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CONCEPT LEVEL NAVAL SURFACE COMBATANT DESIGN IN THE AXIOMATIC APPROACH TO DESIGN FRAMEWORK

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ABSTRACT

The design of ships is an inherently complex process. This complexity is significantly increased when the particular ship being designed is a naval surface combatant. Naval combatant designers, or more appropriately, design teams, must not only address the factors common to all seagoing vessels such as hull form, propulsion, and maneuverability, but additionally must consider the selection, placement, and interaction of sophisticated weapons systems and sensors. The ship design process is traditionally viewed as a highly coupled collection of interrelated physical attributes often determined in an *ad hoc* fashion. Therefore, lack of understanding and documenting the design progression frequently necessitates modification of a completely developed, functionally acceptable portion of the ship because of its adverse effect on other functionally unrelated parameters. This paper proposes a methodology based on axiomatic design principles that strives to eliminate the currently accepted iterative nature of concept level ship design. By implementing this approach, the ship design process follows a repeatable structured format in which functional relationships between physical parameters are mapped, documented, and controlled. The AAD method is applied to a ship synthesis model, and a new ship design process is defined and coded to illustrate the utility of the method.

Keywords: ship design process, axiomatic design, naval surface combatant

INTRODUCTION

Systems engineering is recognized as a key to engineering ships in an effective and affordable manner [Leopold et al., (1982)], [Rains (1990)], [Reed (1981)], [Tibbetts, et al. (1988)]. Naval engineering has long been the title associated with the system design and engineering of naval warships. "Total ship system engineering" (TSSE) has been recently defined in an attempt to describe this systems view, and provide a framework for ship designer's to follow. Implementation of TSSE has always been complicated due to the need to integrate the working of engineering teams with differing warfare perspectives, principally 'naval architecture' and 'combat systems'. A new challenge is arising as total ship system boundaries are being redefined to include new integrated and joint warfighting aspects in the design process. TSSE concentrates on the ship as the object of design, but this must be done in the context of all the interconnected system aspects external to the ship simultaneously. This introduces not only an expansion to new subsystems as part of the process, but adds new complexity to the designer's consideration. This paper defines a method to engineer the total ship as part of the joint warfare system by applying axiomatic design theory. Specifically, by complying with the Independence Axiom, the inherent system complexity and physical couplings are managed by dividing the design process into understandable, tractable portions.

EXISTING SHIP DESIGN METHODOLOGIES

Naval architecture and marine engineering are the traditional disciplines associated with defining the design of ship hull, mechanical, and electrical systems. Recently, naval engineering and TSSE have taken the place of naval architecture to broaden the engineering toward the naval warship system. These engineering disciplines include the consideration of combat systems as part of the design process, though not necessarily to the same level that combat system engineers would in their designs. For purposes of this discussion, however, the identifier 'naval architecture' will be used to represent the TSSE ship designer's point of view. For the naval architect, combat systems are treated as fixed inputs to the ship design, so that interfacing physical parameters such as weight, volume, centers of gravity, arcs of fire, electromagnetic radiation interference, and sensor coverage ensure a properly designed physical total ship system.

The naval architect's view of ship system design consists of a process that is traditionally viewed as a highly coupled collection of interrelated physical attributes. For instance, the selection of a power level for ship propulsion requires knowledge of the resistance of the ship hull. The ship hull geometry cannot be fully determined until the entire weight and volume required to be carried, including that of the propulsion system, is known. The same is true of many other physical aspects of the design as they directly impact other physical aspects. Therefore, once one aspect is fully developed, it often requires modification based on its relationship with other functionally unrelated parameters. This philosophy is extensively discussed in the literature, as an iterative process commonly referred to as "The Design Spiral" [Evans (1959)]. Since its introduction, several variations have been developed. The spiral itself is consistent between all variations, but the "spokes" defining each aspect of the design differs somewhat from version to version, Figure 1.

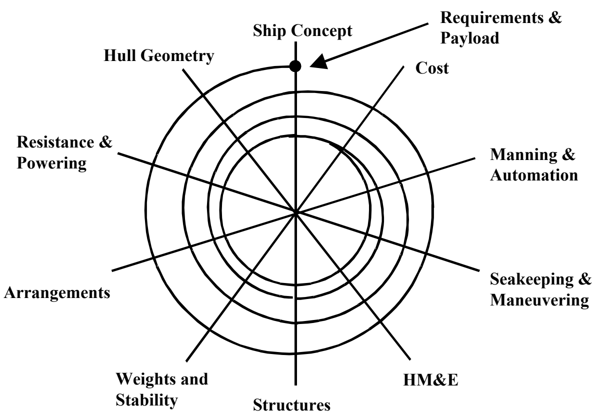

Figure 1. MIT Design Spiral

The spiral's spokes represent the set of all major areas that must be addressed throughout the design process to completely define the ship. The spiral itself depicts the current practice of independently developing each required parameter in a sequential manner, evaluating the relationship between design attributes, iterating to resolve conflicts, and repeating the evaluation/iteration process until all conflicts are resolved. Thus, following each successive iteration, the design progresses closer and closer to the spiral's center until convergence is attained at a constant radius from the center.

Methods to expand the usefulness of the design spiral have been developed. The factor of time was added to the model [Andrews (1981)]. The essential concept remains the same, but the visual representation moved into three dimensions, with the added third dimension representing time. Figure 2 is the resulting cone shaped model. The design progresses through time by "cork-screwing" down the cone following a helical path. A cross section of the cone, essentially a spiral, represents a snapshot of the design process at a given instance. Design convergence is achieved at the cone's apex.

Limitations of the spiral method description have been recognized, specifically, the inadequate addressing of concurrent engineering practices and life cycle concerns. One proposed solution to remedy these shortfalls is Decision-Based Design for the design of ships [Mistree, et al. (1990)]. This method divides the design process into subproblems that are solved in hierarchical order. The primary challenge to

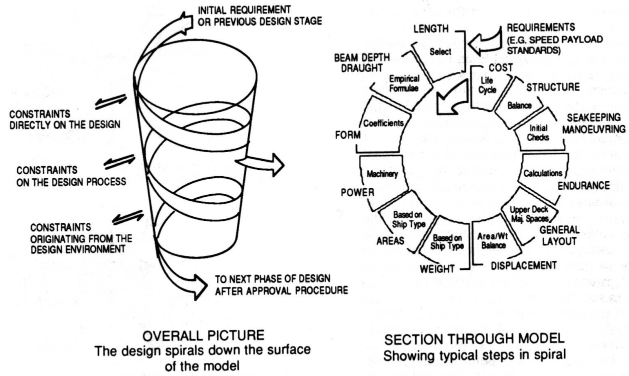

Figure 2. Enhanced Design Spiral [Andrews, 1981]

implementing this method is to define the hierarchical decomposition of the design process subproblems. No rigorous and generalizable methods are defined as part of this implementation.

More recent discussions view the ship design process as a combination of non-hierarchical and hierarchical subproblems interacting in ways that are difficult to define and therefore nearly impossible to implement in practice [Brown (1993)]. The concept of decomposing the process seems the best way to accomplish ship design, but there is no currently defined method to do this, with coordination of the decomposed process becoming the major challenge.

THE SHIP DESIGN CHALLENGE

The ship design challenge is to define a methodology that allows both naval architects and combat system engineers to perform design using a method that formalizes design semantics and maintains the decomposed subsystem interconnections. A generalized method for implementing design that allows mapping of function to form while eliminating, or at least bounding, iteration would assist in creating an environment for the domains to work independently while achieving an integrated system. Determining iterative coupling allows design teams to work independently, with the subsystem couplings defining the context for cross team interactions at the interfaces. Such a generalized method has been defined, and is proposed as a framework for redefining the process of engineering warfare systems. The method is neutral, and does not advocate a need to train engineers as designers in all areas, but allows domain specific engineering with due consideration of coupling interfaces. The method is based on the axiomatic approach to design (AAD) [Suh (1990 and 2000)]. The AAD method has been implemented in a computational ship synthesis model to study the applicability of the process. A short description of the model is presented, along with the formulation of the AAD for ship design.

SHIP SYNTHESIS MODEL

The MIT XIII-A Ship Synthesis Model, simply called "The Math Model", is used for concept level design of monohull surface combatants. The model was first developed by Reed in 1976 using two earlier codes, DD07 and CODESHIP, as its basis. The model has been revised and improved by a long series of naval officer students and faculty over the past two decades. The current version is more consistent with the Naval Surface Warfare Center's Advanced Surface Ship Evaluation Tool (ASSET) regarding the regression-based equations for weight, area, and electric power. The model performs all necessary calculations using commercially available software packages, either MathSoft, Inc's Mathcad or Microsoft''s Excel.

The math model is a parametric design tool. Parametric models link gross parameters to more detailed characteristics through regression analyses, trend analyses, and ratiocination. Some of the parametrics used to generate the model were derived from the standard U.S. naval surface vessel design lanes [Saunders (1957)]. Since parametric based models are limited to the range of data analyzed, significant deviations from the established design lanes degrade the fidelity of the resulting concept design. The math model level of fidelity is high for ship designs with characteristics similar to existing ships, i.e. evolutionary ships. Likewise, the math model level of fidelity is low for revolutionary ship designs.

Given an extensive set of gross design parameters and a specific mission payload (weapons system configuration), the math model provides the designer a means to balance a ship in six aspects: weight, propulsion power, electrical power, volume, area, and transverse intact stability. The model also incorporates a weight-based cost model to calculate the initial acquisition cost and life cycle cost of a ship class. The sum of these two costs defines a program's total ownership cost (TOC). Figure 3 shows the basic iterative process followed to achieve design convergence.

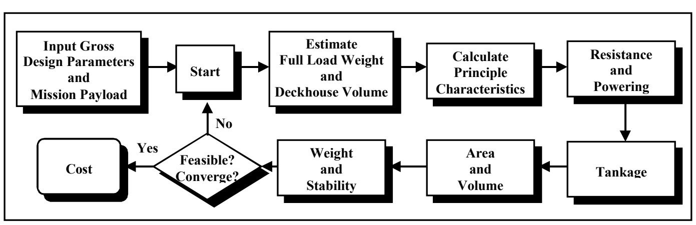

Figure 3. Math Model Process

The model does not conduct a longitudinal weight balance, nor does it consider any other important naval ship design aspects such as seakeeping, maneuverability, structural strength, hull subdivision, and damaged stability. These factors could be incorporated to enhance the model's capability with significant effort. Modifying the math model is not within the scope of this study. Therefore, only the above mentioned six aspects along with TOC represent the spokes of a simplified design spiral.

Essentially, this tool gives a first order approximation of a concept's feasibility. If the design cannot be balanced with the parameters input, iteration is required to achieve a balanced design. The model does not automatically balance the ship by iterating the necessary parameters, but rather this iteration is accomplished manually. In other words, the designer must strategically vary the parameters suspected to cause design convergence and then check the result of each successive variation. Through experience, the designer's intuition improves and the number of required iterations decreases. The iterative nature of this often time consuming manual balancing process is essentially *ad hoc*.

Typically, several iterations are required to balance a ship in the six stated areas. The balanced design does not necessarily incorporate all the attributes envisioned by the designer. For example, the final synthesized design may be longer or shorter than originally desired, have a wider or narrower beam than first envisioned, or have a larger or smaller displacement than initially conceptualized. The final balanced math model level of fidelity ship produces a reasonable starting point to begin feasibility level design. Once the gross characteristics of a design are determined with the math model, more detailed analyses can proceed using more sophisticated design tools.

AAD FORMULATION

The ship design process is formulated using the AAD. First, constraints are defined, followed by the identification of FRs and DPs. The software package Acclaro was used to facilitate the AAD formulation.

As in all designs, certain constraints are initially placed on the overall design. In this case, the first initial constraints become an integral part of the overall design philosophy. The first set of constraints result from the underlying motive of the Department of Defense (DoD) acquisition reform policy, ensure TOC does not exceed the mandated value. TOC includes the initial acquisition cost and the life cycle cost (calculated by multiplying the average hourly operating cost by the total operating hours). These constraints are stated as follows.

C1 = Initial acquisition cost < $ XXM (say,$ 750M)
C2 = Average hourly operating cost < $ XX (say, $ 2,600/hr)

Due to the demands for accountable budgets, the current DoD acquisition strategy requires fully capable weapons systems for a reasonable cost. Each acquisition program operates on a strict budget that cannot be exceeded, currently using the cost as an independent variable (CAIV) concept [Dalton, 1998]. This concept is synonymous with evaluating potential systems not only on their capabilities, but also on their projected costs. In some cases, the philosophy may even result in limiting or eliminating specific capabilities based on a cost-benefit analysis. In other words, designs are judged on their ability to incorporate capabilities without exceeding the applicable cost threshold. Therefore, major program managers strive to develop a design that achieves "the most bang for the buck."

By applying the principles of axiomatic design, it is reasonable to postulate that cost savings are realizable due to increased design efficiency and improved understanding of systems interrelationships. By keeping cognizant of the relevant cost constraints while developing the design solution, even greater savings are potentially achievable.

The next set of constraints result from the physics governing ship operations. The ship must operate on the water's surface. Since the combatant chosen for evaluation is a conventional monohull, it relies on buoyancy to support its weight. The hull form's displaced volume creates this buoyant force. The ship's total weight equals the weight of the hull plus the weight of all shipboard systems, equipment, stores, and personnel. The weight of the displaced volume of water (termed the full load displacement) is equal to the total weight of the ship according to Archimedes' Principle. If the hull is shaped in such a manner that the total weight is well supported, the design is sound. If the total weight of the ship exceeds the weight of the maximum amount of water that can be displaced by the ship hull volume, the ship sinks. Since prudent naval architecture practice dictates that a surface vessel should always float, the following design constraint is imposed.

C3 = Full load displacement = Total weight

In addition to floating, the ship must remain upright in stable equilibrium. A ship in stable equilibrium returns to its original position when heeled by an external inclining force that is applied and subsequently removed. Conversely, a ship in unstable equilibrium does not return to its original position resulting in capsizing. Metacentric height (GM) indicates the ship's stability in an intact (non-damaged) condition. GM is determined by the location of the ship's center of gravity (G) in relation to its metacenter (M). M is related to hull geometry, and G is determined by the vertical placement of weights on board. If M is above G, intact stability exists. The center of buoyancy (B) is the geometric center of the underwater hull volume. The lowest point on the keel (K) is used as a datum point. Figure 4 illustrates all relevant parameters. A positive metacentric height (GM > 0 ft) is required for intact stable equilibrium. Once again, prudent naval architecture practice imposes the following constraint.

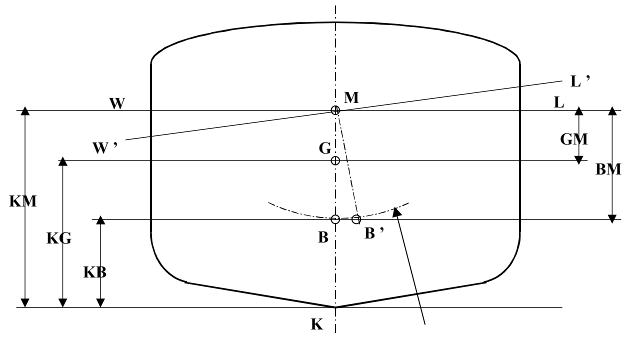

Figure 4. Transverse Metacentric Parameters

C4 = Ensure intact stability (GM > 0 ft)

By complying with C4, the ship remains upright in stable equilibrium. Even though the ship returns to its original position following a heel, does not necessarily ensure this return occurs in an acceptable manner. A measure of this response is transverse dynamic stability. A ship that returns in a noticeably slow time is said to be "tender." A ship that "snaps back" is said to be "stiff". Both cases are uncomfortable for crewmembers and adversely effect shipboard evolutions. Therefore, proper transverse dynamic stability must be maintained according to C5. The metacentric height to beam GM/B ratio verifies compliance with this constraint. A GM/B ratio between the range of 0.090 - 0.122 is the generally acceptable design standard for monohull surface ships. Another indicator of acceptable dynamic performance is the ship's roll period that determines the time required to return to an upright position. The roll period affects various shipboard evolutions requiring a stable platform. These evolutions include launching and recovering helicopters and small boats. A single constraint is imposed to check transverse dynamic stability.

C5 = Ensure acceptable transverse dynamic

As the ship moves through the water, resistance results. As speed (velocity) increases, so do the associated resistive forces. All resistance must be counteracted in order for the ship to continue in the desired path of motion at the desired speed. When traveling at a constant velocity, the total resistance remains constant. The means of counteracting the resistive forces is with installed propulsive power. Therefore, the ship must possess adequate propulsive power to ensure that the resistance encountered at all projected operating speeds can be equaled. Thus, the following design constraint exists.

C6 = Installed propulsive power > Required propulsive power

Numerous shipboard systems require electrical power. While conducting underway operations, the ship is an independent platform. Therefore, the ship must possess the capability of generating its own electrical power. The means of doing this is with the installed electrical system. The following constraint results to ensure the necessary systems receive a sufficient power supply.

C7 = Installed electrical power > Required electrical power

All systems designed to fulfill the functional requirements must fit within the physical confines of the hull and superstructure. This geometric consideration results in placing two additional constraints on the design process. First, all systems must fit within the total volume. Second, the components comprising these systems must fit in the available deck area in such a manner that their functionality is not hindered. Usable deck space is referred to as the arrangeable area. These constraints are stated as follows.

C8 = Total available volume > Total required volume
C9 = Total available area > Total required area

The last initial constraint also affects the overall design philosophy. It arises because certain systems deployed on naval vessels are upgraded due to the long ship lifetime with respect to new technology development cycle time. Also, new systems not even conceivable during the design phase are later developed and then integrated into the existing ship to enhance its warfighting capabilities. To account for stability considerations during upgrades, design growth margins must be incorporated early in the conceptual design process. These design margins allow for the later addition of weight without adversely affecting the ship's ability to operate in a stable condition. Because additional weight is added, additional propulsion power becomes necessary. And, modified systems or components may produce additional electrical power consumption. Both power concerns require design growth margins. This constraint is stated in non-specific terms as follows.

C10 = Incorporate design growth margins (weight, KG, propulsion and electrical power)

With all the initial design constraints clearly outlined, the design process begins. The designer must always consider these constraints when selecting the design parameters to satisfy each functional requirement at all levels within the design hierarchy. An explanation regarding the applicability of these initial constraints to the highest level FRs is further discussed after devising the highest level design equations. Additional constraints may arise as the design process advances.

Highest Level Design Equations

To initiate the process of ship design in the axiomatic design framework, the highest level functional requirements common to all seagoing vessels, as well as those germane only to warships, are formulated. The six FRs listed below state the necessary requirements. The DPs selected to satisfy these FRs are also listed adjacent to their respective FR. An explanation of all FRs and DPs, as well as the design matrix relating the two domains are discussed after presentation of the design equations.

FR1 = Move through water
FR2 = Maintain desired course
FR3 = Neutralize enemy targets
FR4 = Protect from enemy attack
FR5 = Conduct sustained underway operations
FR6 = Operate on surface of water

DP1 = Propulsion system
DP2 = Maneuvering and Control system
DP3 = Combat systems configuration
DP4 = Countermeasures methods
DP5 = Support / Auxiliary systems
DP6 = Hull form

With the definition of the highest level FRs and DPs complete, the next step is to generate the design matrix. Following standard practice, *X*'s and *O*'s are used to populate all matrix elements A_{ij}. These symbols represent the interaction between FRs and DPs. Lowercase *x*'s are also used to signify weak functional dependence. Equation 1 is the highest level design equations in their original form. As stated previously, the goal is to achieve a decoupled design characterized by a lower triangular design matrix. Since the initial design matrix is not triangular, the Independence Axiom is not satisfied. Before continuing with the design process, attempts must be made to achieve a decoupled design. This is possible only if logical justifications for disregarding functional dependencies exist such that reality is not violated solely to achieve the desired end. The following assumptions represent one way, though possibly not the only way, to analyze the design matrix.

$$\begin{Bmatrix} \boldsymbol{FR}1 \\ \boldsymbol{FR}2 \\ \boldsymbol{FR}3 \\ \boldsymbol{FR}4 \\ \boldsymbol{FR}5 \\ \boldsymbol{FR}6 \end{Bmatrix} = \begin{bmatrix} X & x & O & O & O & X \\ x & X & O & O & O & x \\ X & X & X & O & O & x \\ X & X & X & X & O & X \\ X & X & O & O & X & X \\ X & X & X & X & X & X \end{bmatrix} \begin{Bmatrix} \boldsymbol{DP}1 \\ \boldsymbol{DP}2 \\ \boldsymbol{DP}3 \\ \boldsymbol{DP}4 \\ \boldsymbol{DP}5 \\ \boldsymbol{DP}6 \end{Bmatrix} \quad (1)$$

FR1, move through water, is satisfied by DP1, the installed propulsion system. There is also a weak correlation between FR1 and DP2, the ship's maneuvering and control system, since some of the maneuvering systems, such as auxiliary propulsion units (APU's) and bow thrusters, can be used to move the ship through the water. The primary function of these stated systems truly relates to maneuverability alongside a pier, and not to actual open ocean movement. Thus, the removal of the DP2 dependence is justified. Therefore, an *O* replaces the corresponding lowercase *x*.

The ability for the ship to move through the water is highly dependent on the ship's hull form, DP6. Specifically, the dependence occurs because of the hull form's interaction with the water. This interaction affects the speed at which the ship travels due to hull resistance. The magnitude of resistance on the hull depends on two factors, wetted surface area and hull shape at the air-water interface or free surface. Friction drag is directly proportional to the wetted surface area and wave making (residuary) drag depends on the fullness of the hull form at the free surface.

Both of these hull related factors, wetted surface area and hull shape at the free surface, continually change with the ship's displacement. During normal operating conditions, the ship's displacement continually changes as fuel is burned, stores are consumed, and weapons are expended. In order to negate the effect of DP6 on FR1, the ship must operate at a constant displacement (recall the definition of *Aij*). That is, if the ship's displacement does not change, the two important hull related parameters, and therefore the hull resistance, remain constant. Operating at a fixed draft (the vertical distance measured from the keel to the waterline) ensures operating at a fixed displacement. This draft essentially sets the point about which all evaluation occurs, the design point. So, to justify removing the effect of DP6 and replacing the respective *X* with an *O*, an additional constraint must be imposed on the design as follows.

C11 = Always operate at the design waterline (DWL)

FR2, maintain desired course, is achieved primarily by the ship's maneuvering and control system, DP2. DP1, the propulsion system, somewhat affects the ship's maneuvering characteristics. In single screw designs, unbalanced hydrodynamic forces are caused due to propeller rotation. In twin screw designs, manipulating the rotation speed and pitch of each propeller independently actually enhances maneuverability. The number of screws and the propulsion system characteristics are set when fulfilling FR1. Their effect on maneuverability must be considered prior to setting DP2.

The hull form, DP6, may also relate to maneuverability. Certain hull features, such as bulbous bows, fin stabilizers, and skegs, cause hydrodynamic forces on the ship that affect its maneuverability. Following current warship design practice, a bulbous bow is not incorporated into the design of this generic warship, but, conventional bulbous bow-like sonar domes are frequently designed into modern warships. Sonar domes, skegs, and fin stabilizers do not technically comprise the hull form, but are rather additions to the hull form as appendages. By following this logic, an *O* replaces the subject lowercase *x*.

FR3, neutralize enemy targets, is affected by DP1 - DP3 and DP6. The primary DP is DP3, the combat systems configuration. In order to neutralize some enemy targets, the ship must be within the appropriate weapons range. The propulsion system (DP1) allows this. Often, the target must also be positioned in a specific orientation relative to the ship. The maneuvering and control system (DP2) allows this positioning. Ensuring the target is within the appropriate weapons range and acquired at the necessary relative position is not the designer's concern, but rather that of the warfighters operating the ship. Since this study investigates the design process, and not the ship's operating procedures and doctrine, both discussed *X*'s are replaced by *O*'s.

In order to accurately track and engage enemy targets, a stable platform is required. The platform in this case is the ship's hull form (DP6). In this context, stability is not related to the ship's ability to right itself once perturbed; this type of stability is assumed. In this context, stability is related to the ability of the platform supporting the weapons system sensors to prevent excessive oscillations when in a sea state. Current weapons systems technology compensates for, or damps out, almost all encountered platform oscillations. Based on the existence and incorporation of such technology, coupled with the fact that the hull form of the generic warship does not diverge from traditional surface combatant hull forms, an *O* replaces the respective lowercase *x*.

FR4, protect from enemy attack, is affected by DP1- DP4 and DP6. DP4, countermeasures methods, is the principal means of providing protection from enemy attack. Countermeasures methods consist of both passive and active means of defeating enemy weapons. Passive methods include reducing the ship's radar cross section (RCS) and acoustics signature. Active methods include utilizing weapons systems designed to engage incoming enemy threats. Additionally, many of the same combat systems used to neutralize enemy targets (DP3), with modifications to their engagement protocols, can also be used for ship self defense measures (FR4).

The contributions of DP1, DP2, and DP6 parallel the reasoning listed in the preceding paragraph. This reasoning allows the replacement of both *X*'s associated with DP1 and DP2 with *O*'s. But, the uppercase *X* associated with DP6 signifies two additional contributions to FR4. First, the RCS is affected by both the above water portion of the hull and the superstructure. Because the above water portion of the hull set constant by satisfying C11, and by making the conscious design decision to focus RCS reduction efforts on the superstructure alone, the first additional contribution from DP6 is removed. Second, the extent of battle damage a ship is capable of sustaining is directly related to the hull structure. Again, by making the conscious decision to design the hull based on structural strength criteria and not deviating from established warship structural design practices, the final contribution from DP6 is removed from FR4. Thus, an *O* replaces the corresponding *X*.

FR5, conduct sustained underway (at sea) operations, requires DP1, DP2, and DP5 to be fully satisfied, and is affected by DP6. The primary design parameter is DP5, the support and auxiliary systems. This broadly defined DP decomposes to encompass a wide variety of functional requirements including provide electrical power, effectively combat damage, and provide a fuel source. The propulsion system (DP1) and the maneuvering and control system (DP2) also contribute to the ship's ability to conduct extended operations. The rate at which the propulsion system consumes fuel determines the ship's endurance range, thereby affecting the fuel system. The maneuvering and control system assists the ship in detecting and avoiding heavy weather whenever necessary. By avoiding storms and high winds, the ship increases its ability to conduct sustained operations by mitigating potential damage. Proper maneuvering also allows the ship to transit to the desired destination in the most efficient manner, thus avoiding unnecessary fuel consumption. Once again, since this study does not include operating procedures, initially an *O* replaces the *X* corresponding to DP2.

Further consideration is required to remove the *X* signifying the contribution of DP6 to FR5. As stated earlier, the hull causes resistive forces opposing forward movement that must be matched by the propulsion system. The fuel storage system carries the fuel necessary for extended operations. Therefore, the size of the fuel tankage is determined by the fuel required to produce forward motion at a designated speed for a designated range. This motion is opposed by hull resistance. To remove this coupling, the designer must size the fuel storage capacity based on the imposed constraint (C12). By adhering to the following constraint, an *O* replaces the respective *X*.

C12 = Carry adequate fuel to transit endurance range at endurance speed

FR6, operate on surface of water, is affected by all the stated DPs, DP1- DP6. The shape of the hull form, DP6, in large part determines how the ship's weight is supported by the resultant buoyant force. All the DPs comprise the ship's total weight. Due to Archimedes' Principle, the total weight of the ship must equal the weight of the displaced volume of water, so the ship floats and thus operates on the surface of water. Additionally, DP4 contributes to the ship's total resistance characteristics since both the hull and the superstructure contribute to aerodynamic drag.

The rigorous analysis of the interrelationships between the highest level FRs and DPs reveals a decoupled design is in fact achievable. Equation 2 is the highest level design equations resulting in the decoupled design. In order to achieve this decoupled design, two additional constraints were placed on the design process and two decisions amending the overall design philosophy (to remove a single coupling) were made. Logical deductions also eliminated three weak FR-DP relationships. Finally, examining the scope of this analysis eliminated five FR-DP relationships caused by operational concerns vice design considerations. The Independence Axiom is satisfied only if the DPs are changed to satisfy the FRs in the proper sequence shown in the lower triangular design matrix.

$$\begin{Bmatrix} \boldsymbol{FR}1 \\ \boldsymbol{FR}2 \\ \boldsymbol{FR}3 \\ \boldsymbol{FR}4 \\ \boldsymbol{FR}5 \\ \boldsymbol{FR}6 \end{Bmatrix} = \begin{bmatrix} X & O & O & O & O & O \\ x & X & O & O & O & O \\ O & O & X & O & O & O \\ O & O & X & X & O & O \\ X & O & O & O & X & O \\ X & X & X & X & X & X \end{bmatrix} \begin{Bmatrix} \boldsymbol{DP}1 \\ \boldsymbol{DP}2 \\ \boldsymbol{DP}3 \\ \boldsymbol{DP}4 \\ \boldsymbol{DP}5 \\ \boldsymbol{DP}6 \end{Bmatrix} \tag{2}$$

IMPROVEMENTS TO THE SHIP DESIGN PROCESS

Applying axiomatic design theory to the concept level ship design process results in significantly more designer control by completely eliminating the *ad hoc* assigning of DPs and minimizing the need to modify functionally satisfactory DPs once set. Between the upper level FRs, only one possibility for DP reassignment exists. This reassignment is not entirely necessary, but actually more convenient. During satisfaction of FR6, two potential sources for DP redefining exist due the inherent couplings and physics. Constraint evaluation guides the designer to select appropriate DPs at all levels of decomposition. Even if a given constraint is not met, the designer realizes the DPs causing non-compliance that require modification to resolve the conflict. Constraint satisfaction at strategic points in the design process bounds the selection of certain crucial DPs, therefore keeping design realistic. The resulting synthesis model process is shown in Figure 5.

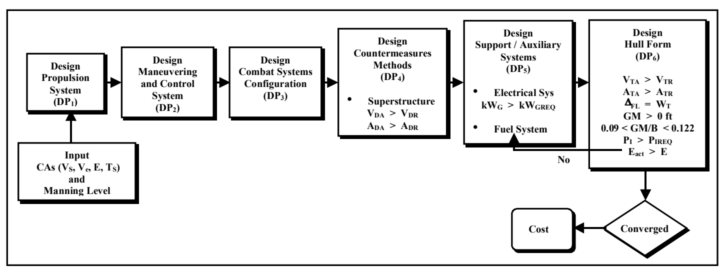

Figure 5. Functional Ship Synthesis Model Process

The following lists some of the features of the MIT XIII-A Functional Ship Synthesis Model which lead to an overall improved concept level design process.

- FRs are listed in the proper order as determined by applying the Independence Axiom, thereby removing the *ad hoc* assigning of DPs.
- Designer is in more control of the design at all stages. All required DPs are highlighted for designer input. The designer is provided minimum required values for pertinent parameters, but may opt to exceed the minimum if required to comply with the design strategy. For example, the deckhouse size may be increased and hull size decreased provided that both total volume and total area are equal to or greater than the required values.

- Re-assignment of DPs is minimized by listing constraint evaluations at strategic points in the design progression.
- A large number of regression based parametrics requiring gross monohull parameters (V_{FL}, L, B, T) and total ship weight are removed from the model. Equations previously requiring these inputs are replaced to reflect complete design decisions, or are replaced with directly input values.
- Designs are automatically balanced with regards to area, volume, and weight. Additionally, all electrical loads are determined prior to designing the electrical system, allowing immediate FR fulfillment.
- The functional math model is suited to synthesize ships with non-conventional, advanced hull forms. To achieve this diversity, a means to predict specific hull type resistance, and a way to accurately model hull volume and stability are required, however, the model is now structured such that this type of module could be added without disrupting the rest of the model.
- The functional math model also demonstrates suitability for integrating a product data manager (PDM) with the design process. This is demonstrated by defining payload DPs using the interactive Excel component. Similar implementations are envisioned for the model once a database of potential DPs, including all required specifications, is established. The ultimate goal involves linking a computer aided design (CAD) package to its associated PDM to allow visualization of the systems. As the designer sees the emerging design, an appreciation for systems placement and hull limitations results. In this way, novel hull forms can be "wrapped around" the subsystem equipment to create various design possibilities. The integration of a CAD/PDM to computer-aided engineering (CAE), computer aided manufacturing (CAM), and enterprise resource planning (ERP) is also possible.

CONCLUSIONS

The effect of design parameter selection on the total ship is always an area of interest. Selection of all DPs physically impacts the entire ship to some extent. Of course, the effect of some DPs is more apparent than others. The MIT XIII-A Functional Ship Synthesis Model more easily (than the iteration based synthesis model) allows these effects to be determined. Since DP assignment proceeds in an exact predetermined order, changing a DP always affects the same downstream aspects. The designer is aware of this as the design matures with each successive design decision.

The axiomatic approach to design provides a means to conduct functional vice physical ship design. Adhering to the design progression defined by the numerous design equations, starting with the most general, highest level functional definitions and increasing in detail as the design decomposes, results in the complete design of a warship. This scientific based methodology identifies functions requiring fulfillment, presents physical design parameters to meet these needs, and maps the interrelationship between the two. Therefore, in theory, couplings between parameters are known *a priori*. Since the design equations exactly list the best order for functional satisfaction, the *ad hoc* approach to ship design is no longer necessary at the concept level. The `Design Spiral' is effectively replaced with the hierarchial set of design equations.

Current naval architecture practices specify design of the hull first. Then, all necessary systems are forced to fit within the physical hull confines. The AAD based approach proposes the exact opposite design approach to control couplings. In other words, the systems are designed first, and then the hull is designed to enclose the cumulative system volume and area. Therefore, when implemented, this approach will most likely be met with resistance from the traditional thinking ship designers.

This design methodology supports analysis of the recently proposed 'modular-mission' ships. In this context, modular means a physical module containing a specific mission package. For example, these modules contain strike missile launching systems, mine hunting equipment, etc. As mission requirements change, the ship reconfigures with the appropriate module while in port and then transits to the mission area. In other words, the ship is only required to fulfill a subset of possible warfare missions at a given time. This modularity is useful to allow risk mitigation as new technologies are developed during the design process, as well as providing the same technology insertion capability over the ship lifetime. The generic surface combatant evaluated during this study is a multi-mission platform. Therefore, individual branches of the FR3, neutralize enemy targets, decomposition support the study of modular-mission ships. The overall ship effect resulting from the addition and subtraction of functions can readily be assessed.

The functional math model is a significant improvement to the existing math model. The salient features of this enhanced ship synthesis tool include reduced iteration, exact ordering of design parameter specification, automated accounting of mission payload parameters, and complete single pass convergence of area, volume, weight, and electrical powering design. The automated accounting of payload parameters paves to way for a completely integrated ship design tool connecting a product data manager (PDM) with a computer aided design (CAD) package.

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