Ship systems synthesis and analysis using holistic design approach: The QFD-AD method

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Abstract. Design complexity is generally experienced in the design development and production of large and complex systems. It is viewed as the key element that would determine the design development cycle and quality. In this context, a study was conducted to demonstrate the ROPAX ship design and development processes applying the QFD-AD method. It is proposed to synthesise and analyse the ship systems design and configurations at the early design phase. This study explored the method applicability to facilitate concurrent design and decision-making, alternative to the conventional ship design spiral model. Moreover, it presented the potential method to support holistic design approach in exploring ship design as large and complex systems.

1. Introduction
Practical ship design is performed based on the Evan’s [1] design spiral and observing design activities in prescriptive sequences. It emphasised on developing and improving prescribed design parameters through design iteration. Therefore, design changes and additional parameters are often treated in ad-hoc, presenting a simplistic approach in handling and resolving design conflicts. This shows the model’s inadequacy to facilitate design complexity, causing long design cycle and poor design quality.

Alternatively, holistic design is proposed to overcome the limitations of the conventional model. It viewed the design processes through goal-oriented and integrated approaches that bring and develop all aspect of design, production and operation in parallel throughout the design cycle. It is the key concept in devising design methodology to facilitate concurrent design. Moreover, the complex systems design development is highly dependent on the systems definitions and interactions, consequently the impacts on the product performance [2]–[5]. These highlights the potential to the concept application on the systems-to-systems and the systems-to-environments interactions.
Tamaskar [2] investigated design complexity based on the systems design information, behaviour and interactions in respect to the systems’ size and topology. It emphasised on the design complexity measurements to observe the systems performance and design parameters empirical relationships and directionality. Importantly, Tamaskar acknowledged the systems directionality and detail definition traits in reducing design uncertainties therefore eliminate iterations and design compromise. Contrarily, Göhler [3] observed design complexity based on the design functions coupling and level of contradiction. Based on the concept, lower functions contradiction is desirable regardless of their coupling characteristics. Therefore, the approach is viewed to be in favours to coupled systems rather than to have fully uncoupled or decoupled design as proposed by Suh’s [6].

As for the design processes and organisational interactions, Bowen [4] and Wynn [5] considered exploring the design space and domains through idea generation and convergence within a multi-disciplinary environment. The works highlighted the advancements in design technology, proposing computer-based design tool and human-computer interactions (HCI) to handle design complexities and conflicts. In detail, Bowen proposed user centred and goal-oriented design approach to drive design quality by manipulating traceable design artefacts. It focussed on the concept of design alternatives and variants to satisfy the customer needs. Furthermore, Wynn suggested systems engineering (SE) and concurrent engineering (CE) to improve and optimise the design models and HCI, incorporating analytical model and multi-criteria decision-making (MCDM) process.

The approaches described are viewed suitable for large and complex systems design synthesis and analysis. However, the processes involved are based on descriptive and heuristic design approaches. More often, the design problems are ill-defined, making the design and processes to be highly iterative and evolving. It is further impacted by the discrepancies in design knowledge representation, expertise and decision-making. Though the studies provided theoretical means to assess design complexity, it entails for systematic modelling thus practical investigations on actual operational systems.

Therefore, this study is formulated to evaluate the SE and CE concepts and holistic design approach for preliminary ship design process. It is carried out to model and develop the roll-on/roll-off passenger (ROPAX) ship design functions and physical systems as well as to analyse their interactions by applying the integrated quality function deployment and axiomatic design (QFD-AD) method [7], [8] and parametric-based design (PBD) approach. Significantly, this work is aimed at demonstrating the concurrent design concept and proposed method applicability as an alternative to the sequential and iterative approaches of the conventional ship design spiral model.
2. Methodology

QFD-AD [7], [8] is adopted to demonstrate the systems synthesis and analysis for the ROPAX ship design based on pre-established requirement analysis. The ROPAX ship systems functional analysis is initiated based on the “mobility” and “profitability” design goals defining the design specifications as in Table 1. Here, the former goal referred to the primary systems required by the ship, while the later presented the components related to ship operation techno-economic and performance trade-offs.

Table 1. Assumed operating specifications.

| Capacity          | Value       |
|-------------------|-------------|
| Passenger, #      | 450 – 550   |
| Vehicle (Car), #  | 80 – 100    |
| Vehicle (Freight) #| 4 – 10      |

The functional analysis systems technique (FAST) [9] is applied to establish the customer needs (CNs) based on the design goals. Once the lower level CNs are identified, the top-level functional requirements (FRs) are synthesised thus presenting the transition from the design planning to synthesis phase. It is executed following the proposed volume-based model as in Figure 1. It continued with the AD functional analysis to establish the ROPAX ship FRs and design parameters (DPs) hence to derive the overall ship systems architecture.

In principle, the ROPAX ship design development is generally constrained by the design criteria, set by regulatory organisations i.e. SOLAS. It is observed to determine the ship systems other than those prescribed by the design goals and CNs. Further, this work demonstrated the AD functional analysis for partial systems synthesis to determine the main engine system and the associated DPs. It observed the space allocations at the tank top of the ship double bottom exploring the cargo capacities, ship size, powering and main engine configuration DPs and variables relationships. It is performed in reference to the actual passenger ship design data summarised as in Table 2.
Table 2. Summary of reference ship principle design parameters data.

| Principle parameter        | Value         |
|----------------------------|---------------|
| Overall length, m          | 90 – 240      |
| Displacement, t            | 3,000 – 27,500|
| Deadweight, t              | 600 – 13,000  |
| Froude number              | 0.17 – 0.37   |

The AD functional analysis is performed to model the ship systems functions and the corresponding physical design solutions. It served to establish the systems relationships and to facilitate their integrations. Practically, it is executed in solution-neutral environment to extract plausible design solutions and to set the intended design space thus to establish the ROPAX ship systems architecture. It continued with the systems synthesis, executed to analyse the systems DPs and variables parametric relationships.

3. Result and discussion

The FAST applied to the ROPAX ship design goals concurrently produced the low level CN1: Carry systems and CN2: Carry cargo, and the top level FR1: Allocate systems and FR2: Utilise hull space. Proceed, the executed AD functional analysis derived the FR-DP hierarchical relationships hence the partial ROPAX ship systems architecture, presented as in Figure 2. The FRs-DPs are also represented as module, Ms and in matrix form.

Observing the hull space allocation, the M11: FR11-DP11 components are grouped into 2 and developed independently. Accordingly, the systems physical interactions can be investigated by observing the DPs-DPs variables relationships using the QFD house of quality (HoQ) chart thus the PBD for the individual sub-systems or components. It is proposed as the future work for the final ROPAX ship systems design selection, validation and optimisation.

Figure 2. AD functional analysis for tank top space allocation and utilisation.
Based on Table 1 and 2, the ship overall length ($L_{OA}$) of 90 m is proposed as the starting point to derive the basis ship design. Therefore, the resulting DPs can be observed as in Table 3 and Figure 3. It is viewed that the hull displacement ($\Delta$) and deadweight (DWT) are strongly related to $L_{OA}$ rather than the cargo capacities. This is mainly due to the different cargo characteristics. However, it is found that the cargo capacity i.e. freight ($N_f$) provided a reasonable DPs variables estimation.

Table 3. Estimated ROPAX ship basis design parameters and model comparison.

| Principle parameter          | $L_{OA}$ driven design | $N_f$ driven design |
|------------------------------|------------------------|---------------------|
| Overall length ($L_{OA}$), m | 90.0                   | 90.0                |
| Breadth ($B$), m             | 17.5                   | 17.5                |
| Draught ($T$), m             | 4.3                    | 4.3                 |
| Depth ($D$), m               | 10.9                   | 10.9                |
| Displacement ($\Delta$), t   | 2,959.7                | Min. 3,138.0        |
| Deadweight (DWT), t          | 625.5                  | Min. 600.0          |
| Passenger capacity ($N_p$), # | 483                    | Min. 390            |
| Car capacity ($N_c$), #      | 91                     | Min. 50             |
| Freight capacity ($N_f$), #  | 10                     | 10                  |
| Service speed ($V_s$), kn    | 15.2                   | 15.3                |
| Total main engine power ($\Sigma P_E$), kW | 3,924.3 | Min. 4,324.0 |

Figure 3. (a) DWT to $N_f$, (b) $\Delta$ to DWT, (c) $\Sigma P_E$ to $\Delta$, and (d) $V_s$ to $\Sigma P_E$ relationships.
While, Table 3 shows that the cargo capacities model to have weak DPs variables interactions in comparison to the ship dimensions. It is mostly factored by difference cargo types and preferences and can be observed using the HoQ. This observation agreed with the proposed volume-based model as in Figure 1 and the $M_{211}$: $FR_{211}$-$DP_{211}$ design problem. Thus, it is acknowledged that the cargo capacities are influenced by the techno-economic analysis as proposed by the profitability goal. As for the $M_{111}$ and $M_{112}$, Figure 2 presented their interactions that is constrained by the ROPAX ship hull DPs variables i.e. total deck area ($\Sigma A_n$), hence the trade-off between the allocated and utilised $A_n$.

![Figure 4.](a) $A_E$ to $\Sigma P_E$, (b) $\Sigma P_E$ to $LOA$ relationships.)

As for the $M_{111}$, the main engine area ($A_E$) is considered as the design constraint to determine the engine room space ($V_{ER}$). In this case, medium-speed diesel engine type is observed. Figure 4(a) presents the DPs variables relationship for the engine area ($A_E$) and $A_E$, thus the $M_{111}$. Here, the main engine configuration i.e. engine number ($N_E$) is generalised as the total main engine power ($\Sigma P_E$) thus viewed as design variant. Therefore, the main engine selection can be determined based on the weight and operational performance. It is observed in Figure 4(b) where the engine variants influenced the ship speed ($V_s$) and the Froude number ($f_n$) or vice-versa.

Based on the study, the initial $M_1$ presented an uncoupled design where the other components can be developed independently for the remaining tank top area ($A_0$). As for coupled systems, $M_1$ is represented as in equation 1 and 2 for $FR_{11}$: Allocate main engine systems, thus is viewed as design alternative. The new $M_{111}$ and $M_{112}$ interactions can be observed using HoQ based on set preferences and developed according to the hull DPs variables.

\[
FR_{11} = \sum FR_n = \sum x_i DP_n
\]  
\[
\sum x_i DP_n = (x_1 + x_4 + x_6)DP_{111} + (x_2 + x_7)DP_{112} + (x_3 + x_8)DP_{113} + x_5 DP_{114} + x_9 DP_{115}
\]

Where, $x_i$ is the mapping function for the FRs-DPs relationships and the sum of $x_i$ for each $DP_n$ is equal to 1. This can be presented in matrix form as in Figure 2 to facilitate systems integrations.

In this work, PBD is mainly applied to explore the design space and to facilitate concurrent design to produce set of near optimal design solutions. Additionally, the QFD-AD functions to observe the ship design complexity according to the number of components and their interactions. Based on the work, it is found that the factor to design iteration is mainly due to design
uncertainties inherited from poor requirement analysis and ill-defined design problem rather than the design complexity.

4. Conclusion
The QFD-AD presents the potential capability to develop large and complex systems design. It is proposed as a formal methodology for holistic design approach and demonstrated to observe the ROPAX ship design development. It is first applied to synthesise the ship systems, sub-systems and components, to establish their relationships and to produce the overall systems architecture. Then, the systems are analysed through the PBD, exploring the FRs, DPs and variables interactions as well as the design variants and alternatives.

Crucially, this work has presented a methodological framework for concurrent design activities in multi-disciplinary design environment observing both the procedural and analytical design models. Moreover, partial ROPAX ship systems architecture is synthesised, analysed and evaluated into developing a preliminary ship design thus concluded the SE and CE applicability to complex systems design development.

Further works on the QFD-AD is recommended in investigating detail ROPAX ship systems. It is proposed through expanding the detail design information and knowledge representation, identifying their complexities and facilitating MCDM based on the ship operational and technical performance requirements. This leads to the needs for computer-based design tool incorporating the HCI, PBD, simulation-based design (SBD) and artificial intelligent (AI) to further support effective holistic and concurrent design approaches.

Based on the findings, it is perceived that the advancements to this work would allow for rapid design and re-design processes through routine and non-routine design problem explorations as well as the design and analysis automation. Therefore, this presents the QFD-AD as the potential alternative to the conventional ship design spiral model.

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