power of the electric machine, PW_B in MW , is calculated as:

$$CA_{EM} = (8805 + 1174 \cdot \ln PW_B) CF_{CA,EM} \quad (\text{J-10})$$

The derived correction factor $CF_{CA,EM}$ developed as a part of the present work, based on known data is:

$$CF_{CA,EM} = 0.5323 \cdot \ln Q_{EM} + 0.7878 \quad (\text{J-11})$$

J.3.2 Generator Sets

Gas Turbine Generators Sets

The acquisition cost CA_{GTG} of a gas turbine generator set (simple cycle based) in $k\text{€}$, is derived from the cost of a simple cycle gas turbine engine CA_{GT} and the cost of the alternator CA_{GTA} , calculated as:

$$CA_{GTG} = 1.15 (CA_{GT} + CA_{GTA}) \quad (\text{J-12})$$

Diesel Engine Generators Sets

The acquisition cost CA_{DG} of a medium speed diesel engine generator set in $k\text{€}$, is calculated based on the below-derived relationship as a present of the present work, as a function of engine brake power PW_B in MW :

$$CA_{DG} = 862.68 P_B - 63.636 PW_B^2 + 502.1 \quad (\text{J-13})$$

J.3.3 Frequency Converter

The acquisition cost CA_{FC} of a PWM FC in $k\text{€}$, based on the relationship published by van Es [98], as a function on brake power of the electric machine, PW_B in MW , is calculated for the IGBT and GTO/IGCT type FC, respectively as:

$$CA_{FC,IGBT} = \left(59 + \frac{1174}{5 + P_B}\right) PW_B \quad (\text{J-14})$$

$$CA_{FC,GTO/IGCT} = \left(59 + \frac{1761}{10 + P_B}\right) PW_B \quad (\text{J-15})$$

J.3.4 Switchboard

The acquisition cost CA_{FC} of a PWM FC in $k\text{€}$, derived as a part of this work, as a function of the electric power handled by the switchboard, PW_e in MWe , is calculated for the MV and LV type switchboards, respectively as:

$$CA_{SB,MV} = 144 PW_e - 35.5 \quad (\text{J-16})$$

$$CA_{SB,LV} = 143 PW_e + 0.6 \quad (\text{J-17})$$

J.3.5 Propellers

The acquisition cost CA_{FC} of a propeller in $k\text{€}$, derived as a part of this work, as a function of the mass of the propeller, m in ton , is calculated for the FPP and CPP type propellers, respectively as:

$$CA_{FPP} = 38.4 m_{FPP} \quad (\text{J-18})$$

$$CA_{CPP} = 37.3 m_{CPP} \quad (\text{J-19})$$

The cost of shafting is included in the above expression.

Appendix K Combined Marine Propulsion Plants

In a combined diesel or gas turbine (CODOG), a relatively small diesel engine (the 'cruise' engine) is used during the low-speed, high-endurance cruising mode, to take advantage of the economy of a diesel engine; or, for maximum-power requirements, the higher-power gas turbine (the 'boost' engine) is brought online. The 'cruise' engine and the 'boost' engine are not designed to be operated together and hence the 'OR' in CODOG. Usually, an overrunning clutch would be used to ensure that either the diesel or the gas turbine, but not both, drive the propeller. While the fuel economy and endurance of the gas turbine would be less than those of the diesel engines, these would be secondary considerations because of the gas turbine's infrequent use. CODOG plants make it possible to minimize the operating hours on the large gas turbine, which is required only for high power requirements, and the presence of two prime movers provides a degree of redundancy.

Combined gas turbine or gas turbine (COGOG) plants are similar to CODOG plants, with the difference being that a small gas turbine is used, instead of a diesel engine, as the cruise engine, with one or more larger gas turbines providing the boost power. At cruising speeds, the fuel economy of the small gas turbine, which operates near its rating, is better than could be obtained with a larger engine operating at a small fraction of its rating.

Combined gas turbine and gas turbine (COGAG) plants contain one or more small gas turbines which are used for economical operations at low cruising power levels, and one or more large gas turbines which are used occasionally at boost power levels. COGAG differs from COGOG in that a COGAG plant is designed to require all gas turbines to be online to develop maximum power.

Combined diesel and gas (CODAG) plants potentially provide the economy of a diesel engine and the almost instant boost power of a gas turbine on demand. Both the diesel engines and gas turbine/s are required to be in operation to develop full power.

Combined diesel-electric and gas turbine (CODELAG) use electric motors as the 'cruise engines' while a gas turbine serves as the 'boost engine'. The electric motors are usually driven by a power grid driven by multiple diesel generator sets. Both the electric motors and gas turbine are required to be in operation to develop full power.

It should be noted that the terms used for combined plants do not exactly represent the architecture of the propulsion system, as, within the same definitions, multiple architectures can be created. This can be seen in the various architectures defined in Chapter 6.

The principal advantages of combined plants are the economy realized during extended cruise engine operations, the ability to declutch and secure unneeded engines during extended periods of low-power operation, and the redundancy provided. In case of combined plants with the 'AND' combination, the cruise engines and boost engines need to work together to provide the rated power of the plant and thus the maximum speed. These plants provide the advantage of lowering the overall installed power to achieve the rated speed. However, the operation of prime movers in independent and combined modes require multi-speed gearboxes. The coordination of the two dissimilar types of power plants also adds complexity to the control systems.

IFEP (Integrated Full Electric Propulsion) architectures use a common set of prime-movers (diesel engines, gas turbines or a combination of both) to provide power for both the ship's propulsion and electrical loads. IFEP power systems are aimed at offering several benefits over traditional marine power systems such as higher engine efficiencies during part-load running, increased reliability and survivability, increased flexibility in machinery allocation and increased operational flexibility [135].

Appendix L DANP Procedure

Consider 'Dimensions' $D_1, D_2, D_3, \dots, D_n$, with each 'Dimension' having the set of criteria, where the set of criteria of i th Dimension being denoted by $c_{i1}, c_{i2}, \dots, c_{im_i}$ where $m_1, m_2, m_3, \dots, m_n$ are the number of criteria for respectively for each of the 'Dimensions'.

1. Create the 'Initial Direct Influence Matrix', X by averaging the 'Expert Direct Influence Matrices' for the 'Dimensions' $D_1, D_2, D_3, \dots, D_n$:

$$X = [x_{ij}]_{n \times n} = \begin{matrix} & \begin{matrix} D_1 & D_2 & \dots & D_n \end{matrix} \\ \begin{matrix} D_1 \\ D_2 \\ \vdots \\ D_n \end{matrix} & \begin{bmatrix} 0 & x_{12} & \dots & x_{1n} \\ x_{21} & 0 & \dots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \dots & 0 \end{bmatrix} \end{matrix}$$

where x_{ij} defines the 'degree of direct influence' of D_i on D_j on a scale of 0-4 with each numeric signifying: 'No influence', 'Low influence', 'Medium influence', 'High influence' and 'Very high influence'.

2. Calculate the 'Normalised Direct Influence Matrix' M as:

$$M = s \cdot X$$

where:

$$s = \min \left[\frac{1}{\max_i \sum_{j=1}^n |x_{ij}|}, \frac{1}{\max_j \sum_{i=1}^n |x_{ij}|} \right]$$

3. Calculate the 'Direct Influence Matrix' T_d using the relationship:

$$T_d = M + M^2 + \dots + M^l = M(I - M)^{-1}$$

where I = Identity matrix.

4. Setting a threshold value to remove the minor influences from the 'Direct Influence Matrix' T_d , to calculate the 'Total Direct Influence Matrix' T_D as follows:

$$T_D = \begin{matrix} & \begin{matrix} D_1 & D_2 & \dots & D_n \end{matrix} \\ \begin{matrix} D_1 \\ D_2 \\ \vdots \\ D_n \end{matrix} & \begin{bmatrix} t_D^{11} & t_D^{12} & \dots & t_D^{1n} \\ t_D^{21} & t_D^{22} & \dots & t_D^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ t_D^{n1} & t_D^{n2} & \dots & t_D^{nn} \end{bmatrix} \end{matrix}$$

5. Calculate U_i and V_j as:

$$U_i = \sum_{j=1}^n t_{ij} (i = 1, 2, \dots, n)$$

$$V_j = \sum_{i=1}^n t_{ij} (j = 1, 2, \dots, n)$$

where U_i denotes the row sum of the i th row of the matrix T_D and shows the sum of direct and indirect effects of 'Dimension' i on the other 'Dimensions'. Similarly, V_j denotes the column sum of the j th column of the matrix T_D and shows the sum of direct and indirect effects that 'Dimension' j has received from other 'Dimensions'.

6. Calculate $(U_i + V_j)$ and $(U_i - V_j)$, where the value of $(U_i + V_j)$ indicates the degree of relationship of each 'Dimension' with the other 'Dimension'. 'Dimensions' having higher values of $(U_i + V_j)$ have stronger relationships with the other 'Dimensions', while those having lower values of $(U_i + V_j)$ have a weaker relationship with the others. A positive value of $(U_i - V_j)$ indicates the degree of cause by a 'Dimension' while a negative value of $(U_i - V_j)$ indicates the degree a 'Dimension' is affected by other 'Dimensions'.
7. Construct a 'Network Relationship Map' (NRM) by plotting $(U_i + V_j)$ and $(U_i - V_j)$ to directly observe the degree of 'cause and effect' between the 'Dimensions'.
8. Construct the 'Normalized Total Direct Influence Matrix' T_D^α as:

$$T_D^\alpha = \begin{matrix} & \begin{matrix} D_1 & D_2 & & D_n \end{matrix} \\ \begin{matrix} D_1 \\ D_2 \\ \vdots \\ D_n \end{matrix} & \begin{bmatrix} t_D^{11}/d_1 & t_D^{12}/d_1 & \cdots & t_D^{1n}/d_1 \\ t_D^{21}/d_2 & t_D^{22}/d_2 & \cdots & t_D^{2n}/d_2 \\ \vdots & \vdots & \ddots & \vdots \\ t_D^{n1}/d_n & t_D^{n2}/d_n & \cdots & t_D^{nn}/d_n \end{bmatrix} \end{matrix}$$

9. Based on the 'Dimensions' with the significant degree of 'cause and effect' between the 'Dimensions', as seen from the 'Total Direct Influence Matrix', repeat the above DEMATEL procedure for the criteria under the 'Dimensions' to calculate the individual 'Normalized Criteria Influence Matrices', denoted by $T_c^{\alpha ij}$ while comparing the criteria of i th 'Dimension' ($c_{i1}, c_{i2}, \dots, c_{im_i}$) with the criteria of j th 'Dimension' ($c_{j1}, c_{j2}, \dots, c_{jm_j}$).

10. Find the 'Normalised Influence Matrix' T_c^α , where $m_1, m_2, m_3, \dots, m_n$ are the number of criteria for the Dimensions $D_1, D_2, D_3, \dots, D_n$, respectively

$$T_c^\alpha = \begin{matrix} & \begin{matrix} & D_1 & & D_2 & & D_n \end{matrix} \\ & \begin{matrix} c_{11} & \cdots & c_{1m_1} & c_{11} & \cdots & c_{1m_2} & c_{11} & \cdots & c_{1m_n} \end{matrix} \\ \begin{matrix} D_1 \\ D_2 \\ \vdots \\ D_n \end{matrix} & \begin{matrix} \begin{matrix} c_{11} \\ \vdots \\ c_{1m_1} \end{matrix} \\ \begin{matrix} c_{11} \\ \vdots \\ c_{1m_2} \end{matrix} \\ \begin{matrix} c_{11} \\ \vdots \\ c_{1m_n} \end{matrix} \end{matrix} \left[\begin{array}{cccc} T_c^{\alpha 11} & T_c^{\alpha 12} & \cdots & T_c^{\alpha 1n} \\ T_c^{\alpha 21} & T_c^{\alpha 22} & & T_c^{\alpha 2n} \\ \vdots & \vdots & \ddots & \vdots \\ T_c^{\alpha n1} & T_c^{\alpha n2} & \cdots & T_c^{\alpha nn} \end{array} \right] \end{matrix}$$

where:

c_{im} is the m th Criteria for i th Dimension;

$T_c^{\alpha ij}$ matrices are written as:

$$T_c^{\alpha ij} = \begin{matrix} & \begin{matrix} c_{j1} & c_{j2} & \cdots & c_{jm_j} \end{matrix} \\ \begin{matrix} c_{i1} \\ c_{i2} \\ \vdots \\ c_{im_i} \end{matrix} & \begin{bmatrix} t_{c_{11}}^{\alpha ij} & t_{c_{12}}^{\alpha ij} & \cdots & t_{c_{1m_j}}^{\alpha ij} \\ t_{c_{21}}^{\alpha ij} & t_{c_{22}}^{\alpha ij} & \cdots & t_{c_{2m_j}}^{\alpha ij} \\ \vdots & \vdots & \ddots & \vdots \\ t_{c_{m_i1}}^{\alpha ij} & t_{c_{m_i2}}^{\alpha ij} & \cdots & t_{c_{m_i m_j}}^{\alpha ij} \end{bmatrix} \end{matrix}$$

with each element $t_{c_{pq}}^{\alpha ij}$ representing $t_c^{\alpha ij}$ for criteria c_{ip} and c_{jq} .

Thereafter, apply the ANP procedure as follows:

11. Arrange the 'Unweighted Supermatrix' W_c as:

$$W_c = \begin{matrix} & \begin{matrix} D_1 & D_2 & & D_n \end{matrix} \\ \begin{matrix} D_1 \\ D_2 \\ \vdots \\ D_n \end{matrix} & \begin{bmatrix} c_{11} & \cdots & c_{1m_1} & c_{21} & \cdots & c_{2m_2} & \cdots & c_{n1} & \cdots & c_{nm_n} \\ W_c^{11} & & W_c^{12} & \cdots & W_c^{1n} \\ W_c^{21} & & W_c^{22} & \cdots & W_c^{2n} \\ \vdots & & \vdots & \ddots & \vdots \\ W_c^{n1} & & W_c^{n2} & \cdots & W_c^{nn} \end{bmatrix} \end{matrix}$$

where each W_c^{ij} is calculated as:

$$W_c^{ij} = (T_c^{\alpha ji})' = \begin{bmatrix} t_{c_{11}}^{\alpha ji} & t_{c_{21}}^{\alpha ji} & \cdots & t_{c_{m_j 1}}^{\alpha ji} \\ t_{c_{12}}^{\alpha ji} & t_{c_{22}}^{\alpha ji} & \cdots & t_{c_{m_j 2}}^{\alpha ji} \\ \vdots & \vdots & \ddots & \vdots \\ t_{c_{1m_i}}^{\alpha ji} & t_{c_{2m_i}}^{\alpha ji} & \cdots & t_{c_{m_j m_i}}^{\alpha ji} \end{bmatrix}$$

12. Calculate the 'Weighted Supermatrix' W_c^* :

$$W_c^* = T_D^\alpha W_c = \begin{bmatrix} t_D^{\alpha 11} \times W_c^{11} & t_D^{\alpha 21} \times W_c^{12} & \cdots & t_D^{\alpha n1} \times W_c^{1n} \\ t_D^{\alpha 12} \times W_c^{21} & t_D^{\alpha 22} \times W_c^{22} & \cdots & t_D^{\alpha n2} \times W_c^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ t_D^{\alpha 1n} \times W_c^{n1} & t_D^{\alpha 2n} \times W_c^{n2} & \cdots & t_D^{\alpha nn} \times W_c^{nn} \end{bmatrix}$$

Raise the 'Weighted Supermatrix' W_c^* to a sufficiently large power h until it converges and becomes a long-term stable super-matrix to obtain the relative weights $w = (w_1, w_2, w_3, \dots)$ for all the criteria under the various 'Dimensions' from

$$\lim_{h \rightarrow \infty} (W_c^*)^h$$

Appendix M AHP Method

Consider a given set of independent criteria ($C_1 \ C_2 \ \dots \ C_n$). The AHP method is applied as follows to determine the weights of the independent set of criteria, as per the following steps:

1. Undertake pair-wise comparisons to create a $n \times n$ 'Pairwise Comparison Matrix' G ,

$$G = [g_{ij}] = \begin{matrix} & \begin{matrix} C_1 & C_2 & \dots & C_n \end{matrix} \\ \begin{matrix} C_1 \\ C_2 \\ \vdots \\ C_n \end{matrix} & \begin{bmatrix} 1 & g_{12} & \dots & g_{1n} \\ g_{12}^{-1} & 1 & \dots & g_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ g_{1n}^{-1} & g_{2n}^{-1} & \dots & 1 \end{bmatrix} \end{matrix}$$

where each upper diagonal element $g_{ij} > 0$ is the recorded judgement generated by comparing the i th element with the j th one using Saaty's scale of 1 to 9 to represent equal importance to extreme importance with $i, j = 1, 2, \dots, n$. The lower diagonal elements of G are the reciprocal values of the upper diagonal elements, as per $g_{ji} = 1/g_{ij}$. The diagonal elements are unity, or $g_{ij} = 1$ when $i = j$.

2. Create a 'Normalized Pairwise Comparison Matrix' as:

$$G^\alpha = [g_{ij}^\alpha] = \begin{matrix} & \begin{matrix} C_1 & C_2 & \dots & C_n \end{matrix} \\ \begin{matrix} C_1 \\ C_2 \\ \vdots \\ C_n \end{matrix} & \begin{bmatrix} 1/s_1 & g_{12}/s_2 & \dots & g_{1n}/s_n \\ g_{12}^{-1}/s_1 & 1/s_2 & \dots & g_{2n}/s_n \\ \vdots & \vdots & \ddots & \vdots \\ g_{1n}^{-1}/s_1 & g_{2n}^{-1}/s_3 & \dots & 1/s_n \end{bmatrix} \end{matrix}$$

where $s_j = \sum_{i=1}^n g_{ij}$, the column sums.

3. Calculated the vector of relative weights, W , by averaging all elements of the rows as:

$$W = [w_i] = \sum_{j=1}^n g_{ij}^\alpha / n$$

4. To evaluate the reliability of the obtained weights, check the consistency of matrix G by creating the 'Consistency Check Matrix' C as:

$$C = [c_{ij}] = \begin{matrix} & \begin{matrix} C_1 & C_2 & \cdots & C_n \end{matrix} \\ \begin{matrix} C_1 \\ C_2 \\ \vdots \\ C_n \end{matrix} & \begin{bmatrix} 1 * w_1 & g_{12} * w_2 & \cdots & g_{1n} * w_n \\ g_{12}^{-1} * w_1 & 1 * w_2 & \cdots & g_{2n} * w_n \\ \vdots & \vdots & \ddots & \vdots \\ g_{1n}^{-1} * w_1 & g_{2n}^{-1} * w_2 & \cdots & 1 * w_n \end{bmatrix} \end{matrix}$$

5. Get the 'Weighted Sum Ratio' WS vector thereafter as:

$$WS = [ws_i] = \begin{matrix} C_1 \\ C_2 \\ \vdots \\ C_n \end{matrix} \begin{bmatrix} \sum_{j=1}^n c_{1j} / w_1 \\ \sum_{j=1}^n c_{2j} / w_2 \\ \vdots \\ \sum_{j=1}^n c_{nj} / w_n \end{bmatrix}$$

6. Calculate the largest eigenvalue λ_{max} using:

$$\lambda_{max} = \sum_{i=1}^n ws_i / n$$

7. Verify the consistency of the comparison matrix using, 'Consistency Index' CI and 'Consistency Ratio' CR using:

$$CR = \frac{CI}{RI}$$

where:

$$CI = \frac{(\lambda_{max} - n)}{n - 1}$$

RI indicates the average consistency index over numerous random entries of the reciprocal matrices with the same orders.

If $CR \leq 0.1$, the estimate is accepted; otherwise, a new comparison matrix is solicited.

Appendix N VIKOR Method

Consider the Lp-metric $L_{p,j}$, or the measure of distance to the ideal solution for the alternative a_j , written for a set of n criteria $C_1, C_2, C_3, \dots, C_i, \dots, C_n$ with corresponding global weights $w_1, w_2, w_3, \dots, w_n$, and r alternatives, $a_1, a_2, \dots, a_j, \dots, a_r$, f_{ij} being the 'evaluated score' for the i th criteria representing a 'benefit function':

$$L_{p,j} = \left\{ \sum_{i=1}^n [w_i(f_i^+ - f_{ij})/(f_i^+ - f_i^-)]^p \right\}^{1/p}$$

$$1 \leq p \leq \infty; j = 1, 2, \dots, r.$$

where

$$f_i^+ = \max_j f_{ij}, f_i^- = \min_j f_{ij}$$

1. Calculate the Lp-metric, for $p = 1$, $L_{1,j}$ (as S_j) and $p = \infty$ and $L_{\infty,j}$ (as R_j) as the basis to form another two-dimensional space $[S_j, R_j]$ of alternatives, with L_1 metric $[Q_j]$ as follows:

$$S_j = \sum_{i=1}^n w_i(f_i^+ - f_{ij})/(f_i^+ - f_i^-)$$

$$R_j = \max_i [w_i(f_i^+ - f_{ij})/(f_i^+ - f_i^-)]$$

$$Q_j = v(S_j - S^+)/(S^- - S^+) + (1 - v)(R_j - R^+)/(R^- - R^+)$$

where:

$$S^+ = \min_j S_j, S^- = \max_j S_j$$

$$R^+ = \min_j R_j, R^- = \max_j R_j$$

Coefficient v is the 'strategy coefficient with' $v \in [0,1]$, where values higher than 0.5 indicate that the decision-maker is more focused on satisfying most

of the criteria, while values lower than 0.5 indicate that the decision-maker is more focussed on minimizing individual differences from the ideal solution. Coefficient v is usually set to a value of 0.5 to start the procedure.

2. Rank the alternatives $a_1, a_2, \dots, a_j, \dots, a_r$ in the order of priorities based on the values of S_j, R_j, Q_j with their lower values considered as 'better' values leading to alternatives arranged in terms of priority as $a_S^1, a_S^2, a_S^3 \dots a_S^H; a_R^1, a_R^2, a_R^3 \dots a_R^H$ and $a_Q^1, a_Q^2, a_Q^3 \dots a_Q^H$ where a^1 is the highest or best-ranked alternative while a_S^H, a_R^H, a_Q^H are the lowest or worse ranked alternatives with the highest of S_j, R_j, Q_j values respectively.
3. Select the 'best alternative' or the most suitable 'compromise solution', as the one ranked by the lowest value of Q or a_Q^1 .
4. Check the 'best alternative' for validity. The selection is considered to be directly valid if the following two conditions are satisfied:

- Condition 1: 'Acceptable degree of advantage':

$$Q(a_Q^2) - Q(a_Q^1) \geq DQ$$

where a_Q^2 the alternative with the second position in the ranking list by Q ;
 $\min(0.25, DQ = \frac{1}{r-1})$ where r is the total number of alternatives.

- Condition 2: 'Acceptable stability in decision making':

Alternative a_Q^1 must also be the best ranked by S_j, R_j or a_Q^1 corresponds to the same alternative as a_S^1 and a_R^1 .

5. If one of the conditions is not satisfied, then the following set of 'compromise solutions' is proposed, which the decision-makers may select based on additional negotiations:
 - Alternatives a_Q^1 and a_Q^2 , if only Condition 2 is not satisfied, or
 - Alternatives $a_Q^1, a_Q^2, \dots, a_Q^H$, if Condition 1 is not satisfied; $Q(a_Q^H) - Q(a_Q^1) < DQ$ or the positions of the alternatives are 'close' in the decision space.

Appendix O Gas Turbine Performance Simulation Results

O.1 MGT Rated at 7.5 MW

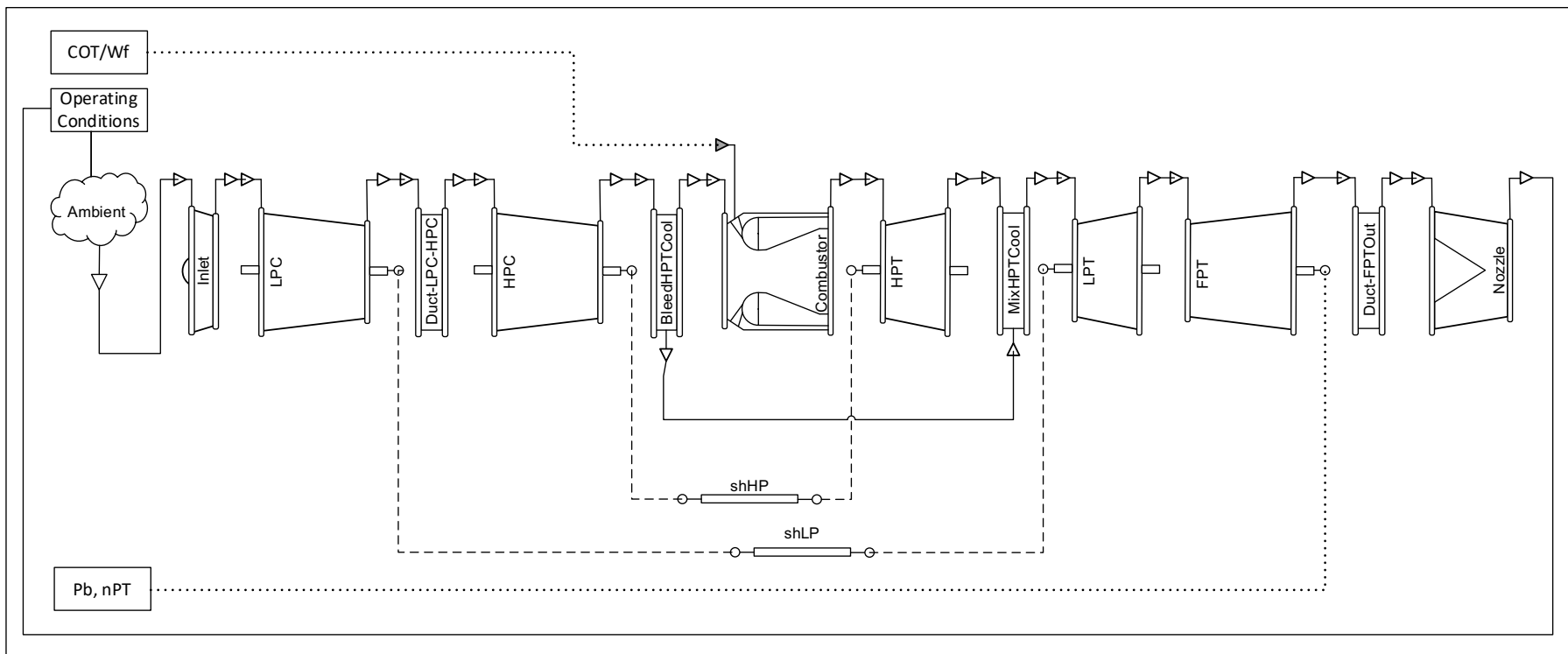
The modelled engine has a twin-spool gas generator with a free power turbine that is connected to the load or the propeller through the transmission system. The layout of the engine is shown in Figure O-1. The primary parameters of the engine are shown in Table O-1. The detailed model input file used is shown in Appendix P.2.

Table O-1 Primary design point parameters for 7.5 MW MGT

Parameter	Unit	Value
Inlet mass flow	kg/s	32.5
LP Compressor pressure ratio	-	4
LP Compressor isentropic efficiency	%	90
HP Compressor pressure ratio	-	3.5
HP Compressor isentropic efficiency	%	90
Compressor bleed for HP Turbine cooling	%	8
Combustor outlet temperature	K	1300
Fuel type	-	Diesel
HP Turbine isentropic efficiency	%	85
LP Turbine isentropic efficiency	%	90
FP Turbine isentropic efficiency	%	88

LP: High Pressure; HP: High Pressure, FP: Free Power

The simulation results presented below for this engine have been calculated for ISA SLS conditions with the power turbine speed fixed at its rated speed. The OD simulations were undertaken using the combustor outlet temperature as the handle. The generated engine characteristics for the engine are shown from Figure O-2 to Figure O-24.



1

2 **Figure O-1 Model block diagram for 7.5 MW MGT**

3

4

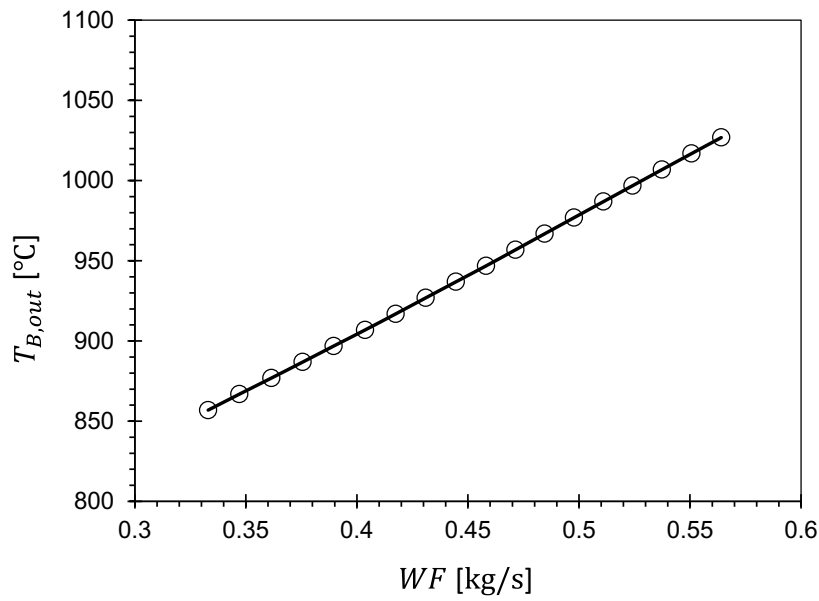


Figure O-2 Computed variation of combustor outlet temperature ($T_{B,out}$) against fuel flow (WF) for 7.5 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

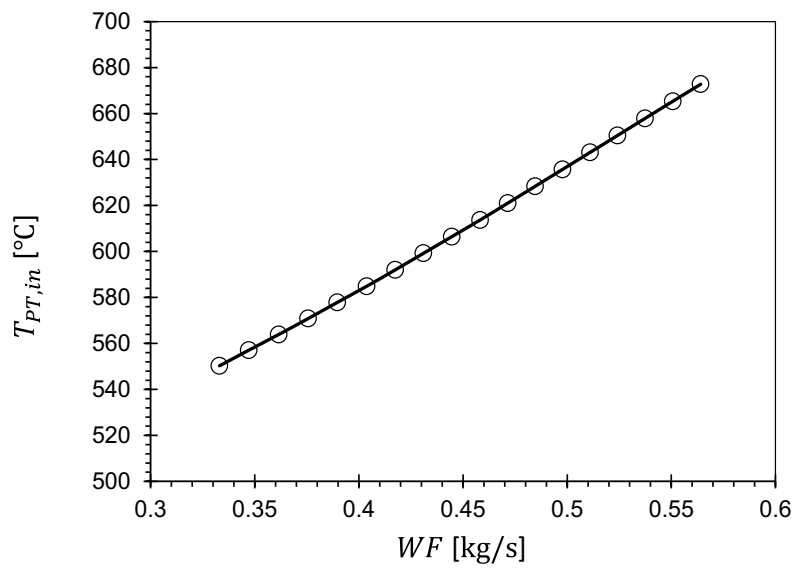


Figure O-3 Computed variation of power turbine inlet temperature ($T_{PT,in}$) against fuel flow (WF) for 7.5 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

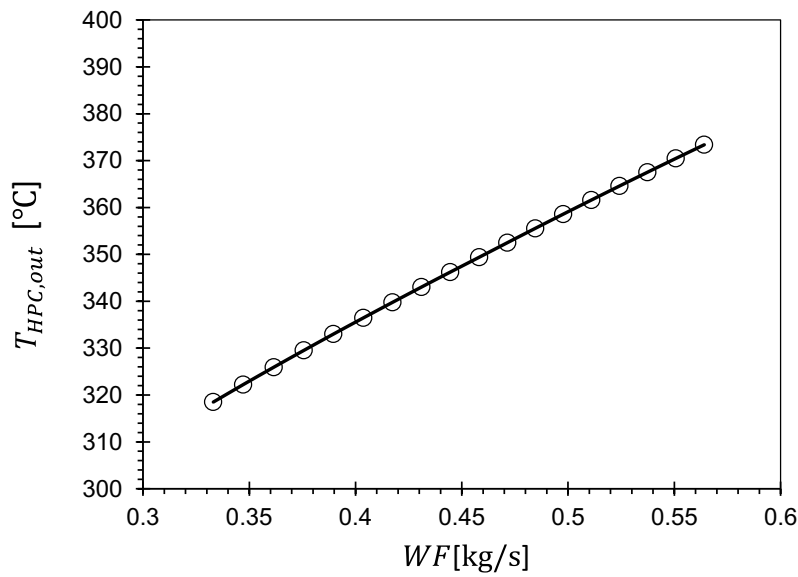


Figure O-4 Computed variation of high-pressure compressor (HPC) outlet temperature ($T_{HPC,out}$) against fuel flow (WF) for 7.5 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

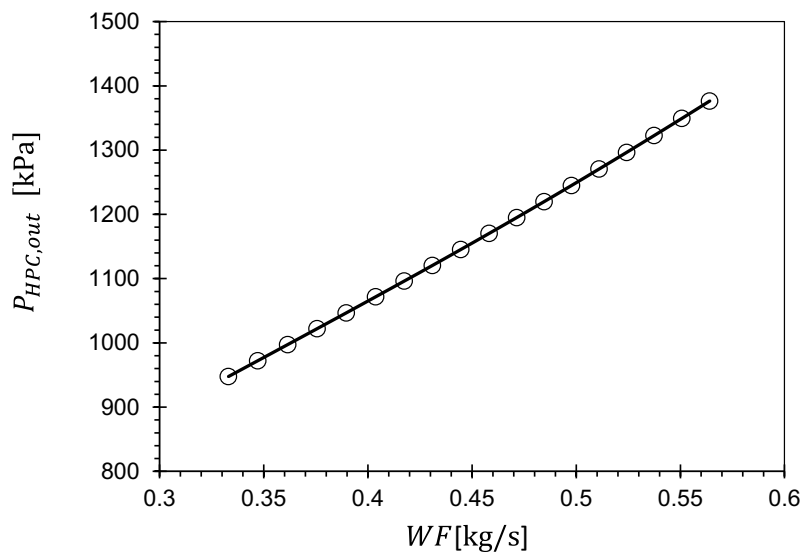


Figure O-5 Computed variation of high-pressure compressor outlet pressure ($P_{HPC,out}$) against fuel flow (WF) for 7.5 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

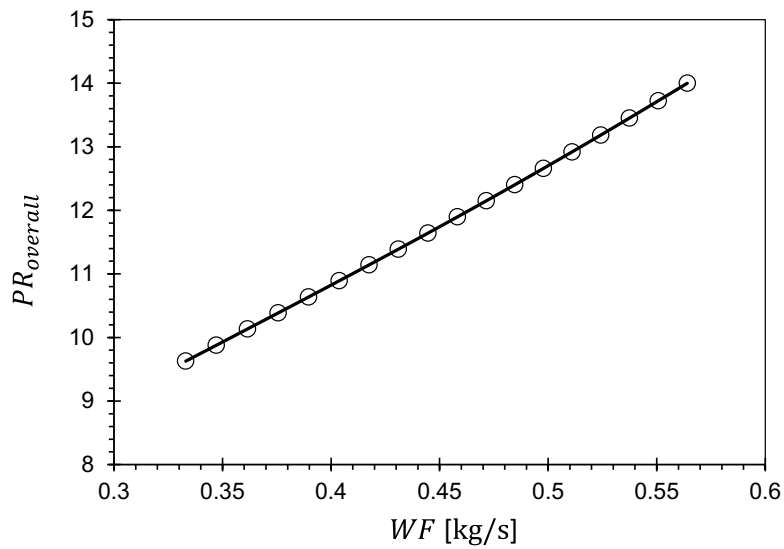


Figure O-6 Computed variation of overall compressor pressure ratio (PR) against fuel flow (WF) for 7.5 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

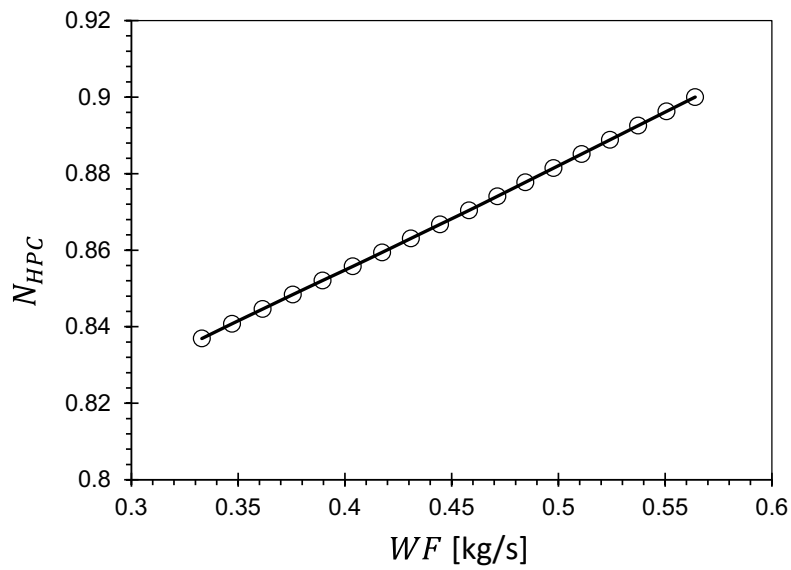


Figure O-7 Computed variation of high-pressure compressor speed ratio (N_{HPC}) against fuel flow (WF) for 7.5 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

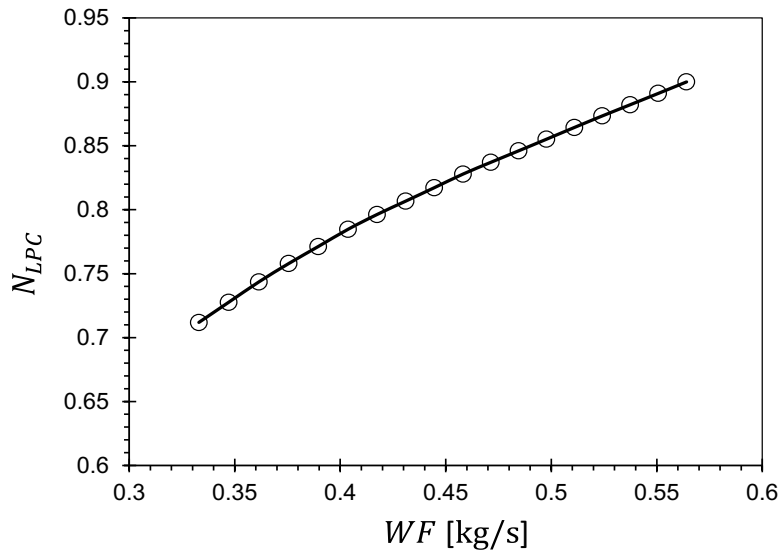


Figure O-8 Computed variation of low-pressure compressor speed ratio (N_{LPC}) against fuel flow (WF) for 7.5 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

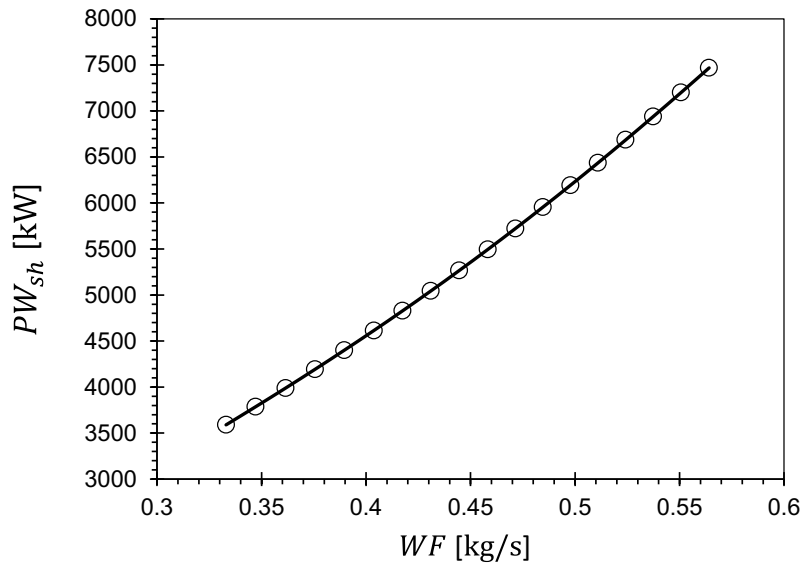


Figure O-9 Computed variation of power turbine shaft power or engine brake power ($PW_{sh,out}$) against fuel flow (WF) for 7.5 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

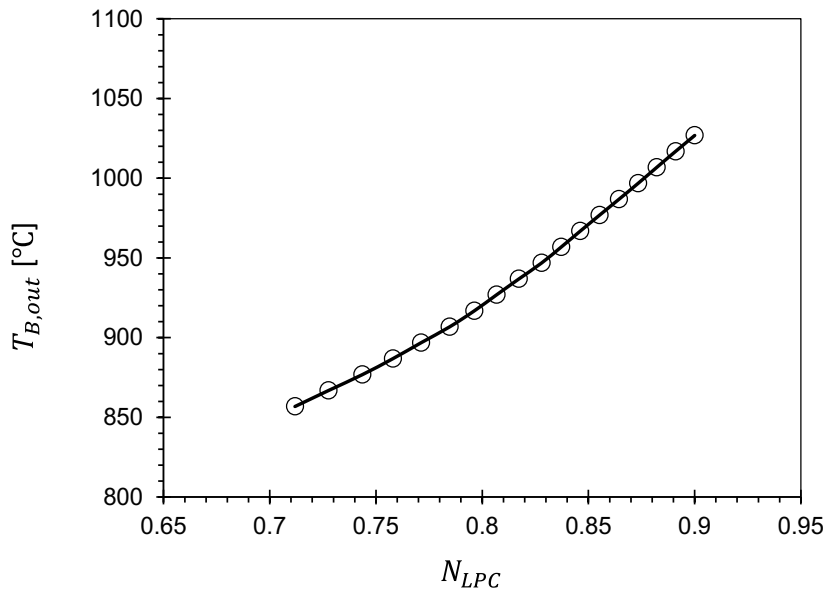


Figure O-10 Computed variation of combustor outlet temperature ($T_{B,out}$) against low pressure compressor speed ratio (N_{LPC}) for 7.5 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15^{\circ}C$.

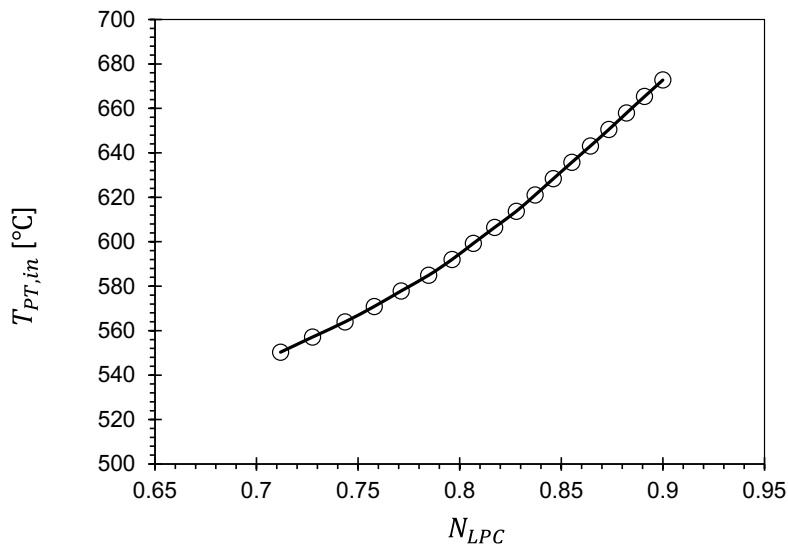


Figure O-11 Computed variation of power turbine inlet temperature ($T_{PT,in}$) against low pressure compressor speed ratio (N_{LPC}) for 7.5 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15^{\circ}C$.

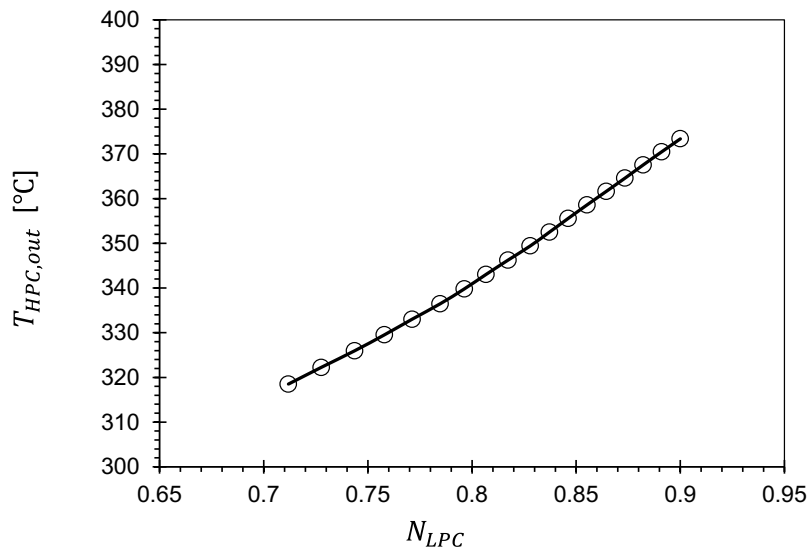


Figure O-12 Computed variation of high compressor outlet temperature ($T_{HPC,out}$) against low pressure compressor speed ratio (N_{LPC}) for 7.5 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

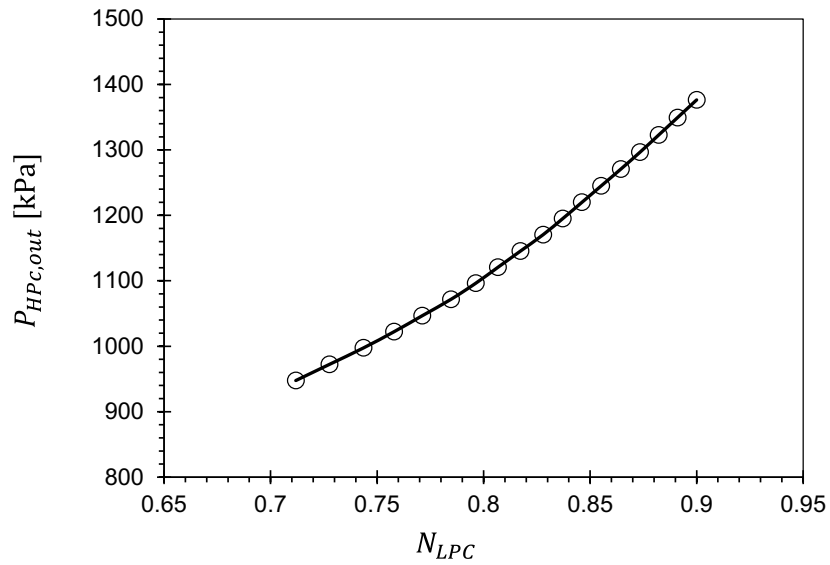


Figure O-13 Computed variation of high-pressure compressor outlet pressure ($P_{HPC,out}$) against low pressure compressor speed ratio (N_{LPC}) for 7.5 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

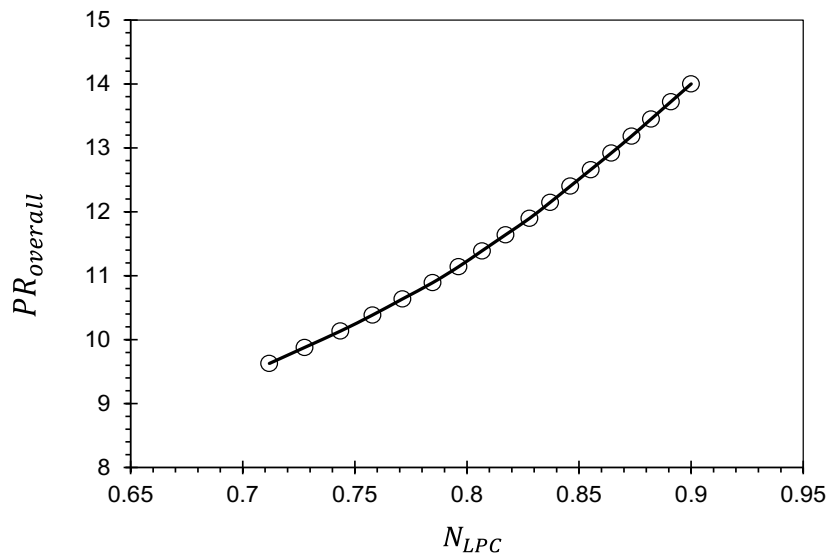


Figure O-14 Computed variation of overall compressor pressure ratio (PR) against low pressure compressor speed ratio (N_{LPC}) for 7.5 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15\text{ }^{\circ}\text{C}$.

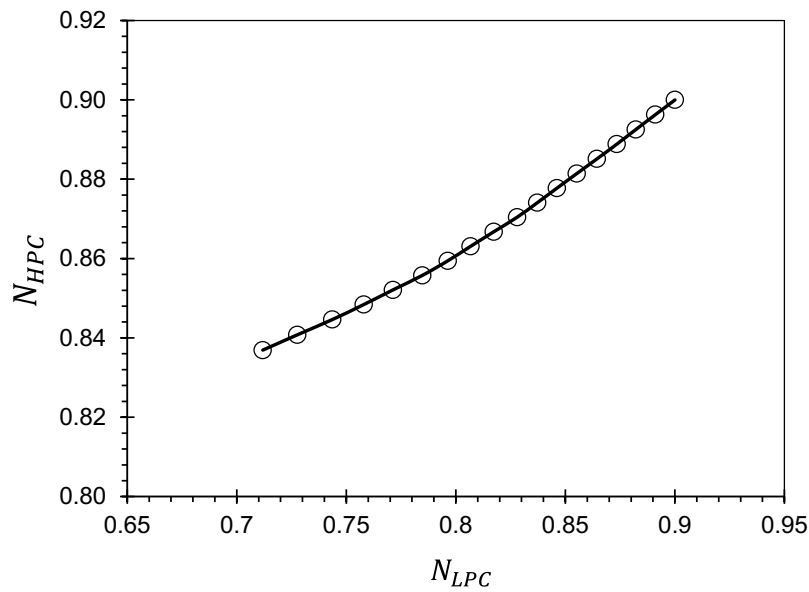


Figure O-15 Computed variation of high-pressure compressor speed ratio (N_{HPC}) against low pressure compressor speed ratio (N_{LPC}) for 7.5 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15\text{ }^{\circ}\text{C}$.

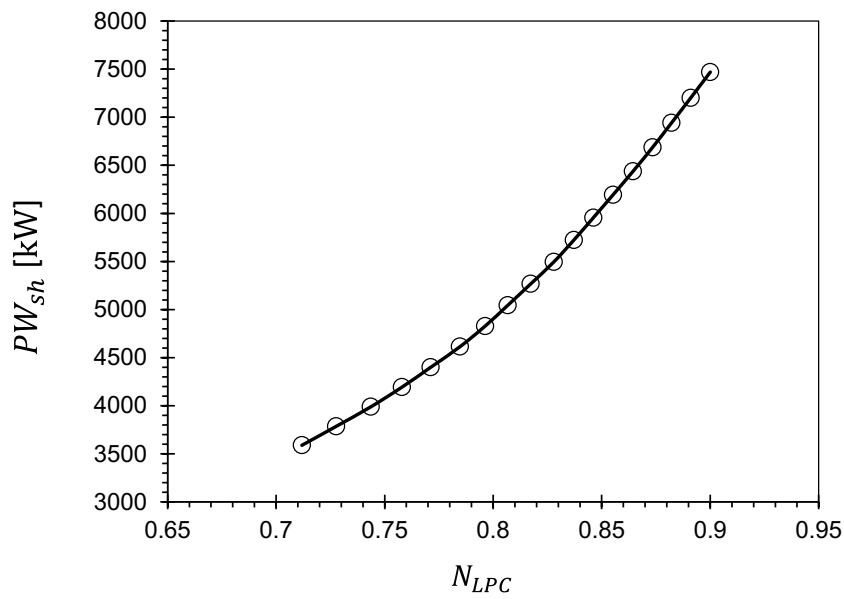


Figure O-16 Computed variation of power turbine shaft power or engine brake power (PW_{sh}) against low pressure compressor speed ratio (N_{LPC}) for 7.5 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15^\circ\text{C}$.

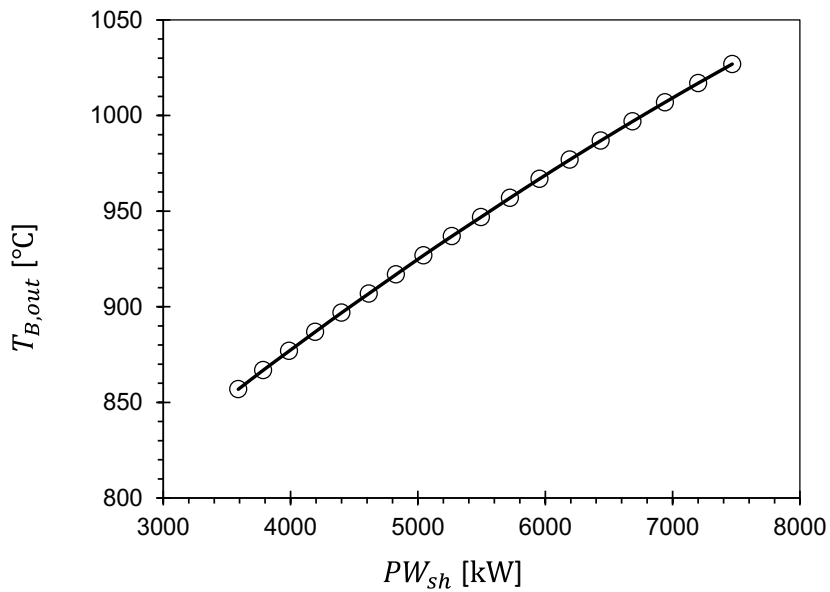


Figure O-17 Computed variation of combustor outlet temperature ($T_{B,out}$) against engine shaft power (PW_{sh}) for 7.5 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15^\circ\text{C}$.

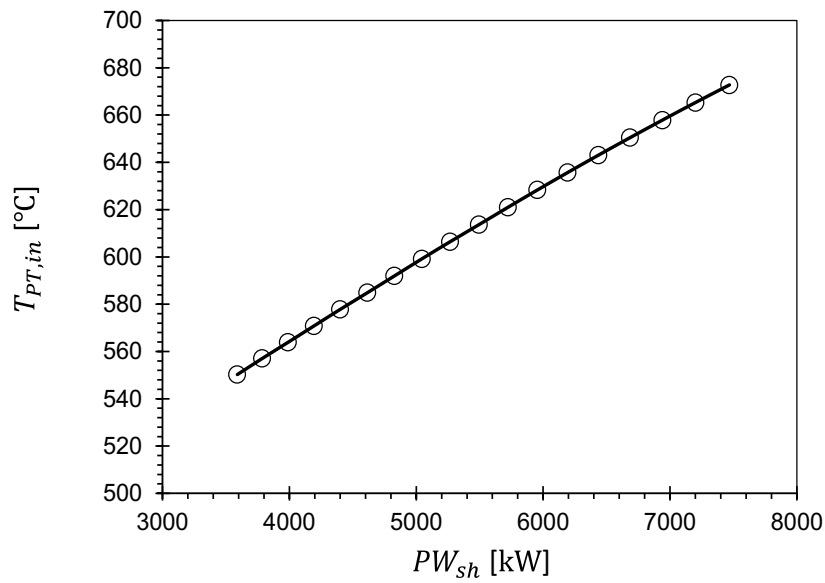


Figure O-18 Computed variation of power turbine inlet temperature ($T_{PT,in}$) against engine shaft power (PW_{sh}) for 7.5 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

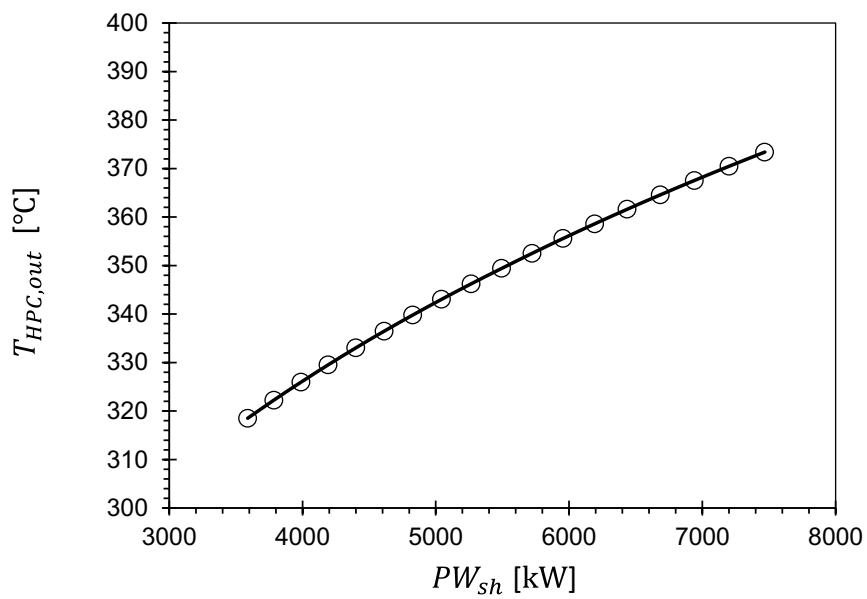


Figure O-19 Computed variation of high-pressure compressor outlet temperature ($T_{HPC,out}$) against engine shaft power (PW_{sh}) for 7.5 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

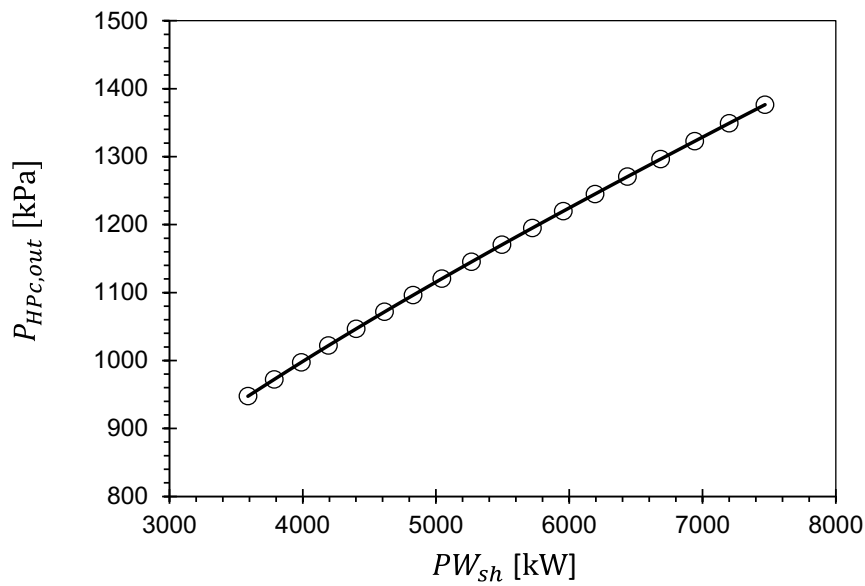


Figure O-20 Computed variation of high-pressure compressor outlet pressure ($P_{HPC,out}$) against engine shaft power (PW_{sh}) for 7.5 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

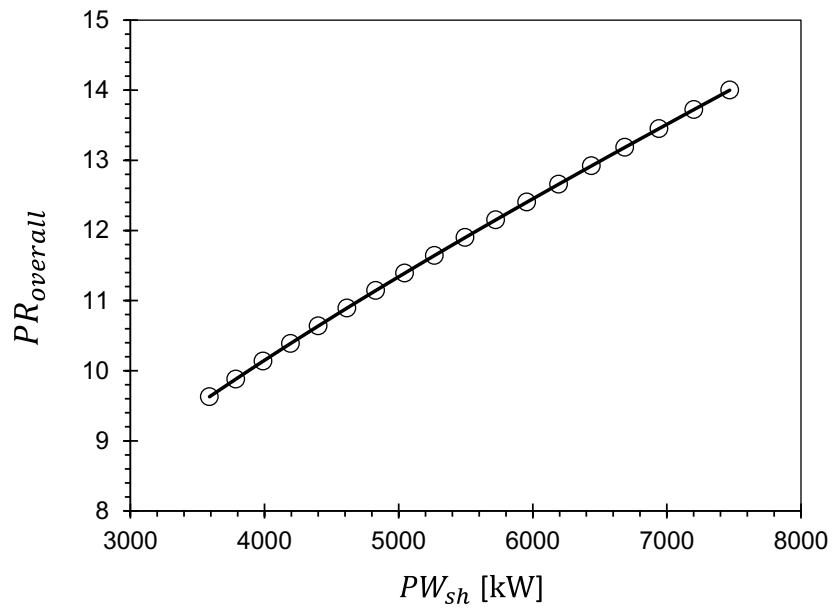


Figure O-21 Computed variation of overall compressor pressure ratio (PR) against engine shaft power (PW_{sh}) for 7.5 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

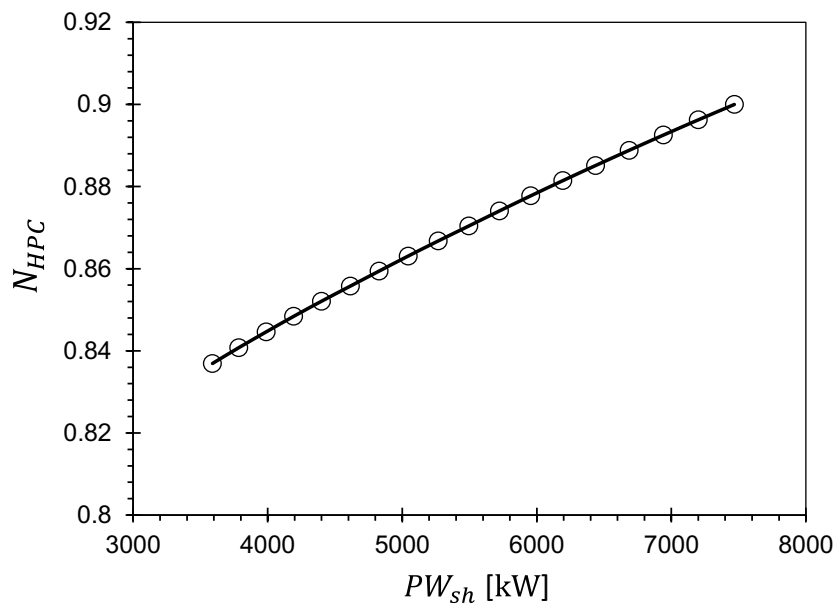


Figure O-22 Computed variation of high-pressure compressor speed ratio (N_{HPC}) against engine shaft power (PW_{sh}) for 7.5 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15^\circ\text{C}$.

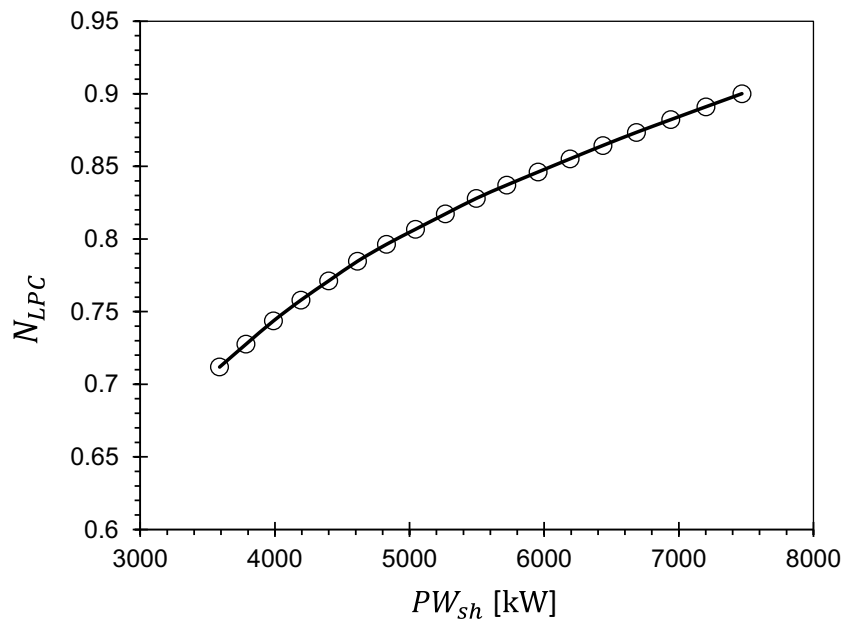


Figure O-23 Computed variation of low-pressure compressor speed ratio (N_{LPC}) against engine shaft power (PW_{sh}) for 7.5 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15^\circ\text{C}$.

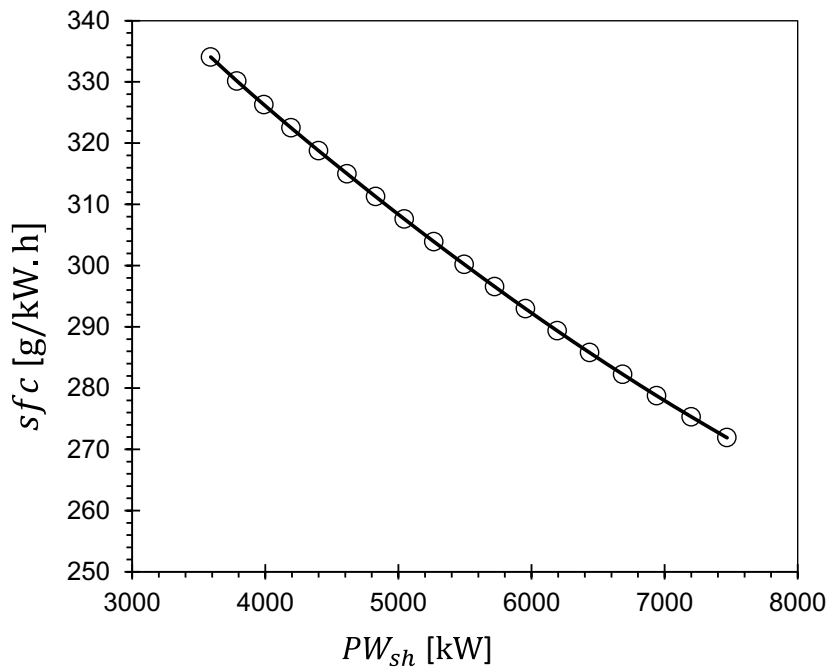


Figure O-24 Computed variation of specific fuel consumption (sfc) against engine shaft power (PW_{sh}) for 7.5 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

O.2 MGT Rated at 15 MW

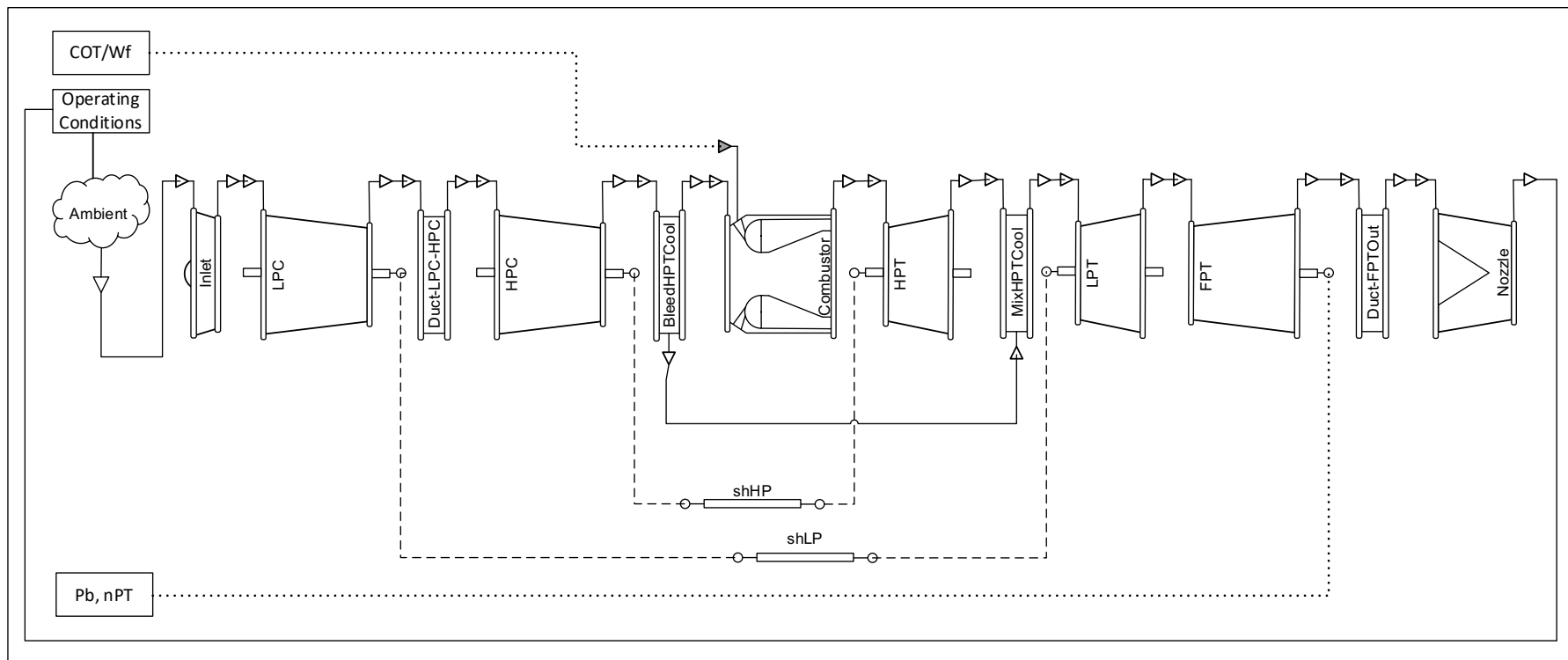
The modelled engine has a twin-spool gas generator with a free power turbine that is connected to the load or the propeller through the transmission system. The layout of the engine is shown in Figure O-25. The primary parameters of the engine are shown in Table O-2. The detailed model input file is shown in Appendix P.2.

The simulation results presented below for this engine have been run for ISA SLS conditions with the power turbine speed fixed at its rated speed. The OD simulations were undertaken using the combustor outlet temperature as the handle. The generated engine characteristics for the engine are shown from Figure O-26 to Figure O-48.

Table O-2 Primary design point parameters for 15 MW MGT

Parameter	Unit	Value
Inlet mass flow	kg/s	90
LP Compressor pressure ratio	-	3.8
LP Compressor isentropic efficiency	%	92
HP Compressor pressure ratio	-	3.1
HP Compressor isentropic efficiency	%	91
Compressor bleed for HP Turbine cooling	%	8
Combustor outlet temperature	K	1200
Fuel type	-	Diesel
HP Turbine isentropic efficiency	%	86
LP Turbine isentropic efficiency	%	90
FP Turbine isentropic efficiency	%	88

LP: High Pressure; HP: High Pressure, FP: Free Power



1

2 **Figure O-25 Model block diagram for 15 MW MGT**

3

4

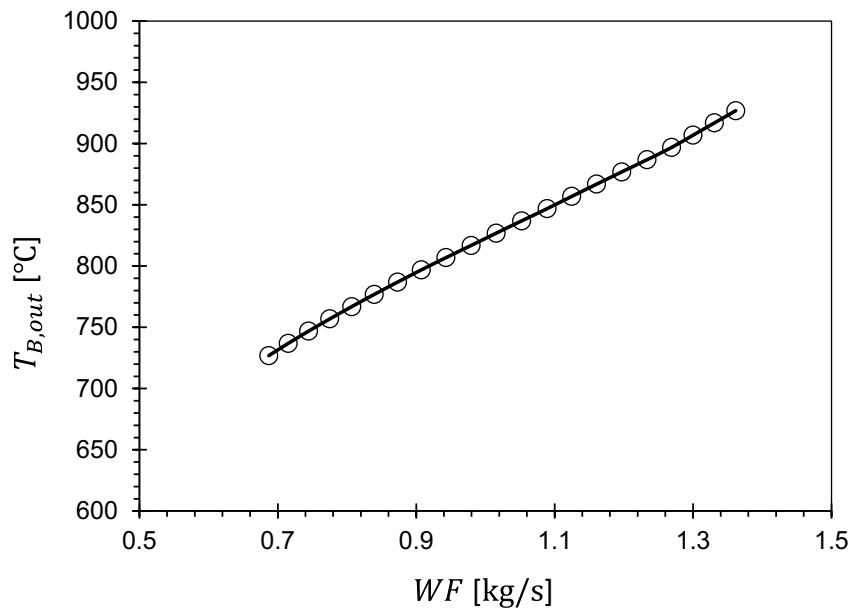


Figure O-26 Computed variation of combustor outlet temperature ($T_{B,out}$) against fuel flow (WF) for 15 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

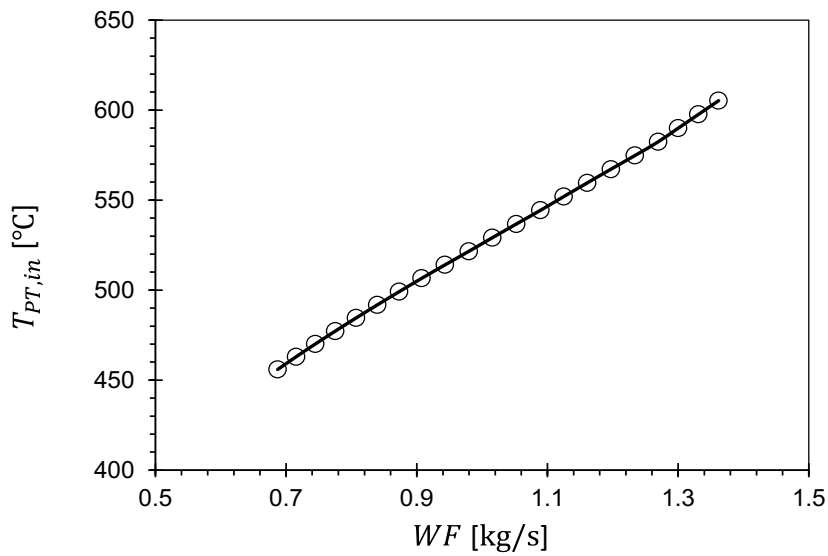


Figure O-27 Computed variation of power turbine inlet temperature ($T_{PT,in}$) against fuel flow (WF) for 15 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

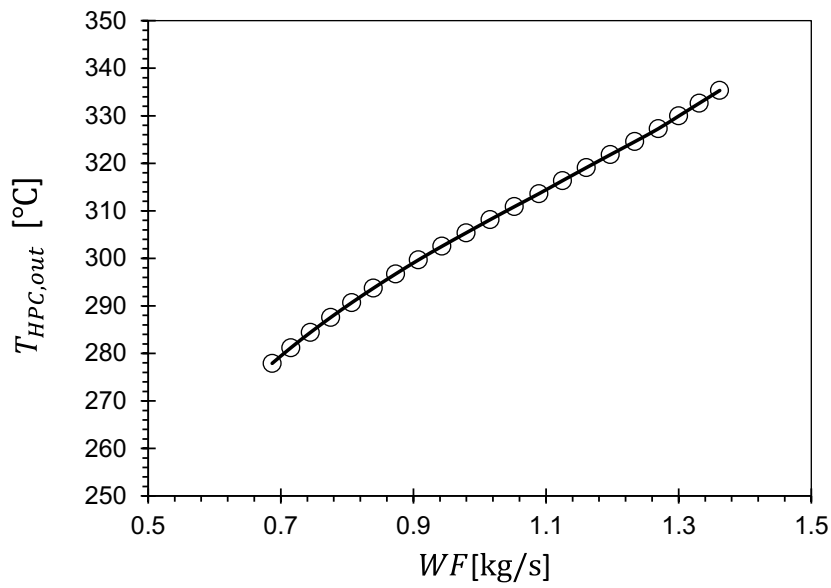


Figure O-28 Computed variation of high-pressure compressor (HPC) outlet temperature ($T_{HPC,out}$) against fuel flow (WF) for 15 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

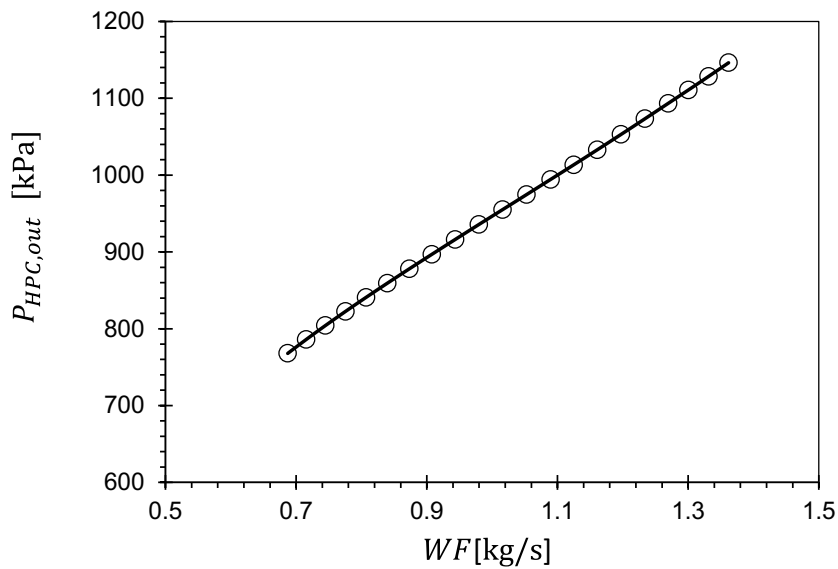


Figure O-29 Computed variation of high-pressure compressor outlet pressure ($P_{HPC,out}$) against fuel flow (WF) for 15 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

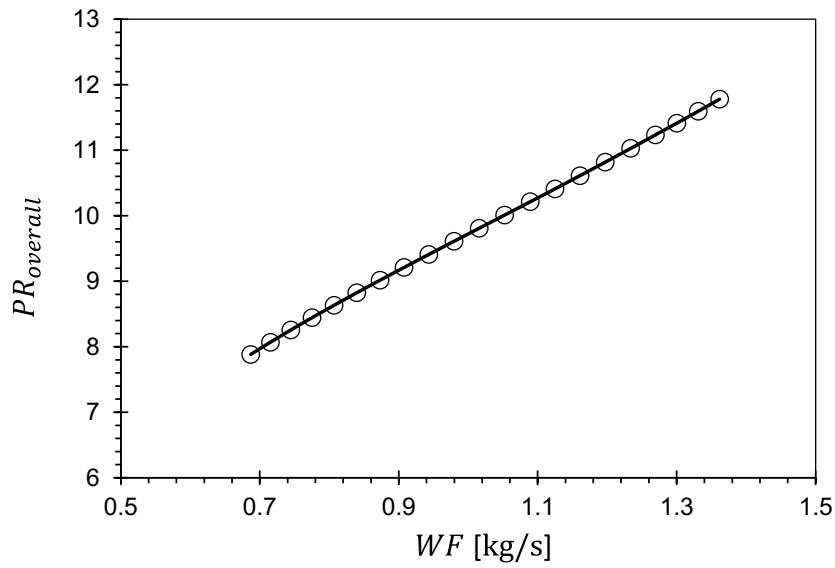


Figure O-30 Computed variation of overall compressor pressure ratio (PR) against fuel flow (WF) for 15 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15^\circ\text{C}$.

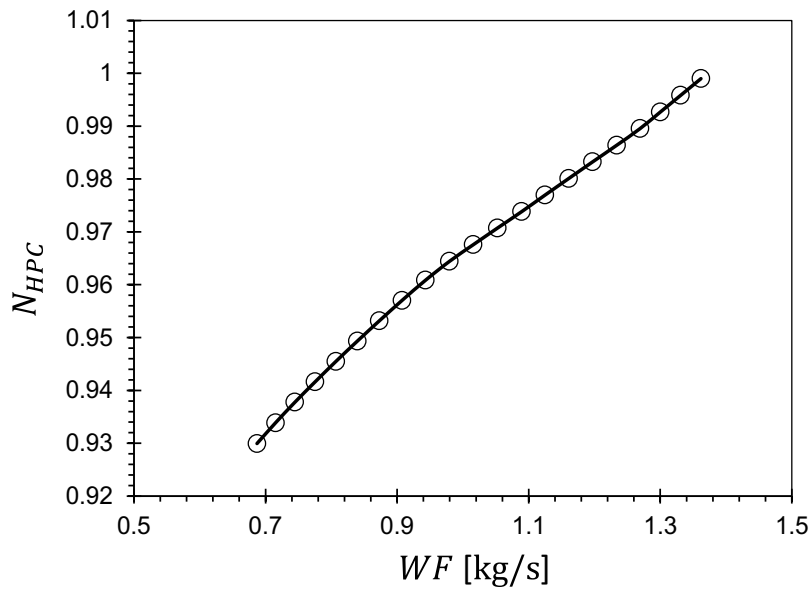


Figure O-31 Computed variation of high-pressure compressor speed ratio (N_{HPC}) against fuel flow (WF) for 15 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15^\circ\text{C}$.

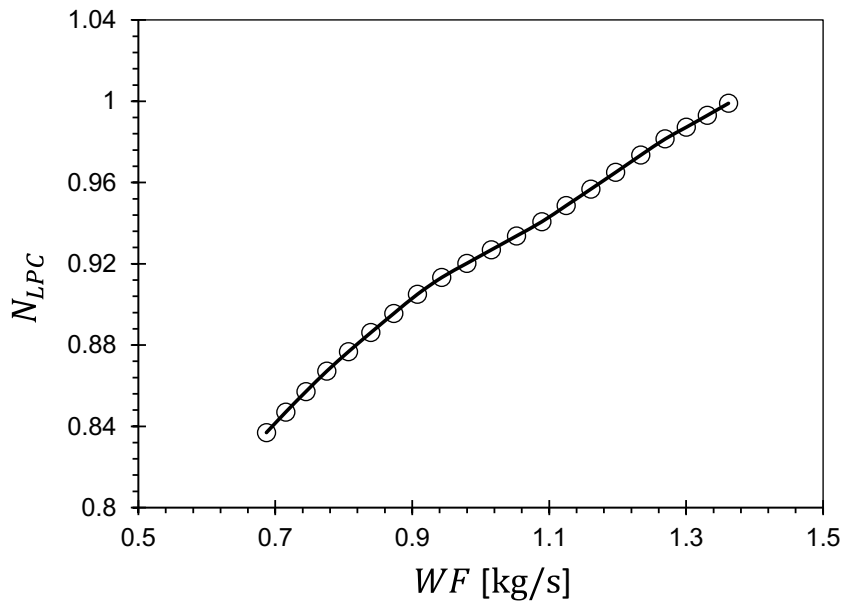


Figure O-32 Computed variation of low-pressure compressor speed ratio (N_{LPC}) against fuel flow (WF) for 15 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15^\circ\text{C}$.

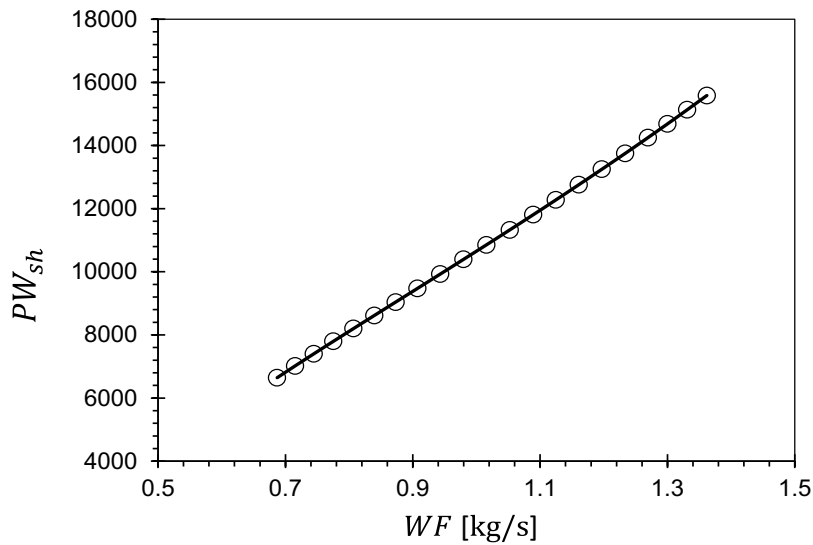


Figure O-33 Computed variation of power turbine shaft power or engine brake power ($PW_{sh,out}$) against fuel flow (WF) for 15 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15^\circ\text{C}$.

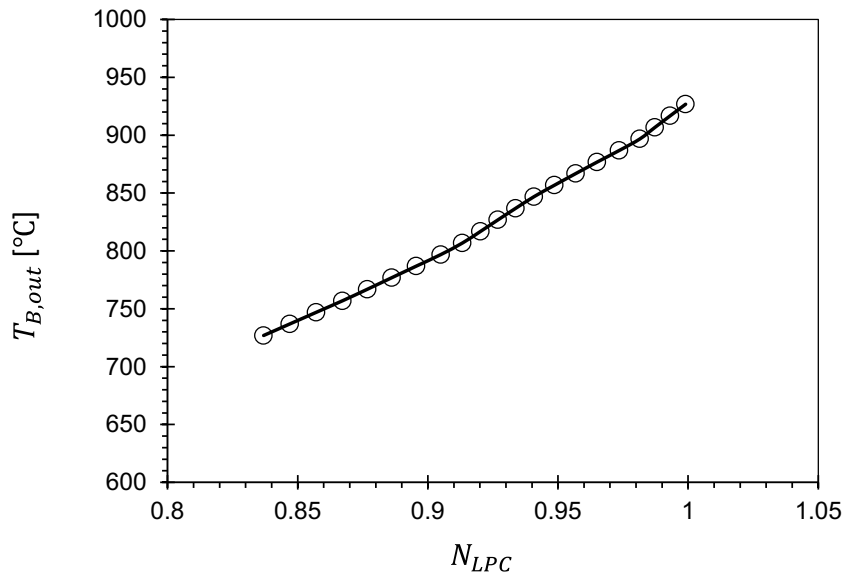


Figure O-34 Computed variation of combustor outlet temperature ($T_{B,out}$) against low pressure compressor speed ratio (N_{LPC}) for 15 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

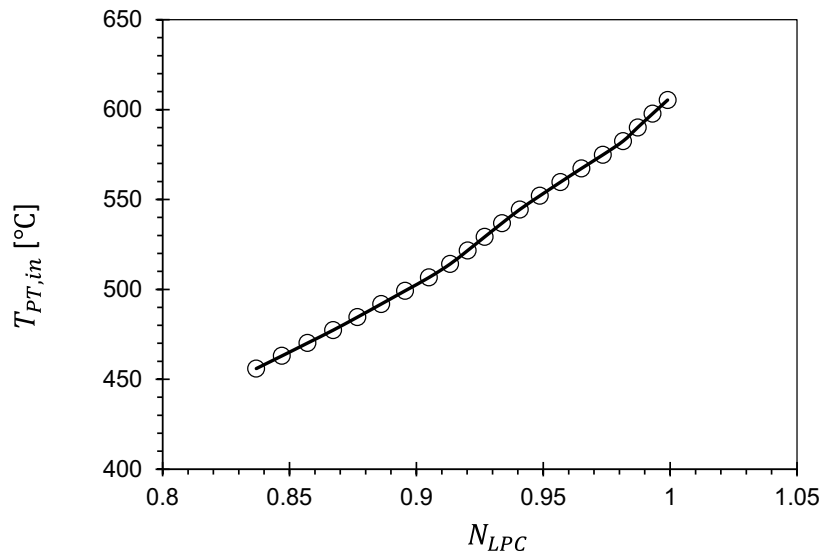


Figure O-35 Computed variation of power turbine inlet temperature ($T_{PT,in}$) against low pressure compressor speed ratio (N_{LPC}) for 15 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

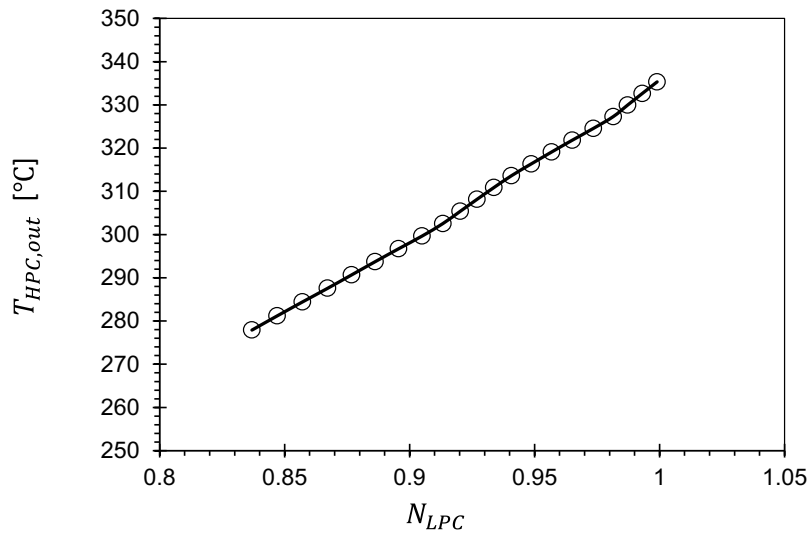


Figure O-36 Computed variation of high compressor outlet temperature ($T_{HPC,out}$) against low pressure compressor speed ratio (N_{LPC}) for 15 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

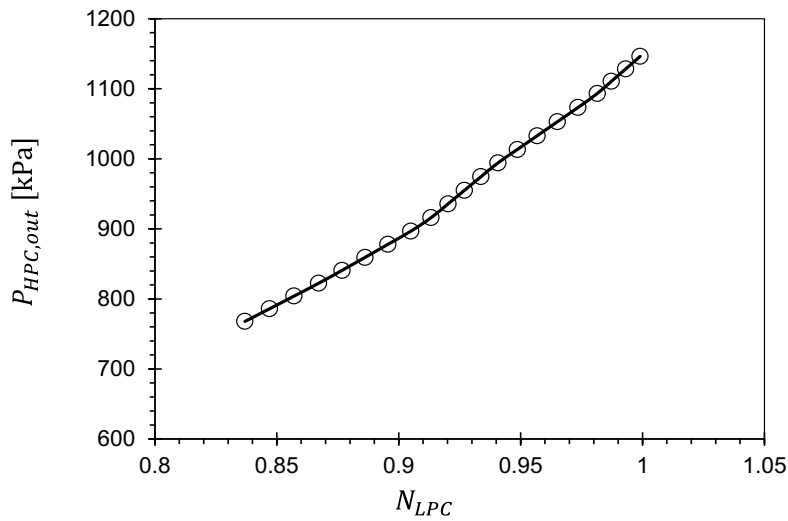


Figure O-37 Computed variation of high-pressure compressor outlet pressure ($P_{HPC,out}$) against low pressure compressor speed ratio (N_{LPC}) for 15 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

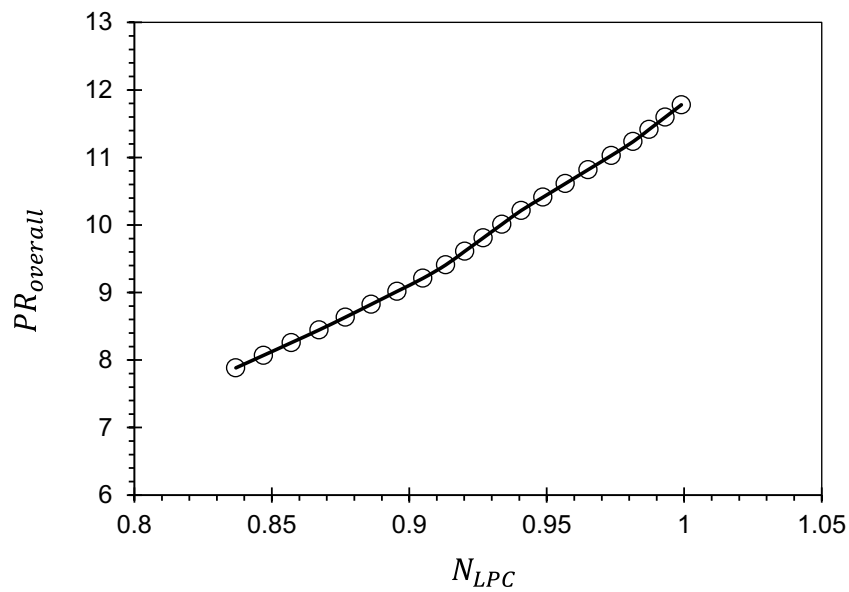


Figure O-38 Computed variation of overall compressor pressure ratio (PR) against low pressure compressor speed ratio (N_{LPC}) for 15 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15\text{ }^{\circ}\text{C}$.

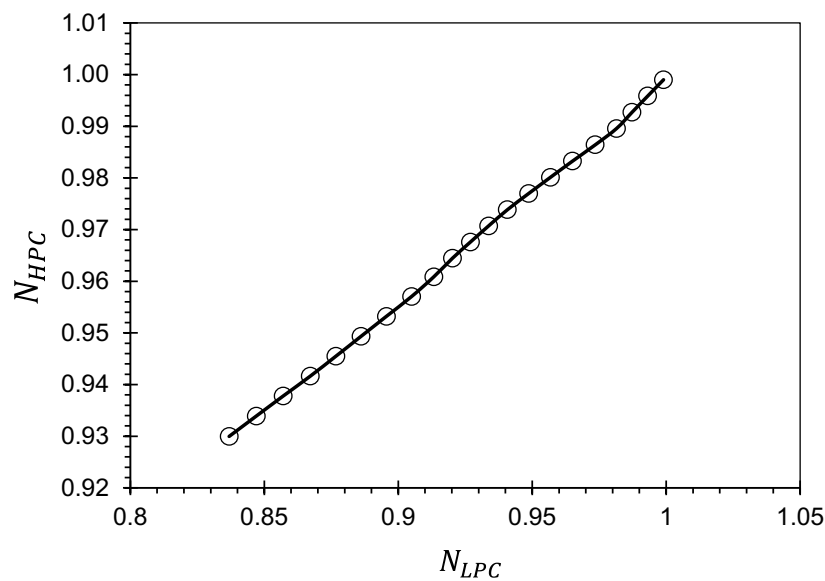


Figure O-39 Computed variation of high-pressure compressor speed ratio (N_{HPC}) against low pressure compressor speed ratio (N_{LPC}) for 15 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15\text{ }^{\circ}\text{C}$.

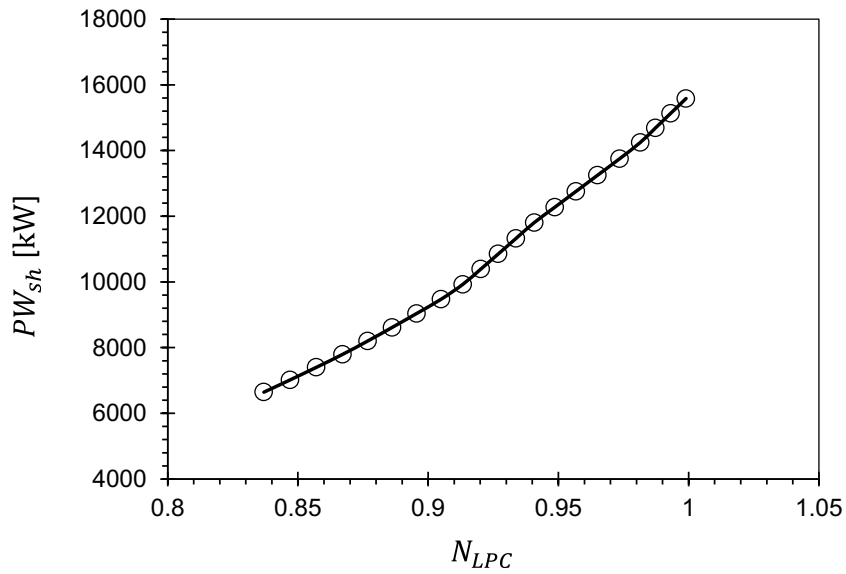


Figure O-40 Computed variation of power turbine shaft power or engine brake power (PW_{sh}) against low pressure compressor speed ratio (N_{LPC}) for 15 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15^\circ\text{C}$.

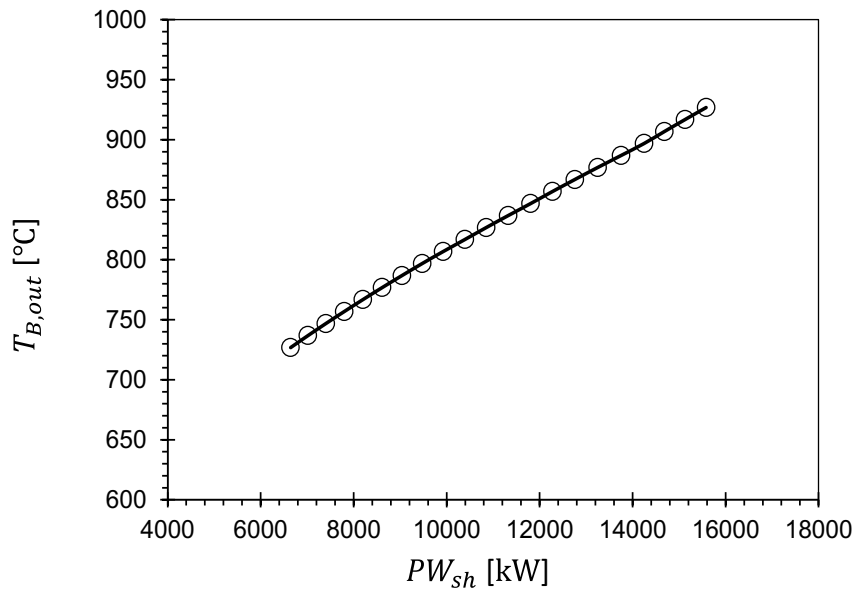


Figure O-41 Computed variation of combustor outlet temperature ($T_{B,out}$) against engine shaft power (PW_{sh}) for 15 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15^\circ\text{C}$.

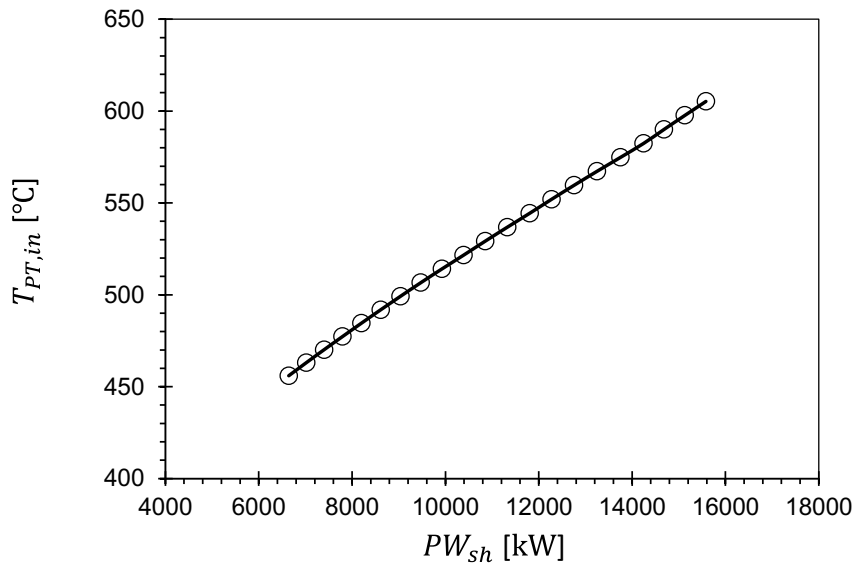


Figure O-42 Computed variation of power turbine inlet temperature ($T_{PT,in}$) against engine shaft power (PW_{sh}) for 15 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

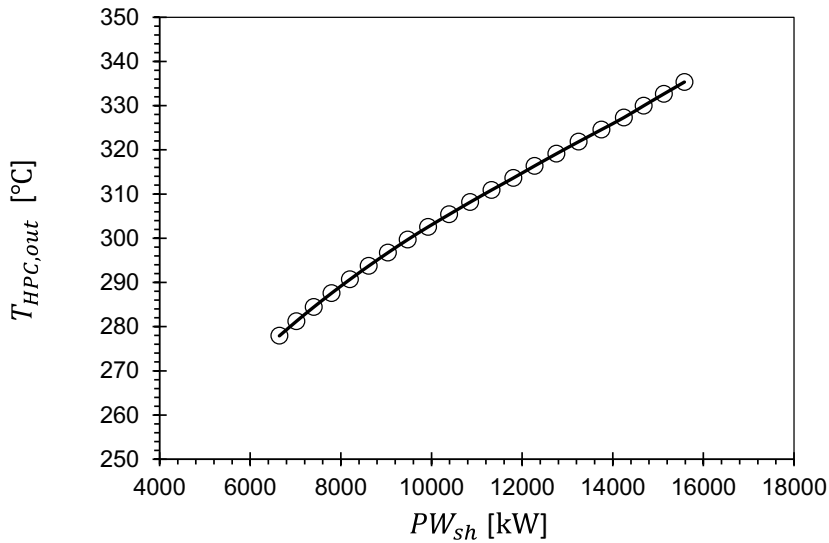


Figure O-43 Computed variation of high pressure compressor outlet temperature ($T_{HPC,out}$) against engine shaft power (PW_{sh}) for 15 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

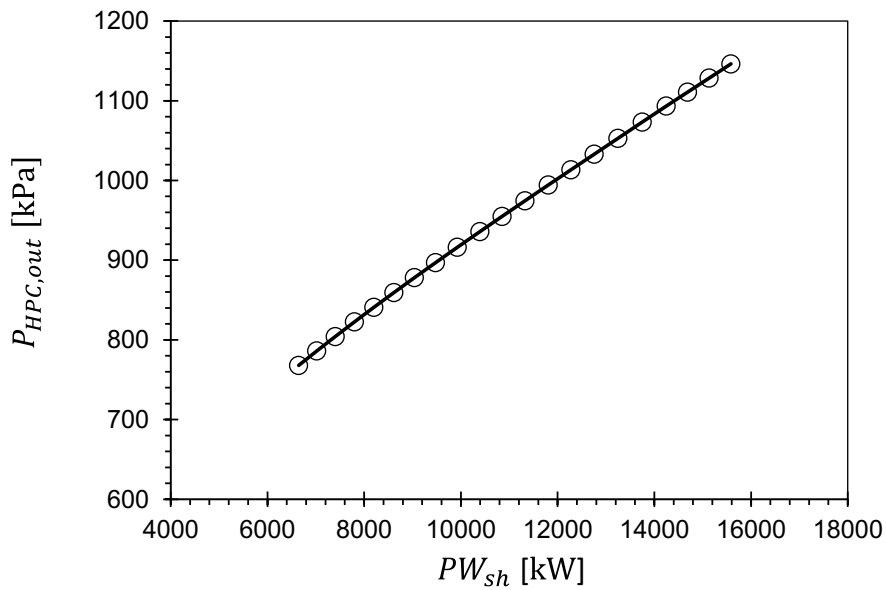


Figure O-44 Computed variation of high-pressure compressor outlet pressure ($P_{HPC,out}$) against engine shaft power (PW_{sh}) for 15 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

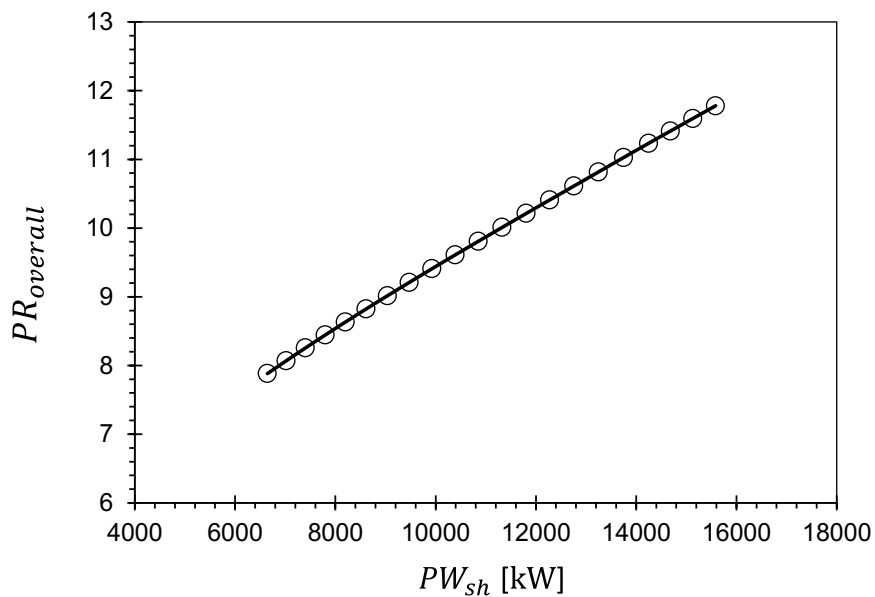


Figure O-45 Computed variation of overall compressor pressure ratio (PR) against engine shaft power (PW_{sh}) for 15 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

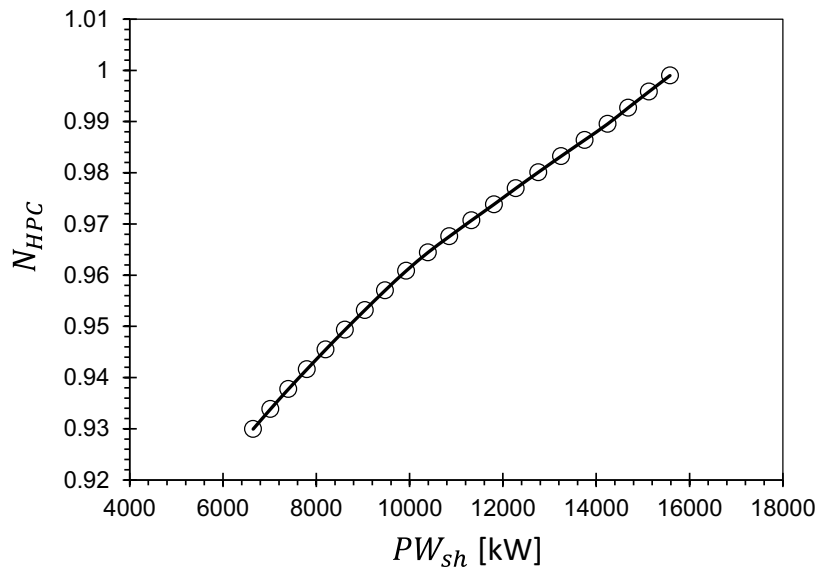


Figure O-46 Computed variation of high-pressure compressor speed ratio (N_{HPC}) against engine shaft power (PW_{sh}) for 15 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

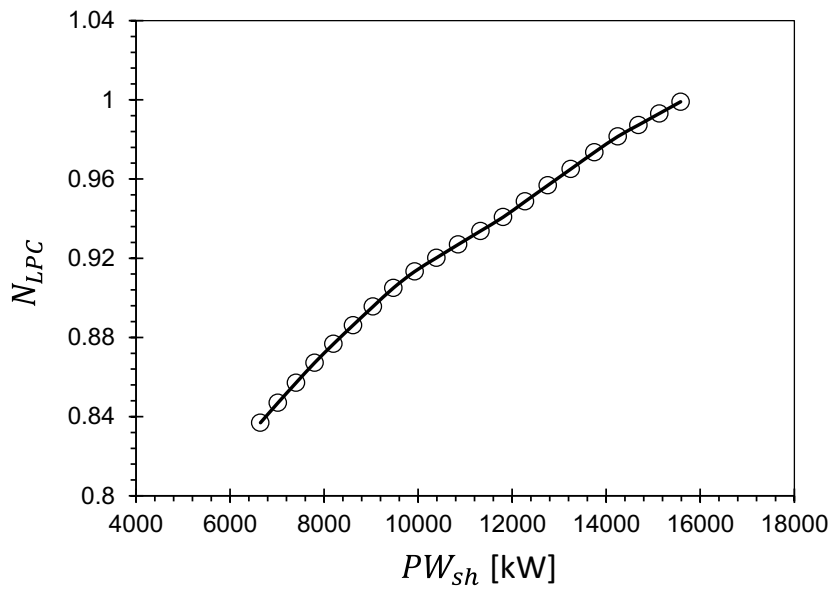


Figure O-47 Computed variation of low-pressure compressor speed ratio (N_{LPC}) against engine shaft power (PW_{sh}) for 15 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

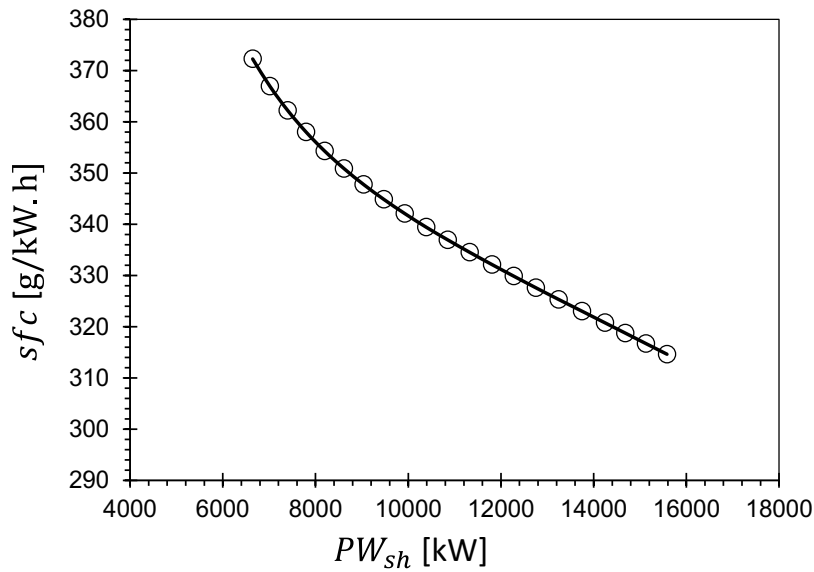


Figure O-48 Computed variation of specific fuel consumption (sfc) against engine shaft power (PW_{sh}) for 15 MW MGT, with power turbine speed $N_{PT} = 1$ and ambient temperature at $T_{amb} = 15$ °C.

O.3 MGT Rated at 36 MW

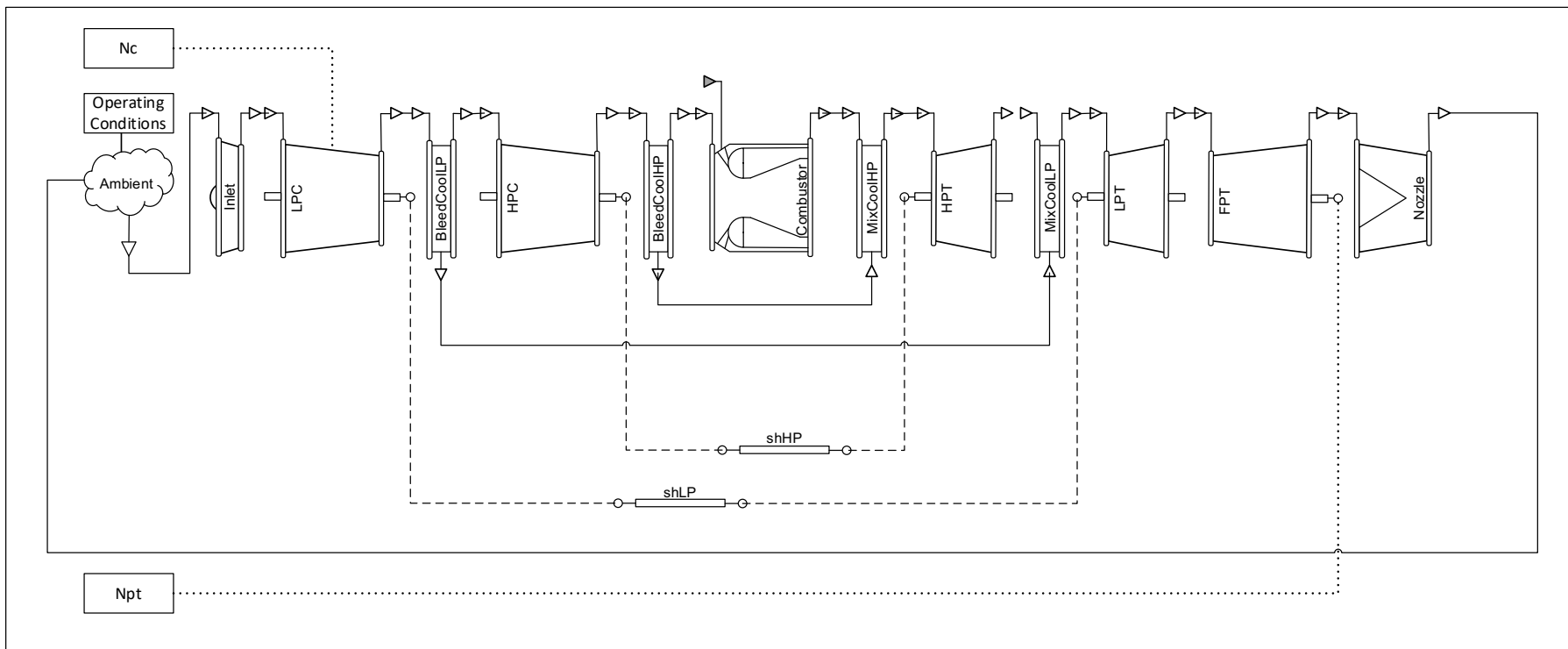
The modelled engine has a twin-spool gas generator with a free power turbine that is connected to the load or the propeller through the transmission system. The layout of the engine is shown in Figure O-49. The primary parameters of the engine are shown in Table O-3. The detailed model input file used is shown in Appendix P.5.

The simulation results presented below for this engine have been run for ISA SLS conditions with the power turbine speed varied as per the loading by a propeller, with the load curve shown in Figure O-73. **Error! Reference source not found..** The OD simulations were undertaken using the power turbine shaft power as the handle. The generated engine characteristics for the engine are shown from Figure O-50 to Figure O-72.

Table O-3 Primary design point parameters for 36 MW MGT

Parameter	Unit	Value
Inlet mass flow	kg/s	115
LP Compressor pressure ratio	-	5.71
LP Compressor isentropic efficiency	%	89
HP Compressor pressure ratio	-	4.2
HP Compressor isentropic efficiency	%	88
Compressor bleed for LP Turbine cooling	%	1.5
Compressor bleed for HP Turbine cooling	%	15
Combustor outlet temperature	K	1510
Fuel type	-	Diesel
HP Turbine isentropic efficiency	%	90
LP Turbine isentropic efficiency	%	91
FP Turbine isentropic efficiency	%	92

LP: High Pressure; HP: High Pressure, FP: Free Power



1

2 **Figure O-49 Model block diagram for 36 MW MGT**

3

4

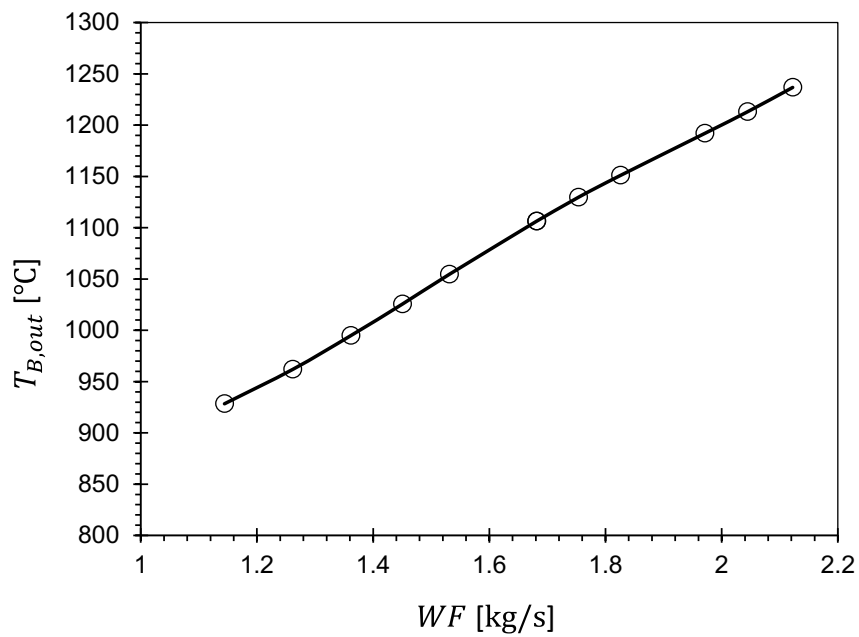


Figure O-50 Computed variation of combustor outlet temperature ($T_{B,out}$) against fuel flow (WF) for 36 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 15$ °C.

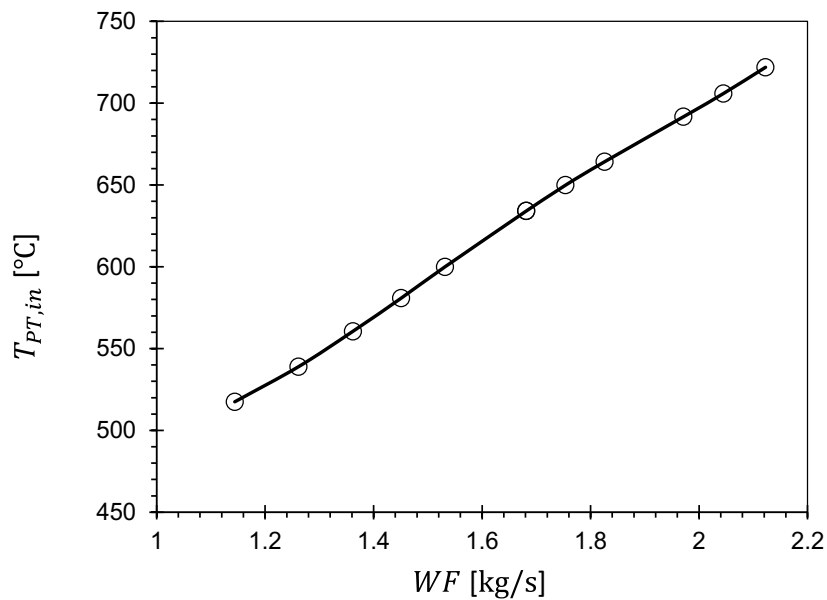


Figure O-51 Computed variation of power turbine inlet temperature ($T_{PT,in}$) against fuel flow (WF) for 36 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 15$ °C.

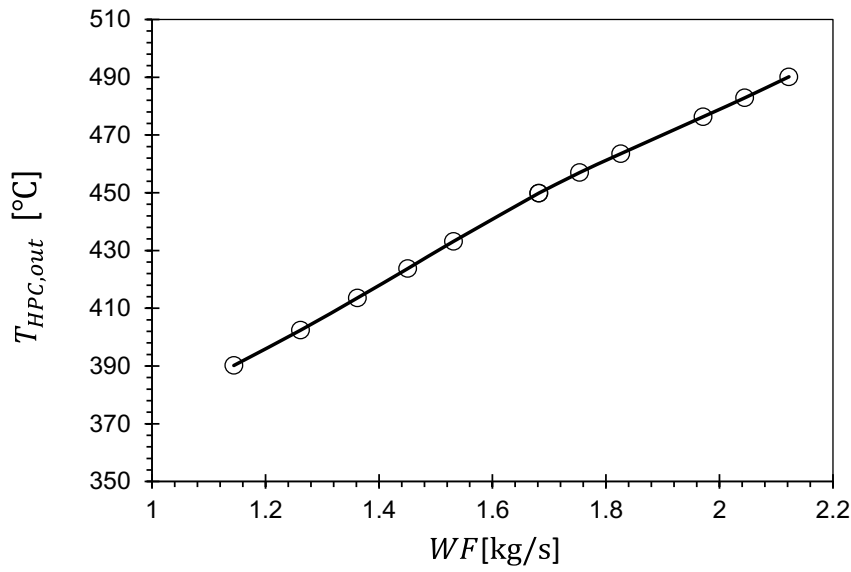


Figure O-52 Computed variation of high-pressure compressor (HPC) outlet temperature ($T_{HPC,out}$) against fuel flow (WF) for 36 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 15^\circ\text{C}$.

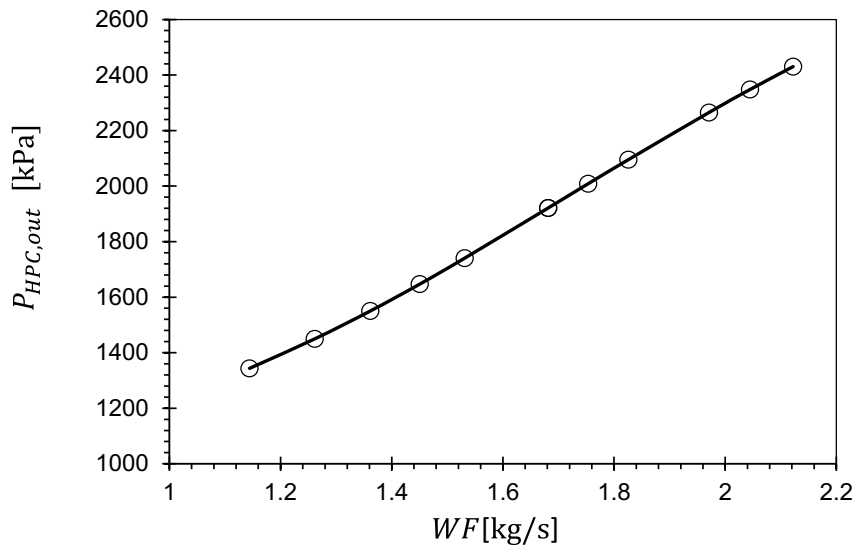


Figure O-53 Computed variation of high-pressure compressor outlet pressure ($P_{HPC,out}$) against fuel flow (WF) for 36 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 15^\circ\text{C}$.

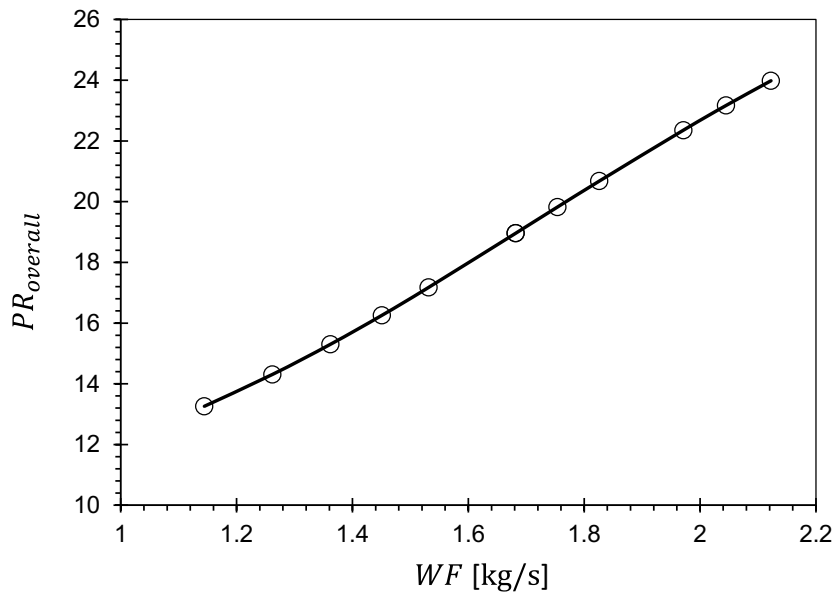


Figure O-54 Computed variation of overall compressor pressure ratio (PR) against fuel flow (WF) for 36 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 15\text{ }^{\circ}\text{C}$.

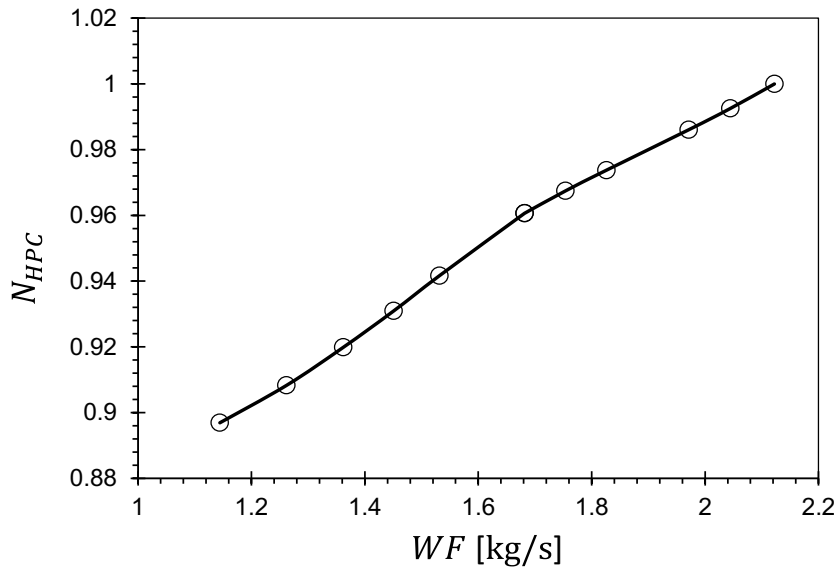


Figure O-55 Computed variation of high-pressure compressor speed ratio (N_{HPC}) against fuel flow (WF) for 36 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 15\text{ }^{\circ}\text{C}$.

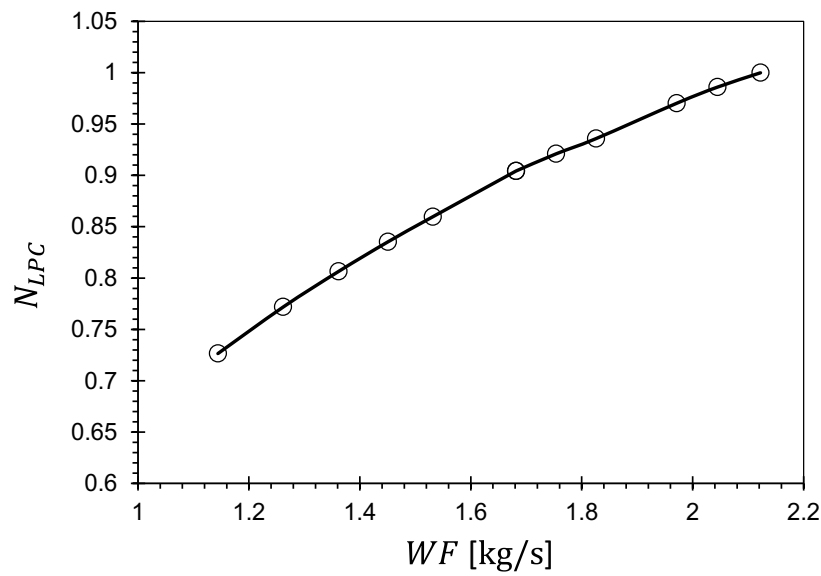


Figure O-56 Computed variation of low-pressure compressor speed ratio (N_{LPC}) against fuel flow (WF) for 36 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 15^\circ\text{C}$.

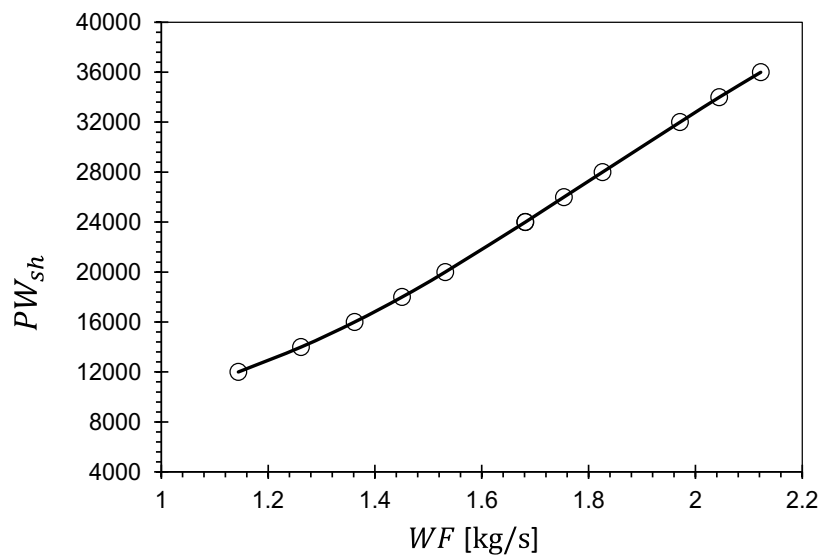


Figure O-57 Computed variation of power turbine shaft power or engine brake power ($PW_{sh,out}$) against fuel flow (WF) for 36 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 15^\circ\text{C}$.

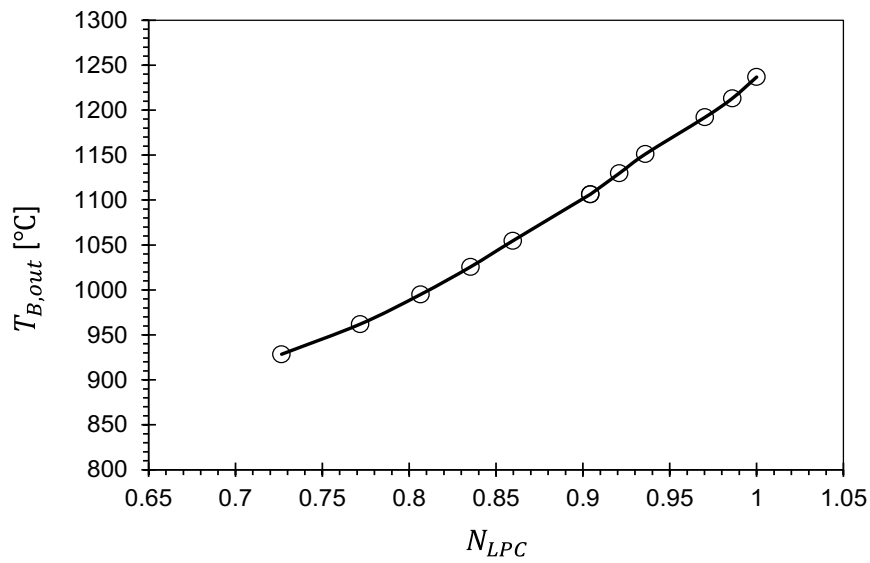


Figure O-58 Computed variation of combustor outlet temperature ($T_{B,out}$) against low pressure compressor speed ratio (N_{LPC}) for 36 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 15^{\circ}C$.

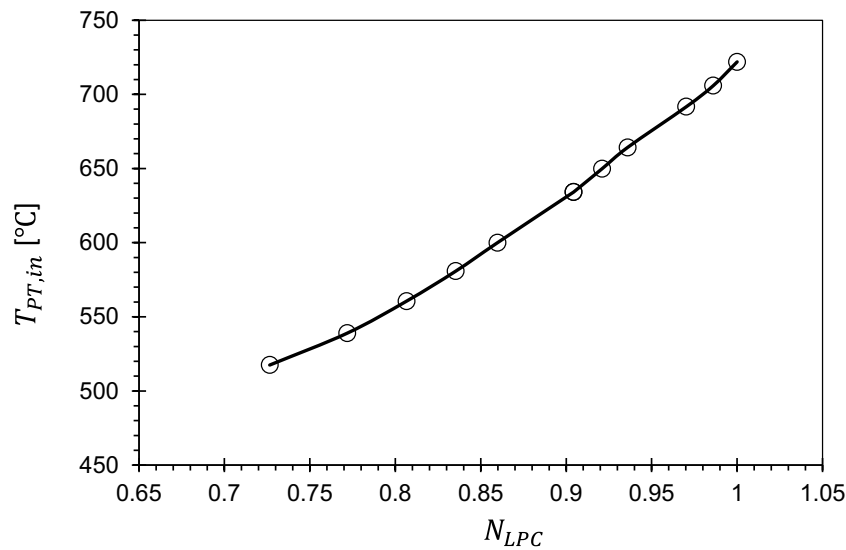


Figure O-59 Computed variation of power turbine inlet temperature ($T_{PT,in}$) against low pressure compressor speed ratio (N_{LPC}) for 36 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 15^{\circ}C$.

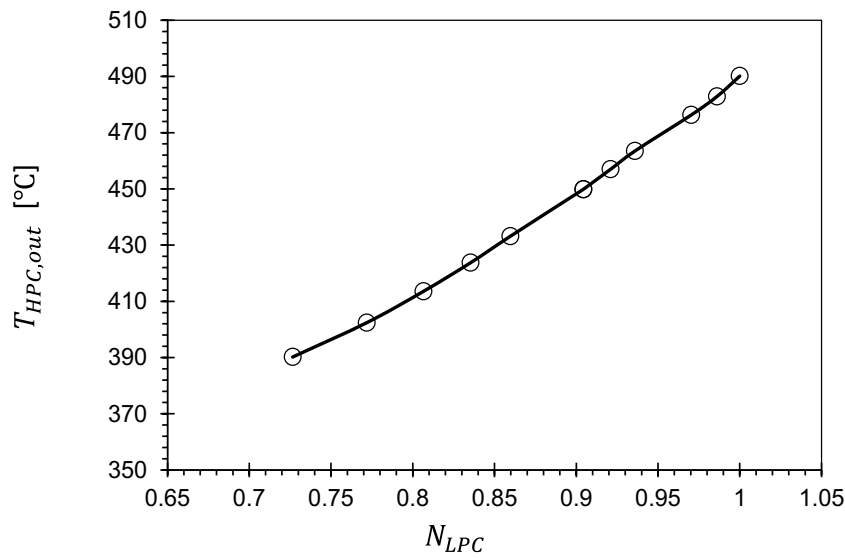


Figure O-60 Computed variation of high compressor outlet temperature ($T_{HPC,out}$) against low pressure compressor speed ratio (N_{LPC}) for 36 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 15$ °C.

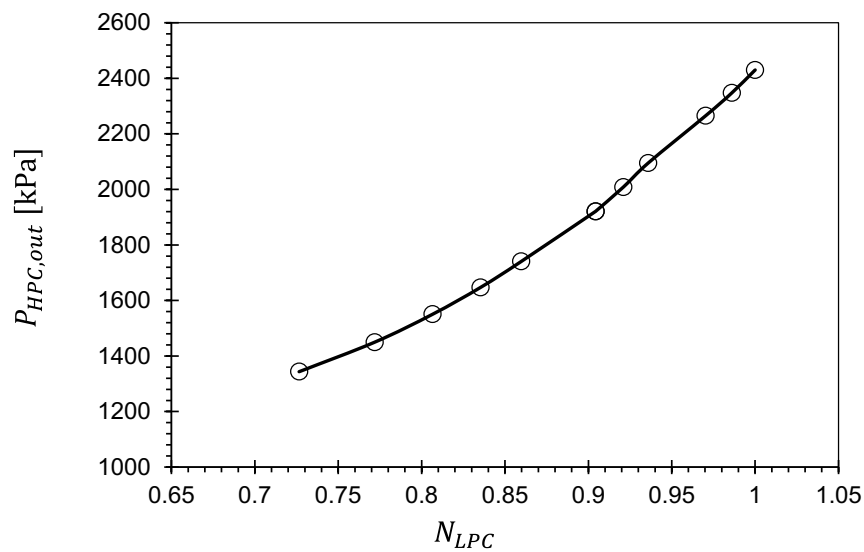


Figure O-61 Computed variation of high-pressure compressor outlet pressure ($P_{HPC,out}$) against low pressure compressor speed ratio (N_{LPC}) for 36 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 15$ °C.

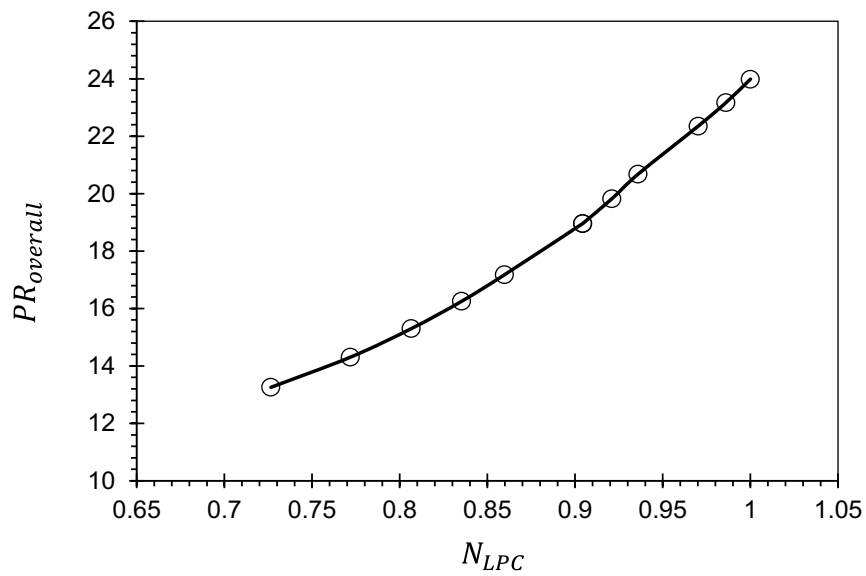


Figure O-62 Computed variation of overall compressor pressure ratio (PR) against low pressure compressor speed ratio (N_{LPC}) for 36 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 15\text{ }^{\circ}\text{C}$.

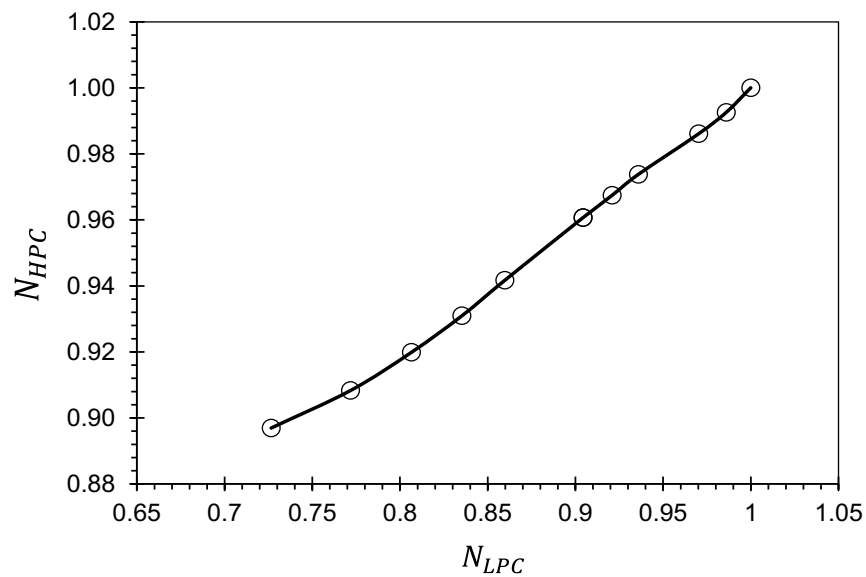


Figure O-63 Computed variation of high-pressure compressor speed ratio (N_{HPC}) against low pressure compressor speed ratio (N_{LPC}) for 36 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 15\text{ }^{\circ}\text{C}$.

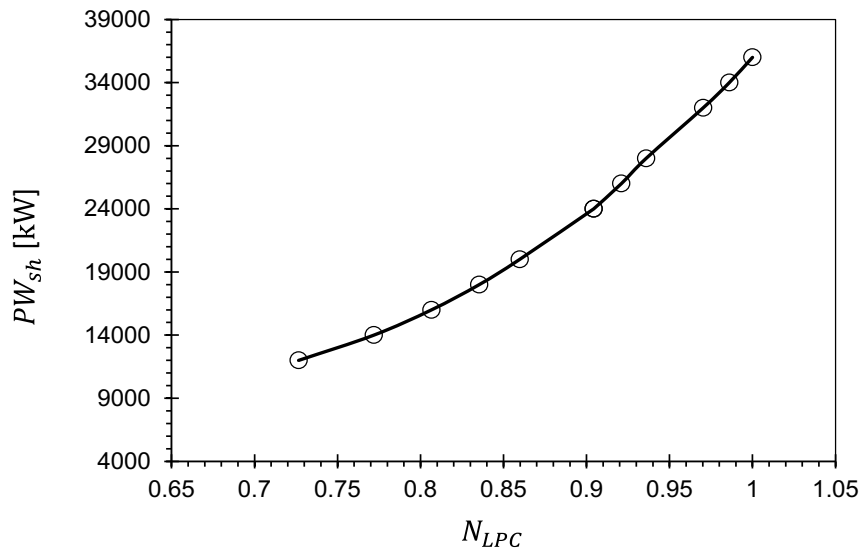


Figure O-64 Computed variation of power turbine shaft power or engine brake power (PW_{sh}) against low pressure compressor speed ratio (N_{LPC}) for 36 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 15^\circ\text{C}$.

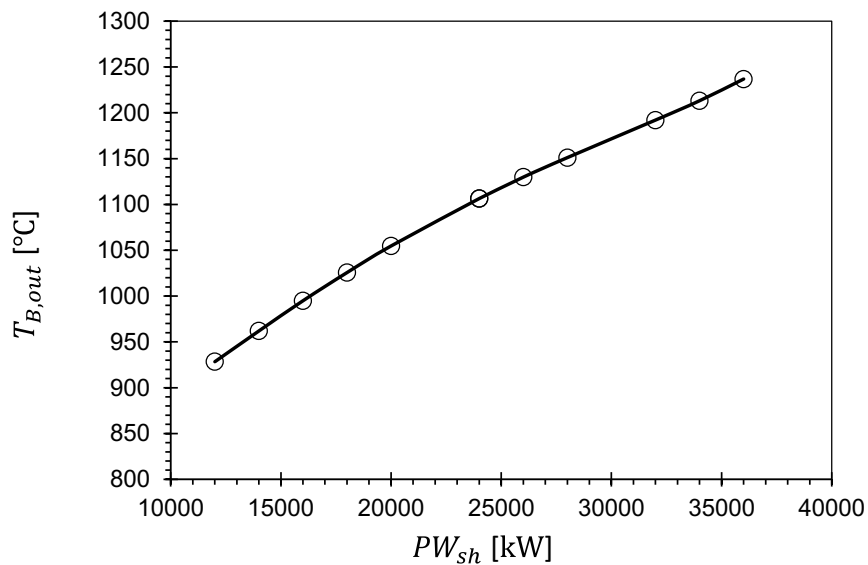


Figure O-65 Computed variation of combustor outlet temperature ($T_{B,out}$) against engine shaft power (PW_{sh}) for 36 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 15^\circ\text{C}$.

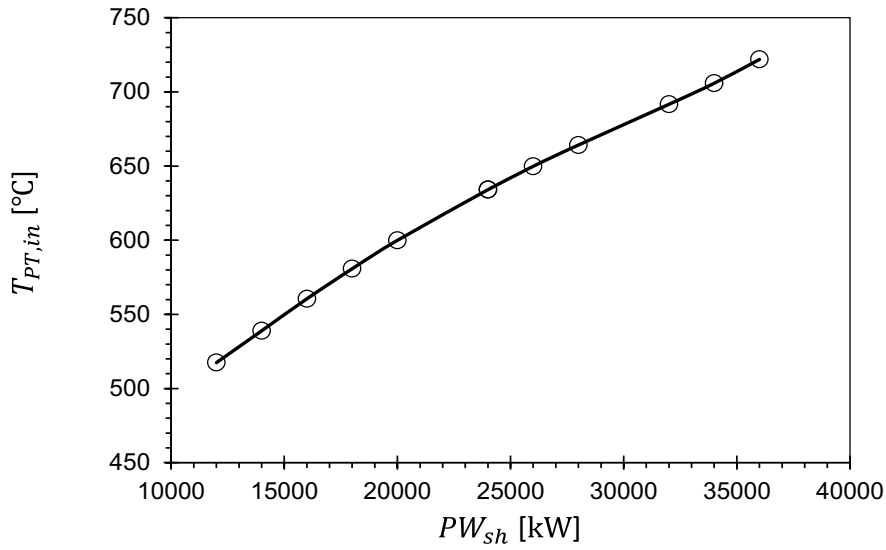


Figure O-66 Computed variation of power turbine inlet temperature ($T_{PT,in}$) against engine shaft power (PW_{sh}) for 36 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 15$ °C.

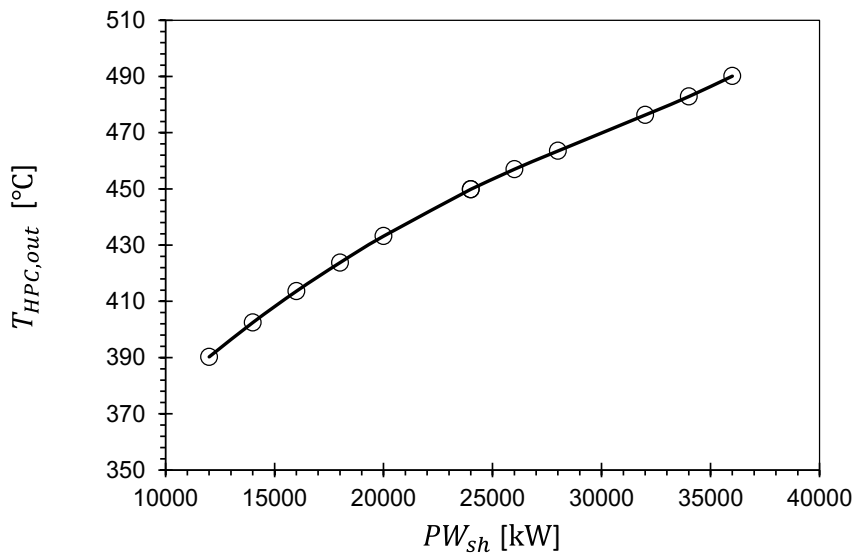


Figure O-67 Computed variation of high-pressure compressor outlet temperature ($T_{HPC,out}$) against engine shaft power (PW_{sh}) for 36 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 15$ °C.

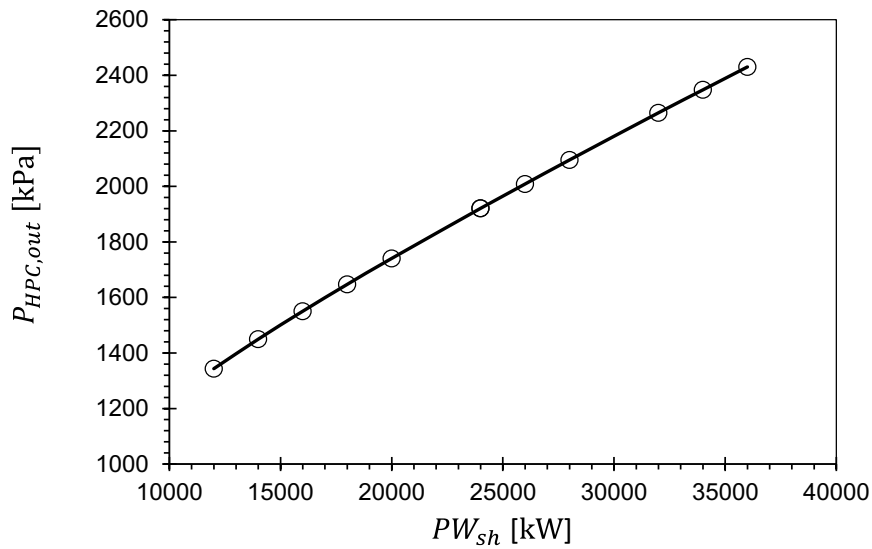


Figure O-68 Computed variation of high-pressure compressor outlet pressure ($P_{HPC,out}$) against engine shaft power (PW_{sh}) for 36 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 15^\circ\text{C}$.

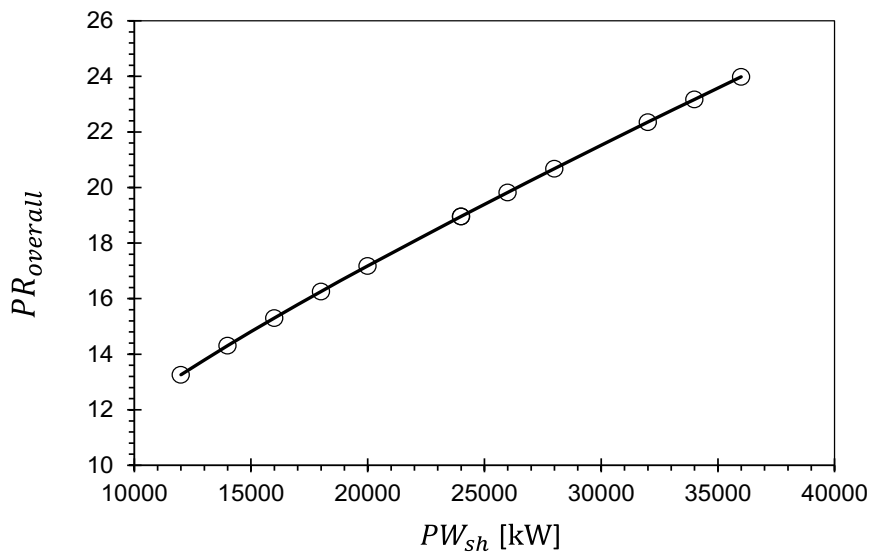


Figure O-69 Computed variation of overall compressor pressure ratio (PR) against engine shaft power (PW_{sh}) for 36 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 15^\circ\text{C}$.

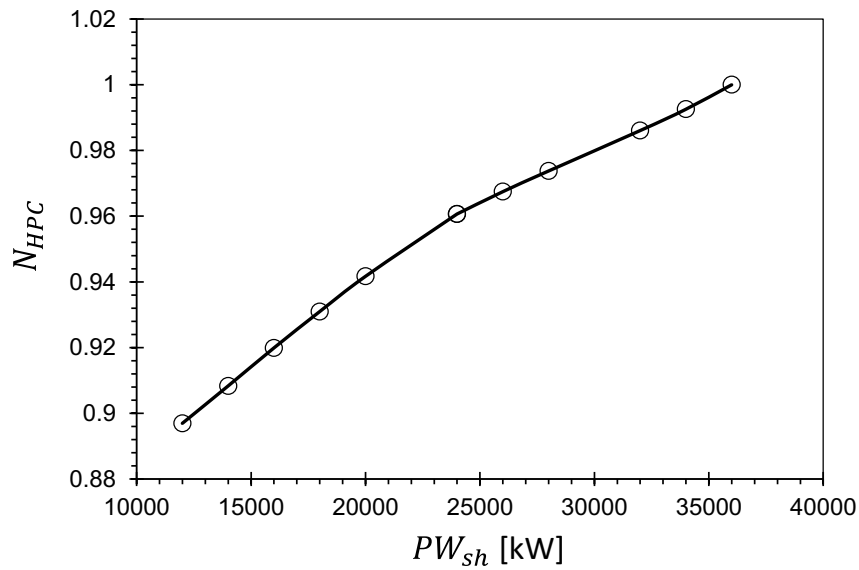


Figure O-70 Computed variation of high-pressure compressor speed ratio (N_{HPC}) against engine shaft power (PW_{sh}) for 36 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 15^\circ\text{C}$.

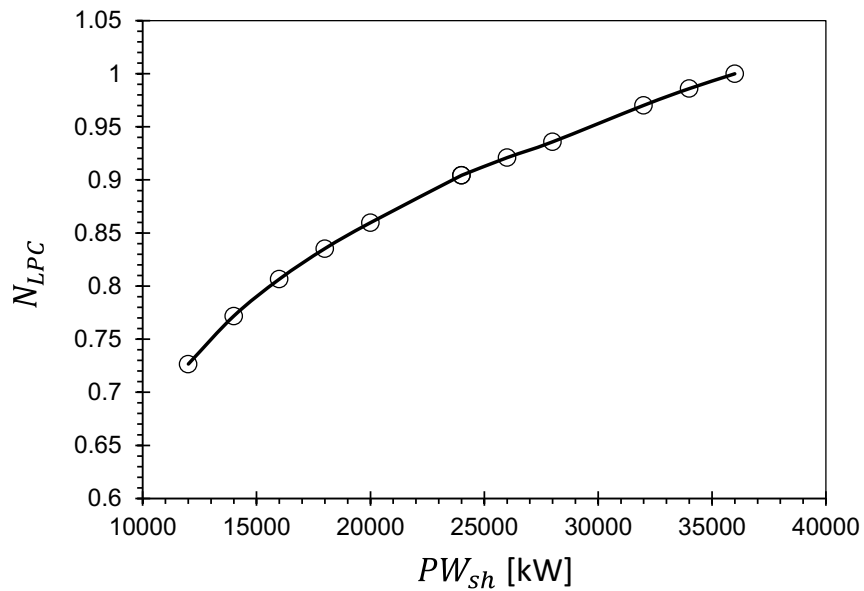


Figure O-71 Computed variation of low-pressure compressor speed ratio (N_{LPC}) against engine shaft power (PW_{sh}) for 36 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 15^\circ\text{C}$.

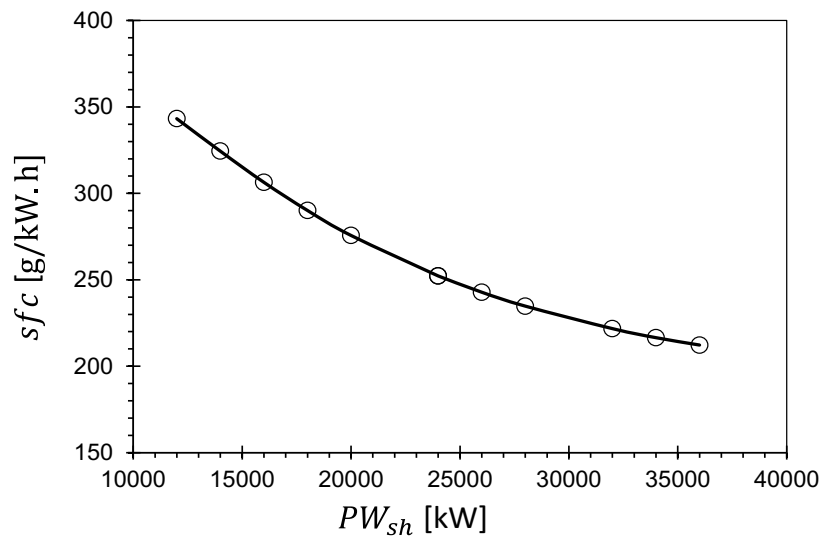


Figure O-72 Computed variation of specific fuel consumption (sfc) against engine shaft power (PW_{sh}) for 36 MW MGT, with power turbine speed (N_{PT}) varying as per propeller law and ambient temperature at $T_{amb} = 15^\circ\text{C}$.

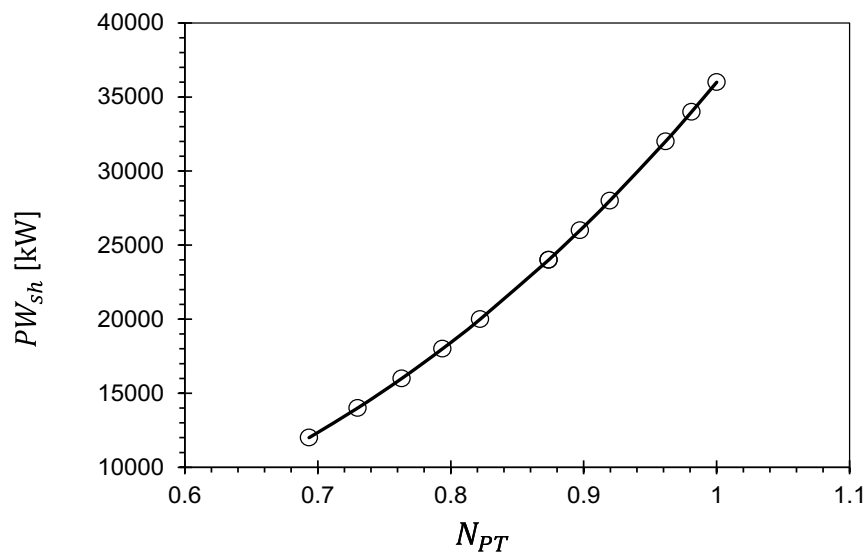


Figure O-73 Applied propeller law expressed as the variation of engine shaft power (PW_{sh}) against power turbine speed ratio (N_{PT}) for 36 MW MGT with ambient temperature at $T_{amb} = 15^\circ\text{C}$.

Appendix P Gas Turbine Engine Input Files

P.1 Turbojet

```
//Turbojet

Engine: Turbojet
{
    EngineDefinition
    {
        UnitSystem= SI ;
        Fuel= Kerosene ;
        EngineType= Turbojet ;
    }

    Ambient
    {
        Altitude= 11000 ;           //unit: length in m
        FlightMachNo= 0.8 ;         //for Aero Engines; unit: number
    }

    EngineComponents
    {
        Component Intake: Inlet
        {
            Win= 20 ;
        }

        Component Compressor: Comp
        {
            MapOpPtPressRatio= 0.85 ; //PR along speed line: (PRdesign -PRchoke)/ (PRsurge-PRchoke)
                                      //Z in TM

            MapOpPtNRatio= 1 ;        //Ratio: Nactual/ Ndesign

            PressRatio= 25 ;          //Pressure ratio, for DP
            EffyIsen= 0.85 ;          //Isentropic efficiency, for DP
            Map
            {
                MapStyle= TM ;        //TM (Turbomatch)
                MapDef= Std ;          //Std or User: Std or User Defined Map
                MapFileName= COMPRE3 ; //MapFileName: File name of Map minus extn(.txt)
            }
        }

        Component Splitter: BleedCoolTurb
        {
            FlowFraction= 0.1 ;
            FlowOffset= 0 ;
            PressFraction= 1 ;
            PressOffset= 0 ;
        }

        Component Combustor: Comb
        {
            CombParaType= COT ;       //WFin or COT
            CombParaVal= 1400 ;       //Value of selected ParaType: K
            PressLossRatio= 0.03 ;     //Press Ratio
            EffyComb= 0.999 ;          //Comb Effy

            Map
            {
                MapStyle= TM ;        //TM (Turbomatch) or BS (Beta Style)
                MapDef= Std ;          //Std or User: Std or User Defined Map
                MapFileName= BURNER1 ; //MapFileName: File name of Map minus extn(.txt)
            }
        }

        Component Mixer: MixCoolTurb
        {
            SwCalcPressChange = False ; //True if Press Change for Mixing Stream is to be calc
                                      //Default: False: even not specified
        }
    }
}
```



```

Component Turbine: Turb
{
    MapOpPtDelHT= 0.8 ;           //TurbDelHTRatio: (ZT in TM) = (dH/T)/(dH/T)max,
                                   //default value = 0.8
    MapOpPtNRatio= 0.6 ;          //Speed ratio: N/Ndesign
    EffyIsen= 0.8973 ;            //TurbEff

    ExtractedShaftOpWork= 0;       //Extracted Shaft Wk
    ExtractedAuxWork= 0;           //Extracted Aux Wk

    Map
    {
        MapStyle= TM ;            //TM (Turbomatch)
        MapDef= Std ;             //Std or User: Std or User Defined Map
        MapFileName= TUR5 ;       //MapFileName
    }
}

Component NozzleConv: Nozz
{
    SwFixedAreaCalc= True;        //Default: False : even if you dont specify

    Map
    {
        MapStyle= TM ;            //TM (Turbomatch)
        MapDef= Std ;             //Std or User: Std or User Defined Map
        MapFileName= NOZZLE ;     //MapFileName
    }
}

}

FluidConnections
{
    Connection: con10 { Inlet(Out); Comp(In)}
    Connection: con20 { Comp(Out); BleedCoolTurb(In)}
    Connection: con50 { BleedCoolTurb(Out); Comb(In)}
    Connection: con60 { Comb(Out); MixCoolTurb(In)}
    Connection: con70 { MixCoolTurb(Out); Turb(In)}
    Connection: con100 { Turb(Out); Nozz(In)}

    Connection: bcon1 { BleedCoolTurb(Bleed); MixCoolTurb(Mix)}
}

MechConnections
{
    Connection: sh {Comp; Turb}
}
}

```

```

SimulationODParameters
{
    Handle
    {
        Component Compressor: Comp
        {
            MapOpPtNRatio ;          //PCN
        }
    }

    Variables          //handle parameter cannot be included here
    {
        Component Intake: Inlet
        {
            Win ;                  //Win
        }

        Component Compressor: Comp
        {
            MapOpPtPressRatio ;    //Z
        }

        Component Combustor: Comb
        {
            COT ;
        }

        Component Turbine: Turb
        {
            MapOpPtDe1HT ;        //ZT
        }
    }
}

//No SimRun infor required, if passed by the Marine Plant Ip File
SimulationRun: SimRunID;      //SimRunName
{
    RunType: OD ;    //OD or DP

    ODHandle1Value: 0.6 ;    //handle for OD Sim

    Ambient
    {
        //Altitude= 9000 ;          //unit: length in m
        //FlightMachNo= 0.6 ;        //for Aero Engines; unit: number
    }
}

```

P.2 7.5 MW Marine Gas Turbine

```

Engine: 7.5MWMGT
{

    EngineDefinition
    {
        UnitSystem= SI; //Options: SI/IM
        Fuel= Diesel; //Options: Kerosene, Diesel
    }

    Ambient
    {
        Altitude= 0 ; //height in m
        FlightMachNo= 0 ; //for Aero Engines, flight mach no.

        DevFmISATemp= 0 ; //temp deviation from ISA in K
        DevFmISAPress= 0 ; //press deviation from ISA in bar
        RelHumidity= 0 ; //relative humidity as fraction
    }

    EngineComponents
    {

        Component Intake: Inlet
        {
            Win= 32.5; //inlet air flow, kg/s
            PressLoss= 0.98 ; //Loss pressure ratio
        }

        Component Compressor: LPC
        {
            MapOpPtPressRatio= 0.85 ; //Z or pressure ratio along speed line
            // (PRdesign -PRchoke)/ (PRsurge-PRchoke)

            MapOpPtNRatio= 0.9 ; //Nactual/ Ndesign

            PressRatio= 4.0 ; //pressure ratio
            EffyIsen= 0.9 ; //isentropic efficiency
            Map
            {
                MapStyle= TM ; //TM (Turbomatch)
                MapDef= Std ; //Std or User: Std or User Defined Map
                MapFileName= COMPRES3 ; //MapFileName: File name of Map minus extn(.txt)
            }
        }

        Component Duct: DuctLPCHPC
        {
            PressLossRatio= 0.01 ; //Press Loss Ratio
        }

        Component Compressor: HPC
        {
            MapOpPtPressRatio= 0.85 ; // Z or pressure ratio along speed line:
            // (PRdesign -PRchoke)/ (PRsurge-PRchoke)

            MapOpPtNRatio= 0.9 ; //Ratio: Nactual/ Ndesign

            PressRatio= 3.5 //pressure ratio
            EffyIsen= 0.9 ; //isentropic efficiency
            Map
            {
                MapStyle= TM ; //TM (Turbomatch)
                MapDef= Std ; //Std or User: Std or User Defined Map
                MapFileName= COMPRES3 ; //MapFileName: File name of Map minus extn(.txt)
            }
        }
    }
}

```

```

Component Splitter: BleedHPTCooling
{
    FlowFraction= 0.08 ;
    FlowOffset= 0 ;
    PressFraction= 1 ;
    PressOffset= 0 ;
}

Component Combustor: Comb
{
    CombParaType= COT ;      //WFin or COT
    CombParaVal= 1300 ;      //Value of selected ParaType: K or kg/s
    PressLossRatio= 0.05 ;   //Press loss ratio
    EffyComb= 0.98 ;         //Comb Effy

    Map
    {
        MapStyle= TM ;      //TM (Turbomatch)
        MapDef= Std ;       //Std or User: Std or User Defined Map
        MapFileName= BURNER1 ; //MapFileName: File name of Map minus extn(.txt)
    }
}

Component Turbine: HPT
{
    MapOpPtDelHT= 0.7 ;      //TurbDelHTRatio: (ZT in TM) = (dH/T)/(dH/T)max
                                //default value = 0.8,
                                //akin to Surge Margin Z in Compressor

    MapOpPtNRatio= 0.6 ;     //Speed ratio: N/Ndesign
    EffyIsen= 0.85 ;         //TurbEff

    ExtractedShaftOpWork= 0;  //Extracted Shaft Wk
    ExtractedAuxWork= 0;     //Extracted Aux Wk

    Map
    {
        MapStyle= TM ;      //TM (Turbomatch)
        MapDef= Std ;       //Std or User: Std or User Defined Map
        MapFileName= TUR5 ;  //MapFileName: File name of Map minus extn(.txt)
    }
}

Component Mixer: MixHPTCooling
{
    SwCalcPressChange = False ; //True if Press Change for Mixing Stream is to be calc;
                                //Default: False: even if you dont specify
}

Component Turbine: LPT
{
    MapOpPtDelHT= 0.7 ;      //TurbDelHTRatio: (ZT in TM) = (dH/T)/(dH/T)max
                                //default value = 0.8, choked turbine,
                                //akin to Surge Margin Z in Compressor

    MapOpPtNRatio= 0.6 ;     //Speed ratio: N/Ndesign
    EffyIsen= 0.9 ;         //TurbEff

    ExtractedShaftOpWork= 0;  //Extracted Shaft Wk
    ExtractedAuxWork= 0;     //Extracted Aux Wk

    Map
    {
        MapStyle= TM ;      //TM (Turbomatch)
        MapDef= Std ;       //Std or User: Std or User Defined Map
        MapFileName= TUR5 ;  //MapFileName: File name of Map minus extn(.txt)
    }
}

```

```

Component FPTurbine: FPT
{
    MapOpPtDelHT= 0.7 ;           //TurbDelHTRatio: (ZT in TM) = (dH/T)/(dH/T)max
                                   //default value = 0.8
                                   //akin to Surge Margin in Compressor
    MapOpPtNRatio= 0.6 ;          //Speed ratio: N/Ndesign
    EffyIsen= 0.88 ;              //TurbEff

    NRatio= 0.9;                  //Shaft Speed NRatio
    ExtractedShaftOpWork= 7350;    //Extracted Shaft Wk in kW
    ExtractedAuxWork= 0 ;          //Extracted Aux Wk in kW

    Map
    {
        MapStyle= TM ;           //TM (Turbomatch)
        MapDef= Std ;             //Std or User: Std or User Defined Map
        MapFileName= TUR5 ;       //MapFileName: File name of Map minus extn(.txt)
    }
}

Component Duct: DuctFPTOut
{
    PressLossRatio= 0.01 ;        //Press Ratio
}

Component NozzleConv: NozzC1
{
    SwFixedAreaCalc= True;        //Default: False : even if you dont specify

    Map
    {
        MapStyle= TM ;           //TM (Turbomatch)
        MapDef= Std ;             //Std or User: Std or User Defined Map
        MapFileName= NOZZLE ;     //MapFileName: File name of Map minus extn(.txt)
    }
}

}

FluidConnections
{
    Connection: con1 { Inlet(Out); LPC(In)}
    Connection: con2 { LPC(Out); DuctLPCHPC(In)}
    Connection: con3 { DuctLPCHPC(Out); HPC(In)}
    Connection: con4 { HPC(Out); BleedHPTCooling(In)}
    Connection: con5 { BleedHPTCooling(Out); Comb(In)}
    Connection: con6 { Comb(Out); HPT(In)}
    Connection: con8 { HPT(Out); MixHPTCooling(In)}
    Connection: con9 { MixHPTCooling(Out); LPT(In)}
    Connection: con11 { LPT(Out); FPT(In)}
    Connection: con12 { FPT(Out); DuctFPTOut(In)}
    Connection: con13 { DuctFPTOut(Out); NozzC1(In)}

    Connection: bcon1 { BleedHPTCooling(Bleed); MixHPTCooling(Mix)}
}

MechConnections
{
    Connection: mcon1 {LPC; LPT}
    Connection: mcon2 {HPC; HPT}
}
}

```

```

SimulationODParameters
{
    Handle
    {
        Component Combustor: Comb
        {
            COT;                //PCN
        }

        Component FPTurbine: FPT
        {
            NRatio;
        }
    }

    Variables    //handle parameter cannot be included here
    {
        Component Intake: Inlet
        {
            Win ;                //Win
        }

        Component Compressor: LPC
        {
            MapOpPtPressRatio;    //Z
            MapOpPtNRatio;        //PCN
        }

        Component Turbine: LPT
        {
            MapOpPtDe1HT;        //ZT
        }

        Component Compressor: HPC
        {
            MapOpPtPressRatio;    //Z
            MapOpPtNRatio;        //PCN
        }

        Component Turbine: HPT
        {
            MapOpPtDe1HT;        //ZT
        }

        Component FPTurbine: FPT
        {
            MapOpPtDe1HT;        //ZT
            ExtractedShaftOpWork; //Extracted Shaft Wk
        }
    }
}

SimulationRun: SimRunID;    //SimRunName
{
    EngineModel: 7.5MWMTGT; //tells the program the name

    RunType: OD;    //DP/OD/TR

    ODHandle1Value: 1300; //required only for OD Sim

    ODHandle2Value: 1;    //required only for OD Sim
}

```

P.3 15 MW Marine Gas Turbine

Engine: 15MW MGT

```
{
    EngineDefinition
    {
        UnitSystem= SI; //Options:SI/IM
        Fuel= Diesel; //Options:Kerosene, Diesel
    }

    Ambient
    {
        Altitude= 0 ; //height in m
        FlightMachNo= 0 ; //for Aero Engines, flight mach no.

        DevFmISATemp= 0 ; //temp deviation from ISA in K
        DevFmISAPress= 0 ; //press deviation from ISA in bar
        RelHumidity= 0 ; //relative humidity as fraction
    }

    EngineComponents
    {
        Component Intake: Inlet
        {
            Win= 90; //inlet air flow
            PressLoss= 0.970 ; //Press loss ratio
        }

        Component Compressor: LPC
        {
            MapOpPtPressRatio= 0.85 ; //Z or pressure ratio along speed line
            // (PRdesign -PRchoke)/ (PRsurge-PRchoke)

            MapOpPtNRatio= 0.999 ; //Nactual/ Ndesign

            PressRatio= 3.8 ; //pressure ratio
            EffyIsen= 0.92 ; //isentropic efficiency
            Map
            {
                MapStyle= TM ; //TM (Turbomatch)
                MapDef= Std ; //Std or User: Std or User Defined Map
                MapFileName= COMPRE3 ; //MapFileName: File name of Map minus extn(.txt)
            }
        }

        Component Duct: DuctLPCHPC
        {
            PressLossRatio= 0.01 ; //Press Loss Ratio
        }

        Component Duct: DuctLPCHPC
        {
            PressLossRatio= 0.01 ; //Press Loss Ratio
        }

        Component Compressor: HPC
        {
            MapOpPtPressRatio= 0.85 ; //Z or pressure ratio along speed line:
            // (PRdesign -PRchoke)/ (PRsurge-PRchoke)

            MapOpPtNRatio= 0.999 ; //Nactual/ Ndesign

            PressRatio= 3.1 ; //pressure ratio
            EffyIsen= 0.91 ; //isentropic efficiency
            Map
            {
                MapStyle= TM ; //TM (Turbomatch)
                MapDef= Std ; //Std or User: Std or User Defined Map
                MapFileName= COMPRE3 ; //MapFileName: File name of Map minus extn(.txt)
            }
        }
    }
}
```

```

Component Splitter: BleedHPTCooling
{
    FlowFraction= 0.08 ;
    FlowOffset= 0 ;
    PressFraction= 1 ;
    PressOffset= 0 ;
}

Component Combustor: Comb
{
    CombParaType= COT ;      //Options: WFin or COT
    CombParaVal= 1200 ;      //Value of selected ParaType: K or kg/s
    PressLossRatio= 0.05 ;   //Press Ratio
    EffyComb= 0.998 ;        //Comb Effy

    Map
    {
        MapStyle= TM ;      //TM (Turbomatch)
        MapDef= Std ;       //Std or User: Std or User Defined Map
        MapFileName= BURNER1 ; //MapFileName: File name of Map minus extn(.txt)
    }
}

Component Mixer: MixHPTCooling
{
    SwCalcPressChange = False ;    //True if Press Change for Mixing Stream is to be calc;
                                     //Default: False: even if you dont specify
}

Component Turbine: LPT
{
    MapOpPtDelHT= 0.7 ;           //TurbDelHTRatio: (ZT in TM) = (dH/T)/(dH/T)max,
                                     //default value = 0.8,
                                     //akin to Surge Margin Z in Compressor

    MapOpPtNRatio= 0.6 ;         //Speed ratio: N/Ndesign
    EffyIsen= 0.9 ;              //Turb. Efficiency Isentropic

    ExtractedShaftOpWork= 0;      //Extracted Shaft Wk
    ExtractedAuxWork= 0;          //Extracted Aux Wk

    Map
    {
        MapStyle= TM ;          //TM (Turbomatch)
        MapDef= Std ;           //Std or User: Std or User Defined Map
        MapFileName= TUR5 ;     //MapFileName: File name of Map minus extn(.txt)
    }
}

Component FPTurbine: FPT
{
    MapOpPtDelHT= 0.8 ;           //TurbDelHTRatio: (ZT in TM) = (dH/T)/(dH/T)max,
                                     //default value = 0.8,
                                     //akin to Surge Margin Z in Compressor

    MapOpPtNRatio= 0.6 ;         //Speed ratio: N/Ndesign
    EffyIsen= 0.88 ;             //Turb. Efficiency Isentropic

    NRatio= 1;                   //Shaft Speed NRatio
    ExtractedShaftOpWork= 15520;  //Extracted Shaft Wk in kW
    ExtractedAuxWork= 0 ;         //Extracted Aux Wk in kW

    Map
    {
        MapStyle= TM ;          //TM (Turbomatch)
        MapDef= Std ;           //Std or User: Std or User Defined Map
        MapFileName= TUR5 ;     //MapFileName: File name of Map minus extn(.txt)
    }
}

```



```

Component FPTurbine: FPT
{
    MapOpPtDelHT= 0.8 ;           //TurbDelHTRatio: (ZT in TM) = (dH/T)/(dH/T)max,
                                   //default value = 0.8, |
                                   //akin to Surge Margin Z in Compressor
    MapOpPtNRatio= 0.6 ;         //Speed ratio: N/Ndesign
    EffyIsen= 0.88 ;             //Turb. Efficiency Isentropic

    NRatio= 1;                   //Shaft Speed NRatio
    ExtractedShaftOpWork= 15520; //Extracted Shaft Wk in kW
    ExtractedAuxWork= 0 ;         //Extracted Aux Wk in kW

    Map
    {
        MapStyle= TM ;           //TM (Turbomatch)
        MapDef= Std ;             //Std or User: Std or User Defined Map
        MapFileName= TUR5 ;       //MapFileName: File name of Map minus extn(.txt)
    }
}

Component Duct: DuctFPTOut
{
    PressLossRatio= 0.01 ;       //Press Ratio
}

Component NozzleConv: NozzC1
{
    SwFixedAreaCalc= True;       //Default: False : even if you dont specify

    Map
    {
        MapStyle= TM ;           //TM (Turbomatch)
        MapDef= Std ;             //Std or User: Std or User Defined Map
        MapFileName= NOZZLE ;     //MapFileName: File name of Map minus extn(.txt)
    }
}

}

FluidConnections
{
    Connection: con1 { Inlet(Out); LPC(In)}
    Connection: con2 { LPC(Out); DuctLPCHPC(In)}
    Connection: con3 { DuctLPCHPC(Out); HPC(In)}
    Connection: con4 { HPC(Out); BleedHPTCooling(In)}
    Connection: con5 { BleedHPTCooling(Out); Comb(In)}
    Connection: con6 { Comb(Out); HPT(In)}
    Connection: con8 { HPT(Out); MixHPTCooling(In)}
    Connection: con9 { MixHPTCooling(Out); LPT(In)}
    Connection: con11 { LPT(Out); FPT(In)}
    Connection: con12 { FPT(Out); DuctFPTOut(In)}
    Connection: con13 { DuctFPTOut(Out); NozzC1(In)}

    Connection: bcon1 { BleedHPTCooling(Bleed); MixHPTCooling(Mix)}
}

MechConnections
{
    Connection: mcon1 {LPC; LPT}
    Connection: mcon2 {HPC; HPT}
}
}

```

```

SimulationODParameters
{
    Handle
    {
        Component Combustor: Comb
        {
            COT;                //PCN
        }

        Component FPTurbine: FPT
        {
            NRatio;
        }
    }

    Variables //handle parameter cannot be included here
    {
        Component Intake: Inlet
        {
            Win ;                //Win
        }

        Component Compressor: LPC
        {
            MapOpPtPressRatio;    //Z
            MapOpPtNRatio;        //PCN
        }

        Component Turbine: LPT
        {
            MapOpPtDelHT;        //ZT
        }

        Component Compressor: HPC
        {
            MapOpPtPressRatio;    //Z
            MapOpPtNRatio;        //PCN
        }

        Component Turbine: HPT
        {
            MapOpPtDelHT;        //ZT
        }

        Component FPTurbine: FPT
        {
            MapOpPtDelHT;        //ZT
            ExtractedShaftOpWork; //Extracted Shaft Wk
        }
    }
}

//No SimRun infor required, if passed by the Marine Plant Ip File
SimulationRun: EngineODRun //SimRunName
{
    EngineModel: 15MW; //tells the program the name

    RunType: DP; //DP/OD

    ODHandle1Value: 1000;
    ODHandle2Value: 1; //required only for OD Sim

    Ambient
    {
        //Altitude= 0 ; //height in m
        //FlightMachNo= 0 ; //for Aero Engines;

        //DevFmISATemp= 15 ; //temp in K
        //DevFmISAPress= 0 ; //unit: press in bar
        //RelHumidity= 0 ; //unit: fraction
    }
}

```

P.4 25 MW Marine Gas Turbine

```

Engine: 25MWMT //EngineName
{
    EngineDefinition
    {
        UnitSystem= SI; //Options: SI/IM
        Fuel= Diesel; //Options: Kerosene, Diesel
    }

    Ambient
    {
        Altitude= 0 ; //height in m
        FlightMachNo= 0 ; //for Aero Engines, flight mach no.

        DevFmISATemp= 0 ; //for Aero Engines, flight mach no.
        DevFmISAPress= 0 ; //press deviation from ISA in bar
        RelHumidity= 0 ; //relative humidity as fraction
    }

    EngineComponents
    {

        Component Intake: Inlet
        {
            Win= 68 ; //inlet air flow, kg/s
            PressLoss= 0.9951 ; //Loss pressure ratio
        }

        Component Compressor: Compr
        {
            MapOpPtPressRatio= 0.85 ; //Z or pressure ratio along speed line
            // (PRdesign -PRchoke)/ (PRsurge-PRchoke)

            MapOpPtNRatio= 0.9 ; //Nactual/ Ndesign

            PressRatio= 19.25; //pressure ratio
            EffyIsen= 0.87 ; //isentropic efficiency
            Map
            {
                MapStyle= TM ; //TM (Turbomatch)
                MapDef= Std ; //Std or User: Std or User Defined Map
                MapFileName= COMPRE4 ; //MapFileName: File name of Map minus extn(.txt)
            }
        }

        Component Splitter: BleedTurbCool
        {
            FlowFraction= 0.1 ;
            FlowOffset= 0 ;
            PressFraction= 1 ;
            PressOffset= 0 ;
        }

        Component Combustor: Comb
        {
            CombParaType= COT ; //WFin or COT
            CombParaVal= 1550 ; //Value of selected ParaType
            PressLossRatio= 0.04 ; //Press Loss Ratio
            EffyComb= 0.999 ; //Comb Effy

            Map
            {
                MapStyle= TM ; //TM (Turbomatch)
                MapDef= Std ; //Std or User: Std or User Defined Map
                MapFileName= BURNER1 ; //MapFileName: File name of Map minus extn(.txt)
            }
        }

        Component Duct: DuctCombTurb
        {
            PressLossRatio= 0.01 ; //Press Loss Ratio
        }
    }
}

```

```

Component Mixer: MixTurbCool
{
    SwCalcPressChange = False ;      //True if Press Change for Mixing Stream is to be calc
                                     //Default: False: even if you dont specify
}

Component Turbine: ComprTurb
{
    MapOpPtDelHT= 0.85 ;              //TurbDelHTRatio: (ZT in TM) = (dH/T)/(dH/T)max
                                     //default value = 0.8
                                     //akin to Surge Margin Z in Compressor
    MapOpPtNRatio= 0.65 ;             //Speed ratio: N/Ndesign
    EffyIsen= 0.89 ;                 //Turbine Isentropic Efficiency

    ExtractedShaftOpWork= 0;          //Extracted Shaft Wk
    ExtractedAuxWork= 0;             //Extracted Aux Wk

    Map
    {
        MapStyle= TM ;               //TM (Turbomatch)
        MapDef= Std ;                //Std or User: Std or User Defined Map
        MapFileName= TUR5 ;          //MapFileName: File name of Map minus extn(.txt)
    }
}

Component FPTurbine: FPTurb
{
    MapOpPtDelHT= 0.8 ;              //TurbDelHTRatio: (ZT in TM) = (dH/T)/(dH/T)max,
                                     //default value = 0.8
                                     //akin to Surge Margin Z in Compressor
    MapOpPtNRatio= 0.6 ;             //Speed ratio: N/Ndesign
    EffyIsen= 0.91 ;                 //Turbine Isentropic Efficiency

    NRatio= 1;                      //Shaft Speed NRatio
    ExtractedShaftOpWork= 25000;     //Extracted Shaft Wk in kW
    ExtractedAuxWork= 0 ;            //Extracted Aux Wk in kW

    Map
    {
        MapStyle= TM ;               //TM (Turbomatch)
        MapDef= Std ;                //Std or User: Std or User Defined Map
        MapFileName= TUR5 ;          //MapFileName: File name of Map minus extn(.txt)
    }
}

Component Duct: DuctFPTOut
{
    PressLossRatio= 0.02 ;           //Press Loss Ratio
}

Component NozzleConv: Nozz
{
    SwFixedAreaCalc= True;           //Default: False, if you dont specify

    Map
    {
        MapStyle= TM ;               //TM (Turbomatch)
        MapDef= Std ;                //Std or User: Std or User Defined Map
        MapFileName= NOZZLE ;        //MapFileName: File name of Map minus extn(.txt)
    }
}
}

```

```

FluidConnections
{
    Connection: con1 { Inlet(Out); Compr(In)}
    Connection: con2 { Compr(Out); BleedTurbCool(In)}
    Connection: con3 { BleedTurbCool(Out); Comb(In)}
    Connection: con4 { Comb(Out); DuctCombTurb(In)}
    Connection: con5 { DuctCombTurb(Out); MixTurbCool(In)}
    Connection: con6 { MixTurbCool(Out); ComprTurb(In)}
    Connection: con7 { ComprTurb(Out); FPTurb(In)}
    Connection: con8 { FPTurb(Out); DuctFPTOut(In)}
    Connection: con9 { DuctFPTOut(Out); Nozz(In)}
    Connection: bcon1 { BleedTurbCool(Bleed); MixTurbCool(Mix)}

}

MechConnections
{
    Connection: shLP{ Compr; ComprTurb}
}

SimulationODParameters
{
    Handle
    {
        Component FPTurbine: FPTurb
        {
            ExtractedShaftOpWork; //Extracted Shaft Wk
            NRatio;
        }
    }

    Variables //handle parameter cannot be included here
    {
        Component Intake: Inlet
        {
            Win ; //Win
        }

        Component Compressor: Compr
        {
            MapOpPtPressRatio; //Z
            MapOpPtNRatio; //PCN
        }

        Component Combustor: Comb
        {
            COT; //PCN
        }

        Component Turbine: ComprTurb
        {
            MapOpPtDelHT; //ZT
        }

        Component FPTurbine: FPTurb
        {
            MapOpPtDelHT; //ZT
        }
    }
}

```

```

SimulationRun: Hd1-OpPwr-NPT;    //SimRunName
{
    RunType: OD ;    //DP/OD/TR

    ODHandle1Value: 7830 ; //required only for OD Sim, here COT

    ODHandle2Value: 0.7047 ; //required only for OD Sim, here NPT

    Ambient
    {
        //Altitude= 0 ;           //height in m for aero engines
        //FlightMachNo= 0 ;       //for Aero Engines;

        DevFmISATemp= 20 ;       //unit: temp in K
        DevFmISAPress= 0.456 ;   //unit: press in bar
        RelHumidity= 0 ;         //unit: fraction
    }
}

```

P.5 36 MW Marine Gas Turbine

```

Engine: 36MW
{
    EngineDefinition
    {
        UnitSystem= SI; //Options:SI/IM
        Fuel= Diesel; //Options: Kerosene, Diesel
        EngineType= Turboshaft ; //Options:Turbogjet, Turbofan, Turboprop, Turboshaft
    }

    Ambient
    {
        Altitude= 0 ; //flight altitude in m
        FlightMachNo= 0 ; //for Aero Engines;

        DevFmISATemp= 0 ; //temp deviation from ISA in K
        DevFmISAPress= 0 ; //press deviation from ISA in bar
        RelHumidity= 0 ; //relative humidity |
    }

    EngineComponents
    {
        Component Intake: Inlet
        {
            Win= 115; //inlet air flow
            PressLoss= 0.995 ; //Press loss
        }

        Component Compressor: LPC
        {
            MapOpPtPressRatio= 0.8 ; //pressure ratio along speed line
            // (PRdesign -PRchoke)/ (PRsurge-PRchoke)

            MapOpPtNRatio= 1 ; //Nactual/ Ndesign

            PressRatio= 5.71 ; //Pressure ratio. for DP
            EffyIsen= 0.89 ; //Isentropic efficiency, for DP
            Map
            {
                MapStyle= TM ; //TM (Turbomatch) style
                MapDef= Std ; //Std or User: Std or User Defined Map
                MapFileName= COMPRES3 ; //MapFileName: File name of Map minus extn(.txt)
            }
        }

        Component Splitter: BleedCoolLP
        {
            FlowFraction= 0.015 ;
            FlowOffset= 0 ;
            PressFraction= 1 ;
            PressOffset= 0 ;
        }

        Component Compressor: HPC
        {
            MapOpPtPressRatio= 0.8 ; //pressure ratio along speed line
            // (PRdesign -PRchoke)/ (PRsurge-PRchoke)

            MapOpPtNRatio= 1 ; //Nactual/ Ndesign: Can be specified in both DP and OD

            PressRatio= 4.2 ; //pressure ratio, for DP
            EffyIsen= 0.88 ; //isentropic efficiency, for DP
            Map
            {
                MapStyle= TM ; //TM (Turbomatch) or BS (Beta Style)
                MapDef= Std ; //Std or User: Std or User Defined Map
                MapFileName= COMPRES5 ; //MapFileName: File name of Map minus extn(.txt)
            }
        }
    }
}

```

```

Component Splitter: BleedCoolHP
{
    FlowFraction= 0.15 ;
    FlowOffset= 0 ;
    PressFraction= 1 ;
    PressOffset= 0 ;
}

Component Combustor: Comb
{
    CombParaType= COT ; //WFin or COT
    CombParaVal= 1510 ; //Value of selected ParaType in: kg/s or K
    PressLossRatio= 0.04 ; //Press Ratio
    EffyComb= 0.999 ; //Comb Effy

    Map
    {
        MapStyle= TM ; //TM (Turbomatch)
        MapDef= Std ; //Std or User: Std or User Defined Map
        MapFileName= BURNER1 ; //MapFileName: File name of Map minus extn(.txt)
    }
}

Component Mixer: MixCoolHP
{
    SwCalcPressChange = False ; //True if Press Change for Mixing Stream is to be calc;
                                //configComp01; Default: False: even if you dont specify
}

Component Turbine: HPT
{
    MapOpPtDelHT= 0.8 ; //TurbDelHTRatio: (ZT in TM) = (dH/T)/(dH/T)max,
                       //akin to Surge Margin in Compressor
    MapOpPtNRatio= 0.6 ; //default value = 0.8, Speed ratio: N/Ndesign
    EffyIsen= 0.9 ; //TurbEff

    ExtractedShaftOpWork= 0; //Extracted Shaft Wk
    ExtractedAuxWork= 0; //Extracted Aux Wk

    Map
    {
        MapStyle= TM ; //TM (Turbomatch)
        MapDef= Std ; //Std or User: Std or User Defined Map
        MapFileName= TUR1 ; //MapFileName: File name of Map minus extn(.txt)
    }
}

Component Mixer: MixCoolLP
{
    SwCalcPressChange = False ; //True if Press Change for Mixing Stream is to be calc;
                                //configComp01; Default: False: even if you dont specify
}

Component Turbine: LPT
{
    MapOpPtDelHT= 0.8 ; //TurbDelHTRatio: (ZT in TM) = (dH/T)/(dH/T)max,
                       //default value = 0.8, akin to Surge Margin in Compressor
    MapOpPtNRatio= 0.6 ; //Speed ratio: N/Ndesign
    EffyIsen= 0.91 ; //TurbEff

    ExtractedShaftOpWork= 0; //Extracted Shaft Wk
    ExtractedAuxWork= 0; //Extracted Aux Wk

    Map
    {
        MapStyle= TM ; //TM (Turbomatch) or BS (Beta Style)
        MapDef= Std ; //Std or User: Std or User Defined Map
        MapFileName= TUR3 ; //MapFileName: File name of Map minus extn(.txt)
    }
}

```



```

Component FPTurbine: FPT
{
    MapOpPtDelHT= 0.8 ;           //TurbDelHTRatio: (ZT in TM) = (dH/T)/(dH/T)max,
                                   //default value = 0.8, akin to Surge Margin in Compressor
    MapOpPtNRatio= 0.6 ;          //Speed ratio: N/Ndesign
    EffyIsen= 0.92 ;              // TurbEff

    NRatio= 1;                    //Shaft Speed NRatio
    ExtractedShaftOpWork= 36000;   //Extracted Shaft Wk in kW
    ExtractedAuxWork= 0 ;          //Extracted Aux Wk in kW

    Map
    {
        MapStyle= TM ;           //TM (Turbomatch)
        MapDef= Std ;             //Std or User: Std or User Defined Map
        MapFileName= TUR5;        //MapFileName: File name of Map minus extn(.txt)
    }
}

Component NozzleConv: Nozz
{
    SwFixedAreaCalc= True;        //Default: False : even if you dont specify

    Map
    {
        MapStyle= TM ;           //TM (Turbomatch)
        MapDef= Std ;             //Std or User: Std or User Defined Map
        MapFileName= NOZZLE ;     //MapFileName: File name of Map minus extn(.txt)
    }
}

}

FluidConnections
{
    Connection: con10 { Inlet(Out); LPC(In)}
    Connection: con20 { LPC(Out); BleedCoolLP(In)}
    Connection: con30 { BleedCoolLP(Out); HPC(In)}
    Connection: con40 { HPC(Out); BleedCoolHP(In)}
    Connection: con50 { BleedCoolHP(Out); Comb(In)}
    Connection: con60 { Comb(Out); MixCoolHP(In)}
    Connection: con61 { MixCoolHP(Out); HPT(In)}
    Connection: con70 { HPT(Out); MixCoolLP(In)}
    Connection: con71 { MixCoolLP(Out); LPT(In)}
    Connection: con90 { LPT(Out); FPT(In)}
    Connection: con100 { FPT(Out); Nozz(In)}

    Connection: bcon1 { BleedCoolHP(Bleed); MixCoolHP(Mix)}
    Connection: bcon2 { BleedCoolLP(Bleed); MixCoolLP(Mix)}

}

MechConnections
{
    Connection: shaftLP {LPC; LPT}
    Connection: shaftHP {HPC; HPT}

}
}

```

```

SimulationODParameters
{
    Handle
    {
        Component Compressor: LPC
        {
            MapOpPtNRatio;          //ODHandle1
        }

        Component FPTurbine: FPT
        {
            NRatio;                //ODHandle2
        }
    }

    Variables          //handle parameter cannot be included here
    {
        Component Intake: Inlet
        {
            Win ;                  //Win
        }
        Component Combustor: Comb
        {
            COT;
        }
        Component Compressor: LPC
        {
            MapOpPtPressRatio;      //Z
        }

        Component Turbine: LPT
        {
            MapOpPtDelHT;           //ZT
        }

        Component Compressor: HPC
        {
            MapOpPtPressRatio;      //Z
            MapOpPtNRatio;          //PCN
        }

        Component Turbine: HPT
        {
            MapOpPtDelHT;           //ZT
        }

        Component FPTurbine: FPT
        {
            ExtractedShaftOpWork;
            MapOpPtDelHT;           //ZT
        }
    }
}

//No SimRun infor required, if passed by the Marine Plant Ip File
SimulationRun: SimRunID;          //SimRunName
{
    EngineModel: MT30 ; //tells the program the name

    RunType: OD;      //DP/OD

    ODHandle1Value: 0.8;    //required only for OD Sim

    ODHandle2Value: 0.7;    //required only for OD Sim
}

```

Appendix Q Propulsion System Model Input Files

Q.1 Notional Light Frigate COGAG

```
//LightFrigate
Plant: FrigateCOGAGWithCCG
{
    PlantDefinition
    {
        PlantType= Marine;           //can be Aero
        UnitSystem= SI;               //SI/IM
        SpeedRangeMax= 35;            //in knots
        SpeedRangeMin= 4;             //in knots: if not specified: default 5 knts

        ResistanceCurvesDataPoints= 20; //optional: default 50 points
        PropellerCurvesDataPoints= 20; //optional: default 50 points

        EnduranceDistance= 5000;      //nm
        TankageCapacity= 500;         //metric t

        SeaStateFoulingFactor= 1;
        PlantDeteriorationFactor= 1;

        GensetAverageLoad= 600;       //kW. For Aux Gensets only, effects endurance, tankage calc.
        GensetSfc= 0.275;              //kg/kW.h. For Aux Gensets only, effects endurance, tankage calc.
        NoOfGensetsRunning= 2;        //For Aux Gensets only, to include effect in endurance, tankage calc.

        EnduranceCalculationMode= 3;   //1=calc tankage (dist given),
                                      //2=calc dist (tankage given), 3= calc both (default)
    }

    Ambient
    {
        DevFmISATemp= 0;              //unit: temp
        DevFmISAPress= 0;             //unit: press
        RelHumidity= 0.60;            //unit: fraction

        WaterType= SW;                //SW=seawater; FW= fresh water: if not entered, SW assumed by default
        DevFmStdWaterTemp= 0;
        DevFmStdSalinity=0;           //sea water salinity in SP (practical salinity)
    }

    PlantComponents
    {
        Component Hull: Frigate
        {
            HullModelType= Calc;      //Curve OR Calc: user defined curve
                                      //or calculate based on regression models
            HullModelCurve= curvename; //if HullModelType= Curve
            HullCalcType= F&L;        //if HullModelType= Calc: H&M or F&L or Hollenbach

            //Gen Paras (not method specific)

            Lpp= 123.5;                //Length between perpendiculars: m
            Lwl= 116.92 ;              //Length on waterline: m
            Beam= 14.2 ;               //Beam: m
            Tf= 4.7 ;                  //Draft Fwd: m
            Ta= 4.7 ;                  //Draft Aft: m
            DispTons= 3900 ;            //Disp: metric tons.

            Cm= 0.82 ;                 //Coeff Midship Area : 0<Cm<1
            Cwp= 0.774 ;               //Coeff Waterplane: 0<Cwp<1

            At= 6 ;                    //Area transverse transom immersed

            iE= 10;                    //Half angle of entrance, if not entered, calc by prog

            Sapp= 200;                 //SA of appendages: m^2
            AppResisFac= 3 ;           //1+k2: Appendages Resistance factor

            Ap= 195;                   //air frontal area, m^2

            //Fung
            Bt= 10 ;                   //Beam at transom
        } //hull end
    }
}
```

```

Component Propeller: PropStbd
{
    PropType= FPP;                //FPP or CPP
    PropModelType= Calc;          //Curve OR Calc: calculate based on series
    PropCalcType= WB              //if PropModelType= Calc WB:Wangeningen B Series

    Dia= 3.52;                    //Propeller Dia in m
    DesignPitch= 3.4;             //Design Pitch in m
    EAR= 0.98;                    //Expanded Area Ratio
    nBlades= 5;                   //no of blades
    MaxPropSpeed= 307;            //maximum speed in rpm 307
}

Component Propeller: PropPort
{
    PropType= FPP;                //FPP or CPP
    PropModelType= Calc;          //Curve OR Calc: calculate based on series
    PropCalcType= WB              //if PropModelType= Calc WB:Wangeningen B Series

    Dia= 3.52;                    //double: Propeller Dia in m
    DesignPitch= 3.4;             //double: Design Pitch in m
    EAR= 0.98;                    //double: Expanded Area Ratio
    nBlades= 5;                   //int: no of blades
    MaxPropSpeed= 307;            //double: maximum speed in rpm 307
}

Component PropShaft: PSStbd
{
    ShaftLossFactor= 0.01;
}

Component PropShaft: PSPort
{
    ShaftLossFactor= 0.01;
}

Component DriveAdder: StbdBRGAdder //Junction
{
    DriveAdderLossType= NoLoss;    //0= NoLoss (default); 1= Constant; 2= Curve
}

Component Gearing: StbdBRGGearing
{
    GearingReductionRatio= 12.766; //>1 for reduction, >0 and <1 for multiplier
    GearingLossFactor= 0.035;      //for DP
}

Component Clutch: StbdBRGClutch
{
    ClutchLossType= NoLoss;        //0= NoLoss (default); 1= Constant; 2= Curve
}

Component Gearing: PortBRGGearing
{
    GearingReductionRatio= 12.766; //>1 for reduction, >0 and <1 for multiplier
    GearingLossFactor= 0.035;      //for DP
}

Component Clutch: PortBRGClutch
{
    ClutchLossType= NoLoss;        //0= NoLoss (default); 1= Constant; 2= Curve
}

Component DriveAdder: StbdCRGAdder //Junction
{
    DriveAdderLossType= NoLoss;    //0= NoLoss (default); 1= Constant; 2= Curve
}

```

```

Component Propeller: PropStbd
{
    PropType= FPP;                //FPP or CPP
    PropModelType= Calc;           //Curve OR Calc: calculate based on series
    PropCalcType= WB               //if PropModelType= Calc WB:Wangeningen B Series

    Dia= 3.52;                    //Propeller Dia in m
    DesignPitch= 3.4;             //Design Pitch in m
    EAR= 0.98;                    //Expanded Area Ratio
    nBlades= 5;                   //no of blades
    MaxPropSpeed= 307;            //maximum speed in rpm 307
}

Component Propeller: PropPort
{
    PropType= FPP;                //FPP or CPP
    PropModelType= Calc;           //Curve OR Calc: calculate based on series
    PropCalcType= WB               //if PropModelType= Calc WB:Wangeningen B Series

    Dia= 3.52;                    //double: Propeller Dia in m
    DesignPitch= 3.4;             //double: Design Pitch in m
    EAR= 0.98;                    //double: Expanded Area Ratio
    nBlades= 5;                   //int: no of blades
    MaxPropSpeed= 307;            //double: maximum speed in rpm 307
}

Component PropShaft: PSSStbd
{
    ShaftLossFactor= 0.01;
}

Component PropShaft: PSStbd
{
    ShaftLossFactor= 0.01;
}

Component DriveAdder: StbdBRGAdder //Junction
{
    DriveAdderLossType= NoLoss;    //0= NoLoss (default); 1= Constant; 2= Curve
}

Component Gearing: StbdBRGGearing
{
    GearingReductionRatio= 12.766; //>1 for reduction, >0 and <1 for multiplier
    GearingLossFactor= 0.035;      //for DP
}

Component Clutch: StbdBRGClutch
{
    ClutchLossType= NoLoss;        //0= NoLoss (default); 1= Constant; 2= Curve
}

Component Gearing: PortBRGGearing
{
    GearingReductionRatio= 12.766; //>1 for reduction, >0 and <1 for multiplier
    GearingLossFactor= 0.035;      //for DP
}

Component Clutch: PortBRGClutch
{
    ClutchLossType= NoLoss;        //0= NoLoss (default); 1= Constant; 2= Curve
}

Component DriveAdder: StbdCRGAdder //Junction
{
    DriveAdderLossType= NoLoss;    //0= NoLoss (default); 1= Constant; 2= Curve
}

```

```

PlantConnections
{
    //Stbd side train

    Connection: con1 { StbdCGT(Out); StbdCRG2SpdGearing(In)}
    Connection: con2 { StbdCRG2SpdGearing(Out); StbdCRGAdder(Inline1); }
    Connection: con3 { StbdCRGAdder(Inline2); StbdBRGAdder(Crossline)}
    Connection: con4 { StbdBGT(Out); StbdBRGClutch(In)}
    Connection: con5 { StbdBRGClutch(Out); StbdBRGGearing(In)}
    Connection: con6 { StbdBRGGearing(Out); StbdBRGAdder(Inline1)}
    Connection: con7 { StbdBRGAdder(Inline2); PSStd(In)}
    Connection: con8 { PSStd(Out); PropStbd(In)}

    //Port side train

    Connection: con11 { PortCGT(Out); PortCRG2SpdGearing(In)}
    Connection: con12 { PortCRG2SpdGearing(Out); PortCRGAdder(Inline1)}
    Connection: con13 { PortCRGAdder(Inline2); PortBRGAdder(Crossline)}
    Connection: con14 { PortBGT(Out); PortBRGClutch(In)}
    Connection: con15 { PortBRGClutch(Out); PortBRGGearing(In)}
    Connection: con16 { PortBRGGearing(Out); PortBRGAdder(Inline1)}
    Connection: con17 { PortBRGAdder(Inline2); PSPort(In)}
    Connection: con18 { PSPort(Out); PropPort(In)}

    //Cross Connect
    Connection: con21 { StbdCRGAdder(Crossline); StbdClutchCCG(In)}
    Connection: con22 { StbdClutchCCG(Out); CCG(In)}
    Connection: con23 { CCG(Out); PortClutchCCG(In)}
    Connection: con24 { PortClutchCCG(Out); PortCRGAdder(Crossline) }
}

PlantDriveModes
{
    //Standard Modes
    DriveMode: 2CGT { PortCGT(On); StbdCGT(On); PortCRG2SpdGearing(Speed20n); StbdCRG2SpdGearing(Speed20n)}

    DriveMode: 2BGT { PortBGT(On); StbdBGT(On); PortBRGClutch(On); StbdBRGClutch(On)}

    DriveMode: PortCGTDrivingBothProps { PortCGT(On); PortCRG2SpdGearing(Speed10n); PortClutchCCG(On);
                                         StbdClutchCCG(On)}

    DriveMode: StbdCGTDrivingBothProps { StbdCGT(On); StbdCRG2SpdGearing(Speed10n); PortClutchCCG(On);
                                         StbdClutchCCG(On)}

    DriveMode: COGAG { PortCGT(On); StbdCGT(On); PortCRG2SpdGearing(Speed20n); StbdCRG2SpdGearing(Speed20n);
                      PortBGT(On); StbdBGT(On); PortBRGClutch(On); StbdBRGClutch(On)}

    //Special Modes
    DriveMode: PortCGTStbdPropTrail { PortCGT(On); PortCRG2SpdGearing(Speed20n)}

    DriveMode: PortBGTStbdPropTrail { PortBGT(On); PortBRGClutch(On)}
}

} //plant end

```

```

PlantSimulationRun: SimRunName|
{
    DriveMode= COGAG ;

    Ambient                //to set Amb paras in OD: optional
    {
        DevFmISATemp= 0;      //unit: temp
        DevFmISAPress= 0;     //unit: press
        RelHumidity= 0.60;    //unit: fraction
    }

    PlantComponents
    {
        Component GasTurbineDrive: StbdCGT
        {
            PowerSetting= 1300;      // COT in K
        }

        Component GasTurbineDrive: StbdBGT
        {
            PowerSetting= 1050;      // COT in K
        }

        Component GasTurbineDrive: PortCGT
        {
            PowerSetting= 1300;      // COT in K
        }

        Component GasTurbineDrive: PortBGT
        {
            PowerSetting= 1050;      // COT in K
        }
    }
} //plantSimRun end

```

Q.2 Notional Light Frigate CODAG

```
//LightFrigate
Plant: FrigateCODAGPropPlant
{
    PlantDefinition
    {
        PlantType= Marine;           //can be Aero
        UnitSystem= SI;              //SI/IM
        SpeedRangeMax= 35;           //in knots
        SpeedRangeMin= 4;            //in knots: if not specified: default 5 knts

        ResistanceCurvesDataPoints= 20; //optional: default 50 points
        PropellerCurvesDataPoints= 20; //optional: default 50 points

        EnduranceDistance= 5000;     //nm
        TankageCapacity= 500;        //metric t

        SeaStateFoulingFactor= 1;
        PlantDeteriorationFactor= 1;

        GensetAverageLoad= 600;      //kW. For Aux Gensets only, to include effect in endurance, tankage
        GensetSfc= 0.275;            //kg/kW.h. For Aux Gensets only, to include effect in endurance, tankage
        NoOfGensetsRunning= 2;       //For Aux Gensets only, to include effect in endurance, tankage calc.

        EnduranceCalculationMode= 3; //1=calc tankage (dist given),
                                     //2=calc dist (tankage given), 3= calc both (default)
    }

    Ambient
    {
        DevFmISATemp= 0;            //unit: temp
        DevFmISAPress= 0;           //unit: press
        RelHumidity= 0.60;          //unit: fraction

        WaterType= SW;              //SW=seawater; FW= fresh water: if not entered, SW assumed by default
        DevFmStdWaterTemp= 0;
        DevFmStdSalinity=0;         //sea water salinity in SP (practical salinity)
    }

    PlantComponents
    {
        Component Hull: Frigate
        {
            HullModelType= Calc;     //Curve OR Calc: user defined curve
                                     //or calculate based on regression models
            HullModelCurve= curvename; //if HullModelType= Curve
            HullCalcType= F&L;       //if HullModelType= Calc: H&M or F&L or Hollenbach

            //Gen Paras (not method specific)

            Lpp= 123.5;              //Length between perpendiculars: m
            Lwl= 116.92;            //Length on waterline: m
            Beam= 14.2;             //Beam: m
            Tf= 4.7 ;               //Draft Fwd: m
            Ta= 4.7 ;               //Draft Aft: m
            DispTons= 3900;          //Disp: metric tons.

            Cm= 0.82;               //Coeff Midship Area : 0<Cm<1
            Cwp= 0.774 ;            //Coeff Waterplane: 0<Cwp<1

            At= 6 ;                 //Area transverse transom immersed
            |

            iE= 10;                //Half angle of entrance, if not entered, calc by prog

            Sapp= 200;              //SA of appendages: m^2
            AppResisFac= 3 ;        //1+k2: Appendages Resistance factor used with Appendage resistance

            Ap= 195;                //air frontal area, m^2

            //Fung
            Bt= 10 ;                //Beam at transom
        } //hull end
    }
}
```



```

Component Propeller: PropStbd
{
    PropType= FPP;           //FPP or CPP
    PropModelType= Calc;     //Curve OR Calc: calculate based on series
    PropCalcType= WB        //if PropModelType= Calc .. WB: B Series

    Dia= 3.52;               //Propeller Dia in m
    DesignPitch= 3.4;        //Design Pitch in m
    EAR= 0.98;               //Expanded Area Ratio
    nBlades= 5;              //no of blades
    MaxPropSpeed= 307;       //maximum speed in rpm ..307
}

Component Propeller: PropPort
{
    PropType= FPP;           //FPP or CPP
    PropModelType= Calc;     //Curve OR Calc: calculate based on series
    PropCalcType= WB        //if PropModelType= Calc .. WB: B Series

    Dia= 3.52;               //Propeller Dia in m
    DesignPitch= 3.4;        //Design Pitch in m
    EAR= 0.98;               //Expanded Area Ratio
    nBlades= 5;              //no of blades
    MaxPropSpeed= 307;       //maximum speed in rpm 307
}

Component PropShaft: PSStbd
{
    ShaftLossFactor= 0.01;
}

Component PropShaft: PSPort
{
    ShaftLossFactor= 0.01;
}

Component DriveAdder: StbdBRGAdder //Junction
{
    DriveAdderLossType= NoLoss;     //0= NoLoss (default); 1= Constant; 2= Curve
}

Component Gearing: StbdBRGGearing
{
    GearingReductionRatio1= 12.766; //also used as GR1 for dimensioning
    GearingLossFactor= 0.035;       //for DP
}

Component Clutch: StbdBRGClutch
{
    ClutchLossType= NoLoss;         //0= NoLoss (default); 1= Constant; 2= Curve
}

Component DriveAdder: PortBRGAdder //Junction
{
    DriveAdderLossType= NoLoss;     //0= NoLoss (default); 1= Constant; 2= Curve
}

Component Gearing: PortBRGGearing
{
    GearingReductionRatio1= 12.766; //also used as GR1 for dimensioning
    GearingLossFactor= 0.035;       //for DP
}

Component Clutch: PortBRGClutch
{
    ClutchLossType= NoLoss;         //0= NoLoss (default); 1= Constant; 2= Curve
}

Component DriveAdder: StbdCRGAdder //Junction
{
    DriveAdderLossType= NoLoss;     //0= NoLoss (default); 1= Constant; 2= Curve
}

```

```

Component MultiSpeedGearing: StbdCRG2SpdGearing
{
    Speed1GearingReductionRatio= 4.425;    ///<1 for reduction, >0 and <1 for multiplier
    Speed2GearingReductionRatio= 2.958;    ///<1 for reduction, >0 and <1 for multiplier
    |
    ClutchLossType= NoLoss;                ///<0= NoLoss (default); 1= Constant; 2= Curve

    Speed1GearingLossFactor= 0.035;        ///

```

```

PlantConnections
{
    //Stbd side train
    Connection: con1 { StbdDE(Out); StbdCRG2SpdGearing(In)}
    Connection: con2 { StbdCRG2SpdGearing(Out); StbdCRGAdder(Inline1)}
    Connection: con3 { StbdCRGAdder(Inline2); StbdBRGAdder(Crossline)}
    Connection: con4 { StbdBGT(Out); StbdBRGClutch(In)}
    Connection: con5 { StbdBRGClutch(Out); StbdBRGGearing(In)}
    Connection: con6 { StbdBRGGearing(Out); StbdBRGAdder(Inline1)}
    Connection: con7 { StbdBRGAdder(Inline2); PSStbd(In)}
    Connection: con8 { PSStbd(Out); PropStbd(In)}

    //Port side train
    Connection: con11 { PortDE(Out); PortCRG2SpdGearing(In)}
    Connection: con12 { PortCRG2SpdGearing(Out); PortCRGAdder(Inline1)}
    Connection: con13 { PortCRGAdder(Inline2); PortBRGAdder(Crossline)}
    Connection: con14 { PortBGT(Out); PortBRGClutch(In)}
    Connection: con15 { PortBRGClutch(Out); PortBRGGearing(In)}
    Connection: con16 { PortBRGGearing(Out); PortBRGAdder(Inline1)}
    Connection: con17 { PortBRGAdder(Inline2); PSPort(In)}
    Connection: con18 { PSPort(Out); PropPort(In)}

    //Cross Connect
    Connection: con21 { StbdCRGAdder(Crossline); StbdClutchCCG(In)}
    Connection: con22 { StbdClutchCCG(Out); CCG(In)}
    Connection: con23 { CCG(Out); PortClutchCCG(In)}
    Connection: con24 { PortClutchCCG(Out); PortCRGAdder(Crossline) }
}

PlantDriveModes
{
    //Standard Modes
    DriveMode: 2CDE { PortDE(On); StbdDE(On); PortCRG2SpdGearing(Speed20n); StbdCRG2SpdGearing(Speed20n)}

    DriveMode: 2BGT { PortBGT(On); StbdBGT(On); PortBRGClutch(On); StbdBRGClutch(On)}

    DriveMode: PortDEDrivingBothProps { PortDE(On); PortCRG2SpdGearing(Speed10n);
                                         PortClutchCCG(On); StbdClutchCCG(On)}

    DriveMode: StbdDEDrivingBothProps { StbdDE(On); StbdCRG2SpdGearing(Speed10n);
                                         PortClutchCCG(On); StbdClutchCCG(On)}

    DriveMode: CODAG { PortDE(On); StbdDE(On); PortCRG2SpdGearing(Speed20n); StbdCRG2SpdGearing(Speed20n);
                      PortBGT(On); StbdBGT(On); PortBRGClutch(On); StbdBRGClutch(On)}

    //Special Modes
    DriveMode: PortDEStbdPropTrail { PortDE(On); PortCRG2SpdGearing(Speed20n)}

    DriveMode: PortBGTStbdPropTrail { PortBGT(On); PortBRGClutch(On)}
}

} //plant end

```

```

PlantSimulationRun: CODAG-2DE
{
    DriveMode= 2CDE;

    Ambient                //to set Amb paras in OD: optional
    {
        DevFmISATemp= 0;    //unit: temp
        DevFmISAPress= 0;   //unit: press
        RelHumidity= 0.60;   //unit: fraction
    }

    PlantComponents
    {
        //stbd
        Component DieselDrive: StbdDE
        {
            FuelFlowRatio= 0.25;
        }

        Component DieselDrive: PortDE
        {
            FuelFlowRatio= 0.25;
        }

        Component GasTurbineDrive: StbdBGT
        {
            PowerSetting= 950;           // COT in K
        }

        Component GasTurbineDrive: PortBGT
        {
            PowerSetting= 950;           // COT in K
        }
    }
} //plantSimRun end

```

Q.3 Notional Light Frigate CODELAG

```
//LightFrigate
Plant: FrigateCODELAGPropPlant
{
    PlantDefinition
    {
        PlantType= Marine;           //can be Aero
        UnitSystem= SI;               //SI/IM
        SpeedRangeMax= 35;            //in knots
        SpeedRangeMin= 4;             //in knots: if not specified: default 5 knts

        ResistanceCurvesDataPoints= 20; //optional: default 50 points
        PropellerCurvesDataPoints= 20;  //optional: default 50 points
    }

    Ambient
    {
        DevFmISATemp= 0;              //unit: temp
        DevFmISAPress= 0;             //unit: press
        RelHumidity= 0.60;            //unit: fraction

        WaterType= SW;                //SW=seawater; FW= fresh water: if not entered, SW assumed by default
        DevFmStdWaterTemp= 0;
        DevFmStdSalinity=0;           //sea water salinity in SP (practical salinity)
    }

    PlantComponents
    {
        Component Hull: LightFrigate
        {
            HullModelType= Calc;      //Curve OR Calc: user defined curve
                                      //or calculate based on regression models
            HullModelCurve= curvename; //if HullModelType= Curve
            HullCalcType= F&L;        //if HullModelType= Calc: H&M or F&L or Hollenbach

            //Gen Paras (not method specific)

            Lpp= 123.5;                //Length between perpendiculars: m
            Lwl= 116.92;               //Length on waterline: m
            Beam= 14.2;                //Beam: m
            Tf= 4.7 ;                  //Draft Fwd: m
            Ta= 4.7 ;                  //Draft Aft: m
            DispTons= 3900;             //Disp: metric tons.

            Cm= 0.82;                  //Coeff Midship Area : 0<Cm<1
            Cwp= 0.774 ;               //Coeff Waterplane: 0<Cwp<1

            At= 6 ;                    //Area transverse transom immersed

            iE= 10;                    //Half angle of entrance, if not entered, calc by prog

            Sapp= 200;                  //SA of appendages: m^2
            AppResisFac= 3 ;            //1+k2: Appendages Resistance factor used with Appendage resistance

            Ap= 195;                    //air frontal area, m^2

            //Fung
            Bt= 10 ;                    //Beam at transom
        } //hull end

        Component Propeller: PropStbd
        {
            PropType= FPP;              //FPP or CPP
            PropModelType= Calc;         //Curve OR Calc: calculate based on series
            PropCalcType= WB             //if PropModelType= Calc, WB:B Series

            Dia= 3.52;                  //Propeller Dia in m
            DesignPitch= 3.4;           //Design Pitch in m
            EAR= 0.98;                  //Expanded Area Ratio
            nBlades= 5;                 //no of blades
            MaxPropSpeed= 307;          //maximum speed in rpm
        }
    }
}
```

```

Component Propeller: PropPort
{
    PropType= FPP;           //FPP or CPP
    PropModelType= Calc;     //Curve OR Calc: calculate based on series
    PropCalcType= WB        //if PropModelType= Calc, WB:B Series

    Dia= 3.52;               //Propeller Dia in m
    DesignPitch= 3.4;        //Design Pitch in m
    EAR= 0.98;               //Expanded Area Ratio
    nBlades= 5;              //no of blades
    MaxPropSpeed= 307;       //maximum speed in rpm
}

Component PropShaft: PSStbd
{
    ShaftLossFactor= 0.01;
}

Component PropShaft: PSPort
{
    ShaftLossFactor= 0.01;
}

Component DriveAdder: StbdBRGAdder //Junction
{
    DriveAdderLossType= NoLoss;     //0= NoLoss (default); 1= Constant; 2= Curve
}

Component Gearing: StbdBRGGearing
{
    GearingReductioRatio= 12.766;   //>1 for reduction, >0 and <1 for multiplier
    GearingLossFactor= 0.035;       //for DP
}

Component Clutch: StbdBRGClutch
{
    ClutchLossType= NoLoss;         //0= NoLoss (default); 1= Constant; 2= Curve
}

Component DriveAdder: PortBRGAdder //Junction
{
    DriveAdderLossType= NoLoss;     //0= NoLoss (default); 1= Constant; 2= Curve
}

Component Gearing: PortBRGGearing
{
    GearingReductioRatio= 12.766;   //>1 for reduction, >0 and <1 for multiplier
    GearingLossFactor= 0.035;       //for DP
}

Component Clutch: PortBRGClutch
{
    ClutchLossType= NoLoss;         //0= NoLoss (default); 1= Constant; 2= Curve
}

Component DriveAdder: PortBRGAdder //Junction
{
    DriveAdderLossType= NoLoss;     //0= NoLoss (default); 1= Constant; 2= Curve
}

Component Gearing: PortBRGGearing
{
    GearingReductioRatio= 12.766;   //>1 for reduction, >0 and <1 for multiplier
    GearingLossFactor= 0.035;       //for DP
}

Component Clutch: PortBRGClutch
{
    ClutchLossType= NoLoss;         //0= NoLoss (default); 1= Constant; 2= Curve
}

```

```

Component ElectricDrive: PortEM
{
    ElectricDriveType= PTI;
    ElectricDriveCat= Induction;
    ElDriveVoltageRated= 6600;      //Volts
    ElDriveCurrentRated= 620;       //Amp
    ElDrivePowerFacRated= 0.9;

    FreqDriveCat= PWM;
}

Component ElectricDrive: StbdEM
{
    ElectricDriveType= PTI;
    ElectricDriveCat= Induction;
    ElDriveVoltageRated= 6600;      //Volts
    ElDriveCurrentRated= 620;       //Amp
    ElDrivePowerFacRated= 0.9;

    FreqDriveCat= PWM;              //1=PWM;
}

Component GasTurbineDrive: PortBGT
{
    ModelFileName= GT15MW;
    SimType= Internal;              //based on model(Internal)
                                    //or maps (External)..currently only model

    PowerNom= 15520;                //Shaft power nom in kW
    SpeedNom= 4300;                 //PT nom spd in rpm
}

Component GasTurbineDrive: StbdBGT      //ID for the text file
{
    ModelFileName= GT15MW;
    SimType= Internal;              //based on model(Internal)
                                    //or maps (External)..currently only model

    PowerNom= 15520;                //Shaft power nom in kW
    SpeedNom= 4300;                 //PT nom spd in rpm
}

//Electric Grid:
Component DieselDrive: DG1
{
    DieselDriveType= Genset;
    PowerNom= 2720;                 //in kW
    SpeedNom= 1000;                 //rpm
    PowerRatioDP= 1;
    SpeedRatioDP= 1;
    sfcDP= 194.4;                   //in g/kW-hr
    ShapingFnFac= 0.7;
}

Component DieselDrive: DG2
{
    DieselDriveType= Genset;
    PowerNom= 2720;                 //in kW
    SpeedNom= 1000;                 //rpm
    PowerRatioDP= 1 ;
    SpeedRatioDP= 1;
    sfcDP= 194.4;                   //in g/kW-hr
    ShapingFnFac= 0.7;
}

Component DieselDrive: DG3
{
    DieselDriveType= Genset;
    PowerNom= 2720;                 //in kW
    SpeedNom= 1000;                 //rpm
    PowerRatioDP= 1 ;
    SpeedRatioDP= 1;
    sfcDP= 194.4;                   //in g/kW-hr
    ShapingFnFac= 0.7;
}

```

```

Component DieselDrive: DG4      |
{
    DieselDriveType= Genset;
    PowerNom= 2720;              //in kW
    SpeedNom= 1000;              //rpm
    PowerRatioDP= 1 ;
    SpeedRatioDP= 1;
    sfcDP= 194.4;                //in g/kW-hr
    ShapingFnFac= 0.7;
}

Component ElectricSwitchBoard: SB1
{
    ELSBEtaRated= 0.995;        //optional
}

Component ElectricSwitchBoard: SB2
{
    ELSBEtaRated= 0.995;        //optional
}

} //end components

PlantConnections
{
    //Stbd side train
    Connection: con1 { StbdEM(Out); StbdBRGAdder(Crossline)}
    Connection: con4 { StbdBGT(Out); StbdBRGClutch(In)}
    Connection: con5 { StbdBRGClutch(Out); StbdBRGGearing(In)}
    Connection: con6 { StbdBRGGearing(Out); StbdBRGAdder(Inline1)}
    Connection: con7 { StbdBRGAdder(Inline2); PropStbd(In)}

    //Port side train
    Connection: con11 { PortEM(Out); PortBRGAdder(Crossline)}
    Connection: con14 { PortBGT(Out); PortBRGClutch(In)}
    Connection: con15 { PortBRGClutch(Out); PortBRGGearing(In)}
    Connection: con16 { PortBRGGearing(Out); PortBRGAdder(Inline1)}
    Connection: con17 { PortBRGAdder(Inline2); PropPort(In)}
}

PlantElConnections
{
    //Elec Conn
    ElConnection: elCon01 { DG1(Out); SB1(In1)}
    ElConnection: elCon02 { DG2(Out); SB1(In2)}
    ElConnection: elCon03 { DG3(Out); SB2(In1)}
    ElConnection: elCon04 { DG4(Out); SB2(In2)}

    ElConnection: elCon05 { SB1(Out); StbdEM(In)}
    ElConnection: elCon06 { SB2(Out); PortEM(In)}
}

PlantDriveModes
{
    //Standard Modes
    DriveMode: 2EM { PortEM(On); StbdEM(On); }

    DriveMode: 2BGT { PortBGT(On); PortBRGClutch(On); StbdBGT(On); StbdBRGClutch(On)}

    DriveMode: CODELAG {PortEM(On); StbdEM(On); PortBGT(On); PortBRGClutch(On);
                        StbdBGT(On); StbdBRGClutch(On)}
}

} //plant end

```



```

PlantSimulationRun: SimRunID    //SimRunName
{
    DriveMode= CODELAG;

    Ambient                      //to set Amb paras in OD: optional
    {
        DevFmISATemp= 0;        //unit: temp
        DevFmISAPress= 0;       //unit: press
        RelHumidity= 0.60;      //unit: fraction
    }

    PlantComponents
    {
        Component DieselDrive: DG1
        {
            FuelFlowRatio= 0.75;
        }

        Component DieselDrive: DG3
        {
            FuelFlowRatio= 0.75;
        }

        Component ElectricSwitchBoard: SB1
        {
            AuxLoad= 600;    //kWe
        }

        Component ElectricSwitchBoard: SB2
        {
            AuxLoad= 600;    //kWe
        }

        Component GasTurbineDrive: PortBGT
        {
            PowerSetting= 1100;    // COT in K
        }

        Component GasTurbineDrive: StbdBGT
        {
            PowerSetting= 1100;    // COT in K
        }
    }
} //plantSimRun end

```

Q.4 Notional Light Frigate IFEP

```
//LightFrigate
Plant: IFEPPropPlant
{
    PlantDefinition
    {
        PlantType= Marine;           //can be Aero
        UnitSystem= SI;               //SI/IM      |

        SpeedRangeMax= 35;            //in knots
        SpeedRangeMin= 4;              //in knots: if not specified: default 5 knts

        ResistanceCurvesDataPoints= 20; //optional: default 50 points
        PropellerCurvesDataPoints= 20;  //optional: default 50 points

        EnduranceDistance= 5000;        //nm
        TankageCapacity= 500;           //metric t

        SeaStateFoulingFactor= 1;
        PlantDeteriorationFactor= 1;

        EnduranceCalculationMode=3;     //1=calc tankage (dist given),
                                       //2=calc dist (tankage given), 3= calc both (default)
    }

    Ambient
    {
        DevFmISATemp= 0;              //unit: temp
        DevFmISAPress= 0;             //unit: press
        RelHumidity= 0.60;             //unit: fraction

        WaterType= SW;                //SW=seawater; FW= fresh water: if not entered, SW assumed by default
        DevFmStdWaterTemp= 0;
        DevFmStdSalinity=0;           //sea water salinity in SP (practical salinity)
    }

    PlantComponents
    {
        Component Hull: Frigate3900t
        {
            HullModelType= Calc;       //Curve OR Calc: user defined curve
                                       //or calculate based on regression models
            HullModelCurve= curvename; //if HullModelType= Curve
            HullCalcType= F&L;         //if HullModelType= Calc: H&M or F&L or Hollenbach

            //Gen Paras (not method specific)

            Lpp= 123.5;                //Length between perpendiculars: m
            Lwl= 116.92;               //Length on waterline: m
            Beam= 14.2;                //Beam: m
            Tf= 4.7 ;                  //Draft Fwd: m
            Ta= 4.7 ;                  //Draft Aft: m
            DispTons= 3900;             //Disp: metric tons.

            Cm= 0.82;                  //Coeff Midship Area : 0<Cm<1
            Cwp= 0.774 ;               //Coeff Waterplane: 0<Cwp<1

            At= 6 ;                    //Area transverse transom immersed

            iE= 10;                    //Half angle of entrance, if not entered, calc by prog

            Sapp= 200;                 //SA of appendages: m^2
            AppResisFac= 3 ;           //1+k2: Appendages Resistance factor used with Appendage resistance

            Ap= 195;                   //air frontal area, m^2

            //Fung
            Bt= 10 ;                   //Beam at transom
        } //hull end
    }
}
```

```

Component Propeller: PropStbd
{
    PropType= FPP;           //FPP or CPP
    PropModelType= Calc;     //Curve OR Calc: calculate based on series
    PropCalcType= WB        //if PropModelType= Calc .. WB: B Series

    Dia= 3.52;               //Propeller Dia in m
    DesignPitch= 3.4;        //Design Pitch in m
    EAR= 0.98;               //Expanded Area Ratio
    nBlades= 5;              //no of blades
    MaxPropSpeed= 307;       //maximum speed in rpm ..307
}

Component Propeller: PropPort
{
    PropType= FPP;           //FPP or CPP
    PropModelType= Calc;     //Curve OR Calc: calculate based on series
    PropCalcType= WB        //if PropModelType= Calc .. WB:B Series

    Dia= 3.52;               //Propeller Dia in m
    DesignPitch= 3.4;        //Design Pitch in m
    EAR= 0.98;               //Expanded Area Ratio
    nBlades= 5;              //no of blades
    MaxPropSpeed= 307;       //maximum speed in rpm 307
}

Component PropShaft: PSStbd
{
    ShaftLossFactor= 0.01;   //for DP
}

Component PropShaft: PSPort
{
    ShaftLossFactor= 0.01;   //for DP
}

Component ElectricDrive: PortEM
{
    ElectricDriveType= PTI;
    ElectricDriveCat= Induction; //Induction or AdvInduction

    E1DriveVoltageRated= 6600; //Volts
    E1DriveCurrentRated= 1555; //Amp
    E1DrivePowerFacRated= 0.9;

    FreqDriveCat= PWM;        //1=PWM;
    SpeedNom= 320;            //rpm
}

Component ElectricDrive: StbdEM
{
    ElectricDriveType= PTI;
    ElectricDriveCat= Induction; //Induction or AdvInduction

    E1DriveVoltageRated= 6600; //Volts
    E1DriveCurrentRated= 1555; //Amp
    E1DrivePowerFacRated= 0.9;
    //E1DriveEtaRated= 0.96; //optional

    FreqDriveCat= PWM;        //1=PWM;
    SpeedNom= 320;            //rpm
}

```

```

Component GasTurbineDrive: GTA
{
    ModelFileName= GT25MW;
    SimType= Internal;          //based on model(Internal)
                                //or maps (External)..currently only model
    PowerNom= 23000;             //Shaft power nom in kW
    SpeedNom= 3600;              //PT nom spd in rpm
    GTDriveType= GenSet;         //Direct or GenSet
}

Component DieselDrive: DG1
{
    DieselDriveType= GenSet;
    PowerNom= 5200;              //(mech power of engine) in kW
    SpeedNom= 900;               //rpm
    PowerRatioDP= 0.85;
    SpeedRatioDP= 1;
    sfcDP= 0.198;                //kg/kW-hr
    ShapingFnFac= 0.7;
}

Component DieselDrive: DG2      //ID for the text file
{
    DieselDriveType= GenSet;
    PowerNom= 5200;              //(mech power of engine) in kW
    SpeedNom= 900;               //rpm
    PowerRatioDP= 0.85;
    SpeedRatioDP= 1;
    sfcDP= 0.198;                //kg/kW-hr
    ShapingFnFac= 0.7;
}

Component ElectricSwitchBoard: SB
{
    ElSBEtaRated= 0.995;
}

} //end components

PlantConnections
{
    //Stbd side train
    Connection: con1 { StbdEM(Out); PSStbd(In)}
    Connection: con2 { PSStbd(Out); PropStbd(In)}

    //Port side train
    Connection: con6 { PortEM(Out); PSPort(In)}
    Connection: con7 { PSPort(Out); PropPort(In)}
}

PlantElConnections
{
    //Elec Conn
    ElConnection: elCon01 { GTA(Out); SB(In1)}
    ElConnection: elCon02 { DG1(Out); SB(In2)}
    ElConnection: elCon04 { DG2(Out); SB(In3)}

    ElConnection: elCon05 { SB(Out1); StbdEM(In)}
    ElConnection: elCon06 { SB(Out2); PortEM(In)}
}

PlantDriveModes
{
    //Standard Modes
    DriveMode: 2EMAllGensets { PortEM(On); StbdEM(On); GTA(On); DG1(On); DG2(On)}
    DriveMode: 2EMGTA { PortEM(On); StbdEM(On); GTA(On)}
    DriveMode: 2EM1GTA1DG { PortEM(On); StbdEM(On); GTA(On); DG1(On)}
    DriveMode: 2EM2DG { PortEM(On); StbdEM(On); DG1(On); DG2(On)}
}

} //plant end

```

```

PlantSimulationRun: 2EM //SimRunName
{
    DriveMode= 2EM2DG;

    Ambient          //to set Amb paras in OD: optional
    {
        |
        DevFmISATemp= 0;          //unit: temp
        DevFmISAPress= 0;        //unit: press
        RelHumidity= 0.60;       //unit: fraction
    }

    PlantComponents
    {
        Component GasTurbineDrive: GTA
        {
            PowerSetting= 1250;          // COT in K
        }

        Component DieselDrive: DG1
        {
            FuelFlowRatio= 0.5;
        }

        Component DieselDrive: DG2
        {
            FuelFlowRatio= 0.5;
        }

        Component ElectricSwitchBoard: SB
        {
            AuxLoad= 1200; //kW
        }
    }
} //plantSimRun end

```

Q.5 Notional Destroyer COGAG

```
//9600t Destroyer
Plant: COGAGPropPlant
{
    PlantDefinition
    {
        PlantType= Marine;           //can be Aero
        UnitSystem= SI;              //SI/IM

        SpeedRangeMax= 35;           //double: in knots
        SpeedRangeMin= 4;            //double: in knots:
                                    //if not specified: default 5 knts

        ResistanceCurvesDataPoints= 20; //int, optional: default 50 points
        PropellerCurvesDataPoints= 20; //int, optional: default 50 points

        EnduranceDistance= 5000;     //nm
        TankageCapacity= 1200;       //metric t

        SeaStateFoulingFactor= 1;
        PlantDeteriorationFactor= 1;

        GensetAverageLoad= 2100;     //kW
        GensetSfc= 0.3405;           //kg/kW.h
        NoOfGensetsRunning= 2;

        EnduranceCalculationMode=3;  //1=calc tankage (dist given),
                                    //2=calc dist (tankage given),
                                    //3= calc both (default)
    }

    Ambient
    {
        DevFmISATemp= 0;             //unit: temp
        DevFmISAPress= 0;            //unit: press
        RelHumidity= 0.60;           //unit: fraction

        WaterType= SW;               //SW=seawater;
                                    //FW= fresh water
                                    //if not entered, SW assumed by default

        DevFmStdWaterTemp= 0;
        DevFmStdSalinity=0;          //sea water salinity in SP (practical salinity)
                                    //Std value of 3.5 assumed by default
    }

    Component Hull: 9600tDestroyer
    {
        HullModelType= Calc;         //Curve OR Calc:
                                    //user defined curve
                                    //or calculate based on regression models
        HullModelCurve= curvename;   //if HullModelType= Curve
        HullCalcType= F&L;           //if HullModelType= Calc: H&M or F&L or Hollenbach

        //Gen Paras (not method specific)

        Lpp= 154;                    //Length between perpendiculars: m
        Lwl= 144.68;                 //Length on waterline: m
        Beam= 18.5;                  //Beam: m
        Tf= 6.5 ;                    //Draft Fwd: m
        Ta= 7.5 ;                    //Draft Aft: m
        DispTons= 9585;              //Disp: metric tons.
    }
}
```

```

Cm= 0.8280;           //Coeff Midship Area : 0<Cm<1
Cwp= 0.7910 ;         //Coeff Waterplane: 0<Cwp<1

At= 12 ;              //Area transverse transom immersed

iE= 10.9;             //Half angle of entrance, if not entered, calc by prog

Sapp= 300;            //SA of appendages: m^2
AppResisFac= 3 ;      //1+k2: Appendages Resistance factor |

Ap= 420;              //air frontal area, m2

//F&L
Bt= 12 ;              //Beam at transom

} //hull end

Component Propeller: PropStbd
{
    PropType= CPP;           //FPP or CPP
    PropModelType= Calc;     //Curve OR Calc: calculate based on series

    //PropModelCurve= curvename; //if PropModelType= Curve

    PropCalcType= WB;        //if PropModelType= Calc .. WB:Wangenin B Series

    Dia= 5.18;               //Propeller Dia in m
    DesignPitch= 7.271;      //Design Pitch in m
    EAR= 0.5957;             //Expanded Area Ratio
    nBlades= 5;              //no of blades
    MaxPropSpeed= 203.57;    //maximum speed in rpm
}

Component Propeller: PropPort
{
    PropType= CPP;           //FPP or CPP
    PropModelType= Calc;     //Curve OR Calc: calculate based on series

    //PropModelCurve= curvename; //if PropModelType= Curve

    PropCalcType= WB;        //if PropModelType= Calc .. WB:Wangenin B Series

    Dia= 5.18;               //Propeller Dia in m
    DesignPitch= 7.271;      //Design Pitch in m
    EAR= 0.5957;             //Expanded Area Ratio
    nBlades= 5;              //no of blades
    MaxPropSpeed= 203.57;    //maximum speed in rpm
}

Component PropShaft: PSStbd
{
    ShaftLossFactor= 0.01;
}

Component PropShaft: PSPort
{
    ShaftLossFactor= 0.01;
}

Component GasTurbineDrive: GT1 //ID for the text file
{
    ModelFileName= GT25MW ;
    SimType= Internal;        //based on model(Internal)
                                //or maps (External)

    PowerNom= 25000;          //Shaft power nom in kW
    SpeedNom= 3600;           //PT nom spd in rpm
}

```

```

Component GasTurbineDrive: GT2 //ID for the text file
{
    ModelFileName= GT25MW ;
    SimType= Internal; //based on model(Internal)
                        //or maps (External)

    PowerNom= 25000; //Shaft power nom in kW
    SpeedNom= 3600; //PT nom spd in rpm
}

Component GasTurbineDrive: GT3 //ID for the text file
{
    ModelFileName= GT25MW ;
    SimType= Internal; //based on model(Internal)
                        //or maps (External)..currently only model

    PowerNom= 25000; //Shaft power nom in kW
    SpeedNom= 3600; //PT nom spd in rpm
}

Component GasTurbineDrive: GT4 //ID for the text file
{
    ModelFileName= GT25MW ;
    SimType= Internal; //based on model(Internal)
                        //or maps (External)..currently only model

    PowerNom= 25000; //Shaft power nom in kW
    SpeedNom= 3600; //PT nom spd in rpm
}

Component Gearing: GearingGT1
{
    GearingReductionRatio1= 18.98 ; //>1 for reduction, >0 and <1 for multiplier
    GearingLossFactor= 0.027; //at nominal conditon
}

Component Gearing: GearingGT2
{
    GearingReductionRatio1= 18.98 ; //>1 for reduction, >0 and <1 for multiplier
    GearingLossFactor= 0.027; //at nominal conditon
}

Component Gearing: GearingGT3
{
    GearingReductionRatio1= 18.98 ; //double: >1 for reduction, >0 and <1 for multiplier
    GearingLossFactor= 0.027; //at nominal conditon
}

Component Gearing: GearingGT4
{
    GearingReductionRatio1= 18.98 ; //double: >1 for reduction, >0 and <1 for multiplier
    GearingLossFactor= 0.027; //double: for fixed factor losses only
}

Component Clutch: ClutchGT1
{
    ClutchLossType= NoLoss; //0= NoLoss (default); 1= Constant; 2= Curve
}

Component Clutch: ClutchGT2
{
    ClutchLossType= NoLoss; //0= NoLoss (default); 1= Constant; 2= Curve
}

```



```

Component Clutch: ClutchGT3
{
    ClutchLossType= NoLoss;          //0= NoLoss (default); 1= Constant; 2= Curve
}

Component Clutch: ClutchGT4
{
    ClutchLossType= NoLoss;          //0= NoLoss (default); 1= Constant; 2= Curve
}

Component DriveAdder: AdderPort      //Same as Junction
{
    DriveAdderLossType= NoLoss;      //string: 0= NoLoss (default); 1= Constant; 2= Curve
}

Component DriveAdder: AdderStbd //summation of 2 drives to one or divide 1 drive into 2
{
    DriveAdderLossType= NoLoss;      //string: 0= NoLoss (default); 1= Constant; 2= Curve
}

} //end components

PlantConnections
{
    //Stbd side train

    Connection: con1 { GT1(Out); ClutchGT1(In)}
    Connection: con2 { ClutchGT1(Out); GearingGT1(In)}
    Connection: con3 { GearingGT1(Out); AdderStbd(Crossline)}
    Connection: con4 { GT3(Out); ClutchGT3(In)}
    Connection: con5 { ClutchGT3(Out); GearingGT3(In)}
    Connection: con6 { GearingGT3(Out); AdderStbd(Inline1)}
    Connection: con7 { AdderStbd(Inline2); PSStd(In)}
    Connection: con8 { PSStd(Out); PropStbd(In)}

    //Port side train

    Connection: con11 { GT4(Out); ClutchGT4(In)}
    Connection: con12 { ClutchGT4(Out); GearingGT4(In)}
    Connection: con13 { GearingGT4(Out); AdderPort(Crossline)}
    Connection: con14 { GT2(Out); ClutchGT2(In)}
    Connection: con15 { ClutchGT2(Out); GearingGT2(In)}
    Connection: con16 { GearingGT2(Out); AdderPort(Inline1)}
    Connection: con17 { AdderPort(Inline2); PSPORT(In)}
    Connection: con18 { PSPORT(Out); PropPort(In)}
}

PlantDriveModes
{
    //Standard Modes

    DriveMode: Full { GT1(On); GT3(On); GT2(On); GT4(On);
                     ClutchGT1(On); ClutchGT3(On); ClutchGT2(On); ClutchGT4(On)}

    DriveMode: Split { GT1(On); GT4(On); ClutchGT1(On); ClutchGT4(On)}

    //Special Modes

    DriveMode: PortTwinGTStbdTrail { GT2(On); GT4(On); ClutchGT2(On); ClutchGT4(On)}

    DriveMode: PortSingleGT2StbdTrail { GT2(On); ClutchGT2(On)}
}

} //plant end

```

```

PlantSimulationRun: RunSplit0.55
{
    DriveMode= Split ;

    Ambient                //to set Amb paras in OD: optional
    {
        DevFmISATemp= 0;      //unit: temp
        DevFmISAPress= 0;     //unit: press
        RelHumidity= 0; //unit: fraction
    }

    PlantComponents
    {
        Component GasTurbineDrive: GT1
        {
            PowerSetting= 0.55 ;           // PCN
        }

        Component GasTurbineDrive: GT3
        {
            PowerSetting= 0 ;              // PCN
        }

        Component GasTurbineDrive: GT2
        {
            PowerSetting= 0 ;              // PCN
        }

        Component GasTurbineDrive: GT4
        {
            PowerSetting= 0.55 ;           // PCN
        }
    }
} //plantSimRun end

```

Q.6 Notional Destroyer CODAG

```
//9600t Destroyer CODAG
Plant: CODAGPropPlant
{
    PlantDefinition
    {
        PlantType= Marine;           //can be Aero
        UnitSystem= SI;               //SI/IM

        SpeedRangeMax= 35;            //in knots
        SpeedRangeMin= 4;             //in knots: if not specified: default 5 knts

        ResistanceCurvesDataPoints= 20; //optional: default 50 points
        PropellerCurvesDataPoints= 20; //optional: default 50 points

        EnduranceDistance= 5000;      //nm
        TankageCapacity= 1200;        //metric t

        SeaStateFoulingFactor= 1;
        PlantDeteriorationFactor= 1;

        GensetAverageLoad= 2100;      //kW
        GensetSfc= 0.202;             //kg/kW.h
        NoOfGensetsRunning= 2;

        EnduranceCalculationMode=3;   //1=calc tankage (dist given),
                                     //2=calc dist (tankage given),
                                     //3= calc both (default)
    }

    Ambient
    {
        DevFmISATemp= 0;             //unit: temp
        DevFmISAPress= 0;            //unit: press
        RelHumidity= 0.60;           //unit: fraction

        WaterType= SW;               //SW=seawater; FW= fresh water:
                                     //if not entered, SW assumed by default

        DevFmStdWaterTemp= 0;
        DevFmStdSalinity=0;          //sea water salinity in SP (practical salinity)
    }

    PlantComponents
    {
        Component Hull: 9600tDestroyer
        {
            HullModelType= Calc;      //Curve OR Calc: user defined curve
                                     //or calculate based on regression models
            HullModelCurve= curvename; //if HullModelType= Curve
            HullCalcType= F&L;        //if HullModelType= Calc: H&M or F&L or Hollenbach

            //Gen Paras (not method specific)

            Lpp= 154;                 //Length between perpendiculars: m
            Lwl= 144.68;              //Length on waterline: m
            Beam= 18.5;               //Beam: m
            Tf= 6.5 ;                 //Draft Fwd: m
            Ta= 7.5 ;                 //Draft Aft: m
            DispTons= 9585;            //Disp: metric tons.

            Cm= 0.8280;               //Coeff Midship Area : 0<Cm<1
            Cwp= 0.7910 ;             //Coeff Waterplane: 0<Cwp<1

            At= 12 ;                  //Area transverse transom immersed

            iE= 10.9;                 //Half angle of entrance, if not entered, calc by prog
                                     //If in H&M this fac should not be applied, set =1.

            Sapp= 300;                //SA of appendages: m^2
            AppResisFac= 3 ;          //1+k2: Appendages Resistance factor
            Ap= 420;                  //air frontal area, m^2

            //Fung
            Bt= 12 ;                  //Beam at transom
        } //hull end
    }
}
```

```

Component Propeller: PropStbd
{
    PropType= CPP;                //FPP or CPP
    PropModelType= Calc;          //Curve OR Calc: calculate based on series

    //PropModelCurve= curvename;  //if PropModelType= Curve

    PropCalcType= WB;             //if PropModelType= Calc .. WB:Wangenin B Series

    Dia= 5.18;                   //Propeller Dia in m
    DesignPitch= 7.271;          //Design Pitch in m
    EAR= 0.5957;                 //Expanded Area Ratio
    nBlades= 5;                  //no of blades
    MaxPropSpeed= 203.57;        //maximum speed in rpm
}

Component Propeller: PropPort
{
    PropType= CPP;                //FPP or CPP
    PropModelType= Calc;          //Curve OR Calc: calculate based on series

    //PropModelCurve= curvename;  //if PropModelType= Curve

    PropCalcType= WB;             //if PropModelType= Calc .. WB:Wangenin B Series

    Dia= 5.18;                   //Design Pitch in m
    EAR= 0.5957;                 //Expanded Area Ratio
    nBlades= 5;                  //no of blades
    MaxPropSpeed= 203.57;        //maximum speed in rpm
}

Component PropShaft: PSStbd
{
    ShaftLossFactor= 0.01;
}

Component PropShaft: PSPort
{
    ShaftLossFactor= 0.01;
}

Component DriveAdder: AdderStbd //same as Junction
{
    DriveAdderLossType= NoLoss;   //0= NoLoss (default); 1= Constant; 2= Curve
}

Component DriveAdder: AdderPort //same as Junction
{
    DriveAdderLossType= NoLoss;   //0= NoLoss (default); 1= Constant; 2= Curve
}

Component Gearing: GearingGTStbd
{
    GearingReductionRatio1= 18.233 ; //also used as GR1 for dimensioning
    GearingLossFactor= 0.035;        //at DP
}

Component Gearing: GearingGTPort
{
    GearingReductionRatio1= 18.233 ; //also used as GR1 for dimensioning
    GearingLossFactor= 0.035;        //for fixed factor losses only
}

Component Clutch: ClutchGTStbd
{
    ClutchLossType= NoLoss;        //0= NoLoss (default); 1= Constant; 2= Curve
}

Component Clutch: ClutchGTPort
{
    ClutchLossType= NoLoss;        //0= NoLoss (default); 1= Constant; 2= Curve
}

```

```

Component MultiSpeedGearing: Gearing2SpdDEStbd
{
    Speed1GearingReductionRatio= 7.032 ;    ///<1 for reduction, >0 and <1 for multiplier
    Speed2GearingReductionRatio= 4.137 ;    ///<1 for reduction, >0 and <1 for multiplier

    ClutchLossType= NoLoss;                ///<0= NoLoss (default); 1= Constant; 2= Curve

    Speed1GearingLossFactor= 0.030; ///

```

```

PlantConnections
{
    //Stbd side train

    Connection: con1 { GTStbd(Out); ClutchGTStbd(In)}
    Connection: con2 { ClutchGTStbd(Out); GearingGTStbd(In)}
    Connection: con3 { GearingGTStbd(Out); AdderStbd(Inline1)}
    Connection: con4 { DEStbd(Out); Gearing2SpdDEStbd(In)}
    Connection: con6 { Gearing2SpdDEStbd(Out); AdderStbd(Crossline)}
    Connection: con7 { AdderStbd(Inline2); PSStbd(In)}
    Connection: con8 { PSStbd(Out); PropStbd(In)}

    //Port side train

    Connection: con11 { GTPort(Out); ClutchGTPort(In)}
    Connection: con12 { ClutchGTPort(Out); GearingGTPort(In)}
    Connection: con13 { GearingGTPort(Out); AdderPort(Inline1)}
    Connection: con14 { DEPort(Out); Gearing2SpdDEPort(In)}
    Connection: con16 { Gearing2SpdDEPort(Out); AdderPort(Crossline)}
    Connection: con17 { AdderPort(Inline2); PSPort(In)}
    Connection: con18 { PSPort(Out); PropPort(In)}
}

PlantDriveModes
{
    //Standard Modes
    DriveMode: 2DE { DEPort(On); DEStbd(On); Gearing2SpdDEPort(Speed10n);
        Gearing2SpdDEStbd(Speed10n)} //all other engines, clutches automatically set to off

    DriveMode: 2GT { GTPort(On); GTStbd(On); ClutchGTPort(On); ClutchGTStbd(On)}

    DriveMode: CODAG { DEPort(On); DEStbd(On); Gearing2SpdDEPort(Speed20n); Gearing2SpdDEStbd(Speed20n);
        GTPort(On); GTStbd(On); ClutchGTPort(On); ClutchGTStbd(On)}

    //Special Modes
    DriveMode: PortDEStbdTrail { DEPort(On); Gearing2SpdDEPort(Speed10n)}

    DriveMode: PortGTStbdTrail { GTPort(On); ClutchGTPort(On)}
}

} //plant end

PlantSimulationRun: SimRun0.3
{
    DriveMode= PortDEStbdTrail ;

    Ambient //to set Amb paras in OD: optional
    {
        DevFmISATemp= 0; //unit: temp
        DevFmISAPress= 0; //unit: press
        RelHumidity= 0; //unit: fraction
    }

    PlantComponents
    {
        Component GasTurbineDrive: GTPort
        {
            PowerSetting= 0 ;
        }

        Component GasTurbineDrive: GTStbd
        {
            PowerSetting= 0 ;
        }

        Component DieselDrive: DEPort
        {
            FuelFlowRatio= 0.3 ;
        }

        Component DieselDrive: DEStbd
        {
            FuelFlowRatio= 0 ;
        }
    }
}

} //plantSimRun end

```

Q.7 Notional Destroyer CODAG-E

```
//9600t Destroyer CODAG-E
Plant: CODAG-E-PropPlant
{
    PlantDefinition
    {
        PlantType= Marine;           //can be Aero
        UnitSystem= SI;               //SI/IM

        SpeedRangeMax= 35;           //in knots
        SpeedRangeMin= 4;             //in knots: if not specified: default 5 knts

        ResistanceCurvesDataPoints= 20; //optional: default 50 points
        PropellerCurvesDataPoints= 20; //optional: default 50 points

        EnduranceDistance= 5000;      //nm
        TankageCapacity= 1200;        //metric t

        SeaStateFoulingFactor= 1;
        PlantDeteriorationFactor= 1;

        EnduranceCalculationMode=3;    //1=calc tankage (dist given),
                                      //2=calc dist (tankage given), 3= calc both (default)
    }

    Ambient
    {
        DevFmISATemp= 0;             //unit: temp
        DevFmISAPress= 0;            //unit: press
        RelHumidity= 0.60;           //unit: fraction

        WaterType= SW;               //SW=seawater; FW= fresh water: if not entered, SW assumed by default
        DevFmStdWaterTemp= 0;
        DevFmStdSalinity=0;          //sea water salinity in SP (practical salinity)
    }

    PlantComponents
    {
        Component Hull: 9600tDestroyer
        {
            HullModelType= Calc;      //Curve OR Calc:
                                      //user defined curve or calculate based on regression models
            HullModelCurve= curvename; //if HullModelType= Curve
            HullCalcType= F&L;        //if HullModelType= Calc: H&M or F&L or Hollenbach

            //Gen Paras (not method specific)

            Lpp= 154;                 //Length between perpendiculars: m
            Lwl= 144.68;              //Length on waterline: m
            Beam= 18.5;               //Beam: m
            Tf= 6.5 ;                 //Draft Fwd: m
            Ta= 7.5 ;                 //Draft Aft: m
            DispTons= 9585;            //Disp: metric tons.

            Cm= 0.8280;               //Coeff Midship Area : 0<Cm<1
            Cwp= 0.7910 ;             //Coeff Waterplane: 0<Cwp<1

            At= 12 ;                  //Area transverse transom immersed

            iE= 10.9;                 //Half angle of entrance, if not entered, calc by prog

            Sapp= 300;                //SA of appendages: m^2
            AppResisFac= 3 ;          //1+k2: Appendages Resistance factor used

            Ap= 420;                  //air frontal area, m^2

            //Fung

            Bt= 12 ;                  //Beam at transom
        } //hull end
    }
}
```

```

Component Propeller: PropStbd
{
    PropType= CPP;                //FPP or CPP
    PropModelType= Calc;          //Curve OR Calc: calculate based on series
    PropCalcType= WB;            //if PropModelType= Calc .. WB:Wangenin B Series

    Dia= 5.18;                   //Propeller Dia in m
    DesignPitch= 7.271;          //Design Pitch in m
    EAR= 0.5957;                 //Expanded Area Ratio
    nBlades= 5;                  //no of blades
    MaxPropSpeed= 203.57;        //maximum speed in rpm
}

Component Propeller: PropPort
{
    PropType= CPP;                //FPP or CPP
    PropModelType= Calc;          //Curve OR Calc: calculate based on series
    PropCalcType= WB;            //if PropModelType= Calc .. WB:Wangenin B Series

    Dia= 5.18;                   //Propeller Dia in m
    DesignPitch= 7.271;          //Design Pitch in m
    EAR= 0.5957;                 //Expanded Area Ratio
    nBlades= 5;                  //no of blades
    MaxPropSpeed= 203.57;        //maximum speed in rpm
}

Component PropShaft: PSSStbd
{
    ShaftLossFactor= 0.01;
}

Component PropShaft: PSStbd
{
    ShaftLossFactor= 0.01;
}

Component DriveAdder: AdderStbd //Junction
{
    DriveAdderLossType= NoLoss; //0= NoLoss (default); 1= Constant; 2= Curve
}

Component DriveAdder: AdderPort //Junction
{
    DriveAdderLossType= NoLoss; //NoLoss (default); 1= Constant; 2= Curve
}

Component DriveAdder: AdderStbd2 //Junction
{
    DriveAdderLossType= NoLoss; //0= NoLoss (default); 1= Constant; 2= Curve
}

Component DriveAdder: AdderPort2 //Junction
{
    DriveAdderLossType= NoLoss; //0= NoLoss (default); 1= Constant; 2= Curve
}

Component Gearing: GearingGTStbd
{
    GearingReductionRatio1= 18.233 ; //also used as GR1 for dimensioning
    GearingLossFactor= 0.035;        //for DP
}

Component Gearing: GearingGTPort
{
    GearingReductionRatio1= 18.233 ; //also used as GR1 for dimensioning
    GearingLossFactor= 0.035;        //for DP
}

Component Clutch: ClutchGTStbd
{
    ClutchLossType= NoLoss; //0= NoLoss (default); 1= Constant; 2= Curve
}

Component Clutch: ClutchGTPort
{
    ClutchLossType= NoLoss; //0= NoLoss (default); 1= Constant; 2= Curve
}

```



```

Component MultiSpeedGearing: Gearing2SpdDEPort
{
    Speed1GearingReductionRatio= 7.032 ;    //>1 for reduction, >0 and <1 for multiplier
    Speed2GearingReductionRatio= 4.137 ;    //>1 for reduction, >0 and <1 for multiplier

    GearingLossType= Constant;    //0= NoLoss (default); 1= Constant; 2= Curve
    ClutchLossType= NoLoss;    //0= NoLoss (default); 1= Constant; 2= Curve

    Speed1GearingLossFactor= 0.030; //for fixed factor losses only
    Speed2GearingLossFactor= 0.020; //for fixed factor losses only
}

Component Clutch: ClutchDEStbd
{
    ClutchLossType= NoLoss;    //0= NoLoss (default); 1= Constant; 2= Curve
}

Component Clutch: ClutchDEPort
{
    ClutchLossType= NoLoss;    //0= NoLoss (default); 1= Constant; 2= Curve
}

Component GasTurbineDrive: GTStbd
{
    ModelFileName= GT36MW ;
    SimType= Internal;    //based on model(Internal) or maps (External)

    PowerNom= 36000;    //Shaft power nom in kW
    SpeedNom= 3300;    //PT nom spd in rpm
}

Component GasTurbineDrive: GTPort
{
    ModelFileName= GT36MW ;
    SimType= Internal;    //based on model(Internal) or maps (External)..currently only model

    PowerNom= 36000;    //Shaft power nom in kW
    SpeedNom= 3300;    //PT nom spd in rpm
}

Component DieselDrive: DEStbd
{
    DieselDriveType= Direct;    //Genset or Direct
    PowerNom= 6960;    //in
    SpeedNom= 750;    //rpm
    PowerRatioDP= 1 ;
    SpeedRatioDP= 1;
    sfcDP= 0.184;    //in kg/kW-hr
    ShapingFnFac= 0.7;    //default= 0.7
}

Component DieselDrive: DEPort    //ID for the text file
{
    DieselDriveType= Direct;    //Genset or Direct
    PowerNom= 6960;    //in kW
    SpeedNom= 750;    //rpm
    PowerRatioDP= 1 ;
    SpeedRatioDP= 1;
    sfcDP= 0.184;    //in kg/kW-hr
    ShapingFnFac= 0.7;    //default= 0.7
}

Component DieselDrive: DG1
{
    DieselDriveType= Genset ;    //Genset or Direct
    PowerNom= 2925;    //in kW
    SpeedNom= 900;    //rpm
    PowerRatioDP= 1 ;
    SpeedRatioDP= 1;
    sfcDP= 0.191;    //in kg/kW-hr
    ShapingFnFac= 0.7;    //default= 0.7
}

```

```

Component DieselDrive: DG2
{
    DieselDriveType= Genset ;           //Genset or Direct
    PowerNom= 2925;                      //in kW
    SpeedNom= 900;                       //rpm
    PowerRatioDP= 1 ;
    SpeedRatioDP= 1;
    sfcDP= 0.191;                       //in kg/kW-hr
    ShapingFnFac= 0.7;                  //default= 0.7
}

Component DieselDrive: DG3
{
    DieselDriveType= Genset ;           //Genset or Direct
    PowerNom= 2925;                      //in kW
    SpeedNom= 900;                       //rpm
    PowerRatioDP= 1 ;
    SpeedRatioDP= 1;
    sfcDP= 0.191;                       //in kg/kW-hr
    ShapingFnFac= 0.7;                  //default= 0.7
}

Component ElectricDrive: EMPort
{
    ElectricDriveType= PTI ;
    ElectricDriveCat= Induction ;        //Induction or AdvInduction
    ElDriveVoltageRated= 690 ;           //Volts
    ElDriveCurrentRated= 1210 ;          //Amp
    ElDrivePowerFacRated= 0.9;
    FreqDriveCat= PWM;                   //1=PWM;
    SpeedNom= 57 ;                      //rpm
}

Component ElectricDrive: EMStbd
{
    ElectricDriveType= PTI ;
    ElectricDriveCat= Induction ;        //Induction or AdvInduction
    ElDriveVoltageRated= 690 ;           //Volts
    ElDriveCurrentRated= 1210 ;          //Amp
    ElDrivePowerFacRated= 0.9;
    FreqDriveCat= PWM;                   //1=PWM;
    SpeedNom= 57 ;                      //rpm
}

Component ElectricSwitchBoard: SB        //ID for the text file
{
    ElSBEtaRated= 0.995;                //default 0.995
}

} //end components

PlantConnections
{
    //Stbd side train

    Connection: con1 { GTStbd(Out); ClutchGTStbd(In)}
    Connection: con2 { ClutchGTStbd(Out); GearingGTStbd(In)}
    Connection: con3 { GearingGTStbd(Out); AdderStbd(Inline1)}
    Connection: con4 { DEStbd(Out); Gearing2SpdDEStbd(In)}
    Connection: con6 { Gearing2SpdDEStbd(Out); AdderStbd(Crossline)}
    Connection: con7 { AdderStbd(Inline2); AdderStbd2(Inline1)}
    Connection: con8 { AdderStbd2(Inline2); PSStbd(In)}
    Connection: con9 { EMStbd(Out); AdderStbd2(Crossline)}
    Connection: con10 { PSStbd(Out); PropStbd(In)}

    //Port side train

    Connection: con11 { GTPort(Out); ClutchGTPort(In)}
    Connection: con12 { ClutchGTPort(Out); GearingGTPort(In)}
    Connection: con13 { GearingGTPort(Out); AdderPort(Inline1)}
    Connection: con14 { DEPort(Out); Gearing2SpdDEPort(In)}
    Connection: con16 { Gearing2SpdDEPort(Out); AdderPort(Crossline)}
    Connection: con19 { EMPort(Out); AdderPort2(Crossline)}
    Connection: con17 { AdderPort(Inline2); AdderPort2(Inline1)}
    Connection: con18 { AdderPort2(Inline2); PSPort(In)}
    Connection: con20 { PSPort(Out); PropPort(In)}
}

```

```

PlantElConnections
{
    ElConnection: elCon01 { DG1(Out); SB(In1)}
    ElConnection: elCon02 { DG2(Out); SB(In2)}
    ElConnection: elCon04 { DG3(Out); SB(In3)}

    ElConnection: elCon05 { SB(Out1); EMStbd(In)}
    ElConnection: elCon06 { SB(Out2); EMPort(In)}
}

PlantDriveModes
{
    //all engines/ cluthched not set on, assumed to be off

    //Standard Modes
    DriveMode: 2DE { DEPort(On); DEStbd(On); Gearing2SpdDEPort(Speed10n); Gearing2SpdDEStbd(Speed10n)}

    DriveMode: 2GT { GTPort(On); GTStbd(On); ClutchGTPort(On); ClutchGTStbd(On)}

    DriveMode: 2EM3DG { EMPort(On); EMStbd(On); DG1(On); DG2(On); DG3(On);}

    DriveMode: CODAG { DEPort(On); DEStbd(On); Gearing2SpdDEPort(Speed20n); Gearing2SpdDEStbd(Speed20n);
        GTPort(On); GTStbd(On); ClutchGTPort(On); ClutchGTStbd(On)}

    //Special Modes
    DriveMode: PortDEStbdTrail { DEPort(On); Gearing2SpdDEPort(Speed10n)}

    DriveMode: PortGTStbdTrail { GTPort(On); ClutchGTPort(On)}
}

} //plant end

PlantSimulationRun: SimRunName
{
    DriveMode= 2EM3DG ;

    Ambient //to set Amb paras in OD: optional
    {
        DevFmISATemp= 0; //unit: temp
        DevFmISAPress= 0; //unit: press
        RelHumidity= 0; //unit: fraction
    }

    PlantComponents
    {
        Component GasTurbineDrive: GTPort
        {
            PowerSetting= 0 ;
        }

        Component GasTurbineDrive: GTStbd
        {
            PowerSetting= 0 ;
        }

        Component DieselDrive: DEPort
        {
            FuelFlowRatio= 0 ;
        }

        Component DieselDrive: DEStbd
        {
            FuelFlowRatio= 0 ;
        }

        Component DieselDrive: DG1
        {
            FuelFlowRatio= 0.5 ;
        }

        Component DieselDrive: DG2
        {
            FuelFlowRatio= 0.5 ;
        }

        Component DieselDrive: DG3
        {
            FuelFlowRatio= 0.5 ;
        }

        Component ElectricSwitchBoard: SB
        {
            AuxLoad= 4200; //2*2100kWe
        }
    }
}

} //plantSimRun end

```

Q.8 Notional Destroyer CODELAG

```
//9600t Destroyer
Plant: CODELAG-PropPlant
{
    PlantDefinition
    {
        PlantType= Marine;           //can be Aero
        UnitSystem= SI;              //SI/IM

        SpeedRangeMax= 35;           //in knots
        SpeedRangeMin= 4;            //in knots, optional: default 5 knts

        ResistanceCurvesDataPoints= 20; //optional: default 50 points
        PropellerCurvesDataPoints= 20; //optional: default 50 points

        EnduranceDistance= 5000;     //nm
        TankageCapacity= 1200;       //metric t

        SeaStateFoulingFactor= 1;
        PlantDeteriorationFactor= 1;

        EnduranceCalculationMode=3;  //1=calc tankage (dist given),
                                   //2=calc dist (tankage given), 3= calc both (default)
    }

    Ambient
    {
        DevFmISATemp= 0;            //unit: temp
        DevFmISAPress= 0;           //unit: press
        RelHumidity= 0.60;          //unit: fraction

        WaterType= SW;              //SW=seawater; FW= fresh water: if not entered, SW assumed by default
        DevFmStdWaterTemp= 0;
        DevFmStdSalinity=0;         //sea water salinity in SP (practical salinity)
    }

    PlantComponents
    {
        Component Hull: 9600tDestroyer
        {
            HullModelType= Calc;     //Curve OR Calc: user defined curve
                                   //or calculate based on regression models
            HullModelCurve= curvename; //if HullModelType= Curve
            HullCalcType= F&L;       //if HullModelType= Calc: H&M or F&L or Hollenbach

            //Gen Paras (not method specific)

            Lpp= 154;                //Length between perpendiculars: m
            Lwl= 144.68;             //Length on waterline: m
            Beam= 18.5;              //Beam: m
            Tf= 6.5 ;                //Draft Fwd: m
            Ta= 7.5 ;                //Draft Aft: m
            DispTons= 9585 ;         //Disp: metric tons.

            Cm= 0.8280 ;             //Coeff Midship Area : 0<Cm<1
            Cwp= 0.7910 ;           //Coeff Waterplane: 0<Cwp<1
            At= 12 ;                 //Area transverse transom immersed

            iE= 10.9 ;              //Half angle of entrance, if not entered, calc by prog

            Sapp= 300;               //SA of appendages: m^2
            AppResisFac= 3 ;         //1+k2: Appendages Resistance factor used with Appendage resistance

            Ap= 420 ;                //air frontal area, m2

            //Fung
            Bt= 12 ;                 //Beam at transom
        } //hull end
    }
}
```

```

Component Propeller: PropStbd
{
    PropType= CPP;                //FPP or CPP
    PropModelType= Calc;          //Curve OR Calc: calculate based on series
    PropCalcType= WB;            //if PropModelType= Calc .. WB:Wangenin B Series

    Dia= 5.18;                   //Propeller Dia in m
    DesignPitch= 7.271;          //Design Pitch in m
    EAR= 0.5957;                 //Expanded Area Ratio
    nBlades= 5;                  //no of blades
    MaxPropSpeed= 203.57;        //maximum speed in rpm
}

Component Propeller: PropPort
{
    PropType= CPP;                //FPP or CPP
    PropModelType= Calc;          //Curve OR Calc: calculate based on series
    PropCalcType= WB;            //if PropModelType= Calc .. WB:Wangenin B Series

    Dia= 5.18;                   //Propeller Dia in m
    DesignPitch= 7.271;          //Design Pitch in m
    EAR= 0.5957;                 //Expanded Area Ratio
    nBlades= 5;                  //no of blades
    MaxPropSpeed= 203.57;        //maximum speed in rpm
}

Component PropShaft: PSStbd
{
    ShaftLossFactor= 0.01;        //at DP
}

Component PropShaft: PSPort
{
    ShaftLossFactor= 0.01;        //at DP
}

Component DriveAdder: AdderStbd //Junction
{
    DriveAdderLossType= NoLoss;    //0= NoLoss (default); 1= Constant; 2= Curve
}

Component DriveAdder: AdderPort //Junction
{
    DriveAdderLossType= NoLoss;    //0= NoLoss (default); 1= Constant; 2= Curve
}

Component Gearing: GearingGTStbd
{
    GearingReductionRatio1= 18.233 ; //also used as GR1 for dimensioning
    GearingLossFactor= 0.035;        //for fixed factor losses only
}

Component Clutch: ClutchGTStbd
{
    ClutchLossType= NoLoss;        //0= NoLoss (default); 1= Constant; 2= Curve
}

Component Clutch: ClutchGTPort
{
    ClutchLossType= NoLoss;        //0= NoLoss (default); 1= Constant; 2= Curve
}

Component GasTurbineDrive: GTStbd
{
    ModelFileName= GT36MW ;
    SimType= Internal;             //based on model(Internal)
                                    //or maps (External)..currently only model

    PowerNom= 36000;               //Shaft power nom in kW
    SpeedNom= 3300;                //PT nom spd in rpm
}

```

```

Component GasTurbineDrive: GTPort
{
    ModelFileName= GT36MW ;
    SimType= Internal;          //based on model(Internal)
                                //or maps (External)..currently only model

    PowerNom= 36000;           //Shaft power nom in kW
    SpeedNom= 3300;            //PT nom spd in rpm
}

Component DieselDrive: DG1
{
    DieselDriveType= Genset ;    //Genset or Direct
    PowerNom= 6720;              //in kW
    SpeedNom= 720;               //rpm
    PowerRatioDP= 1 ;
    SpeedRatioDP= 1;
    sfcDP= 0.185;                //in kg/kW-hr
    ShapingFnFac= 0.7;           //default= 0.7
}

Component DieselDrive: DG2
{
    DieselDriveType= Genset ;    //Genset or Direct
    PowerNom= 6720;              //in kW
    SpeedNom= 720;               //rpm
    PowerRatioDP= 1 ;
    SpeedRatioDP= 1;
    sfcDP= 0.185;                //in kg/kW-hr
    ShapingFnFac= 0.7;           //default= 0.7
}

Component DieselDrive: DG3
{
    DieselDriveType= Genset ;    //Genset or Direct
    PowerNom= 6720;              //in kW
    SpeedNom= 720;               //rpm
    PowerRatioDP= 1 ;
    SpeedRatioDP= 1;
    sfcDP= 0.185;                //in kg/kW-hr
    ShapingFnFac= 0.7;           //default= 0.7
}

Component ElectricDrive: EMPort
{
    ElectricDriveType= PTI ;
    ElectricDriveCat= Induction ; //Induction or AdvInduction

    ElDriveVoltageRated= 6600 ;   //Volts
    ElDriveCurrentRated= 450;     //Amp
    ElDrivePowerFacRated= 0.9;
    FreqDriveCat= PWM;
    SpeedNom= 87 ;                //rpm
}

Component ElectricDrive: EMStbd
{
    ElectricDriveType= PTI ;
    ElectricDriveCat= Induction ; //Induction or AdvInduction
    ElDriveVoltageRated= 6600 ;   //Volts
    ElDriveCurrentRated= 450 ;    //Amp
    ElDrivePowerFacRated= 0.9;
    FreqDriveCat= PWM;            //1=PWM;
    SpeedNom= 87 ;                //rpm
}

Component ElectricSwitchBoard: SB1 //ID for the text file
{
    ElSBEtaRated= 0.995;          //optional
}

Component ElectricSwitchBoard: SB2 //ID for the text file
{
    ElSBEtaRated= 0.995;          //optional
}

} //end components

```

```

PlantConnections
{
    //Stbd side train

    Connection: con1 { GTStbd(Out); ClutchGTStbd(In)}
    Connection: con2 { ClutchGTStbd(Out); GearingGTStbd(In)}
    Connection: con3 { GearingGTStbd(Out); AdderStbd(Inline1)}
    Connection: con8 { AdderStbd(Inline2); PSStd(In)}
    Connection: con9 { EMStbd(Out); AdderStbd(Crossline)}
    Connection: con10 { PSStd(Out); PropStbd(In)}

    //Port side train

    Connection: con11 { GTPort(Out); ClutchGTPort(In)}
    Connection: con12 { ClutchGTPort(Out); GearingGTPort(In)}
    Connection: con13 { GearingGTPort(Out); AdderPort(Inline1)}
    Connection: con19 { EMPort(Out); AdderPort(Crossline)}
    Connection: con18 { AdderPort(Inline2); PSPort(In)}
    Connection: con20 { PSPort(Out); PropPort(In)}
}

PlantElConnections
{
    ElConnection: elCon01 { DG1(Out); SB1(In1)}
    ElConnection: elCon02 { DG2(Out); SB1(In2)}

    ElConnection: elCon03 { DG3(Out); SB2(In2)}
    ElConnection: elCon04 { DG4(Out); SB2(In3)}

    ElConnection: elCon05 { SB1(Out1); EMStbd(In)}
    ElConnection: elCon06 { SB2(Out1); EMPort(In)}
}

PlantDriveModes
{
    DriveMode: 2GT { GTPort(On); GTStbd(On); ClutchGTPort(On); ClutchGTStbd(On)}

    DriveMode: 2EM2DG { EMPort(On); EMStbd(On); DG1(On); DG3(On)}

    DriveMode: 2EM3DG { EMPort(On); EMStbd(On); DG1(On); DG2(On); DG3(On)}

    DriveMode: CODELAG { EMPort(On); EMStbd(On); DG1(On); DG2(On);
                        DG3(On); GTPort(On); GTStbd(On); ClutchGTPort(On); ClutchGTStbd(On)}
}

} //plant end

PlantSimulationRun: CODELAG //SimRunName
{
    DriveMode= 2EM2DG ;

    Ambient //to set Amb paras in OD: optional
    {
        DevFmISATemp= 0; //unit: temp
        DevFmISAPress= 0; //unit: press
        RelHumidity= 0; //unit: fraction
    }
}

```

```

PlantComponents
{
    Component GasTurbineDrive: GTPort
    {
        PowerSetting= 0 ;
    }

    Component GasTurbineDrive: GTStbd
    {
        PowerSetting= 0 ;
    }

    Component DieselDrive: DG1
    {
        FuelFlowRatio= 0.5 ;
    }

    Component DieselDrive: DG2
    {
        FuelFlowRatio= 0.5 ;
    }

    Component DieselDrive: DG3
    {
        FuelFlowRatio= 0.5 ;
    }

    Component ElectricSwitchBoard: SB1
    {
        AuxLoad= 2100; //kWe
    }

    Component ElectricSwitchBoard: SB2
    {
        AuxLoad= 2100; //kWe
    }
}

} //plantSimRun end

```


Q.9 Notional Destroyer IFEP

```
//9600t Destroyer
Plant: CODAGPropPlant
{
    PlantDefinition
    {
        PlantType= Marine;           //can be Aero
        UnitSystem= SI;              //SI/IM

        SpeedRangeMax= 35;           //in knots
        SpeedRangeMin= 4;            //in knots: if not specified: default 5 knts

        ResistanceCurvesDataPoints= 20; //optional: default 50 points
        PropellerCurvesDataPoints= 20; //optional: default 50 points

        EnduranceDistance= 5000;      //nm
        TankageCapacity= 1200;        //metric t

        SeaStateFoulingFactor= 1;
        PlantDeteriorationFactor= 1;

        EnduranceCalculationMode=3;    //1=calc tankage (dist given),
                                      //2=calc dist (tankage given), 3= calc both (default)
    }

    Ambient
    {
        DevFmISATemp= 0;             //unit: temp
        DevFmISAPress= 0;            //unit: press
        RelHumidity= 0.60;           //unit: fraction

        WaterType= SW;               //SW=seawater; FW= fresh water: if not entered, SW assumed by default
        DevFmStdWaterTemp= 0;
        DevFmStdSalinity=0;          //sea water salinity in SP (practical salinity)
    }

    PlantComponents
    {
        Component Hull: 9600tDestroyer
        {
            HullModelType= Calc;      //Curve OR Calc: user defined curve
                                      //or calculate based on regression models
            HullModelCurve= curvename; //if HullModelType= Curve
            HullCalcType= F&L;        //if HullModelType= Calc: H&M or F&L or Hollenbach

            //Gen Paras (not method specific)

            Lpp= 154;                 //Length between perpendiculars: m
            Lwl= 144.68;              //Length on waterline: m
            Beam= 18.5;               //Beam: m
            Tf= 6.5 ;                 //Draft Fwd: m
            Ta= 7.5 ;                 //Draft Aft: m
            DispTons= 9585;           //Disp: metric tons.

            Cm= 0.8280;               //Coeff Midship Area : 0<Cm<1
            Cwp= 0.7910 ;             //Coeff Waterplane: 0<Cwp<1

            At= 12 ;                  //Area transverse transom immersed

            iE= 10.9;                 //Half angle of entrance, if not entered, calc by prog

            Sapp= 300;                //SA of appendages: m^2
            AppResisFac= 3 ;          //1+k2: Appendages Resistance factor used with
                                      //Appendage resistance Rapp: Default no effect, unless > 1 specified

            Ap= 420;                  //air frontal area, m^2

            //Fung
            Bt= 12 ;                  //Beam at transom
        } //hull end
    }
}
```

```

Component Propeller: PropStbd
{
    PropType= CPP;                //FPP or CPP
    PropModelType= Calc;          //Curve OR Calc: calculate based on series
    PropCalcType= WB;             //if PropModelType= Calc .. WB:Wangenin B Series

    Dia= 5.18;                   //Propeller Dia in m
    DesignPitch= 7.271;          //Design Pitch in m
    EAR= 0.5957;                 //Expanded Area Ratio
    nBlades= 5;                  //no of blades
    MaxPropSpeed= 203.57;        //maximum speed in rpm
}

Component Propeller: PropPort
{
    PropType= CPP;                //FPP or CPP
    PropModelType= Calc;          //Curve OR Calc: calculate based on series
    PropCalcType= WB;             //if PropModelType= Calc .. WB:Wangenin B Series

    Dia= 5.18;                   //Propeller Dia in m
    DesignPitch= 7.271;          //Design Pitch in m
    EAR= 0.5957;                 //Expanded Area Ratio
    nBlades= 5;                  //no of blades
    MaxPropSpeed= 203.57;        //maximum speed in rpm
}

Component PropShaft: PSStbd
{
    ShaftLossFactor= 0.01;
}

Component PropShaft: PSPort
{
    ShaftLossFactor= 0.01;
}

Component ElectricDrive: EMPort
{
    ElectricDriveType= PTI ;
    ElectricDriveCat= Induction ; //Induction or AdvInduction
    ElDriveVoltageRated= 11000 ; //Volts
    ElDriveCurrentRated= 2430 ; //Amp
    ElDrivePowerFacRated= 0.9;
    FreqDriveCat= PWM;           //1=PWM;
    SpeedNom= 180 ;              //rpm
}

Component ElectricDrive: EMStbd
{
    ElectricDriveType= PTI ;
    ElectricDriveCat= Induction ; //Induction or AdvInduction
    ElDriveVoltageRated= 11000 ; //Volts
    ElDriveCurrentRated= 2430 ; //Amp
    ElDrivePowerFacRated= 0.9;
    FreqDriveCat= PWM;           //1=PWM;
    SpeedNom= 180 ;              //rpm
}

Component GasTurbineDrive: GTA1
{
    ModelFileName= GT36MW ;
    SimType= Internal;           //based on model(Internal)
                                   //or maps (External)..currently only model
    PowerNom= 36000;             //Shaft power nom in kW
    SpeedNom= 3300;              //PT nom spd in rpm
    GTDriveType= GenSet;         //Direct or GenSet
}

```

```

Component Propeller: PropStbd
{
    PropType= CPP;                //FPP or CPP
    PropModelType= Calc;          //Curve OR Calc: calculate based on series
    PropCalcType= WB;            //if PropModelType= Calc .. WB:Wangenin B Series

    Dia= 5.18;                   //Propeller Dia in m
    DesignPitch= 7.271;          //Design Pitch in m
    EAR= 0.5957;                 //Expanded Area Ratio
    nBlades= 5;                  //no of blades
    MaxPropSpeed= 203.57;        //maximum speed in rpm
}

Component Propeller: PropPort
{
    PropType= CPP;                //FPP or CPP
    PropModelType= Calc;          //Curve OR Calc: calculate based on series
    PropCalcType= WB;            //if PropModelType= Calc .. WB:Wangenin B Series

    Dia= 5.18;                   //Propeller Dia in m
    DesignPitch= 7.271;          //Design Pitch in m
    EAR= 0.5957;                 //Expanded Area Ratio
    nBlades= 5;                  //no of blades
    MaxPropSpeed= 203.57;        //maximum speed in rpm
}

Component PropShaft: PSStbd
{
    ShaftLossFactor= 0.01;
}

Component PropShaft: PSPort
{
    ShaftLossFactor= 0.01;
}

Component ElectricDrive: EMPort
{
    ElectricDriveType= PTI ;
    ElectricDriveCat= Induction ; //Induction or AdvInduction
    ElDriveVoltageRated= 11000 ; //Volts
    ElDriveCurrentRated= 2430 ; //Amp
    ElDrivePowerFacRated= 0.9;
    FreqDriveCat= PWM;           //1=PWM;
    SpeedNom= 180 ;              //rpm
}

Component ElectricDrive: EMStbd
{
    ElectricDriveType= PTI ;
    ElectricDriveCat= Induction ; //Induction or AdvInduction
    ElDriveVoltageRated= 11000 ; //Volts
    ElDriveCurrentRated= 2430 ; //Amp
    ElDrivePowerFacRated= 0.9;
    FreqDriveCat= PWM;           //1=PWM;
    SpeedNom= 180 ;              //rpm
}

Component GasTurbineDrive: GTA1
{
    ModelFileName= GT36MW ;
    SimType= Internal;           //based on model(Internal)
                                   //or maps (External)..currently only model
    PowerNom= 36000;             //Shaft power nom in kW
    SpeedNom= 3300;              //PT nom spd in rpm
    GTDriveType= GenSet;         //Direct or GenSet
}

```

```

Component Propeller: PropStbd
{
    PropType= CPP;                //FPP or CPP
    PropModelType= Calc;          //Curve OR Calc: calculate based on series
    PropCalcType= WB;            //if PropModelType= Calc .. WB:Wangenin B Series

    Dia= 5.18;                   //Propeller Dia in m
    DesignPitch= 7.271;          //Design Pitch in m
    EAR= 0.5957;                 //Expanded Area Ratio
    nBlades= 5;                  //no of blades
    MaxPropSpeed= 203.57;        //maximum speed in rpm
}

Component Propeller: PropPort
{
    PropType= CPP;                //FPP or CPP
    PropModelType= Calc;          //Curve OR Calc: calculate based on series
    PropCalcType= WB;            //if PropModelType= Calc .. WB:Wangenin B Series

    Dia= 5.18;                   //Propeller Dia in m
    DesignPitch= 7.271;          //Design Pitch in m
    EAR= 0.5957;                 //Expanded Area Ratio
    nBlades= 5;                  //no of blades
    MaxPropSpeed= 203.57;        //maximum speed in rpm
}

Component PropShaft: PSStbd
{
    ShaftLossFactor= 0.01;
}

Component PropShaft: PSPort
{
    ShaftLossFactor= 0.01;
}

Component ElectricDrive: EMPort
{
    ElectricDriveType= PTI ;
    ElectricDriveCat= Induction ; //Induction or AdvInduction
    ElDriveVoltageRated= 11000 ; //Volts
    ElDriveCurrentRated= 2430 ; //Amp
    ElDrivePowerFacRated= 0.9;
    FreqDriveCat= PWM;           //1=PWM;
    SpeedNom= 180 ;              //rpm
}

Component ElectricDrive: EMStbd
{
    ElectricDriveType= PTI ;
    ElectricDriveCat= Induction ; //Induction or AdvInduction
    ElDriveVoltageRated= 11000 ; //Volts
    ElDriveCurrentRated= 2430 ; //Amp
    ElDrivePowerFacRated= 0.9;
    FreqDriveCat= PWM;           //1=PWM;
    SpeedNom= 180 ;              //rpm
}

Component GasTurbineDrive: GTA1
{
    ModelFileName= GT36MW ;
    SimType= Internal;           //based on model(Internal)
                                   //or maps (External)..currently only model
    PowerNom= 36000;             //Shaft power nom in kW
    SpeedNom= 3300;              //PT nom spd in rpm
    GTDriveType= GenSet;         //Direct or GenSet
}

```

```

PlantComponents
{
    Component GasTurbineDrive: GTA1
    {
        PowerSetting= 0 ;           //handle PCN
    }

    Component GasTurbineDrive: GTA2
    {
        PowerSetting= 0 ;           //handle PCN
    }

    Component DieselDrive: DG1
    {
        FuelFlowRatio= 0.5 ;       // COT in K or in kg/s, presently COT
    }

    Component DieselDrive: DG2
    {
        FuelFlowRatio= 0.5 ;       // COT in K or in kg/s, presently COT
    }

    Component DieselDrive: DG3
    {
        FuelFlowRatio= 0 ;         // COT in K or in kg/s, presently COT
    }

    Component DieselDrive: DG4
    {
        FuelFlowRatio= 0 ;         // COT in K or in kg/s, presently COT
    }

    Component ElectricSwitchBoard: SB1
    {
        AuxLoad= 2100; //kWe
    }

    Component ElectricSwitchBoard: SB2
    {
        AuxLoad= 2100; //kWe
    }
}

} //plantSimRun end

```

Appendix R Model Input Files for Validation Resistance Model and Propeller Optimizer

R.1 Propeller Optimizer

```
//PropellerOptimizationValidation
//Ref1:Bernistas1982
//Ref2:Radojcic1985
Plant: PropellerOptimizationValidation
{
    PlantDefinition
    {
        PlantType= Marine;
        PropellerCurvesDataPoints= 20; //int, optional: default 50 points
    }

    Ambient
    {
        WaterType= SW; //SW=seawater; FW= fresh water: if not entered, SW assumed by default
        DevFmStdWaterTemp= 0; //deg C, Std Temp = 15 deg C
        DevFmStdSalinity=0; //sea water salinity in SP (practical salinity)
    }

    PlantComponents
    {
        Component Propeller: PropellerOptimizationValidation
        {
            PropellerName= Bernistas;
            PropType= CPP; //FPP or CPP
            PropModelType= Calc; //Curve OR Calc: calculate based on series

            //PropModelCurve= curvename; //if PropModelType= Curve

            PropCalcType= WB //if PropModelType= Calc .. WB:Wangenin B Series

            Dia= 5.4864; //Propeller Dia in m
            DesignPitch= 7.681; //Design Pitch in m
            EAR= 0.6456; //Expanded Area Ratio
            nBlades= 5; //no of blades
            MaxPropSpeed= 100; //maximum speed in rpm
        }

        Component PropellerOptimization: PropellerOptimizationValidation
        {
            PropCalcType= WB //if PropModelType= Calc .. WB:Wangenin B Series
            PropOptimMode= Spd; //Spd: Prop spd is optimized given the Prop Dia;
            //Dia: Prop dia is optimized, given the prop speed.
            //If not specified, Spd is assumed.

            ResistancePropeller= 275.344; //kN, resistance per propeller
            ShipSpeed= 16; //knots
            ThDednFac= 0.155; //Thrust Deduction Factor
            WakeFraction= 0.252; //Wake Fraction
            nBlades= 5;
            PropellerDia= 5.4864; //m, not reqd if Dia is being optimized

            //PropellerSpeed= xx; //rpm, not reqd if Speed is being optimized
            //PropellerDraught= 3.983; //m, can be used to calc,
            //at least the PropellerDraught should be specified,
            //from where it can be approximated
            //considering propeller tip to be in line with base line.

            PropellerCenterDepth= 3.983; //m, depth below waterline,
            //For PropOptimMode= if not specified,
            //atleast the PropellerDraught should be specified,
            //from where it can be approximated
            //considering propeller tip to be in line with base line.

            //EARmax= xx; //Constraint, if not specied applied by prog: 1.05
            //EARmin= xx; //Constraint: 0.3
            //PDmax= xx; //Constraint: 1.4
            //PDmin= xx; //Constraint: 0.5
            //Jmax= xx; //Constraint: 1.7
            //Jmin= xx; //Constraint: 0
        }
    }
}
```

R.2 Resistance Model

```
//DDG51 Flt II
//Ref: HYDROSTATIC AND HYDRODYNAMIC ANALYSIS OF A LENGTHENED DDG-51 DESTROYER MODIFIED
//REPEAT by Justin Hlavin

Plant: DDG51FltIIResistance
{
    PlantDefinition
    {
        PlantType= Marine;      //can be Aero
        UnitSystem= SI;         //SI/IM
        SpeedRangeMax= 32;      //in knots
        SpeedRangeMin= 4;       //In knots: if not specified: default 5 knts

        ResistanceCurvesDataPoints= 20;      //optional: default 50 points
        PropellerCurvesDataPoints= 20;      //optional: default 50 points
    }

    Ambient
    {
        WaterType= SW;          //SW=seawater; FW= fresh water: if not entered, SW assumed by default
        DevFmStdWaterTemp= 0;
        DevFmStdSalinity=0;     //sea water salinity in SP (practical salinity)
    }

    PlantComponents
    {
        Component Hull: DDG51 Flt II
        {
            HullModelType= Calc; //Curve OR Calc: user defined curve
                                //or calculate based on regression models
            //HullModelCurve= curvename; //if HullModelType= Curve
            HullCalcType= F&L;    //if HullModelType= Calc: H&M or F&L or Hollenbach

            //Gen Paras (not method specific)

            Lpp= 154;             //Length between perpendiculars: m
            Lwl= 144.68;          //Length on waterline: m
            Beam= 18.5;           //Beam: m
            Tf= 6.5 ;             //Draft Fwd: m
            Ta= 7.5 ;             //Draft Aft: m
            DispTons= 9584.60;     //Disp: metric tons. 9499.2 m3 moulded vol

            Cm= 0.8280;            //Coeff Midship Area : 0<Cm<1
            Cwp= 0.7910 ;          //Coeff Waterplane: 0<Cwp<1

            At= 12 ;               //Area transverse transom immersed

            iE= 10.9;              //Half angle of entrance, if not entered, calc by prog
            WSA= 3032 ;            //Wetted SA: if not given, calc by prog

            //Ca= 0.9 ;             //Model correlation coeff : if not given, calc by prog
            //HullFormFac = 3 ;      //1+k1: Form factor of hull used with frictional resistance Rf:
                                //Default no effect, unless > 1 specified by user or H&M Method where its calculated.
                                //If in H&M this fac should not be applied, set =1.

            Sapp= 300;             //SA of appendages: m^2 , here taken as about 10%
            AppResisFac= 3 ;       //1+k2: Appendages Resistance factor used with Appendage resistance

            //Ks= 1.2;              //Hull Roughness

            //Cd= xx;               //air drag coeff, optional
            Ap= 420;               //air frontal area, m2

            //H&M

            lcb= -1 ;              //fwd(+) or aft(-) of half of Lwl
            Cstern= 0;             //Coeff stern: V-shaped sections: - 10,
                                //Normal section shape: 0, U-shaped sections with Hoaner stern + 10

            //Fung

            Bt= 12 ;               //Beam at transom

            //Hollenbach

            //Los= xx;              //Length over surface: If not defined, taken same as Lwl.
            //DraftConfig= xx;      //1=design draft, 2=ballast draft,
                                //3=with bulbous bow,
                                //4= without bulbous bow; assumed =1, if not specified.

            Nrudders= 2;           //no of rudders
            Nbrackets= 4;          //no of brackets
            Nbosses= xx;           //no of bosses
            Nthrusters= xx;        //int: no of thrusters

            //User defined Prop Fac..if specified, prog will use these instead of calc
            //WakeFrac = 0.1 ; //wake fraction: can be calc if not
            //ThDednFac= 0.1 ; //Thrust Dedn Fac
            //etaR = 0.98 ;         //Relative rotative efficiency

            //Additional Paras if only resistance module used
            Npropellers= 2;        //No of propellers
            Dp= 5.18;              //Dia of propeller, m
            Pp= 5.18;              //Pitch of propeller, m
            AeAoRatioProp = 0.76 ;
            etaOp= 0.98 ; //openwater efficiency of prop

        } //hull end
    } //end components
} //plantSimRun end
```