INTEGRATION OF SYSTEMS AND CONCURRENT ENGINEERING USING ARTIFICIAL INTELLIGENCE IN IMPROVING PASSENGER SHIP PRELIMINARY DESIGN

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DEDICATION

This thesis is dedicated to all who have supported me throughout my journey especially to my mother, mother- and fathers-in-law, my wife and my children for their loves, cares, patients, and sacrifices

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ABSTRACT

Designing ships having large and complex systems involves prescribed design parameters development and is typically executed exhaustively through iterations. The processes become challenging as the design complexity increases. This is due to the simplistic and sequential approach of the conventional ship design spiral model. To mitigate this, a data-centric and integrated design approach with artificial intelligence (*AI*) was proposed as objective in this thesis. It was applied to simulate the passenger ship's preliminary design developments based on the identified design goals, requirements, and data. The methodology was carried out in deriving a ship design methodological framework, ship design processes, knowledge graph, predictive models, and computer-based design tools. An extension to the integrated Quality Function Deployment and Axiomatic Design (*QFD-AD*) method was proposed to establish and analyse the design functional requirements, parameters, data, and tasks concurrencies. It was further explored using graph theory to represent the ship design, data, and their relationships. Finally, *AI* and deep learning (*DL*) methods were explored to develop and deploy prediction models at the graph nodes to determine the ship preliminary design principal parameters. These steps led to the development of a computer-based design tool to simulate and evaluate the ship design. The method was then applied to investigate and evaluate a generic passenger ship design model. The results from the design modelling, prediction model and empirical approximation were compared, evaluated, and discussed. While the stepwise empirical model algorithm was ten times faster, it was restricted by the set of hard rules that are based on assumptions. Though, the speed was highly influenced by the algorithm complexity and number of iterations till convergence. This phenomenon was observed in the brake power (*P*) prediction where the data-centric approach outperforms the Bailey's rule-based model by four times with a nearly accurate result. This work showed significant impact in terms of simplifying the existing ship design model, evoking design information, and producing fast and nearly optimal solution. It lightened the effort in initiating the design in terms of data collection, requirement analysis and planning in the conceptual and preliminary designs phases. Importantly, it shows the potential for a broad range of applications, scales, and design automation.

ABSTRAK

Merekabentuk kapal dengan sistem yang besar dan kompleks melibatkan pembangunan parameter tetap rekabentuk yang biasa dilakukan secara mendalam melalui lelaran. Proses tersebut lebih mencabar apabila rekabentuk semakin rumit. Ini disebabkan pendekatan simplistik dan berurutan model rekabentuk kapal lingkaran konvensional. Untuk mengurangkan kesan ini, pendekatan berpusatkan data dan rekabentuk bersepadu dengan kecerdasan buatan (*AI*) dicadangkan sebagai objektif tesis ini. Ia dilaksanakan untuk mensimulasi pembangunan rekabentuk awal kapal penumpang berdasarkan matlamat rekabentuk, keperluan dan data. Metodologi ini dilaksanakan bagi menghasilkan satu rangka kerja metodologi rekabentuk kapal, proses rekabentuk kapal, graf pengetahuan, model ramalan, dan alat rekabentuk berbantu komputer. Satu lanjutan kepada kaedah Pembahagian Fungsi Kualiti dan Rekabentuk Aksiomatik (*QFD-AD*) bersepadu telah dicadangkan bagi menghasilkan dan menganalisa keperluan-keperluan fungsi, parameter-parameter, data dan kelarasan tugas rekabentuk. Ia seterusnya diterokai menggunakan teori graf untuk mewakili rekabentuk kapal, data dan hubungannya. Akhirnya, kaedah kecerdasan buatan dan pembelajaran dalam (*DL*) diterokai bagi membangun dan mengatur model ramalan pada nod-nod graf bagi menentukan parameter utama rekabentuk awal kapal. Langkah-langkah ini membawa kepada pembangunan alat rekabentuk berbantu komputer bagi mensimulasikan dan menilai rekabentuk kapal. Kaedah ini seterusnya digunakan untuk mengkaji dan menilai satu model generik rekabentuk kapal penumpang. Keputusan dari permodelan rekabentuk, model ramalan dan anggaran empirikal dibandingkan, dinilai dan dibincangkan. Sementara algoritma model empirikal adalah sepuluh kali lebih pantas, ia terkekang oleh peraturan yang ditetapkan mengikut andaian. Namun, kepantasan tersebut sangat dipengaruhi oleh kerumitan algoritma dan bilangan lelaran sehingga menumpu. Fenomena ini terlihat dalam ramalan kuasa brek (*P*) dimana pendekatan berpusatkan data menjangkau prestasi model berasaskan peraturan Bailey sebanyak empat kali dengan keputusan hampir tepat. Kerja ini menunjukkan impak ketara dalam meringkaskan model rekabentuk kapal sedia ada, membangkitkan maklumat rekabentuk dan menghasilkan penyelesaian yang cepat dan hampir optimum. Ia meringankan usaha dalam memulakan rekabentuk dari segi pengumpulan data, analisa keperluan dan perancangan bagi fasa rekabentuk konsep dan awal. Yang lebih penting, ia menunjukkan potensi untuk pelbagai aplikasi, skala dan automasi rekabentuk.

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LIST OF ABBREVIATIONS

PBD	-	Parametric-based design
SBD	-	Simulation-based design
DBB	-	Design building block
MCDM	-	Multi-Criteria Decision Making
AI	-	Artificial Intelligence
DL	-	Deep Learning
ML	-	Machine Learning
ANN	-	Artificial Neural Network
LBFGS		limited-memory Broyden-Fletcher-Goldfarb-Shanno
SGD	-	Stochastic Gradient Descent
API	-	Application Programming Interface
DWT	-	Deadweight
GT	-	Gross Tonnage
QFD	-	Quality Function Deployment
AD	-	Axiomatic Design
HoQ	-	House of Quality Chart
RINA	-	Royal Institute of Naval Architecture
SNAME	-	Society of Naval Architects and Marine Engineers
SOLAS	-	International Convention for Safety of Life at Sea
ITTC	-	International Towing Tank Conference
ROPAX	-	Roll On/Roll Off Passenger Ship
RORO	-	Roll On/Roll Off Ship
PC	-	Principal Component
PC1	-	First Principal Component
FAST	-	Functional Analysis System Technique
FR	-	Functional Requirement
DP	-	Design Parameters
G	-	Graph
$\tilde{V}$	-	Vertex
E	-	Edge

RDF	-	Resource Description Framework
LPG	-	Labelled Property Graph
CAD	-	Computer Aided Design
GHz	-	Giga Hertz
MHz	-	Mega Hertz
CPU	-	Central Processing Unit
HDD	-	Hard Disk Drive
GPU	-	Graphic Processing Unit
WSL2	-	Windows Subsystem for Linux 2
MAE	-	Mean Absolute Error
MSE	-	Mean Squared Error
RMSE	-	Root Mean Squared Error
ID	-	Identification
Disp	-	Displacement
LCB	-	Longitudinal Centre of Buoyancy
%MCR	-	Percent Maximum Continuous Rating

LIST OF SYMBOLS

ρ_{Water}	-	Freshwater Density
ρ_{Salt}	-	Saltwater Density
g	-	Gravitational Constant
Re	-	Reynold Number
Δ	-	Displacement
∇		Volumetric Displacement
L_{OA}	-	Overall Length
L_{WL}	-	Waterline Length
L_{PP}	-	Length Between the Perpendicular
B	-	Breadth
T	-	Draught
D	-	Depth
L/B	-	Length to Breadth Ratio
B/T	-	Breadth to Draught Ratio
C_B	-	Block Coefficient
Fn	-	Froude Number
V_S	-	Service Speed
N_{Pax}	-	Number of Passenger
N_{Veh}	-	Number of Vehicles
A_{WP}	-	Waterplane Area
A_{Pax}	-	Area for Passenger
A_{Veh}	-	Area for Vehicle
P	-	Brake Power
P_E	-	Effective Power
R_T	-	Total Resistance
R_F	-	Frictional Resistance
R_R	-	Residuary Resistance
R_{App}	-	Appendage Resistance
R_A	-	Air Resistance
C_T	-	Total Resistance Coefficient

C_F	-	Frictional Resistance Coefficient
C_R	-	Residuary Resistance Coefficient
S_{Wetted}	-	Wetted Surface
V	-	Speed
LWT	-	Lightweight
DWT	-	Deadweight
Vol_C	-	Volume for Cargo
Vol_S	-	Volume for Structure
Vol_{Other}	-	Volume for Other
ρ	-	Spearman's Rank Correlation Coefficient
d_i	-	Differences Between Paired Ranks
n	-	Constant
S	-	Covariance Matrix
X	-	Arbitrary $n \times p$ Matrix
r	-	Constant
p	-	Constant
L	-	$r \times r$ Diagonal Matrix
U	-	Variable
A	-	Variable
x'	-	Normalize Value
x	-	Data point
x_{min}	-	Minimum Data Value
x_{max}	-	Maximum Data Value
ω	-	Weightage
f_{cost}	-	Cost function
y_i	-	Constant
F_∇	-	Volumetric Froude Number
Ⓜ	-	Froude Length Constant
L_{Model}	-	Model Length
$R_{R/\Delta}$	-	Residuary Resistance to Displacement Ratio
R_N	-	Reynolds Number
υ	-	Kinematic Viscosity

η_D	-	Propulsive Efficiency
η_T	-	Transmission Efficiency
$°C$	-	Degree Celsius
$L2$	-	Ridge regularization term
R^2	-	Measure of fit

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CHAPTER 1

INTRODUCTION

1.1 Problem Background

The preference to domestic maritime transportation is due to the limited access to other transportation modes and cost. This enables coastal economies to gain benefits through volumes of cargo and frequent travels. Generally, maritime logistic and economic activities are explored on serving incoming and outgoing ships and operations. Additionally, they are identified as the principle for new ships designs and operational requirement.

The ship design and operational criteria dictate her design goals, functional requirements, and design parameters. Often, the ship design information is inter-dependent and conflicting thus require multi-criteria trade off. Particularly, modern passenger ships are described as large and complex systems. It performs multiple roles carrying passengers, vehicles and other cargo types delivering services at speeds and distances. This is further extended considering other design information such as the ship hull, machineries, and other operational requirements.

Conventionally, practical ship design is carried out through the point-based approach known as the design spiral model (Evans, 1959). It describes the early prescriptive ship design model, performed iteratively and heuristically through stepwise procedures. Based on pre-identified concept design, the process estimates, refines, and subsequently converges. The overall process can be observed as in Figure 1-1. In practice, the ship design is initiated through the parametric-based design (*PBD*) approach where the design parameters are estimated using on empirical formulas (Roh & Lee, 2018).

The increase in the design information causes challenges to the design process due to functional requirements incompatibilities. This makes the designers to re-assess the design parameters, and rationally compromise the conflicts. The process continues with design iteration until a balanced one is achieved. Consequently, this causes a longer design development cycle and thus affecting the overall cost and quality. This is widely observed in one-off ship designs. It is noted that the key limitations of the design spiral model are due to; 1) difficulties to explicitly define ship attributes and requirements, 2) solution-centred approach in design thinking and decision-making, and 3) highly constrained optimisation-centred design approach.

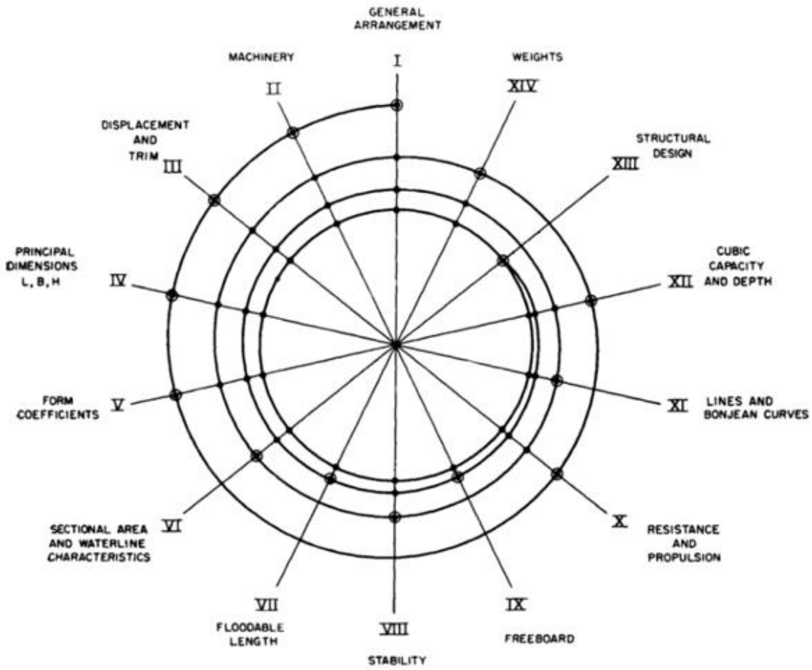

Figure 1-1 Evan’s general ship design model (1959)

The progression to the ship design spiral model continues to introduce many variants. They are developed based on specific ship design perspectives and objectives, and mainly around the operational performance, techno-economic evaluations, and specific features. These criteria introduce more functional requirements and design parameters, prompting design changes and additional iterations. The additional information is typically assessed in an ad-hoc manner (Khairuddin et al., 2019). This makes exploring complex ship design through the design spiral model to be highly challenging. Primarily, the restriction observed is due to the highly constrained sequential design processes.

From the design synthesis context, Pawling et al., (2017) highlights ship design as a nonlinear and non-sequential process, proposing the need to consider alternative ship design approaches. They suggested the ‘problem-centred’ design approach to synthesise and develop complex ship design as opposed to the solution-centred approach. However, the holding back factors in applying the approach are due to implicit design assumptions, insufficient design information and uncertainties, poor requirement analysis and lack of systematic methodology especially for the early design stage.

An approach to designing ship having large and complex systems is the “design building block” (*DBB*) by Andrew (2006) and highlighted again by Pawling et al., (2017). It integrates the *PBD* and simulation-based design (*SBD*) in observing the overall, complex ship design processes. Fundamentally, the method relies on human intervention for the design development and decision-making, outlining a traceable procedure into deducing workable designs using computer-based design tool. Based on the processes, it is acknowledged the requirement elucidation with detail design input serves to minimise uncertainties. This shows that the complex ship design and the design processes complexities are greatly influenced by set design goals, functional requirements and therefore, design parameters and their interactions.

Examining the ship design optimisation, Marzi et al., (2018) explores the approach proposed by Papanikolaou et al., (2010) , termed ‘HOLISHIP’. It applies the systems approach and concurrent engineering for complex ship design processes through *SBD*. Like *DBB*, it considers detailed design inputs at the early design phase to eliminate design uncertainties. The method utilises computer-based applications as a common software platform to integrate and communicate design activities. The concurrent design adopted in the method allows for multi-disciplinary collaborations, aggregated design and analysis modules observing the overall ship design.

In comparison to the *PBD*, the *SBD* approach is initiated based on detailed design requirements, technical analysis, and design validation in the early design stages. However, general *SBD* tends to emphasise on the single design parameter optimisation approach. This is mainly due to disaggregated methods, tools, and complex procedures (Vernengo et al., 2016; Yang & Huang, 2016). Exploring the *PBD*, *SBD* and computer-based platforms seems to provide greater design insight to project members and decision-makers thus reducing design uncertainties. It also delivers better communication especially to multi-disciplinary organisations through common information sharing and architecture.

Another approach is proposed by observing the ships' physical architectures and systems distributions through the 'network-based' method (Brefort, et al., 2018; Brownlow et al., 2021; Pawling & Andrews, 2018; Shields et al., 2017). It is devised to investigate ship physical systems interdependencies. The method is performed by analysing the relationships between the ship design and processes, emphasising on the design intents and functional decompositions leading to the overall ship design formulation. It enables designers to synthesise designs by providing minimum input to generate and tabulate design physical architecture and distributed systems into generating a design solution, assessing the design characteristic and performance (Brefort, et al., 2018; Brownlow et al., 2021).

Whilst it is observed that the conventional ship design processes emphasis on the classical systems approach with focus on the ship design optimisation. Due to the point-based and sequential design approaches, the challenges remain on the design and its organisational parts. To overcome this, research works have been carried out on finding the alternative methods, techniques, and tools particularly in applying the modern systems engineering and concurrent engineering approaches (Khairuddin et al., 2019; Papanikolaou, et al., 2019; Trivyza et al., 2022; Gianni et al., 2021). Recent works are observed exploring the approaches as method improvements to the current ship design and building processes (Dullen et al., 2021; Shallcross et al., 2020; Specking et al., 2018; Sullivan et al., 2021)

1.2 Problem Statement

Design functional requirements and parameters are presented as systems, sub-systems, and components. Conventionally, they are explored heuristically through the *PBD* and *SBD*, often in an ad-hoc basis thus contributing to design and process complexities. Their integrations present significant challenges to the designers and shipbuilders due the sequential model, isolated processes, discrepancy in multi-disciplinary project organisation and decision-making.

Based on the state of the art, it is acknowledged that the ship design complexity is influenced by the modern design and operating requirements. However, the existential issue on how to observe and assess the overall complex ship design and processes are still not well addressed. The issue is also amplified by the lack of systematic methodology in extracting and presenting the design and processes as knowledge. It is also acknowledged that the challenges are due to ineffective and disaggregated design methods, techniques, and tools.

The modern systems engineering, and concurrent engineering approaches have gained considerable attention for its capability to allow multi-disciplinary and integrative design approaches. It centres on solidifying the functional requirements at the early design stage as well performing the design solution synthesis and validation considering the whole design problem. Therefore, the approaches are highlighted as the potential solution, set as the basis for this research.

1.3 Research Goal

The outcome of the study is aimed at producing fast and effective near optimal preliminary ship design process that is scalable, flexible to changes and to support concurrent design process. To achieve this, data-centric, integrated systems and concurrent engineering approaches with artificial intelligence (*AI*) application is proposed.

1.3.1 Research Objectives

The research is achieved through these objectives:

1. To propose and verify integrated systems and concurrent engineering approaches, methods, techniques, and tools for large and complex ship design
2. To model and evaluate generic passenger ship design model, data and characteristics for the design knowledge representation
3. To develop and demonstrate alternative ship design model, methods, techniques, and tool for passenger ship design using the proposed approach
4. To verify and validate the proposed models and computer-based tool for passenger ship design development

1.4 Research Scopes

This study is proposed to investigate ship preliminary design within the planning and preliminary design development phases. It is conducted through the proposed design methodological framework and the use of a developed computer-based design tool.

The ship design modelling is performed by exploring monohull type passenger ship design case study based on the actual data collected from the *RINA* Significant Ships and Significant Small Ships publications, *UTM* towing tank tests reports, and augmented data based on Bailey's (1976) hull series experiment. The cleaned dataset is consisted of up to 110 and 12 features representing the passenger ship design principal parameters; 1) number of passengers (N_{Pax}), 2) number of vehicles (N_{Veh}), 3) waterline length (L_{WL}), 4) breadth (B), 5) draught (T), 6) displacement (Δ), 7) length to breadth ratio (L/B), 8) breadth to draught ratio (B/T), 9) block coefficient (C_B), 10) service speed (V_S), 11) Froude number (Fn), and 12) brake power (P).

The ship design model development and improvement are performed based on the generic preliminary ship design model by Molland (2011) to establish the principal passenger ship design parameters outlined. The model is developed and tested for the data range as in Table 1-1. Additionally, the case study explored for passenger ships carrying either both passengers and vehicles or passenger only.

Table 1-1 Summary of the passenger ship principal design parameters data

	L_{WL} (m)	B (m)	T (m)	L/B	B/T	Δ (t)	C_B	V_S (kn)	N_{Pax}	N_{Veh}	P (kW)
min	86.1	15.8	3.2	3.89	3.52	2519	0.51	14.7	150	25	4324
max	205.7	31.8	7.8	8.60	5.32	26394	0.70	30.0	3200	1340	67200

1.5 Research Significance

This research is carried out to solve the research problem and the identified issues. It highlights the challenges in developing large and complex ship design that is practically observed through conventional ship design spiral models. This work acknowledges the needs to establish ship design information at the early design synthesis stage. Crucially, this work is proposed in-lined to the identified research aim and objectives.

Firstly, this work is proposed to support structured design thinking, knowledge representation and reuse adopting the data centric integrated systems and concurrent engineering approaches with *AI* application to facilitate fast, effective and near optimal preliminary ship design. It emphasises on deriving the overall ship design architecture in extracting and assessing the ship design parameters and processes. Through this, the method is aimed to facilitate better design and processes organisation, assessments, visualisation, and manipulation, providing scalability and flexibility to design changes.

Secondly, the approach emphasises on emulating designers' experience and knowledge into an expert system, thus developed as a computer-based design tool.

Exploiting existing design data and information, it serves to effectively facilitate the ship design development. The application promotes in representing, preserving, and reusing the design knowledge, human-machine interaction and decision making. Therefore, the advantages of the proposed method are targeted at proposing alternative ship design methodology to improve the ship design quality and lead time.

Finally, the proposed methodology is deemed suitable as the basis to incorporate *AI* assisted semi-supervised design. Here, the role of systems engineering, concurrent engineering, and data-centric design approaches are proposed to model and facilitate design solution search and decision-making. Therefore, introducing and implementing *AI* technologies are desirable to semi-automate repetitive design tasks, to support in handling design complexity and to minimise human intervention that can lead to design failure.

The potential benefit of this research is expected to solve the current research needs in complementing if not replacing the conventional design spiral model through the advancement of computer technology and the use of data-centric design approach. Importantly, the proposed approach is devised as a complement to the existing ship design models, particularly observing the problem-centred preliminary design at the planning and preliminary design stages.

1.6 Thesis outline

This thesis encompasses the research works which are further described in the next four chapters. Chapter 2 presents the literature review that provide the background information of the research problem, state-of-the art of the ship design methodology and development approaches, the methods, techniques and tools in engineering design development, and the current *AI* applications in the ship and marine designs, and design process improvements. The chapter is summarised by proposing a systematic methodology and framework to develop an alternative, improved and effective passenger ship preliminary design processes. While chapter 3 describes and summarises the methodological means for developing, demonstrating, evaluating, and validating the proposed method and design tool based on the generic passenger ship design model and actual data. The findings from the research work are described, explained, and discussed in chapter 4 based in the performed illustrative test case. Chapter 4 is summarised by highlighting the significance advantage observed from the proposed method. Finally, the research work is concluded in chapter 5 with recommendations for the future works.

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