2017-09

Using mathematical modeling and set-based design principles to recommend an existing CVL design

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http://hdl.handle.net/10945/56123

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

USING MATHEMATICAL MODELING AND SET-BASED DESIGN PRINCIPLES TO RECOMMEND AN EXISTING CVL DESIGN

by

William H. Ehlies

September 2017

Thesis Advisor: Fotis Papoulias
Second Reader: Gary Parker

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.			
1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** September 2017	**3. REPORT TYPE AND DATES COVERED** Master's thesis	
4. TITLE AND SUBTITLE USING MATHEMATICAL MODELING AND SET-BASED DESIGN PRINCIPLES TO RECOMMEND AN EXISTING CVL DESIGN			**5. FUNDING NUMBERS**
6. AUTHOR(S) William H. Ehlies			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB number ____N/A____.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.			**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

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The size and expense of Nimitz and Ford class aircraft carriers represent a strategic vulnerability in future maritime conflict. Using smaller aircraft carriers will reduce the risk to grand strategy as well as life cycle and operating costs, provided a light aircraft carrier can facilitate the assorted rotary wing, fixed wing, electronic attack, and unmanned systems required for the conflict.

SBD thinking can be used to produce a feasible design for a CVL by mapping a design space to meet the needs of a potential future conflict. This thesis examines the trade space in major design areas such as tonnage, aircraft launch method, propulsion, and performance in order to illustrate the merits of SBD in designing naval assets for a future force.

14. SUBJECT TERMS light aircraft carrier, Hull Design Optimization, set-based design, mathematical modeling			**15. NUMBER OF PAGES** 79
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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USING MATHEMATICAL MODELING AND SET-BASED DESIGN PRINCIPLES TO RECOMMEND AN EXISTING CVL DESIGN

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING ANALYSIS

from the

NAVAL POSTGRADUATE SCHOOL
September 2017

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TABLE OF CONTENTS

LIST OF FIGURES

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LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

A2/AD	anti-access / area denial
AoA	analysis of alternatives
CBRNE	chemical, biological, radiological, nuclear, and enhanced conventional weapons
CVL	aircraft carrier, light
CVN	aircraft carrier, nuclear
DIM	design integration manager
DLR	displacement-length ratio
DOD	Department of Defense
FIAC	fast inshore attack craft
FW	fixed wing
HA/DR	humanitarian assistance / disaster relief
LHA	amphibious assault ship (general purpose)
LHD	amphibious assault ship (multipurpose)
PBD	point-based design
PNT	positioning, navigation, and timing
RW	rotary wing
SBCE	set-based concurrent engineering
SBD	set-based design
SCAR	strike coordination and reconnaissance
SHP	shaft horsepower
SOF	special operations forces
UAV	unmanned aerial vehicle

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EXECUTIVE SUMMARY

This report seeks to use set-based design (SBD) principles and mathematical modeling to create a method by which one can, given a set of existing ship design prototypes, narrow the design space to arrive at an optimal design solution for a Light Aircraft Carrier (CVL). The design requirements for the CVL were derived based on a Maritime-2030 conflict scenario authored in 2016 by Captain Jeff Kline of the Naval Postgraduate School. Based on this scenario, the following stakeholder requirements were derived for the CVL:

1. Must displace a target objective value of 50,000 tons with a minimum objective value of 40,000 tons.
2. Must achieve a target objective for speed of 30 knots with a minimum objective value 27 knots.
3. Must be capable of supporting a minimum of 48 sorties per day.
4. Must be able to support all variety of aircraft supported by a Ford class CVN, i.e., fixed wing strike, fixed wing electronic attack, rotary wing, and unmanned aerial systems.

The method of analysis was developed by collecting a sample of all aircraft-carrying vessels worldwide to build a design space and then examining them for hull design, power plant shaft horsepower (SHP) output, and flight deck design. The hull design optimization was the subject of the mathematical modeling efforts. The hull designs for each ship were graphed and mapped in terms of optimization coefficients used in hydrodynamics and ship design. A linear regression was then applied to each set to establish a formula to predict an optimal value for each coefficient. Each ship prototype could then be analyzed and compared based on its deviation from the ideal coefficient values given the design requirements.

Once the mathematical modeling was complete, it was used in conjunction with SBD principles to narrow the design space. Ultimately, the findings show that the French design, Charles deGaulle, is the ship that is best suited to the Design Reference Mission. It is the ship that meets all of the threshold requirement values. The design space was narrowed down to two possible candidates: The Charles deGaulle, and the Russian Ovel class aircraft carrier. The latter, however, due to its use of a ramp launch system, is not able to support the variety of aircraft required for the future of Naval Aviation.

This report concludes that, for an existing design solution that is a light alternative to Ford class CVNs, a design based on the Charles deGaulle is the best solution. While the finding itself is subject to the interpretation of the design requirements, the method and model developed in the process is feasible for selecting an alternative from a design space given a set of stakeholder requirements.

Suggestions for further research include a cost benefit analysis of the CVL compared to other ships in the class and of the Ford class. Given that the results are based on currently existing designs that are in service, data should be readily available. Further refinement to the modeling process is also recommended to yield three-dimensional values for the hull optimization coefficients instead of two-dimensional gateway values.

Reference

Kline, Jeffery. 2016. “Maritime War of 2030.” Naval Postgraduate School, Monterey, CA.

ACKNOWLEDGMENTS

I extend my personal thanks to Professor Papoulias for acting as thesis advisor, to Mr. Gary Parker for acting as second reader, to Captain Hughes for the inspiration for the study, to Captain Kline for the use of the “Maritime Conflict—2030” scenario, and to Professor Stevens and Lieutenant Commander Naccarato for the stellar support throughout the Naval Postgraduate School experience.

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I. INTRODUCTION

This report addresses the feasibility of applying set-based design (SBD) and mathematical modeling to recommend a design for a light aircraft carrier (CVL) if the United States were to commission such a ship as part of a future force structure. To approach this topic, this report outlines a possible future maritime conflict scenario, offers a justification of why CVLs would be valuable assets in such a scenario, and illustrates how SBD thinking could be used to design a CVL that best facilitates the role of naval aviation in the future. The final result will be a SBD based method to narrow a design space of currently existing ship designs and a recommendation as to which of a given set of designs is most suited to a Design Reference Mission and set of stakeholder requirements.

A. GEO-POLITICAL SITUATION

The Design Reference Mission (DRM) for the ship that is the subject of this report is predicated on a maritime conflict scenario authored by Capt. Jeff Kline of the Naval Postgraduate School's Operations Research department. According to Capt. Kline's scenario, China has continued its trend of military, political, and economic expansion, having terraformed island facilities in the South China Sea to support military assets to control the flow of goods, particularly oil, through the region, despite protest from nations, such as the United States and the Philippines. Additionally, China has threatened to assume governorship of the island of Natuna Basar. Increase energy trade and a more economically liberal Chinese government has led to a non-aggression pact between China and Taiwan, making Taiwan a de-facto Chinese military and economic federation (Kline 2016).

Also in Capt. Kline's maritime conflict scenario, the Russian economy has stabilized through energy trade, and it has maintained control of the Crimean Peninsula. President Putin's successor maintains strong rhetoric about building a greater Russia through expansion given a warming Arctic and the reclamation of traditional Russian lands, particularly Gotland in the Baltic Sea. Additionally, Russia is strengthening its forces in the Kuril Islands in the Sea of Okhotsk. This is done in an effort to extend maritime control from the two islands to support its ships patrolling the entrance to the Arctic passage (Kline 2016).

Also in the Pacific region, tensions on the Korean Peninsula remain high due to North Korea's ballistic and cruise missile capabilities. In Capt. Kline's scenario, Japan and the United States have strengthened ties in order to counter the expansionism of China and Russia. The United States has also strengthened ties with Singapore, Okinawa, and the Philippines for the purposes of ship and aircraft stationing to maintain a strong presence in the region. Australia has also responded to the growing tension by strengthening their air and naval forces, as well as allowing for the stationing of a U.S. battalion landing team in Darwin (Kline 2016).

B. CVL MISSION REQUIREMENTS

Given the scenario described in Section A, the future of maritime conflict will be in the littoral and coastal environments with the goal of achieving economic and political influence with minimal destruction. This can be achieved with detachments of rotary wing (RW) and unmanned aerial vehicles (UAVs). With the evolution of technology, all future conflict will see an increased use of electronic and information warfare; as such, aircraft such as E-2s, EA-18Gs, and drones such as the FIRESCOUT will have an ever-increasing value to fleet commanders. Capital ships will still be necessary for political deterrence through the threat of power projection with FW assets; however, in a future conflict wherein we can expect the enemy to employ unconventional tactics, such as swarm, use of fewer and larger capital ships (Gerald R. Ford-sized CVNs) breeds an inherent vulnerability with respect to Centers of Gravity. Smaller aircraft carriers and LHA/LHDs can potentially accomplish many of the same strategic objectives with less risk to grand strategy and are more cost effective.

1. Projected Operational Environment

Naval aviation assets will be required to operate in three main environments. The first is the traditional blue water battlespace to maintain control of the seas and protect the movement of goods and services. The second is the littoral environment to perform Anti Access/Area Denial (A2/AD) functions in places like the South China Sea, the Baltic Sea, and the Sea of Okhotsk. Finally, naval aviation will be required to operate in an environment where it can project power ashore without undue risk to the aircraft carrier.

2. Potential Tasking

CVL missions will be both offensive and defensive in nature. Based on my interpretation of the Maritime-2030 scenario, possible offensive mission scenarios for aircraft embarked aboard CVLs include:

- overland power projection
- establishment and maintenance of air superiority
- strike coordination and reconnaissance (SCAR) in both overland and ocean environments
- electronic attack

Defensive mission scenarios include displays and use of force to protect sea lanes, deter regional aggression, and protection of amphibious landing forces. Other missions include humanitarian assistance and disaster relief (HA/DR) and command and control (C2) for both U.S. and multinational forces.

It will be necessary for a CVL to be able to defend against air, surface, and subsurface threats. The threats can range from capitol ships, advanced aircraft, and missile systems to FIAC and suicide crafts and mines. The origin of these threats can range from highly organized and sophisticated state actors to non-state sponsored terrorist organizations. Tactics can range from conventional naval tactics, such as an exchange of missile salvos in open ocean, to swarm and suicide tactics.

3. Mission Definition

All necessary operational activities for a CVL are used in order to meet the requirements for mission success. Each mission capability is defined and categorized according to Naval Power 21 (England et al. 2002). Mission capabilities are illustrated using the Joint and Naval Capabilities Terminology List and are presented in Table 1.

The Naval Power 21 model is composed of both Sea Power 21 and Expeditionary Maneuver Warfare capabilities. This model was chosen because the future maritime conflict outlined in the previous section will involve significant support to expeditionary forces. It will be necessary for the CVL to perform this function as well as the blue water missions.

Table 1. Mission Capability Areas. Adapted from Assist. SECNAV (RDA) Chief Engineer (2007).

Sea Shield		
Mission Capability	Definition	Mission Sub-Capability
Force Protection	Preventative measures taken against hostile actions against DOD personnel, resources, facilities, and critical information. Force Protection does not include actions taken to defeat the enemy or protect against accidents, weather, or disease.	Protect against SOF and terrorist threats
		Mitigate effects of CBRNE
Surface Warfare	The ability to conduct maritime operations in order to destroy or neutralize enemy naval surface forces and merchant vessels.	Provide self-defense against surface threats
		Conduct offensive operations against surface threats

Sea Shield		
Mission Capability	Definition	Mission Sub-Capability
Undersea Warfare	The ability to conduct operations to establish battlespace dominance in the underwater environment, which permits friendly forces to accomplish a full range of potential missions and denies an opposing force the effective use of underwater systems and weapons. It includes offensive and defensive subsurface, antisubmarine, and mine warfare operations.	Provide self-defense against subsurface threats
		Neutralize open ocean submarine threats
		Neutralize submarine threats in the littorals
		Counter minefields from deep to shallow water
Theater Air and Missile Defense	All defensive measures designed to destroy attacking enemy aircraft or missiles in the Earth's envelope of atmosphere, or to nullify or reduce the effectiveness of such attacks (JP 1–02). The integration of joint force capabilities to destroy enemy theater missiles in flight or prior to launch or to otherwise disrupt the enemy's theater missile operations through an appropriate mix of mutually supportive passive missile defense, active missile defense, attack operations, and supporting command, control, communications, computers, and intelligence measures.	Provide self-defense against air and missile threats

Table 1. (con't) Mission Capability Areas. Adapted from Assist. SECNAV (RDA) Chief Engineer (2007).

Sea Strike		
Mission Capability	Definition	Mission Sub-Capability
Strike	An attack to damage or destroy an enemy objective or capability.	Conduct strike operations
		Conduct special operations
		Conduct offensive information operations
		Provide aircraft survivability
Strategic Deterrence	The prevention from action by fear of the consequences. A state of mind brought about by the existence of a credible threat of unacceptable counteraction.	Provide Assured Survivability

Table 1. (con't) Mission Capability Areas. Adapted from Assist. SECNAV (RDA) Chief Engineer (2007).

Sea Basing		
Mission Capability	Definition	Mission Sub-Capability
Deploy and Employ	In naval usage, the change from a cruising approach or contact disposition to a disposition for battle. 2. The movement of forces within operational areas. 3. The positioning of forces into a formation for battle. 4. The relocation of forces and materials to a desired area of operations. Deployment encompasses all activities from origin or home station through destination, specifically including the continental United States, intertheater, and intratheater movement legs, staging, and holding areas. The strategic, operational, or tactical use of forces.	Close the force and maintain mobility
		Provide at sea arrival and assembly
		Allow selective offload
		Reconstitute and regenerate at sea
Provide Integrated Joint Logistics	The ability to provide effective, responsive, and efficient movement and sustainment capacity, exercise control from end to end, and provide certainty to the supported Joint Force Commander that forces, equipment, sustainment, and support will arrive where needed and on time in all domains.	Provide sustainment for operations at sea
		Provide shipboard and mobile maintenance
		Provide force medical services

Sea Basing		
Mission Capability	Definition	Mission Sub-Capability
Pre-Position Joint Assets Afloat	To place ships, equipment, or supplies at or near the point of planned use or at a designated location to reduce reaction time, and to ensure timely support of a specific force during initial phases of operation.	Integrate and support joint personnel and equipment
		Provide afloat C2 physical infrastructure
		Provide afloat forward staging base capability for joint operations

Table 1. (con't) Mission Capability Areas. Adapted from Assist. SECNAV (RDA) Chief Engineer (2007).

FORCEnet		
Mission Capability	Definition	Mission Sub-Capability
Communications and Networks/Infrastructure	An organization of stations capable of intercommunications, but not necessarily on the same channel.	Provide communications infrastructure
		Provide network protection
		Provide network synchronization
		Provide information transfer
Battlespace Awareness/Intelligence, Surveillance, and Reconnaissance	The systematic observation of aerospace, surface, or subsurface areas, places, persons, or things, by visual, aural, electronic, photographic, or other means to obtain knowledge and understanding of the operational area's environment, factors, and conditions, to include the status of friendly and adversary forces, neutrals and noncombatants, weather and terrain, that enables timely, relevant, comprehensive, and accurate assessment in order to successfully apply combat power, protect the force, and/or complete the mission.	Conduct sensor management and information processing
		Detect and ID targets
		Provide cueing and targeting information
		Assess engagement results

FORCEnet		
Mission Capability	Definition	Mission Sub-Capability
Command and Control/Decision Support	The exercise of authority and direction by a properly designated commander over assigned and attached forces in the accomplishment of the mission. Command and control functions are performed through an arrangement of personnel, equipment, communications, facilities, and procedures employed by a commander in planning, directing, coordinating, and controlling forces and operations in the accomplishment of a mission.	Provide mission planning
		Provide battlespace management synchronization
		Provide common PNT and environmental information
		Integrate and distribute sensor information
		Track and facilitate engagement of time sensitive targets
		Track and facilitate engagement of non-time sensitive targets

Table 1. (con't) Mission Capability Areas. Adapted from Assist. SECNAV (RDA) Chief Engineer (2007).

Expeditionary Maneuver Warfare		
Mission Capability	Definition	Mission Sub-Capability
Maneuver	1. A movement to place ships, aircraft, or land forces in a position of advantage over the enemy. 2. A tactical exercise carried out at sea, in the air, on the ground, or on a map in imitation of war. 3. The operation of a ship, aircraft, or vehicle to cause it to perform desired movements. 4. Employment of forces in the operational area through movement in combination with fires to achieve a position of advantage in respect to the enemy in order to accomplish the mission.	Forward presence
		Homeland security
		Informational operations
Intelligence	1. The product resulting from collection, processing, integration, analysis, evaluation, and interpretation of available information concerning foreign countries or areas. 2. Information and knowledge about an adversary obtained through observation, investigation, analysis, or understanding.	Support the Commander's planning and decision making process
		Maintain comprehensive ISR network to support multiple concurrent expeditory missions
		Facilitate operational maneuver and precision engagement
		Develop intelligence expertise to meet evolving challenges of the 21st century

Expeditionary Maneuver Warfare		
Mission Capability	Definition	Mission Sub-Capability
Fires	The use of weapon systems to create a specific lethal or non-lethal effect on a target.	Joint and multinational fires
		Aviation fires
Logistics – General across functional areas	The science of planning and carrying out the movement and maintenance of forces.	Sea basing
Logistics - Supply	The procurement, distribution, maintenance while in storage, and salvage of supplies, including the determination of kind and quantity of supplies.	Sea basing
Logistics - Maintenance	1. All action taken to retain material in a serviceable condition or restore it to serviceability. It includes inspection, testing, servicing, classification to serviceability, repair, rebuilding, and reclamation. 2. All supply and repair action taken to keep a force in condition to carry out its mission. 3. The routine recurring work required to keep a facility in such condition that it may be continuously used at its original or designed capacity and efficiency for its intended purpose.	Sea basing

Expeditionary Maneuver Warfare		
Mission Capability	Definition	Mission Sub-Capability
Logistics - Transportation	The carriage of personnel and/or cargo.	Sea basing
Logistics – Health Services	Logistics area supporting the joint force surgeon's health service support mission. Includes supplying class VIII medical supplies, optical fabrication, medical equipment maintenance, blood storage and distribution, and medical gasses.	Sea basing
Command and Control	The ability to exercise authority and direction by a properly designated commander over assigned and attached forces in the accomplishment of the mission. A commander performs command and control functions through an arrangement of personnel, equipment, communications, facilities, and procedures to plan, direct, coordinate, and control forces and operations in the accomplishment of the mission.	Communications
		Situational Awareness
		Information Processing and Storage
		Interoperability
		New Capabilities

Expeditionary Maneuver Warfare		
Mission Capability	Definition	Mission Sub-Capability
Force Protection	Preventative measures taken to prevent hostile actions against Department of Defense resources, personnel, facilities, and critical information. Force protection does not include actions taken to defeat the enemy or protect against accidents, weather, or disease.	CBRN Sense
		CBRN Sustain
		CBRN Shield
		CBRN Shape
		Aircraft Protection
		Aircraft Survivability
		Missile Defense Systems
		Improve Personal Protection
		Improve Personal Recovery Training and Capabilities

4. Mission Success Requirements

The operational situation will determine which of the mission sub-categories listed in Table 1 will need to be completed to determine mission success. These sub-categories identify specific functions that, depending on the nature of the operation, will translate into operational activities necessary to accomplish the mission.

5. Requirements Decomposition

This section presents an interpretation of the necessary requirements for a CVL based on the DRM. The model developed in Chapter IV can be used by any stakeholder regardless of perceived requirements.

Based on the concept of lessening strategic vulnerability and saving cost, I conclude that a viable CVL should be roughly half the tonnage of a Gerald R. Ford class CV (about 90-100 kilotons), making it comparable with an LHA/LHD class ship. This is appropriate because, given the geopolitical situation described in the Maritime-2030 scenario, the CVL will be called upon to support amphibious engagements with Expeditionary Strike Groups in addition to patrolling open ocean. The CVL should have a target speed of 30 knots, with a minimum acceptable speed of 27 knots so that it can transit quickly to provide crisis response.

Also, given that the CVL will be called upon to support Expeditionary Strike Groups, the sortie rate of a CVL must meet or exceed the sortie rate of an LHA/LHD class ship. This sortie rate is calculated based on assumptions regarding the availability of mission capable aircraft and the number of aircraft aboard ship. The America class LHA can carry 30 aircraft (Janes IHS Markit 2017a); assuming that at any given time 20% of these aircraft are mission capable, that leaves 24 aircraft. With a planning factor of 2.0 sorties per aircraft per day, that is a total of 48 sorties per day as a minimum acceptable value for a CVL. To support the movement of aircraft to achieve this sortie rate, the CVL must have a minimum of two flight deck elevators.

Finally, the CVL must be able to carry all variety of aircraft supported by a Ford class CV. This means it must be able to carry fixed wing fighter and attack aircraft, propeller and jet powered electronic surveillance and attack aircraft, rotary wing aircraft, and unmanned systems.

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II. SET-BASED DESIGN

A. HISTORY

Toyota Motor Corporation implemented its set-based concurrent engineering (SBCE), also known as set-based design (SBD), design model in 1995. Jonathan Chan explains in his 2016 thesis titled “Implementing Set Based Design into Department of Defense Acquisition” that SBD operates using delayed decisions, ambiguous communication, and the manufacture of numerous prototypes in order to ultimately build faster and cheaper cars. Through incorporation of SBCE principles, Toyota was able to have prototype models enter the production phase months ahead of its competitors at reduced cost (Chan 2016).

Chan further explains that Toyota’s success with SBD garnered attention from private industries and government acquisition alike. The U.S. Navy began using SBD in 2007 with the preliminary and contract design for the Ship to Shore Connector Program. Use of SBD with the Ship to Shore Connector demonstrated the viability of the method for shipbuilding and its use is encouraged in the shipbuilding acquisitions process (Chan 2016).

B. SBD DEFINED

SBD can be defined as engineers and project designers “reasoning, developing, and communicating about sets of solutions in parallel and relatively independently” (Sobek 1997, 202). A feasible solution is achieved by considering many design alternatives and eliminates infeasible alternatives. This method of systems engineering allows for adaptable and conceptually robust design solutions. Set-based design places an emphasis on use of decentralized manufacturing teams to keep humans in the loop when designing intricate and complex, large-scale systems, (e.g., ships).

Set-based design stands in contrast with the traditional acquisition design method known as Point Based Design (PBD). An example of PBD is the classic design spiral, where each design iteration attempts to create a solution that meets stakeholder requirements. PBD has five basic steps:

- Define the problem.
- Generate a large number of design alternatives.
- Conduct a preliminary AoA leading to a single design concept.
- Modify the selected concept until stakeholder requirements are met.
- If the selected concept fails to satisfy stakeholder requirements, begin again from either step one or two (Singer et al. 2009).

Figure 1 shows the classic PBD design spiral.

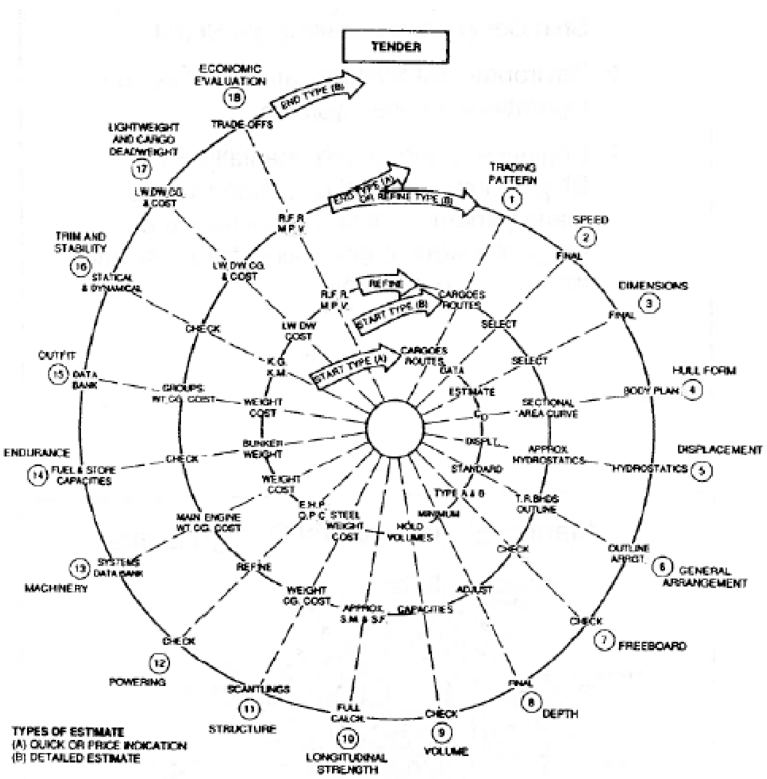

Figure 1. Classic Design Spiral. Source: Singer et al. (2009).

Some disadvantages to the PBD method are, first, that it does not always produce a globally optimal solution, (i.e., a solution that is as good or better than all other feasible solutions). Also, the number of iterations around the spiral are limited by the time and budget available. Thus, there can be a tendency to declare a design complete simply for having run out of time, not through having achieved an optimal solution (Singer et al. 2009).

The Toyota-based SBD process has four main features:

- Define a broad set of design parameters to allow for concurrent design.
- Keep these sets open longer to define tradeoff information.
- Gradually narrow the sets until a globally optimal solution is revealed and refined.
- Increase the design fidelity as the sets narrow (Singer et al. 2009).

One of the major differences between this approach and PBD is that in PBD the critical interfaces are defined by set parameters early on, which constrains the design space before all of the available tradeoff information is obtained. This could result in a less-than optimal solution. Figure 2 illustrates the concept of narrowing the design parameters.

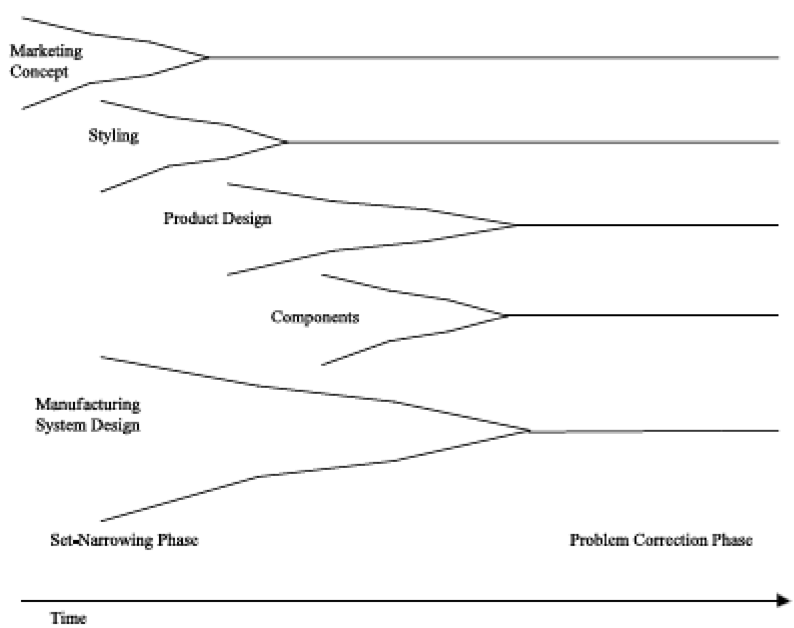

Figure 2. Parallel Set Narrowing Process Illustrated by a Toyota Design Manager. Source: Ward et al. (1995).

Another advantage to the delayed decision making inherent in SBD is the effect that it has on life cycle cost. In PBD, decisions are made early on, having a great effect on the product despite the limited available knowledge. The delayed decision making of SBD has the following effects on the final product:

- It allows the product to achieve a balance between stakeholder requirements and feasibility.
- It allows for the inclusion of the latest available technology.
- It allows for tracking of competitive products and changes to stakeholder requirements (Bernstein 1997).

Overall, contrary to the traditional approach of making design decisions early and sticking to those decisions to the extent possible, it is clear that the SBD method of delayed decision making has great merit.

C. HOW TO DO SBD

The execution of SBD can be broken down into three principle concepts:

- Consider a large number of design alternatives through understanding of the design space.
- Allow specialists to consider the design from their own perspective.
- Use the intersection between individual sets to optimize a design and establish feasibility before commitment. (Singer et al. 2009)

It is important to consider all aspects of the design, including performance, producibility, and acquisition complexity.

Understanding the design space means defining the feasible regions of the space. Once this is established, explore tradeoffs by using multiple designs to find alternatives. The system engineer should then communicate the possible solutions from these alternatives back to the other design team members and the Design Integration Manager (DIM) (Singer et al. 2009).

Once the design space is mapped and the individual design teams have labored on their solutions, it is necessary to integrate the solutions into the larger context through intersection. This is done by identifying the intersections of the feasible regions of each group. The goal is to create a smaller set of unified global concepts. This process requires an increase in design fidelity over time, reducing the design set based on an increased amount of knowledge and detail, not from arbitrary decisions and limitations (Singer et al. 2009). Figure 3 illustrates the SBD/SBCE process.

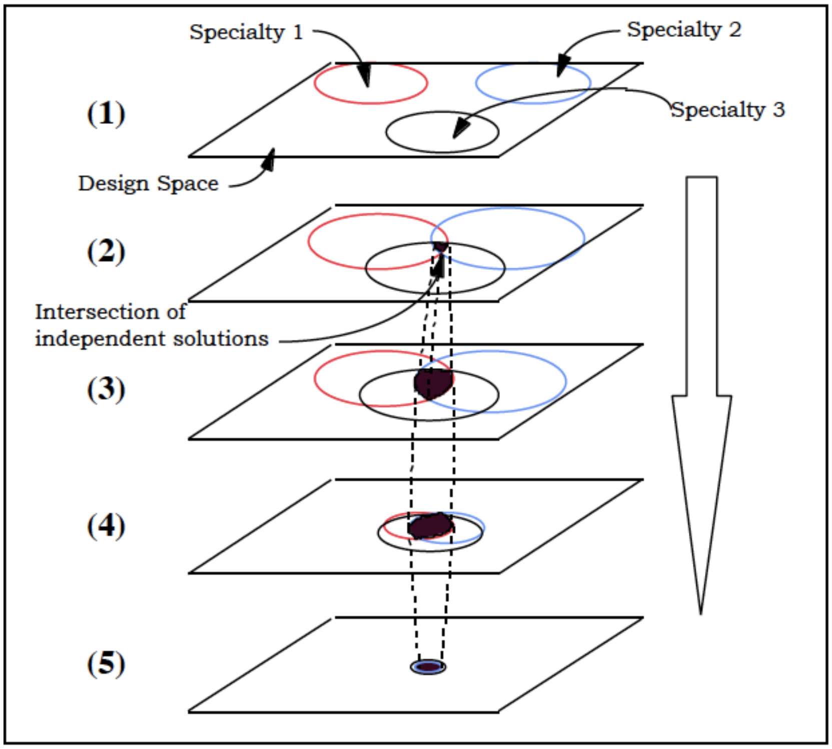

Figure 3. Set-Based Concurrent Engineering. Source: Bernstein (1997).

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III. DESIGN ELEMENTS

In order to narrow the design space of ship designs, we will evaluate the prototypes based on their hull design, power output in terms of shaft horsepower (SHP), and their flight deck design. This chapter focuses on the principles of ship design and hydrodynamic coefficients with which to optimize hull design.

A. HULL OPTIMIZATION COEFFICIENTS

This section defines key coefficients necessary for hull optimization. Later sections will explore how to use these coefficients to optimize hull design.

1. Froude Number

The Froude number is used in hydrodynamics to determine the resistance of a partially submerged object, such as a ship's hull, moving through the water. The Froude number, Fn, is based on the speed-length ratio. It is defined as follows (Watson 1998, 168):

$$Fn = \frac{u_0}{\sqrt{g_0 l_0}}$$

where u_o is the vessel's speed, g_o is, in this case, the force of gravity, and l_o is the waterline length of the vessel. The Froude number figures into many of the relevant calculations necessary in determining the optimum hull design for a ship (Watson 1998, 168).

2. Displacement–Length Ratio

The displacement–length ratio (DLR) is a measure of how heavy a ship is relative to its length at the waterline. DLR is defined as the ratio of displacement Δ (expressed in units of long tons displacement) to the length at the waterline L (in feet), as follows (Watson 1998, 172):

$$DLR = \frac{\Delta}{(0.01L)^3}.$$

This expression can be used to compare the relative mass of ships. Ships with a lower displacement length ratio, i.e., lighter relative to water line length, will be lighter and faster, whereas ships with higher displacement length ratios will be heavier. Because both numerator and denominator are volumetric, the result is non-dimensional (Paris 2015).

3. Prismatic Coefficient

The prismatic coefficient C_p is a ratio of the ship's volume, ∇, to the product of its maximum cross sectional area (A_x) and its length L in feet, as follows (Saunders 1957, 192):

$$C_p = \frac{\nabla}{A_x L}.$$

The prismatic coefficient is a value between 0 and 1 that defines how the ship's displacement is distributed along the hull. It is used to determine the level of hull drag and wave-making resistance by measuring the rate of change in the cross sectional area of a ship's hull (McClary 2017).

4. Length-to-Beam Ratio

The length-to-beam ratio balances wave-making resistance with carrying capacity and internal space. A low length-to-beam ratio yields a wider vessel with a more spacious interior. A high length-to-beam ratio yields a narrower vessel with less resistance moving through the water. Combatants typically have length-to-beam ratios ranging from 7 to 10 (Watson 1998, 65).

5. Beam-to-Draft Ratio

The beam-to-draft ratio is a comparison between the amount of internal cargo space and how shallow the ship can operate. The relationship between these two factors will affect bottom design and stability. The appropriate beam-to-draft ratio will be somewhat determined by the length, but most combatants have a beam-to-draft ratio between 2.5 and 3.5 (Watson 1998, 70).

6. Maximum Section Coefficient

The maximum section coefficient is the comparison of the area largest midship cross section to a rectangle. A higher maximum section coefficient indicates a more box like design, whereas a lower coefficient indicates a more cut away design. The maximum section coefficient C_x is defined as follows, where *T* represents draft and *B* represents (Saunders 1957, 902):

$$C_x = \frac{A_x}{B \times T}.$$

Aircraft carriers are typically very box-like in their midship cross section; this analysis assumes a maximum section coefficient of 0.99 for all the aircraft carriers examined.

7. Block Coefficient

The block coefficient, C_B, is defined as the ratio of the ship's underwater volume by the volume of a rectangular prism with dimensions' length, beam, and draft. It is a measure of the ship's slenderness or fullness of form. It is defined as follows (Saunders 1957, 192):

$$C_B = \frac{\nabla}{L \times B \times T}.$$

B. OPTIMUM COEFFICIENT VALUES

This section defines the range of optimal values for each of the coefficients outlined previously. The value ranges are generalized to combatant ships. A few are specific to aircraft carriers, but some interpretation of data will be required to determine the optimum trade off values.

1. Design Lanes of C_P and Displacement–Length Ratio

Optimum values for the prismatic coefficient and the displacement–length ratio can be determined using a set of design lanes created by Captain H.E. Saunders in his 1957 publication, *Hydrodynamics in Ship Design: Volume Two*.

The upper design lane is bounded by the displacement–length quotient and the fatness ratio (not used in this report), while the lower is bounded by prismatic coefficient values. The model for the ships compared in this report uses the upper design lane, for which normal combatants usually have a DLR value between 40 and 100. Captain Saunders admits, however, that unique design requirements may cause a ship's design parameters to fall outside of the lanes outlined in Figure 4. For example, an ice breaker may have a fatness ratio that falls well above the established design lanes due to the nature of its mission (Saunders 1957, 466).

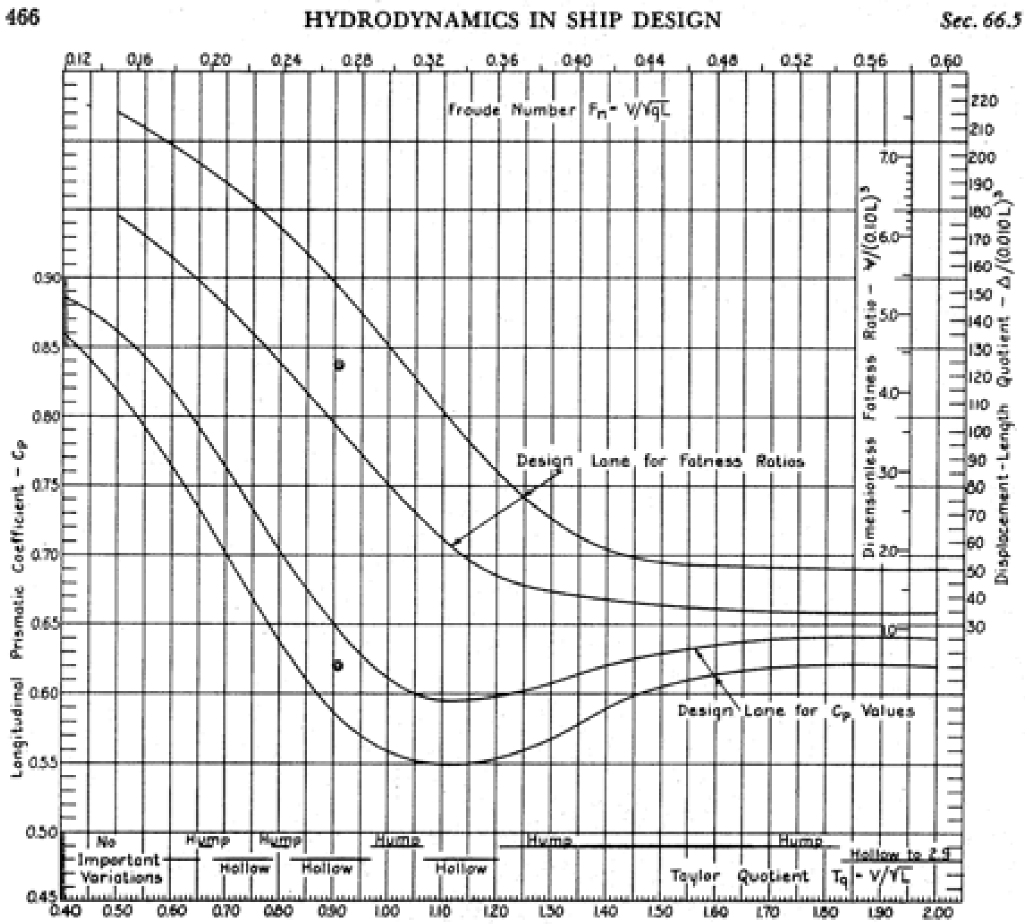


Figure 4. Design Lane of Prismatic Coefficient, Displacement–Length Ratio, and Fatness Ratio. Source: Saunders (1957, 466).

2. Maximum Section Coefficient, Draft, and Beam

Optimal values for these parameters are highly subjective and dependent on the nature of the mission, partially because variations in C_X itself causes little change in hull resistance. Ships intended for higher speeds may utilize higher values for C_X and sacrifice beam length in order to lower the longitudinal waterline curvature and reduce wave-making resistance. Ships that require high internal storage space, deck space (such as a flight deck), and high stability may use lower C_X values (Saunders 1957, 468). Aircraft carriers fall more into the latter category and tend to have C_X values closer to 0.99.

The optimum beam-to-draft ratio is 2.0. This is the most efficient surface area per volume and yields a semi-circular hull. This is rarely achieved, however, and most combatants have a beam-to-draft ratio between 2.5 and 3.0. Length-to-beam ratio is a tradeoff between resistance and stability. Higher length-to-beam ratios are favored in combatants, ranging from 7.0 to 10.0. Figure 5 shows Captain Saunders' graph featuring a mean value for length and beam based on successful ship designs of the past.

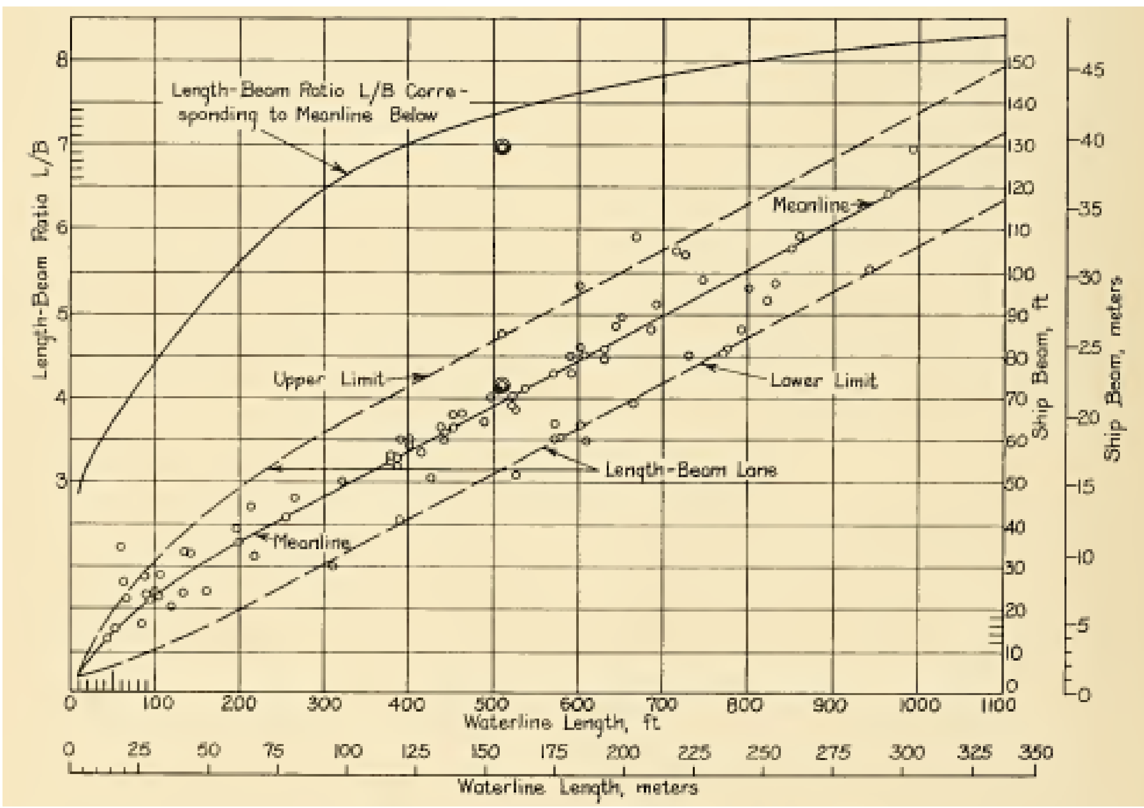


Figure 5. Plot of Length–Beam Ratio and Beam on Ship Length. Source: Saunders (1957, 470).

While Figure 5 represents a range of optimal values based on past ships, this is not to say that a ship design cannot fall outside of the values presented if the DRM calls for it.

IV. MODEL DEVELOPMENT

This report proposes a solution based on currently existing ship designs due to constraints on time and resources. Data was collected using Janes IHS Markit regarding aircraft carrying vessels from around the world. The Appendix contains a full compilation of the collected data. This section contains an analysis of the data based on the factors presented and explained in sections A and B.

A. MATHEMATICAL MODEL

We construct the mathematical model by analyzing the data presented in the Appendix and suggesting a regression formula or applicable range as needed. Table 2 shows a summary of the initial data collected.

Table 2. Baseline Data

Ship	∇(ft^3)	Froude Number	Block Coefficient	C	Ax (ft^2)	Cp	Δ/(0.01L)^3
Gerald R. Ford	3500000	0.270376352	0.583387005	0.006916088	5439.06	0.5892798	76.794848
Queen Elizabeth	2275000	0.253643747	0.533899196	0.003303679	4526.28	0.53929212	80.2907694
Liaoning	2065000	0.28268143	0.528661654	0.004887629	3870.9	0.53400167	59.1773546
Admiral Kuznetzov	2065000	0.28367704	0.532392129	0.004887629	3870.9	0.53776983	60.4389617
Vikramaditya	1575000	0.283519398	0.514302508	0.006481781	3267	0.51949748	56.3078033
America	1575000	0.224077573	0.489661154	0.005196229	3724.38	0.49460723	71.9969617
Charles deGaulle	1470000	0.274523097	0.526355365	0.003439546	3222.45	0.53167209	66.4947606
Sao Paulo	1148000	0.303088972	0.280837306	0.004554327	4656.96	0.28367405	49.9821018
Juan Carlos I	945000	0.227316062	0.516914594	0.003185401	2390.85	0.52213595	62.2409375
Cavour	910000	0.299934935	0.367884864	0.006124806	3168	0.37160087	56.2904689
Hyuga	665000	0.351531109	0.2978622	0.005201563	3421.44	0.30087091	70.4784018
Principe De Asturias	611240	0.293625177	0.383309085	0.004411661	2455.2	0.38718089	65.6917458
Chakri Naruebet	401800	0.316123289	0.334833333	0.004947267	1980	0.33821549	53.1481481
Giusepi Garibaldi	359170	0.36752449	0.251129197	0.00635282	2395.8	0.25366586	49.7129537

Figure 6 shows the displacement to length ratio as a function of the Froude number. Saunders' design lanes are also shown in Figure 6 for reference. Existing data do not fall within the lanes, which suggests that a different model should be applied. A linear regression, also shown in the figure, seems to fit the data very well within the range of applicability of the Froude numbers considered, namely between approximately 0.20 and 0.40.

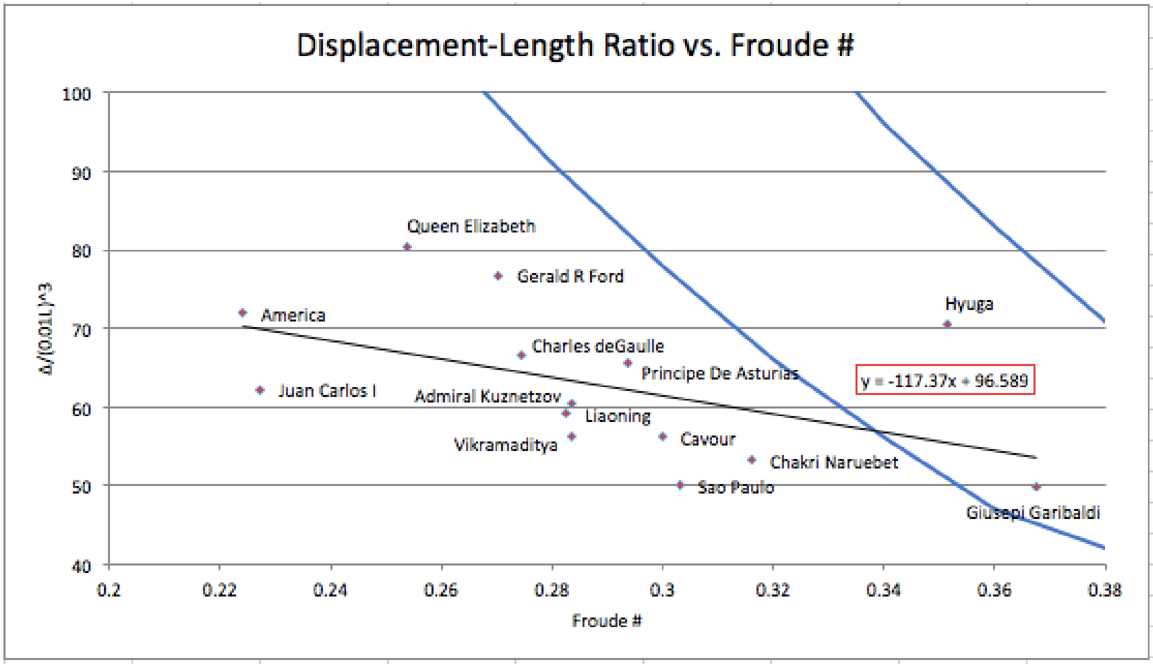


Figure 6. Displacement–Length Ratio vs. Froude Number

From the data, the linear relationship is:

$$\frac{\Delta}{(0.01L)^3} = 96 - 117(Fn)$$.

In this equation, the displacement Δ is in long tons, the length L is in feet, and the Froude number Fn is dimensionless.

Figure 7 shows the prismatic coefficient as a function of the Froude number, along with Saunder's design lanes. Most of the aircraft carriers under consideration fall outside the lanes. This suggests that a different model is needed. From examining Figure 7, it appears that a linear is a reasonable tradeoff between simplicity and accuracy in the applicable range of Froude numbers.

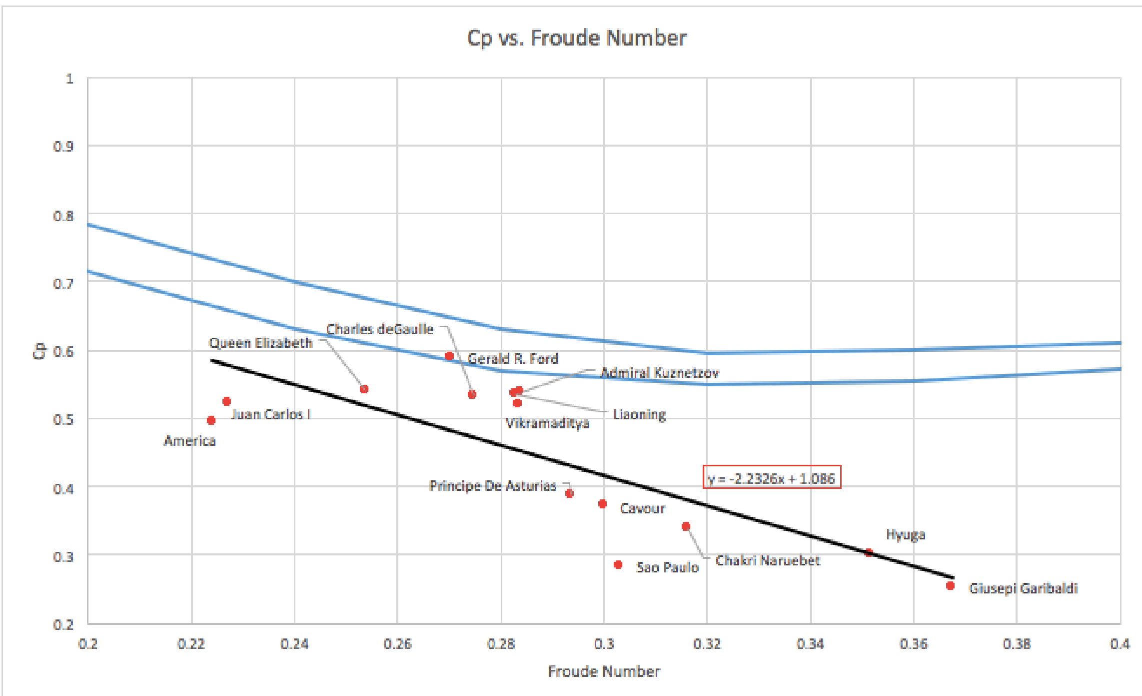


Figure 7. Prismatic Coefficient vs. Froude Number

From the data presented here, the linear regression shows the relationship is:

$$C_p = 1.09 - 2.23(Fn).$$

Figure 8 summarizes the values of the block coefficient from our data.

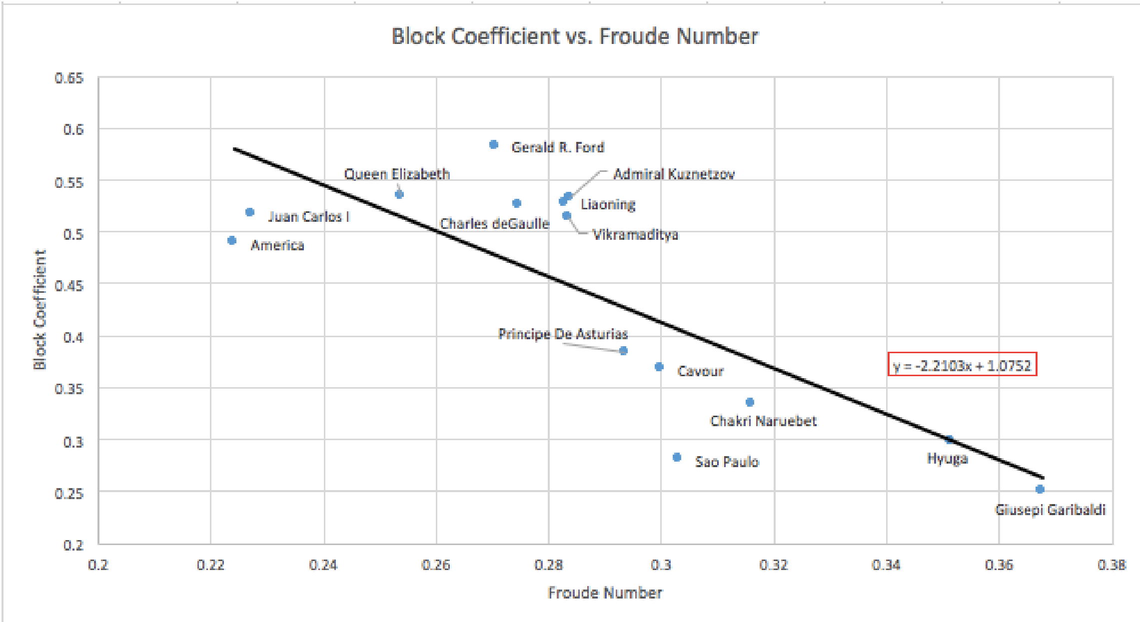


Figure 8. Block Coefficient vs. Froude Number

A linear regression fitting of the data yields the following expression:

$$C_B = 1.08 - 2.21(Fn).$$

Figure 9 shows the length-to-beam ratio distribution.

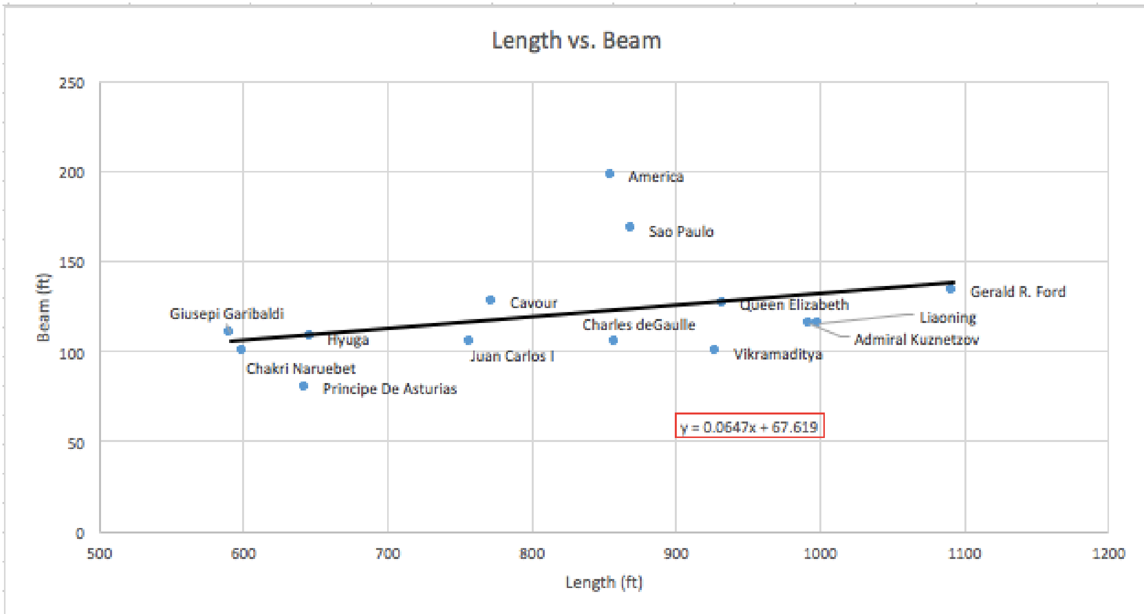


Figure 9. Length vs. Beam

A linear best-fit yields the following relationship:

$$B = 0.065L + 67.6\,.$$

In this expression, both the length and the beam are in feet and the range of applicability is for length between 600 and 1100 feet.

Another quantity that needs to be developed is an estimate for the required shaft horsepower for the ship to make speed. This is a function of both the size and the speed of the ship. Therefore, we need to develop a formula that takes both size and speed into consideration. In general, the shaft horsepower is proportional to a direct product of the resistance and the speed of the ship. The constant of proportionality depends on the particular hull shape and the propulsion mechanism used. The resistance of a ship is directly proportional to its wetted surface and the speed squared. The constant of proportionality is related to the flow field around the hull, as well as other physical parameters such as roughness. It should be noted that the constant of proportionality is not constant but it is taken as such in our case since the intent is to produce an approximate workable model. The wetted surface is proportional to the underwater volume to the (2/3) power. This is of course valid for geometrically similar hulls, which is not an unreasonable assumption for ships of a given class. It will vary from one class to another. Finally, the underwater volume is directly proportional to the ship's displacement. Putting all of the above arguments together, we can arrive at a simple expression relating shaft horsepower (SHP) to speed, V, and displacement Δ, as shown:

$$SHP = c\Delta^{2/3}V^3.$$

In this expression, SHP is in horsepower, displacement is in tons, and speed is in knots. The coefficient, *c*, is usually referred to as the admiralty coefficient and is commonly used in preliminary powering estimates (Watson 1998, 167).

Figure 10 shows the distribution of the admiralty coefficient for the ships in the database.

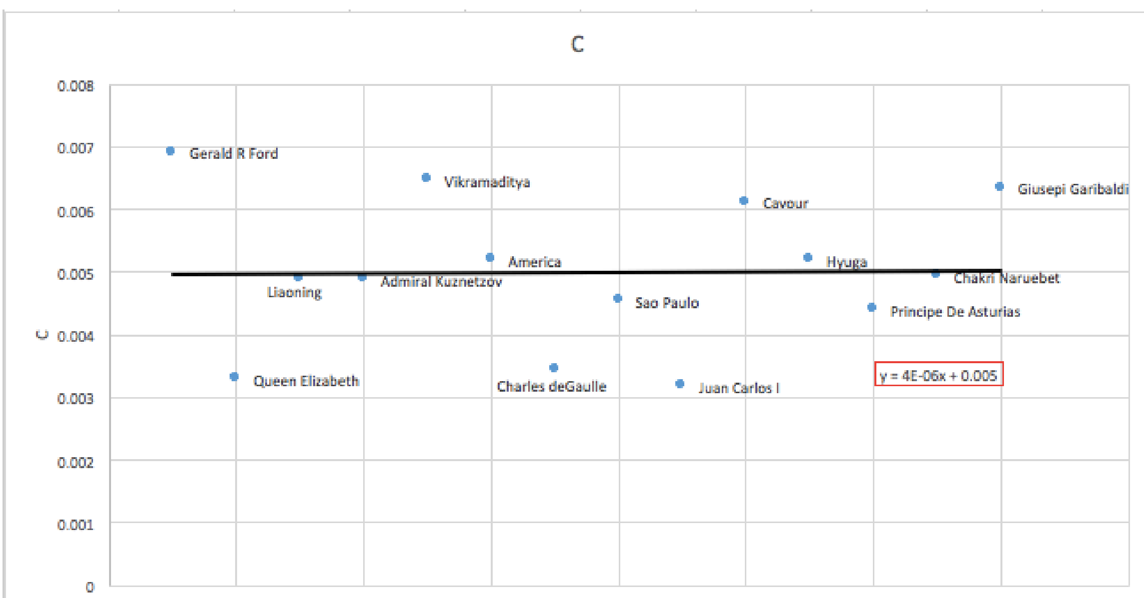


Figure 10. Admiralty Coefficient

From this graph it appears that a constant coefficient, c=0.005, which is the average value for all ships in the selection, is applicable. It should be noted, however, that not all ships in the database have the same speeds, and the admiralty coefficient is a function of the speed. Therefore, we graph the same coefficient as a function of the Froude number (Figure 11).

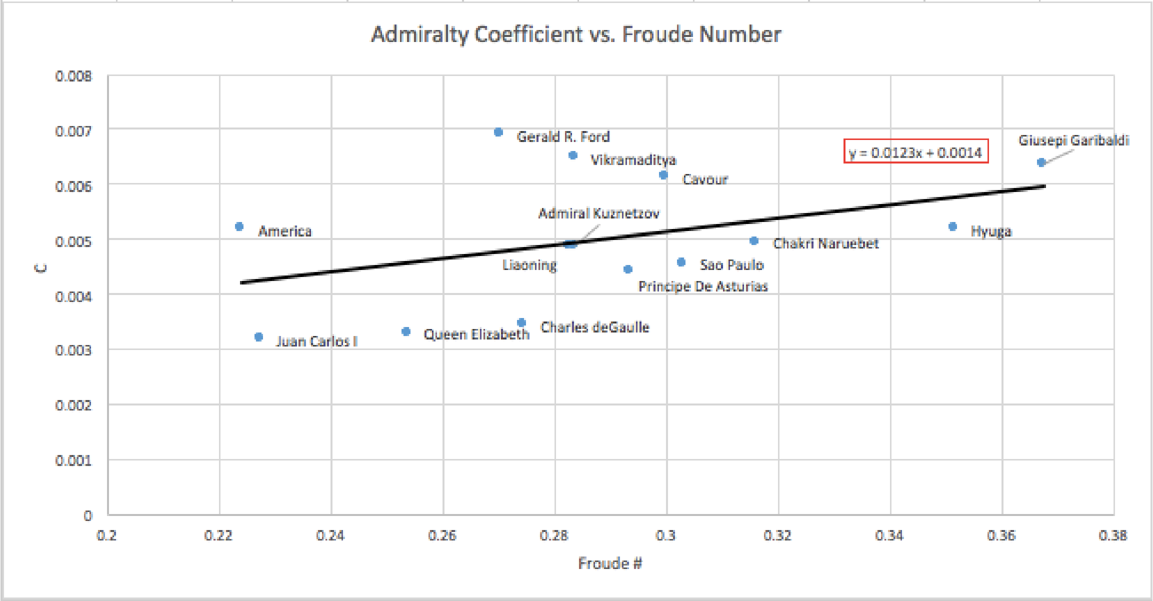


Figure 11. Admiralty Coefficient vs. Froude Number

From this graph, a linear relationship between c and Fn is evident. This relationship is

$$c = 0.0123(Fn) + 0.0014.$$

For the range of Froude numbers 0.2 to 0.4, this expression provides a better estimate of the admiralty coefficient, and thus the required shaft horsepower for a given displacement.

B. APPLICATION EXAMPLE

As an example of application of the formulas developed in section A, let us suppose we want to do a conceptual design for a CVL around 50,000 tons with a sustained speed of about 30 knots or 50 ft/sec.

We can use the displacement/length ratio formula to determine the length.

$$\frac{\Delta}{(0.01L)^3} = 96 - 117(Fn)$$

Substituting the values, we get,

$$\frac{50000 tons}{(0.01L)^3} = 96 - 117\left(\frac{50 ft/s}{\sqrt{32.2L}}\right).$$

From this expression, we can evaluate the required length, L, in feet. Using algebra, this comes out to 930 ft. The beam, B, can then be calculated by

$$B = 0.065L + 67.6 = 0.065(930 ft) + 67.6 = 128 ft.$$

The block coefficient is

$$C_B = 1.08 - 2.21\left(\frac{50 ft/s}{32.2L}\right) = 0.44.$$

The underwater volume of the ship is 50000 tons times 35 or 1,750,000 cubic feet. Recall the definition of the block coefficient,

$$C_B = \frac{1750000 ft^3}{LBT} = \frac{1750000 ft^3}{930 ft \times 128 ft \times T} = 0.44.$$

Using the values for L and B, we can evaluate the expected draft of the ship, T, approximately 33 feet.

Finally, the admiralty coefficient c is calculated.

$$c = 0.0123(Fn) + 0.0014 = 0.0123 \times \left(\frac{50 ft/s}{\sqrt{32.2 \times 930 ft}}\right) + 0.0014 = 0.0050.$$

The required shaft horsepower is

$$SHP = c\Delta^{2/3}V^3 = 0.0050 \times 50000 tons^{2/3} \times 50 ft^3 = 180000 SHP.$$

The above methodology can be easily tailored with different starting values (or initial requirements) and can be used to generate a large number of candidates for trade studies and analyses of alternatives.

V. ANALYSIS OF ALTERNATIVES

We now have enough information, based on the explanation of the DRM and the mathematical modeling illustrated in Chapter IV, to draw some conclusions using SBD principles regarding what sort of ship design should be considered. As explained in Chapter II, SBD is a process wherein design prototypes remain in consideration until infeasibility causes them to be eliminated from consideration. In order to form a conclusion, we will first consider all of the designs listed in the Appendix, then eliminate designs that are rendered infeasible based on the performance criteria set forth in the DRM and the mathematical model.

In this section, we will begin with all 14 ship prototypes and eliminate infeasible designs until we are left with one or a set of feasible solutions. Figure 12 illustrates the initial set of possible designs.

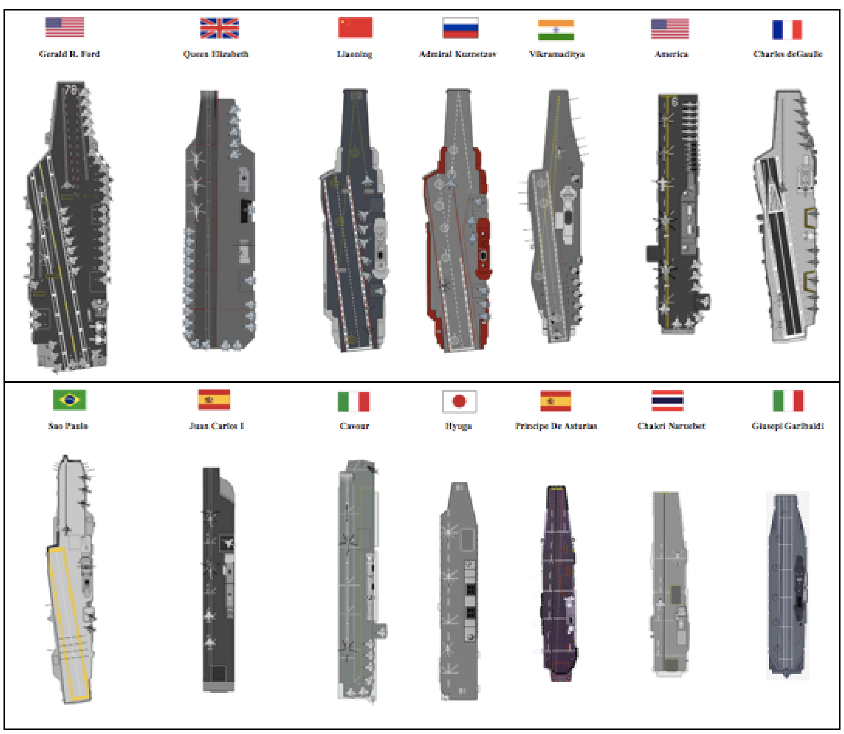


Figure 12. Initial Design Space

Our first criterion is that we would like a ship which displaces about 50,000 tons, based on the logic outlined in Chapter I. We will now consider all design solutions that are 50,000 -± 10,000 tons displacement, and eliminate the infeasible solutions. Figure 13 shows the feasible tonnage solutions.

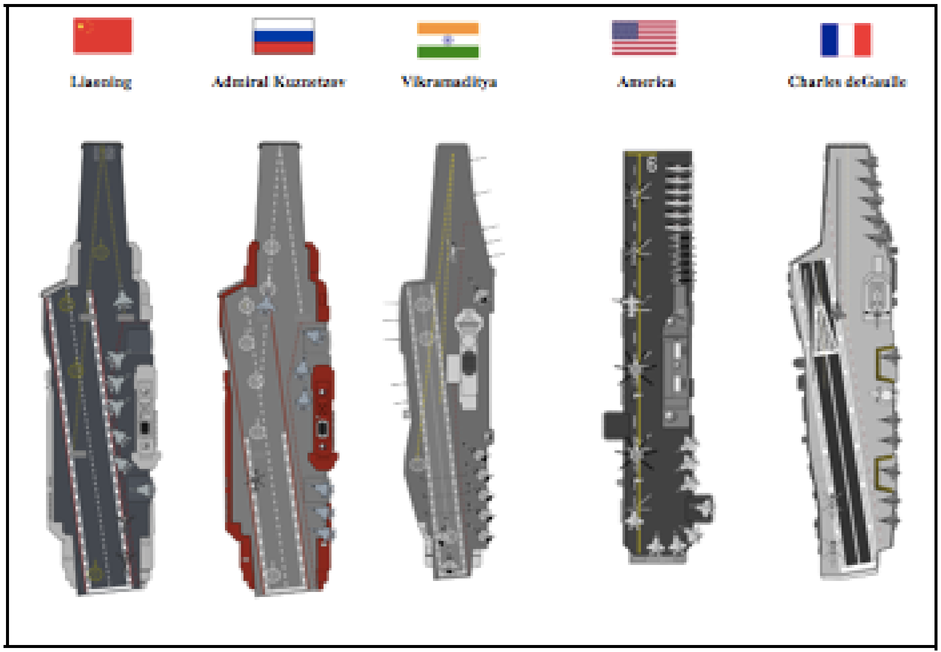


Figure 13. Feasible Tonnage Solutions

We are given a length and beam for each ship. We will next consider length-to-beam ratios. Based on the linear regression in Chapter IV, we can calculate the ideal beam width for each ship and determine the deviation. This ensures the best possible balance between internal carriage capacity and waveform resistance. Table 3 displays the results.

Table 3. Ideal Beam Width

Ideal Beam Width			
	Calculated (ft)	Actual (ft)	Deviation (%)
Liaoning	132	115	13%
Kuznetzov	132	115	13%
Vikramaditya	128	100	22%
America	123	198	38%
Charles deGaulle	123	105	15%
		StDev	11%

Because we are trying to minimize the deviation, we will consider any design that is not within two standard deviations from zero to be infeasible. Figure 14 shows the remaining feasible solutions. All three of the remaining ships meet the objective requirement for number of aircraft to be carried on board (≥ 30 aircraft) (Janes IHS Markit 2017d, 2017j, 2017k).

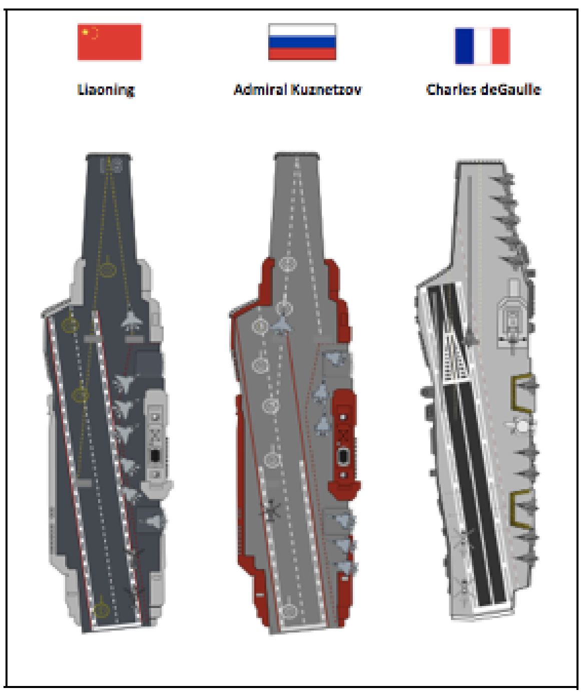


Figure 14. Feasible Length-to-Beam Ratio Solutions

We can further narrow down the feasible set by considering SHP and flight deck design. We already calculated the ideal SHP to achieve our target value of 30 knots (50ft/sec) in the example in Chapter IV.

$$SHP = c\Delta^{2/3}V^3 = 0.0050 \times 50000 tons^{2/3} \times 50 ft^3 = 180000 SHP$$

The Liaoning and Admiral Kuznetzov both have an SHP output of 200,000 SHP and can achieve speeds of 30 knots (Janes IHS Markit 2017j, 2017k). The Charles deGaulle does not meet the target objective value of 30 knots, but does meet the minimum objective value of 27 knots (Janes IHS Markit 2017d).

Having not eliminated any design based on SHP, one must finally consider the flight deck design. All three ships meet the minimum objective value of two flight deck elevators and, based on the length-beam calculations, all three ships can carry a sufficient number of aircraft to meet the target sortie rate outlined in Chapter I. The Liaoning and Admiral Kuznetzov, however, use a ramp for a launch system, while the Charles deGaulle uses a catapult (Janes IHS Markit 2017j, 2017k, 2017d). This is significant because it means that only the Charles deGaulle can meet the final requirement of supporting all aircraft that can be supported by a Ford class CV, particularly the E-2 Hawkeye. This means that any mission task outlined in Table 1 which requires the electronic capabilities of the E-2 cannot be achieved if either the Liaoning of the Admiral Kuznetzov designs are selected. We are left with the Charles deGaulle.

VI. CONCLUSION AND RECOMMENDATIONS

A. CONCLUSION

As this report is predicated on the use of existing designs, it can be concluded that, based on the stated assumptions and analysis of the data, the Charles deGaulle is the existing ship design to recommend as a CVL for the future fleet force. This design will be able to support the future needs of Naval Aviation while lessening strategic vulnerability compared to a Ford class CVN.

It should be emphasized that this is based on the assumptions made as explained in this chapter. These assumptions were made to illustrate the applicability of the proposed mathematical model in the SBD process. Different assumptions might have resulted in different conclusions. While some compromise must be made in speed, it is essential to use the full arsenal of aircraft, including those so necessary for electronic and information warfare, in a future maritime conflict.

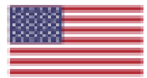
B. RECOMMENDATIONS FOR FURTHER RESEARCH

The cost benefit analysis regarding the CVL is beyond the scope of this report and is a necessary factor to consider before recommending a design. Given that the recommendations in this report are based on currently existing designs, sufficient data should be available to conduct a reliable cost estimation into the life cycle cost of a CVL.

Also, further research should be conducted to incorporate the self defense systems for each ship given modern threats. An analysis of ship defense capability will aid in determining which ship design presents the least strategic vulnerability in terms of operational risk.

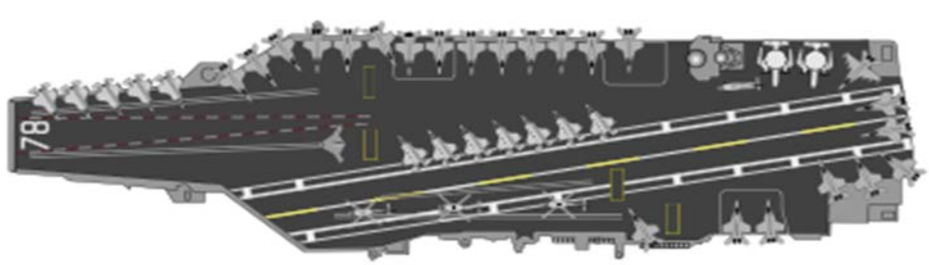
Expanding beyond recommendations regarding existing designs, it would be worth researching the feasibility of varying the launch method on some of the larger light aircraft carriers, such as the Liaoning and Admiral Kuznetzov, so that a CVL could have an increased sortie rate per day while still being able to support the variety of aircraft required for the modern mission.

APPENDIX. BASELINE SHIP DATA



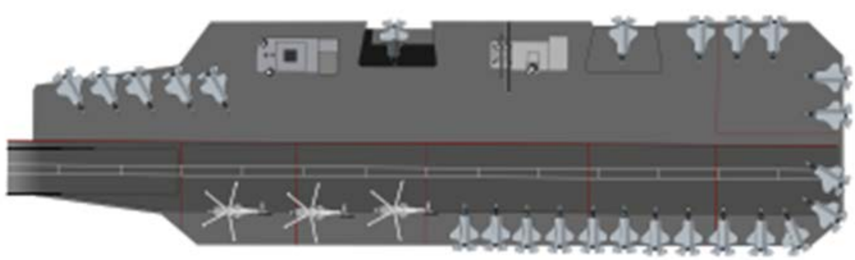
Gerald R. Ford. Source: Janes IHS Markit (2017g).

Displacement (Tonnes)		100000
Length (ft)		1092
Beam (ft)		134
Flight Deck Length (ft)		1092
Flight Deck Width (ft)		256
Draught (ft)		41
# Aircraft		80
Fixed Wing	F-35C F/A-18E/F E/A-18G E-2D UAS	
Rotary Wing	MH-60S MH-60R	
Launch Mechanism	Electric Catapult	
# Aircraft Lift		3
Propulsion	Nuclear 2 A1B Reactors 4 Shafts	
Primary SHP		402307
Top Speed (kt)		30
Range (NM)	N/A	
# Total Manning		4550



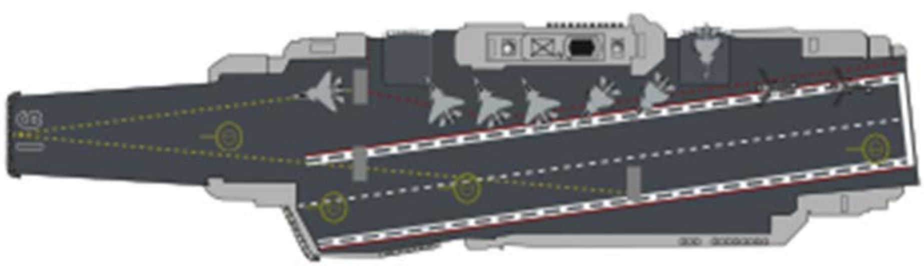
Queen Elizabeth. Source: Janes IHS Markit (2017n).

Displacement (Tonnes)	65000
Length (ft)	932
Beam (ft)	127
Flight Deck Length (ft)	909
Flight Deck Width (ft)	240
Draught (ft)	36
# Aircraft	40
Fixed Wing	F-35B
Rotary Wing	Merlin Wildcat Chinook Apache
Launch Mechanism	Ski Jump
# Aircraft Lift	2
Propulsion	Integrated Full Electric Propulsion 2 gas turbine alternators (93,870 SHP) 2 16V 38B diesel generators (30306 SHP) 2 12V 38B diesel generators (22800 SHP) 4 induction motors (53640 SHP) 2 shafts
Primary SHP	93870
Top Speed (kt)	26
Range (NM)	7000
# Total Manning	1681

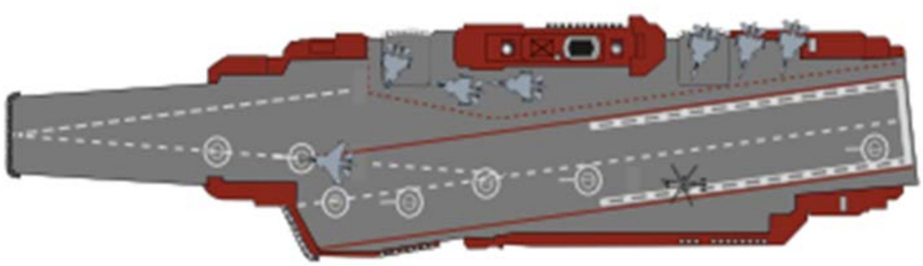


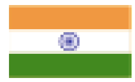
Liaoning. Source: Janes IHS Markit (2017k).

Displacement (Tonnes)	59000
Length (ft)	999
Beam (ft)	115
Flight Deck Length (ft)	999
Flight Deck Width (ft)	230
Draught (ft)	34
# Aircraft	50
Fixed Wing	J-15
Rotary Wing	Z-18 Z-9
Launch Mechanism	Ski Jump
# Aircraft Lift	2
Propulsion	8 boilers 4 turbines (200000 SHP) 4 shafts
Primary SHP	200000
Top Speed (kt)	30
Range (NM)	8500
# Total Manning	2826



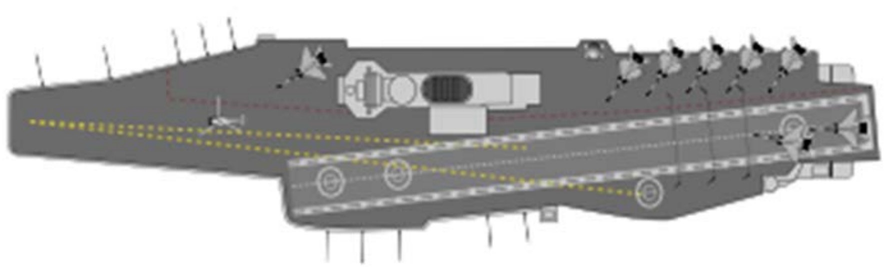
Admiral Kuznetzov. Source: Janes IHS Markit (2017j).	
Displacement (Tonnes)	59000
Length (ft)	992
Beam (ft)	115
Flight Deck Length (ft)	999
Flight Deck Width (ft)	230
Draught (ft)	34
# Aircraft	50
Fixed Wing	Su-33 MiG-29K Su-25
Rotary Wing	Ka-27 Ka-52K Ka-31
Launch Mechanism	Ski Jump
# Aircraft Lift	2
Propulsion	8 boilers 4 turbines (200000 SHP) 4 shafts
Primary SHP	200000
Top Speed (kt)	30
Range (NM)	8500
# Total Manning	3452

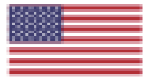




Vikramaditya. Source: Janes IHS Markit (2017l).

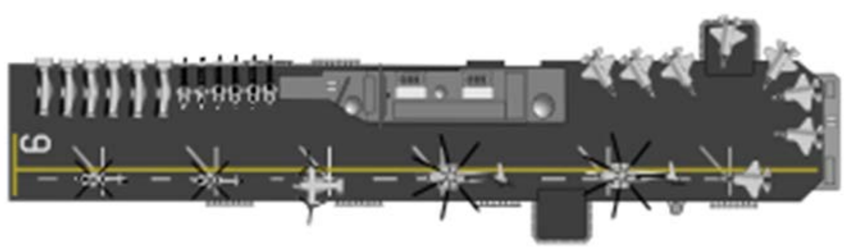
Displacement (Tonnes)		45000
Length (ft)		928
Beam (ft)		100
Flight Deck Length (ft)	not listed	
Flight Deck Width (ft)	not listed	
Draught (ft)		33
# Aircraft		30
Fixed Wing	MiG-29K	
Rotary Wing	Helix 27 Helix 28 Helix 31	
Launch Mechanism	Ski Jump	
# Aircraft Lift		1
Propulsion	8 boilers 4 turbines (200000 SHP) 4 shafts	
Primary SHP		200000
Top Speed (kt)		29
Range (NM)		13800
# Total Manning		1326

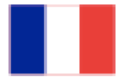




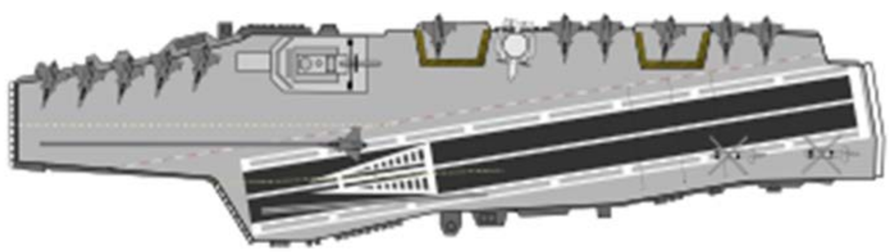
America. Source: Janes IHS Markit (2017a).

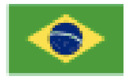
Displacement (Tonnes)		45000
Length (ft)		855
Beam (ft)		198
Flight Deck Length (ft)		819
Flight Deck Width (ft)		118
Draught (ft)		19
# Aircraft		30
Fixed Wing	F-35B	
Rotary Wing	MV-22 AH-1 UH-1 MH-53 MH-60	
Launch Mechanism	none	
# Aircraft Lift		2
Propulsion	2 gas turbines (70000 SHP) 2 auxiliary motors (10000 SHP) 2 shafts	
Primary SHP		70000
Top Speed (kt)		22
Range (NM)		9500
# Total Manning		1204





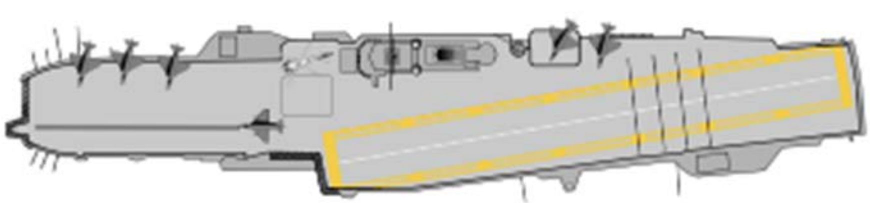
Charles deGaulle. Source: Janes IHS Markit (2017d).	
Displacement (Tonnes)	42000
Length (ft)	858
Beam (ft)	105
Flight Deck Length (ft)	858
Flight Deck Width (ft)	211
Draught (ft)	31
# Aircraft	40
Fixed Wing	Rafale F2 Rafale F3 E-2C
Rotary Wing	AS 565 AS 322 Super Puma Dauphin
Launch Mechanism	Catapult
# Aircraft Lift	2
Propulsion	Nuclear 2 shafts
Primary SHP	81801
Top Speed (kt)	27
Range (NM)	N/A
# Total Manning	2571





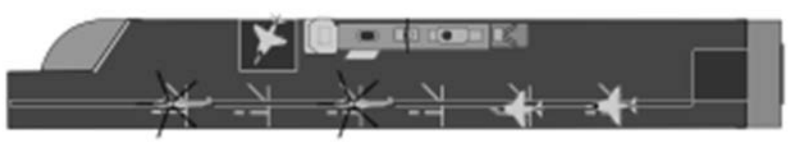
Sao Paulo. Source: Janes IHS Markit (2017e).

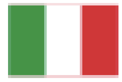
Displacement (Tonnes)	32800
Length (ft)	869
Beam (ft)	168
Flight Deck Length (ft)	850
Flight Deck Width (ft)	154
Draught (ft)	28
# Aircraft	39
Fixed Wing	A-4 Tracker/Trader
Rotary Wing	UH-12/13/14
Launch Mechanism	Catapult
# Aircraft Lift	2
Propulsion	6 boilers 2 turbines (126000 SHP) 2 shafts
Primary SHP	126000
Top Speed (kt)	30
Range (NM)	7000
# Total Manning	2096



Juan Carlos I. Source: Janes IHS Markit (2017i).

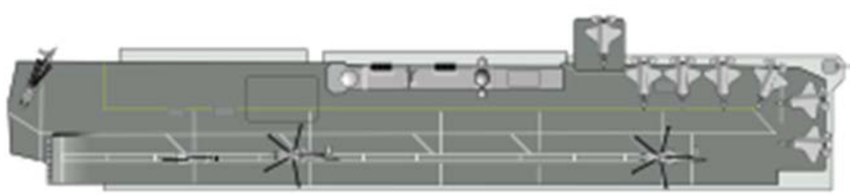
Displacement (Tonnes)		27000
Length (ft)		757
Beam (ft)		105
Flight Deck Length (ft)		664
Flight Deck Width (ft)		105
Draught (ft)		23
# Aircraft		30
Fixed Wing	AV-8	
Rotary Wing	Chinook Sea King NH-90	
Launch Mechanism	Ski Jump	
# Aircraft Lift		1
Propulsion	1 gas turbine (26550 SHP) 2 podded propulsors (29,500 SHP) 2 MAN 324016V (21080 SHP)	
Primary SHP		26550
Top Speed (kt)		21
Range (NM)		9000
# Total Manning		296

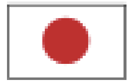




Cavour. Source: Janes IHS Markit (2017b).

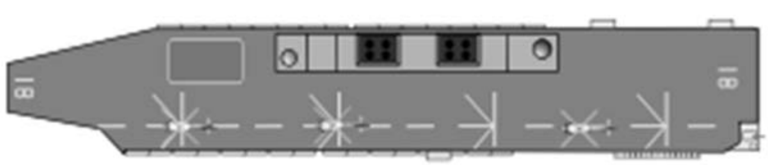
Displacement (Tonnes)	26000
Length (ft)	773
Beam (ft)	128
Flight Deck Length (ft)	722
Flight Deck Width (ft)	112
Draught (ft)	25
# Aircraft	20
Fixed Wing	AV-8B F-35B
Rotary Wing	EH 101 SH 90 AB 212
Launch Mechanism	Ski Jump
# Aircraft Lift	2
Propulsion	4 gas turbines (118000 SHP) 2 shafts
Primary SHP	118000
Top Speed (kt)	28
Range (NM)	7000
# Total Manning	1334





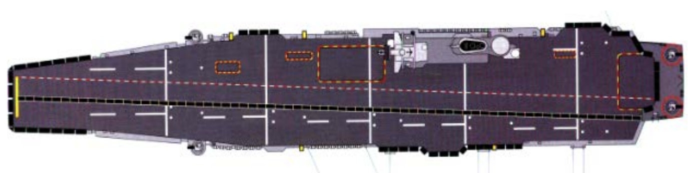
Hyuga. Source: Janes IHS Markit (2017h).

Displacement (Tonnes)		19000
Length (ft)		646
Beam (ft)		108
Flight Deck Length (ft)	not listed	
Flight Deck Width (ft)	not listed	
Draught (ft)		32
# Aircraft		11
Fixed Wing	none	
Rotary Wing	SH-60K MH-101	
Launch Mechanism	none	
# Aircraft Lift		2
Propulsion	4 gas turbines 2 shafts	
Primary SHP		100000
Top Speed (kt)		30
Range (NM)		6000
# Total Manning		372



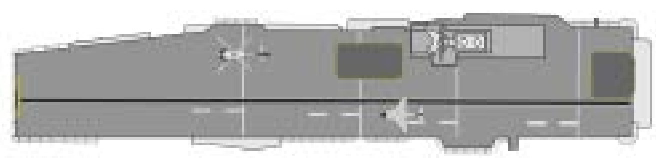
Principe De Asturias. Source: Janes IHS Markit (2017m).

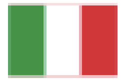
Displacement (Tonnes)		17464
Length (ft)		643
Beam (ft)		80
Flight Deck Length (ft)		575
Flight Deck Width (ft)		95
Draught (ft)		31
# Aircraft		26
Fixed Wing	AV-8B	
Rotary Wing	SH-3 AB 212EW	
Launch Mechanism	Ski Jump	
# Aircraft Lift		2
Propulsion	2 gas turbines (46400 SHP) 1 shaft	
Primary SHP		46400
Top Speed (kt)		25
Range (NM)		6500
# Total Manning		920



Chakri Naruebet. Source: Janes IHS Markit (2017c).

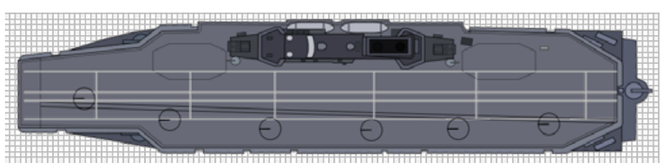
Displacement (Tonnes)	11480
Length (ft)	600
Beam (ft)	100
Flight Deck Length (ft)	573
Flight Deck Width (ft)	90
Draught (ft)	20
# Aircraft	29
Fixed Wing	none
Rotary Wing	S-70-B7 MH-60S Chinook
Launch Mechanism	Ski Jump
# Aircraft Lift	2
Propulsion	2 gas turbines (44250 SHP) 2 diesel (11780 SHP) 2 shafts
Primary SHP	44250
Top Speed (kt)	26
Range (NM)	10000
# Total Manning	813





Giusepi Garibaldi. Source: Janes IHS Markit (2017f).

Displacement (Tonnes)	10262
Length (ft)	591
Beam (ft)	110
Flight Deck Length (ft)	570
Flight Deck Width (ft)	100
Draught (ft)	22
# Aircraft	18
Fixed Wing	none
Rotary Wing	EH 101 SH 90 AH 129 AB 212
Launch Mechanism	Ski Jump
# Aircraft Lift	2
Propulsion	4 Gas Turbines (81000 SHP) 2 shafts
Primary SHP	81000
Top Speed (kt)	30
Range (NM)	7000
# Total Manning	591



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