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SYSTEMS ENGINEERING FOR SHIP CONCEPT DESIGN

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ABSTRACT

Ship design complexity is contributed by customer needs and interacting design parameters therefore requires for rigorous studies and iterative processes. It is generally performed heuristically following ship design spiral model. Consequently, the design produced is restricted in variant and mainly focusing on single design parameter optimisation. This work is carried out to explore systems engineering as design methodology and to exploit ship design data in developing passenger ship concept design. It describes systems approach in design processes and the use of tools, techniques and methods. It proposes and demonstrates alternative prescriptive design model to develop ship having large and complex systems. It emphasises on identifying ship systems, sub-systems and components, and estimating design parameters thus assessing their inter-dependencies. Importantly, it accesses integrated method applicability to facilitate concurrent design, problem-solution exploration and multi-criteria decision-making processes.

Keywords: *Ship concept design; Systems engineering; Concurrent engineering; Design complexities; Quality function deployment; Axiomatic design*

1.0 INTRODUCTION

Ship design complexity is contributed by detail customer needs and interacting design parameters, mainly influenced by pre-established design requirements and criteria. Thus, ship design parameters developments are often conflicting, involving complex systems interactions. It requires for rigorous studies, multi-criteria decision-making and iterative processes. In recent years, the interests on understanding ship design complexity has increase particularly in design processes, tools, techniques and methods [1]–[4].

Conventionally, ship design is performed heuristically following ship design spiral model and based on best available solution such as platform or sister ship. Design exploration is performed in sequence, simplifying and developing design parameters independently to reduce design complexity. It is achieved by compromising weak design parameters, supressing their interactions and inter-dependencies in achieving balanced design. Consequently, design produced is restricted in variant and mainly focused on single design parameter optimisation. More often, design is executed intuitively around single ‘expert’ perspective, constrained by previously known, simplified and workable

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*Corresponding author: jauhari@umt.edu.my technical solutions. However, one-off ship design and multi-role operation often demand for further design requirements and information beyond techno-economic consideration such as human and environmental factors, operation and lifecycle.

Ensue, modern fast passenger ship is designed to carry passengers, vehicles and other cargo at speeds and distances. The needs are amplified in supporting maritime activities covering 80% of world trades [5], [6]. Apart from cargo space, the hull form, machineries, propulsions and structural design parameters interactions and interdependencies further introduce design complexities. Moreover, their integration is challenging due to the conflicting design parameters. To overcome this, ship design development often requires for concurrent design and trade-off approaches in design decision-making rather than being developed sequentially and optimised independently. Therefore, systems engineering is proposed to support integrative approach to ship design development.

Systems engineering applies systems approach to observe large and complex systems design exploration, development and problem solving through systematic and structured processes. It defines systems as set of elements having well-defined behaviour and functions, subjected to common plan, and serving common purpose [7]. It is also described as man-made, designed and utilised in a defined environment serving its functions to achieve set goals [8]. Emphasising on design synthesis, systems engineering models and structures design parameters as systems, sub-systems and components into hierarchical form. It is typically carried out through functional decomposition and re-composition processes [9]–[11]. They are represented as building blocks, arranged and mapped in logical flow or systems architecture. Design exploration is then executed iteratively to deduce and develop concept design.

This work describes and demonstrates systems engineering in developing passenger ship concept design through analytical modelling, exploiting design data, tools and methods. It proposes alternative prescriptive model to systematically and rationally develop ship design having large complex systems. It is also applied to assess design parameters interactions and developments concurrency.

2.0 SYSTEMS ENGINEERING AND PASSENGER SHIP DESIGN

Ship concept design synthesis is initiated based on pre-established planning phase. The relationships between design processes and phases can be referred as in Figure 1. It presents processes transitions between different domains. This work assumes that planning phase has been pre-determined resulting design goals and top-level requirements presented in Figure 2.

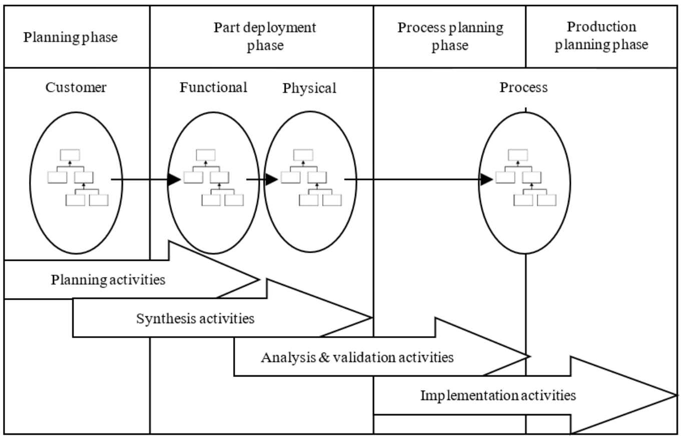


Figure 1: Proposed framework for systems design development

The proposed framework is devised by integrating Akao's "quality function deployment" (QFD) [12] and Suh's "axiomatic design" (AD) [13] methods to facilitate systematic design development and decision-making processes. As in Figure 1, planning phase identifies design goals and top-level "customer needs" (CN). It is carried out in customer domain to identify information and to establish feasibility studies into deducing "functional requirements" (FR). In part deployment phase, FRs are decomposed to deduce "design parameters" (DP) interchangeably within the functional and physical domains. Here, AD function analysis technique facilitates structured transition of vague design idea and needs into concrete design solution represented by DPs. Finally, process and production planning phases describe subsequent activities for construction, test, implementation and others, carried out in the process domain.

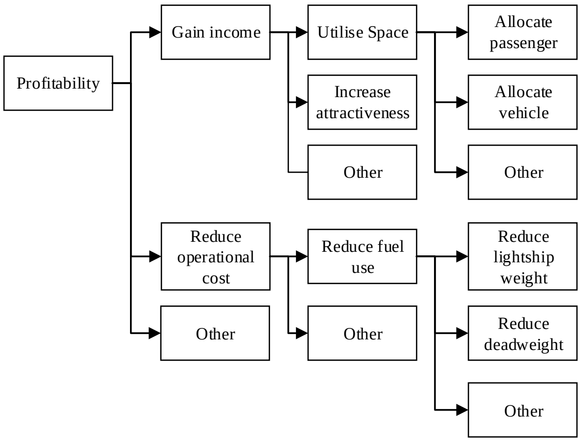


Figure 2: Passenger ship partial owner's requirements functions analysis

Particularly, this work demonstrates systems engineering to synthesis passenger ship concept design following general passenger ship model and volume-based design approach. Based on established planning phase, top-level FRs are deduced and decomposed to derive ship systems structures or DPs. It presents FR-DP mapping that is defined as an integrated system modelled and formulated, assessing their relationships and characteristics.

2.1 Ship functions analysis

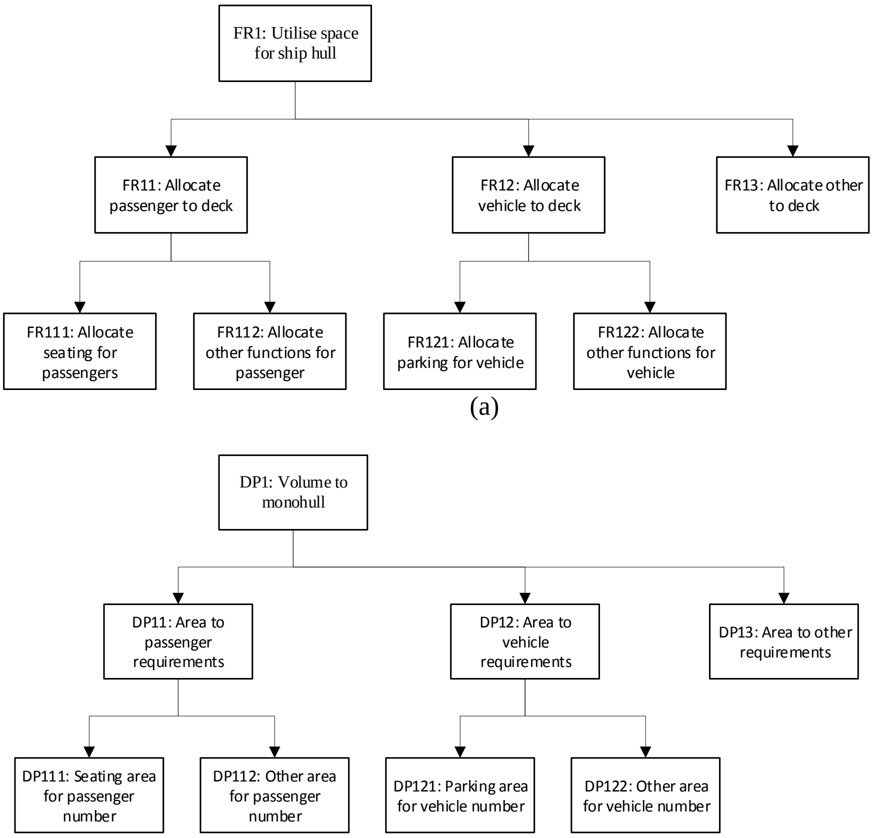
Design synthesis is emphasised in this work as starting point to develop passenger ship concept design. Referring to Figure 2, ship design goal "profitability" is decomposed into deducing primary passenger ship functions thus top-level CNs. Then, design synthesis is initiated by translating the CNs into top-level FRs in functional domain and concurrently, DPs in physical domain. They are represented as Figure 3(a) and Figure 3(b) respectively.

Referring to Figure 3, FR11, FR12 and FR13 highlight "deck" as design constraint, therefore developed independently for specific deck. FR111, FR112, FR121 and FR122 present further functions decompositions, refining design information. Passenger number and vehicle numbers are identified as design constraints for developing DP111, DP112, DP121 and DP122. Thus, FR-DP are formulated as equation 1 and 2. X1, X2, X3 and X4 present mapping functions for FR-DP relationships. As design information is augmented, it is observed that complexity level increases with the increase in FR-DP decompositions.

$$\begin{Bmatrix} \boldsymbol{FR111} \\ \boldsymbol{FR112} \end{Bmatrix} = \begin{bmatrix} \boldsymbol{X1} & \\ & \boldsymbol{X2} \end{bmatrix} \begin{Bmatrix} \boldsymbol{DP111} \\ \boldsymbol{DP112} \end{Bmatrix} \qquad (1)$$

$$\begin{Bmatrix} \boldsymbol{FR121} \\ \boldsymbol{FR122} \end{Bmatrix} = \begin{bmatrix} \boldsymbol{X3} & \\ & \boldsymbol{X4} \end{bmatrix} \begin{Bmatrix} \boldsymbol{DP121} \\ \boldsymbol{DP122} \end{Bmatrix} \tag{2}$$

Equation 1 and 2 present uncoupled design parameters characteristics for specified FR-DP. In this case, FR111-DP111, FR112-DP112, FR121-DP121 and FR122-DP122 are represented as the sum of area correspond to FR11-DP11 and FR12-DP12. As for FR13-DP13, the respective FR-DPs require further decomposition and mapping thus not discussed within this scope of work.



(a)

(b)

Figure 3: Utilise space partial functions decomposition and mapping

3.0 DESIGN PARAMETERS DEVELOPMENT

Based on synthesised FR-DPs, design exploration proceeds with DPs development. Space is defined according to passenger area (A_P), vehicle area (A_V) and container area (A_C), approximated to total waterplane area, (A_W). It is presented as in equation 3 where total load is equal to hydrostatic buoyance force (F_B). Overall length (L_{OA}) is determined from waterline length/overall length (L_{WL}/L_{OA}) correlation, (c_{LOA}). While, A_P, A_V and A_C are modelled as equation 4, 5 and 6.

$$\boldsymbol{A_W = B \times L_{WL} \approx A_P \approx A_V} \tag{3}$$

$$\boldsymbol{A_P = N_P A_s + A_{Other} = c_{LWLB}(B \times L_{LWL})} \tag{4}$$

$$\boldsymbol{A_V = N_V A_V + A_{Other} = c_{LWLB}(B \times L_{LWL})} \tag{5}$$

$$\boldsymbol{A_C = N_C A_C + A_{Other} = c_{LWLB}(B \times L_{LWL})} \tag{6}$$

Where, c_{LWLB} is waterline length/breadth (L_{WL}/B) correlation function. For FR11-DP11 and FR12-DP12, ship hull main dimension estimations continues by estimating L_{OA} based on equation 7 or 8.

$$\boldsymbol{L_{OA} = 1/c_{LOA}\sqrt{A_P}} \tag{7}$$

$$\boldsymbol{L_{OA} = 1/c_{LOA}\sqrt{A_V}} \tag{8}$$

Other design parameters are derived based on established parametric relationships. Main dimension estimation is carried out based on identified passenger ferry design data as summarised in Table 1. In this work, design database is restricted to monohull ship having $L_{OA} \geq 80.0$ m. It is exploited to deduce ship design parameters and assess their relationships. Related design parameters variables, equations and coefficients are summarised as in Table 2.

Powering design parameter is developed by imposing other FRs as in

Figure **4** and Figure 5. Based on the design data, it is acknowledged that hull dimension influences FR2-DP3 relationship. It dictates required propulsive power and travel speed for Froude number (Fn). While, main engine and propulsive power are satisfied by selecting suitable engine and propulsor types identified as DP21 and DP22. Other engine and propulsor alternatives can be decomposed accordingly.

Table 1: Passenger ship design database range

Vessel type	N_p	N_v	N_c
Passenger only	920 – 969	-	-
Passenger-vehicle only	50 – 3,200	25 – 1,340	-
Passenger-vehicle-container only	90 – 1,157	72 - 180	6 - 312
Passenger-container only	295 – 1,000	-	34-293

Table 2: Main dimension design parameter variables and coefficient values

Variables	Monohull	R^2
BxL_{WL} (m^2)	$0.71A_P + 1885.90$ $0.99A_V + 738.75$ $0.32A_C + 2737.00$	0.54 0.89 0.24
A_P (m^2)	$27.69L_{OA}$ - 1855.10	0.50
A_V (m^2)	$32.60L_{OA}$ - 2239.20	0.83
A_C (m^2)	$33.19L_{OA}$ – 3351.40	0.27
A_{ME} (m^2)	$4.10L_{OA}$ – 92.68	0.40
L_{WL}/L_{OA}	0.92	0.98
T/D	0.40	0.48
L/B	5.98	0.62
L/D	11.38	0.44
B/D	1.73	0.34

More often, “travel in short time” requirement suggests for high speed ship operation. It is described by using Froude number (Fn), defining the hull operating mode. Setting Fn as design constrain, FR2 is satisfied based on set travel speed and ship length.

Figure **6** shows passenger ship speeds data and the speed-length relationship represented by equation 9.

$$\boldsymbol{V = 0.07L_{OA} + 9.82} \tag{9}$$

Consequently, power is estimated based on the speed estimated from equation 9 and the relationship presented by equation 10. Finally, ship deadweight is estimated based on ship length through equation 11. It provides the initial estimation for cargo capacity in relation to ship length thus total cargo weight for the passenger, vehicle or cargo. Therefore, this work highlights ship lengths, L_{OA} and L_{WL} as key DP variables to deduce passenger ship concept design observed particularly from income and cost perspectives.

$$\boldsymbol{P_{ME} = 3366.80V - 50222.00} \tag{10}$$
$$\boldsymbol{DWT = 62.52L_{OA} - 5671.83} \tag{11}$$

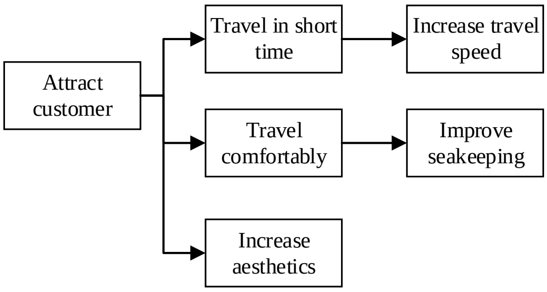


Figure 4: “Attract customer” functions analysis

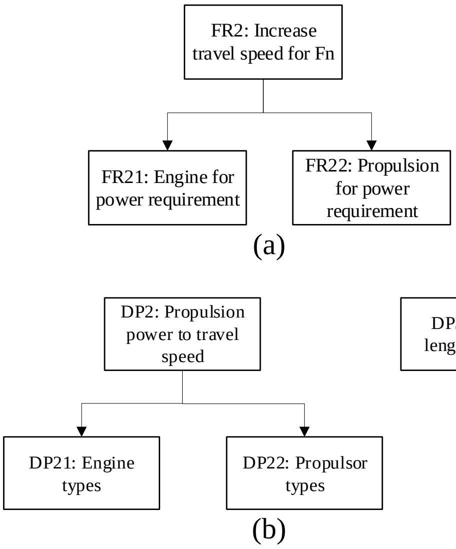


Figure 5: Increase travel speed FR-DP decomposition and mapping

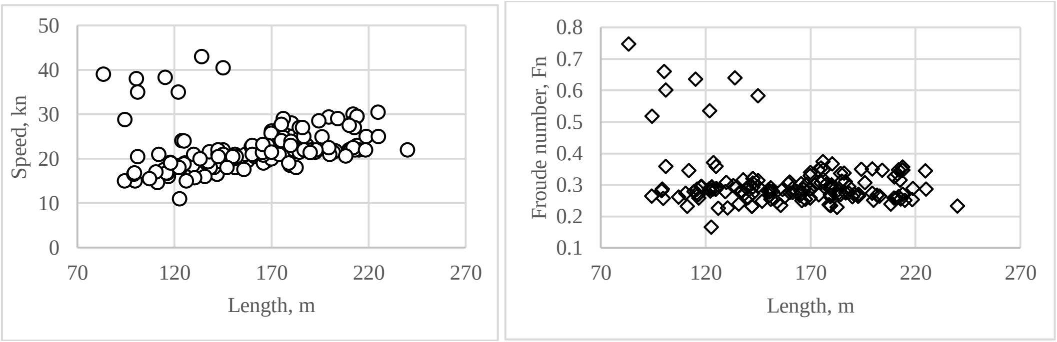


Figure 6: Ship and hull speed to ship length relationship

4.0 CONCLUSIONS

This work presents prescriptive design methodology demonstrated into partially synthesising passenger ship concept design. It is initiated by defining and estimating ship functional spaces and main dimension followed by powering and cargo capacity (weight) requirements.

Figure 7 presents FR-DP coupling characteristics describing DPs dependencies as well as the FR-DP mapping of functional domain to physical domain. Here, it defines potential coupled DP2 and DP3 concurrent development to satisfy FR2. Based on the work, AD domains concept describes systematic DPs development executed based on chosen FRs hence the pre-established CN. While, QFD phases identifies and manages CN-FR-DP coupling characteristics thus to facilitate trade-off and "multi-criteria decision-making", (MCDM) processes. They are proposed as future work for further ship concept and preliminary design developments.

	Design parameter	DP1: Volume to monohull	DP11: Area to passenger requirement	DP111: Seating area for passenger number	DP112: Other area for passenger number	DP12: Area to vehicle requirement	DP121: Parking area for vehicle number	DP122: Other area for vehicle number	DP2: Propulsion power to travel speed	DP21: Engine types	DP22: Propulsor types	DP3: Hull length to Fn
Functional requirement	FR1: Utilise space for ship hull	x										
	FR11: Allocate passenger to deck		x									
	FR111: Allocate seating for passenger			x								
	FR112: Allocate other function for passenger				x							
	FR12: Allocate vehivle to deck					x						
	FR121: Allocate parking for vehicle						x					
	FR122: Allocate other function for vehicle							x				
	FR2: Increase travel speed for Fn								x			x
	FR21: Engine for power requirement									x		
	FR22: Propulsion for power requirement										x	

Figure 7: QFD "house of quality", (HoQ) matrix for FR-DP

As conclusion, proposed integrated QFD-AD method is aimed to facilitate prescriptive design and systematic decision-making processes through systems engineering, alternative to conventional ship design spiral model. Through systems approach, the proposed method presents potential applicability to support modular design and design automation. Therefore, it is also devised as basis to develop computer aided ship design tool purposely to facilitate the design of ship having large and complex systems.

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NOMENCLATURE

QFD	Quality function deployment	F_B	Buoyance force
AD	Axiomatic design	T	Draught
CN	Customer need	∇	Displaced water volume
FR	Functional requirement	c_{LWLB}	L_{WL}/B correlation function
DP	Design parameter	N_P	Number of passenger
L_{OA}	Overall length	N_V	Number of vehicle
A_P	Passenger area	N_C	Number of cargo
A_V	Vehicle area	Fn	Froude number
A_C	Container area	P_{ME}	Main engine power

A_{ME}	Main engine area	V	Travel speed
A_W	Waterplane area	HoQ	House of quality
c_{LOA}	L_{WL}/L_{OA} correlation function	MCDM	Multi-criteria decision-making