Concept Exploration of the Amphibious Combat Vehicle

Dr. John Burrow[1](V), Dr. Norbert Doerry[2] (FL), Mark Earnesty[1] (V), Joe Was[1] (V), Jim Myers[1] (V), Jeff Banko[1] (V), Jeff McConnell[2] (V), Joshua Pepper[1] (V), and COL Tracy Tafolla[1] (V)

1. United States Marine Corps
2. United States Navy

In 2013, the United States Marine Corps (USMC) conducted a study to determine the technical feasibility and affordability of a High Water Speed Amphibious Combat Vehicle, quantify performance, determine capability trade-offs that can be made to reduce cost and reduce technical risk, and compare capabilities with those of a Low Water Speed variant. This paper describes the organizational structure, the study plan, and the innovative Set-Based Design method used by the ACV Directorate to conduct the study.

KEY WORDS

Amphibious Combat Vehicle; Concept Exploration; Set-Based Design

NOMENCLATURE

AAV	Amphibious Assault Vehicle
ACMC	Assistant Commandant of the Marine Corps
ACV	Amphibious Combat Vehicle
AoA	Analysis of Alternatives
APUC	Average Procurement Unit Cost
ASN(RDA)	Assistant Secretary of the Navy for Research, Development and Acquisition
BLT	Battalion Landing Team
BOM	Bill of Material
CDD	Capability Development Document
CLVW	Crew Loaded Vehicle Weight
CONOPS	Concept of Operations
COTS	Commercial Off The Shelf
CW	Curb Weight
DOORS	Dynamic Object-Oriented Requirements System
EFV	Expeditionary Fighting Vehicle
FACT	Framework for Assessing Cost and Technology
FER	Force Exchange Ratio
GFE	Government Furnished Equipment
GR&A	Ground Rules and Assumptions
GVW	Gross Vehicle Weight
HM&E	Hull, Mechanical and Electrical
HWS	High Water Speed
IMS	Integrated Master Schedule
IOC	Initial Operational Capability
IAT&C	Integration, Assembly, Test, and Checkout
LCCE	Life Cycle Cost Estimate
LWS	Low Water Speed
MAGTF	Marine Air-Ground Task Force
MBSE	Model Based Systems Engineering
MEF	Marine Expeditionary Force
MEU	Marine Expeditionary Unit
MRDB	Market Research Database
MTBF	Mean Time Between Failure
MTTR	Mean Time to Repair
NCR	National Capital Region
NDI	Non-Developmental Item
NRE	Non-Recurring Engineering
R&D	Research and Development
SBD	Set-Based Design
SE OPT	Systems Engineering Overarching Product Team
SER	System Exchange Ratio
STOM	Ship-to-Objective Maneuver
USMC	United States Marine Corps
WBS	Work Breakdown Structure

INTRODUCTION

The Amphibious Assault Vehicle (AAV) (Figure 1) has served the United States Marine Corps (USMC) for over forty years. Following cancellation of the program for its intended replacement, the Expeditionary Fighting Vehicle (EFV) (Figure 2), the Marine Corps immediately embarked upon a cost and technical risk-informed concept development effort to explore capability trades in pursuit of a more affordable amphibious combat vehicle (ACV). In parallel, the Marine Corps identified the capability gaps associated with the AAV compared to current and future Concept of Operations (CONOPS). This resulted in the ACV Initial Capabilities Document dated 25 Oct 2011 which eliminated the requirement for high water speed.

Figure 1: Amphibious Assault Vehicle (AAV) (Photo by Mass Communication Specialist 3rd Class Amanda Kitchner)

Figure 2: EFV Prototype in April 2000 (Photo By: Lance Cpl. Brandon R. Holgersen).

The Marine Corps conducted an ACV Analysis of Alternatives (AoA) in 2012. While the AoA reinforced the need for a self-deploying, survivable ACV, the AoA did not attempt to examine the specific operational benefits of high water speed (HWS).

Prior to the initiation of a Low Water Speed (LWS) ACV acquisition, senior Marine Corps leaders expressed concern with the removal of the HWS requirement, citing the operational flexibility and tactical advantage that HWS might provide. Based on this concern, the Assistant Commandant of the Marine Corps (ACMC) and the Assistant Secretary of the Navy for Research, Development and Acquisition (ASN (RD&A)) established the ACV Directorate to perform the following:

1. Determine the technical feasibility and costs of producing a HWS ACV.
2. Identify and assess capability trades resulting in reduced HWS ACV procurement costs.
3. Quantify using modeling and simulation and qualify using active duty Marines the operational benefits of a HWS ACV.
4. Determine the differences in development, procurement, and operational & support (O&S) costs between a LWS and a HWS ACV.
5. Identify the capability costs of a HWS ACV, i.e., capabilities that can be provided on a LWS ACV that cannot be provided on a HWS ACV.
6. Evaluate the opportunity costs of a HWS ACV, i.e., impacts to other Marine Corps programs and accounts required to afford a HWS ACV.

This paper describes the organizational structure, the study plan, and the methodology used by the ACV Directorate to answer these questions. This effort initiated in January 2013 and completed with a brief to senior Marine Corps leadership in January 2014.

ORGANIZATIONAL STRUCTURE

Planning began in January 2013 with a small multi-disciplinary core team focused on precisely defining the problem, specifying the initial set of ground rules and assumptions, and developing the study approach. As the study plan evolved, by the end of February the organization depicted in Figure 3 emerged. Led by a senior executive serving as the ACV Director, the team consisted of about sixty full-time civil servants and Marines co-located in Quantico, VA and was supported by industry (BAE and General Dynamics Land Systems (GDLS)) and Georgia Tech Research Institute (GTRI). Contracts for specific objectives were also awarded to other companies and universities. The Program Integration group consisted of acquisition planning, schedule, contracting, budgeting, public affairs, and Systems Engineering planning. Acquisition planning concentrated on developing and evaluating different acquisition strategies. The public affairs group developed and implemented a comprehensive strategic communications plan.

The affordability team partnered with Deputy Commandant Programs and Resources (P&R) to determine the fiscal impact of the ACV program on Marine Corps programs. This fiscal impact is considered an “opportunity cost,” in that if an ACV of a given price is procured, the Marine Corps may not be able to procure something else of value. The Design Manager, assisted by an Integration Engineer, led three teams: Cost, Trade Study, and Innovation. The Cost Team, supported by industry, developed the acquisition and lifecycle cost models and verified that these models were properly implemented in configuration modeling. The Trade Study Team, also supported by industry, consisted of Technical Modeling of ACV configurations, requirements engineering, and operational effectiveness analysis. While the Trade Study team was constrained by a Ground Rules and Assumptions (GR&A) list to only look at technically mature components and system concepts, the Innovation Team was unconstrained and chartered to seek out unconventional technologies that could apply to ACV in addition to “high-risk with high-payoff” technologies that would require a Research and Development (R&D) investment. The Innovation team would identify mature technology from non-traditional sources and address whether delaying the ACV program to mature promising technologies was advantageous. The Innovation Team also enabled the technical modeling team to concentrate only on mature technology while not ignoring new opportunities.

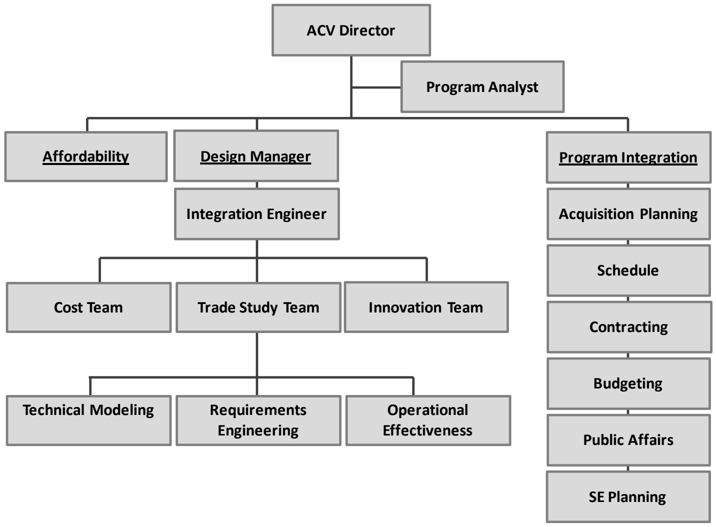


Figure 3: ACV Team Organizational Structure

STUDY APPROACH

The study planning effort used the best practices detailed in Doerry (2010). The study approach employed a set-based design (SBD) strategy. As shown in Figure 4, a traditional approach would have developed several alternative concepts for an ACV, analyzed these alternatives individually, and then compared them as a group. The development of each concept would have consisted of a series of steps that must be followed in order. While multiple concepts could be synthesized and analyzed in parallel as depicted in Figure 4, the minimum study time would be dictated by the need to conduct multiple steps in series. This approach would have taken over a year to complete, much longer than the 6-9 months allocated. Furthermore, definite conclusions would not be made until very late in the study during the comparison of the alternatives.

A close examination of the ACV tasking revealed that the study could instead be partitioned into four relatively independent sets of studies that could be addressed with a Set-Based Design approach: Requirements Analysis, Effectiveness Analysis, Trade Space Analysis, and Affordability Analysis. These different analyses, described in Table 1, were only loosely coupled, could be conducted largely in parallel, and provided study insights through-out the duration of the study. The final recommendation for the ACV would be based on an intersection of these four analyses.

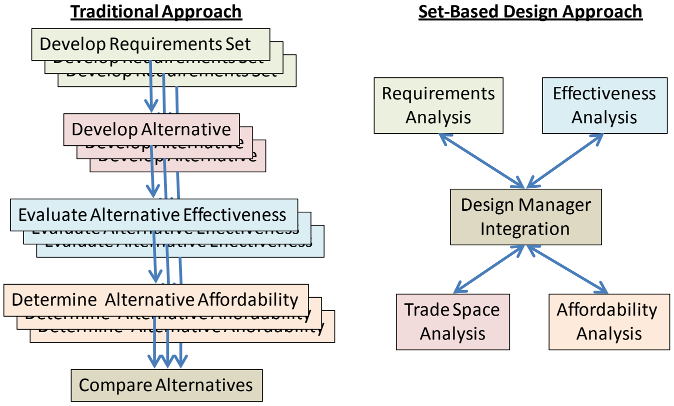


Figure 4: Traditional vs. Set-Based Design Approach

Key to the study approach was the recognition that the Effectiveness Analysis only depended on five major design attributes: High vs Low water speed, number of embarked troops, weapon system, level of under-blast protection, and level of direct fire protection. These major design attributes, designated as “big rocks,” were also the major contributors to cost and weight; the impact of all other tradable requirements could be considered incrementally. In a second application of SBD, the Trade Space Analysis initially assumed high water speed and studied the impact of varying the other four major design attributes; creating thousands of configurations for each set of capabilities. The remaining tradable requirements were studied as part of the Requirements Study. Figure 5 highlights this partitioning of requirements. The Effectiveness Analysis analytically evaluated the operational impact of the five major design attributes independent of specific ACV configurations. Likewise, the Affordability Analysis determined the impact of funding ACVs with different acquisition costs on the overall Marine Corps budget over the acquisition time frame.

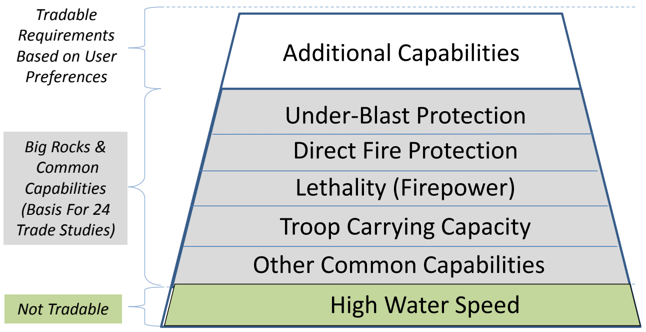


Figure 5: Partitioning of ACV Capabilities

The trade space analysis determined the technical feasibility and the cost for the Baseline Study and the Trade Study. The effectiveness analysis determined the Trade Study performance and effectiveness as well as incorporating the HWS Study. The requirements analysis supported the Requirements Study. The affordability analysis was conducted outside of the studies.

Table 1: ACV Studies

STUDY	PURPOSE	PRODUCTS
Requirements Study	To analyze the Draft ACV Capability Development Document (CDD) to determine the number of requirements specified, the relationship between requirements from both a mission and technical perspective and user preferences for tradable requirements. To develop Draft CDDs for all viable capability concepts.	- Requirements database - Requirements traceability (e.g., inter and intra requirements relationships) - User preferences and values placed on requirements - Draft Capability Concept CDDs - Design strategies(e.g., modularity, future growth, etc)
Baseline Study	To understand and evaluate the design and cost implications of less than acceptable capability concepts, as well as to test and validate the analytical methodologies and tools used to assess Trade Study capability concepts.	- Baseline Capability Concepts assessment (feasibility and costs) - Processes, models and tools validation
Trade Study	To evaluate the technical viability and costs of capability concepts derived from all possible permutations of lethality, troop capacity, under-blast protection and direct fire protection alternatives.	- Trade Capability Concepts assessments (feasibility and costs) - Trade Capability Concepts performance and effectiveness
HWS Study	To determine the performance, effectiveness, operational flexibility and tactical advantages provided by a HWS ACV when compared to a low water speed (LWS) ACV.	- Measures of Performance - Measures of Effectiveness - Operational Contributions

While Figure 4 indicated the four types of analysis could proceed independently and in parallel, in reality they shared required expertise. An Integrated Master Schedule (IMS) was used to identify and resolve competing needs for shared resources. Each team defined the activities and products it was responsible for and highlighted interdependencies with the other teams. A dedicated scheduler integrated the team schedules, helped resolve resource and schedule conflicts, and tracked accomplishment against the schedule. Figure 6 shows the initial plan for how the studies would be accomplished. This plan did not include technical modeling of low water speed options; the results of previous work would be used. The operational effectiveness comparison of high and low water speed would be examined in the Value of Speed Study (aka HWS study). A Baseline Study was planned to develop a "floor" to the cost and capability of a high water speed ACV as well as serve as a test case for implementing and verifying the technical modeling within the Framework for Assessing Cost and Technology (FACT), which will be described in a later section. By establishing the "floor" early in the process, expectations with senior leadership could be managed during the overall conduct of the study. The Trade Study evaluated twenty-four capability concepts for cost and technical feasibility. These twenty-four capability concepts systematically explored the "big rock" trade-space. In the Requirements Study, the Draft CDD was singularized and decomposed to identify about forty tradable requirements in addition to the "big rocks." These tradable requirements were analyzed to determine their weight and cost impact. Additionally, user surveys and workshops were employed to gain insight on user preference for tradable requirements and the "big rocks."

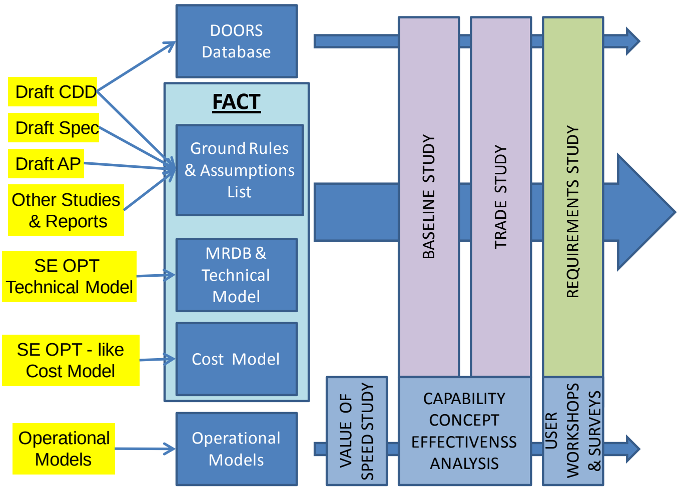


Figure 6: Analysis Plan

As shown in Figure 6, the technical modeling was primarily performed within FACT. The effectiveness analysis relied on operational models, typically discreet event simulations of combat scenarios. The requirements analysis used the Dynamic Object-Oriented Requirements System (DOORS).

CONFIGURATION MODELING

Within this study, a "capability concept" refers to specific levels for each of the "big rocks" along with an associated GR&A list to cover all other requirements. For example, a capability concept would refer to an ACV that carried 17 troops and weapon system "X", and included under-blast protection level "C" and direct fire protection level "B". A configuration is a set of individual component selections that define a complete vehicle meeting the requirements of a capability concept. Potentially thousands of configurations exist for each feasible capability concept. Historically, one, or at most a few, of these configurations would be selected as representative of the capability concept. This was not done in this study; instead the "cloud" of all feasible configurations was used as a basis for estimating the cost of a given capability concept.

Ground Rules and Assumptions

The planning effort identified the data elements required as input by the tools which would be used in the analysis. Default values for these data elements as well as draft Capabilities Description Document (CDD) requirements were established and documented in the GR&A. These GR&A were intentionally austere and at or below anticipated threshold requirements to minimize weight and enable as many feasible configurations with as little cost as possible. The requirements study examined the impact of adding capabilities back to the vehicle in terms of both weight and cost. In a few cases, the requirements study also examined the impact on weight and cost of setting requirements below the values used in the Trade Study.

Market Research Database

The government team and industry partners conducted a market research of possible components suitable for an amphibious vehicle. This market research was used to populate cost and technical data in a Microsoft Excel workbook based Market Research Database (MRDB). The government team and both industry partners developed independent market research databases and submitted them to the government for review. The government team then subsequently "sanitized" specific MRDB entries into one database by removing any proprietary information. A modified version of the EFV Work Breakdown Structure (WBS) was used to organize and standardize the subsystem and component cost and attribute data. This EFV WBS was based on MIL-HDBK-881C *Work Breakdown Structures for Defense Material* items for surface vehicles, with adjustments required for an amphibious vehicle.

The MRDB contains projected cost data for each component option. Depending on the level of knowledge gained by market research of the cost for each option, additional low and high cost bounds could also be entered into the MRDB.

The primary ground rules for the MRDB were as follows:

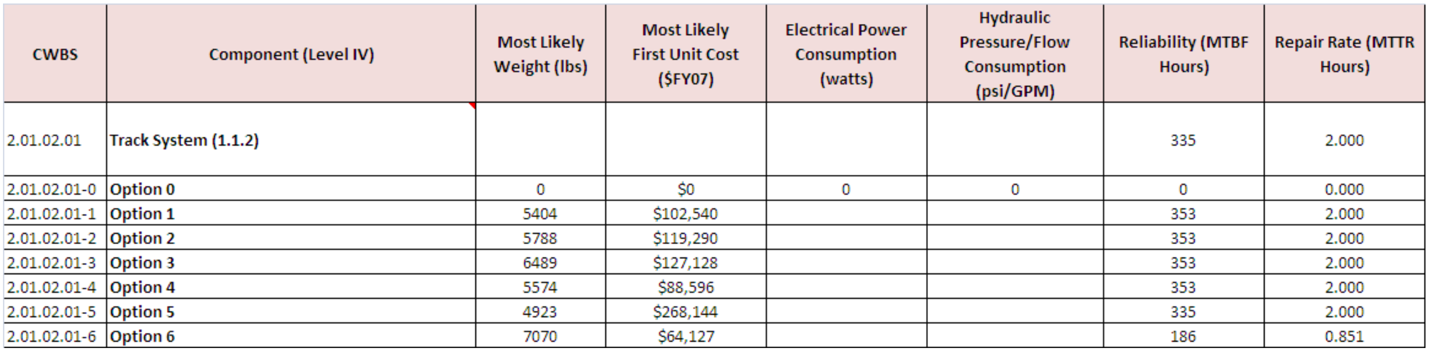
- The data structure organization was based on the WBS to align with Technical and Cost tools.
- The procurement data from MRDB provided first unit costs.
- Cost figures were stored in FY 07 dollars. Any data received from vendors not in FY 07 dollars was converted using a standard formula before entry into the MRDB. With all figures in FY 07 dollars, values can then be scaled to values of any year.
- The MRDB stored traceability of data sources.
- The MRDB contained rules to prevent incompatible designs from populating the results. For instance, the MRDB rules ensured that if the user selected a specific component that could only work with another specific component, then that component was selected also.

Figure 7 displays an example of a section of a MRDB with arbitrary data.

The MRDB also contained non-cost technical data. This data included an assessment of maturity in the form of Commercial Off The Shelf (COTS), Non-Developmental Item (NDI), or

New; weight; electrical power; hydraulic power; reliability (MTBF); repair rate (MTTR), and an assessment of competition for each WBS element (competitive, non-competitive, or GFE). These values were used to calculate vehicle attributes required by the Phase 1 Cost Model.

In addition, the MRDB included WBS component mapping that translated the requirements of each study concept into component selections from the MRDB. This mapping identified the appropriate components that were selectable from the MRDB to develop configurations for each study concept, ensuring the technical performance for each concept was met.



CWBS	Component (Level IV)	Most Likely Weight (lbs)	Most Likely First Unit Cost ($FY07)	Electrical Power Consumption (watts)	Hydraulic Pressure/Flow Consumption (psi/GPM)	Reliability (MTBF Hours)	Repair Rate (MTTR Hours)
2.01.02.01	**Track System (1.1.2)**					335	2.000
2.01.02.01-0	**Option 0**	0	$0	0	0	0	0.000
2.01.02.01-1	**Option 1**	5404	$102,540			353	2.000
2.01.02.01-2	**Option 2**	5788	$119,290			353	2.000
2.01.02.01-3	**Option 3**	6489	$127,128			353	2.000
2.01.02.01-4	**Option 4**	5574	$88,596			353	2.000
2.01.02.01-5	**Option 5**	4923	$268,144			335	2.000
2.01.02.01-6	**Option 6**	7070	$64,127			186	0.851

Figure 7: Example Market Research Database Data

Technical Parameters Tool

The Technical Parameters Tool is a Microsoft Excel application that captures data from the MRDB, Reliability Analysis, and development analysis, and calculates first unit Bill of Material (BOM) cost, technical parameters, and output to the cost tool for specific configurations for each study concept. It was adapted from the previously validated Systems Engineering Overarching Product Team (SE OPT) Procurement Tool. This tool utilized three worksheets to perform the calculations: Base Vehicle, Vehicle Data, and Output to Cost.

For all of the components, assemblies, and sub-systems comprising a vehicle, the Base Vehicle worksheet captures BOM data from the MRDB for specific configurations. The Vehicle Data worksheet contains concept level inputs/assumptions and Nonrecurring Engineering (NRE) attributes, and calculates vehicle level attributes. The inputs/assumptions for each concept in the baseline studies include: Crew Size, Number of Troops Carried, Marine Load, Mission Essential Equipment, Additional Days of Supply, Growth Weight, Ammunition weight (ready and stowed), and number of rounds (ready and stowed) for primary and secondary weapons. These varied depending on the concept being studied. An analysis was conducted to determine the Mean Time Between Failure (MTBF) and Mean Time to Repair (MTTR). The analysis showed that a range would be representative of all concepts; therefore this range was kept constant within the model.

Calculations for vehicle level attributes included Curb Weight (CW), Crew Loaded Vehicle Weight (CLVW), and Gross Vehicle Weight (GVW), which varied based on configuration and concept. CW included the weight of the BOM from the Base Vehicle worksheet, fuel, and service life allowance. The CLVW added the crew load and vehicle ammunition load to the CW. The GVW added embarked Marine Load, Mission Essential Equipment, and Days of Supply to the CLVW. The fuel load was iteratively calculated using the Fuel Capacity and Engine Sizing Tool. The GVW was calculated starting with an initial fuel load and iteratively modified until the fuel load and GVW converged.

The Output to Cost worksheet captured all the calculations and attributes that interfaced with the Phase 1 Cost Model developed by the Cost Team.

The Technical Parameters tool algorithms were incorporated into FACT to automate calculations for the various studies. The Technical Parameters tool itself was used to verify that the FACT tool had correctly implemented the algorithms.

Phase 1 Cost Model

The Phase 1 Cost Model was developed from the original SE OPT LCCE model. This model had been updated several times and extensively reviewed by subject matter experts from organizations such as USMC Operations Analysis Division (OAD), RAND, Naval Center for Cost Analysis (NCCA), and ASN(RD&A).

The Government provided a sanitized version of this model to the industry partners for their review and to provide them a more detailed understanding of how the model worked. Additionally, feedback from the ACV Cost and Technical teams resulted in several updates/enhancements.

The model was initially a Microsoft Excel workbook comprised of multiple worksheets. The model incorporates the BOM from the MRDB to calculate Prototype Manufacturing, Production, and the cost of spares (repairables and consumables). The model takes BOM cost from the MRDB, adds Integration, Assembly, Test, and Checkout (IAT&C) cost, separates cost into labor and material categories, adds the appropriate burdens, and applies a discount for estimated competition savings. Relevant industry production methods and processes are reflected in the IAT&C cost estimates and are assumed not to vary among the configurations. The resulting cost is burdened first unit cost, which is then regressed in a power curve using Learn and Rate parameters.

To improve calculation speed during the conduct of the Trade Studies, the model was directly incorporated into FACT by translating the algorithms into Python code. This Python code was verified against the Microsoft Excel workbook to ensure the Python code generated identical results when given the same inputs.

Framework for Assessing Cost and Technology (FACT)

FACT is a framework providing a rigorous structure to collaboratively conduct tradeoffs for complex systems. FACT uses Model-Based Systems Engineering (MBSE) standards, a browser front-end and open source software to provide a framework for integrating and evolving a series of models. FACT enables understanding the impact of design choices on the system's cost and performance.

For these studies, the MRDB provided FACT a Work Breakdown Structure (WBS) as a structure for the system data. The WBS defines meta-data for each subsystem in the vehicle. Parts must be selected in accordance with the subsystem definitions. The MRDB provided the values for each of the design-level attributes which serve as inputs to the predictive models.

Figure 8 illustrates the process for developing configurations for each capability concept using the MRDB and FACT. A complete vehicle requires about 250 subsystem/component option selections (illustrated by components A, B, and C) FACT explores the trade space by creating multiple configurations; each configuration created by randomly or systematically selecting options for each WBS element (Illustrated by AxByCz). Multiple configurations may incorporate the same WBS element option. FACT provides data visualization of the multiple configurations, including filtering of configurations that are not feasible or violate the GR&A.

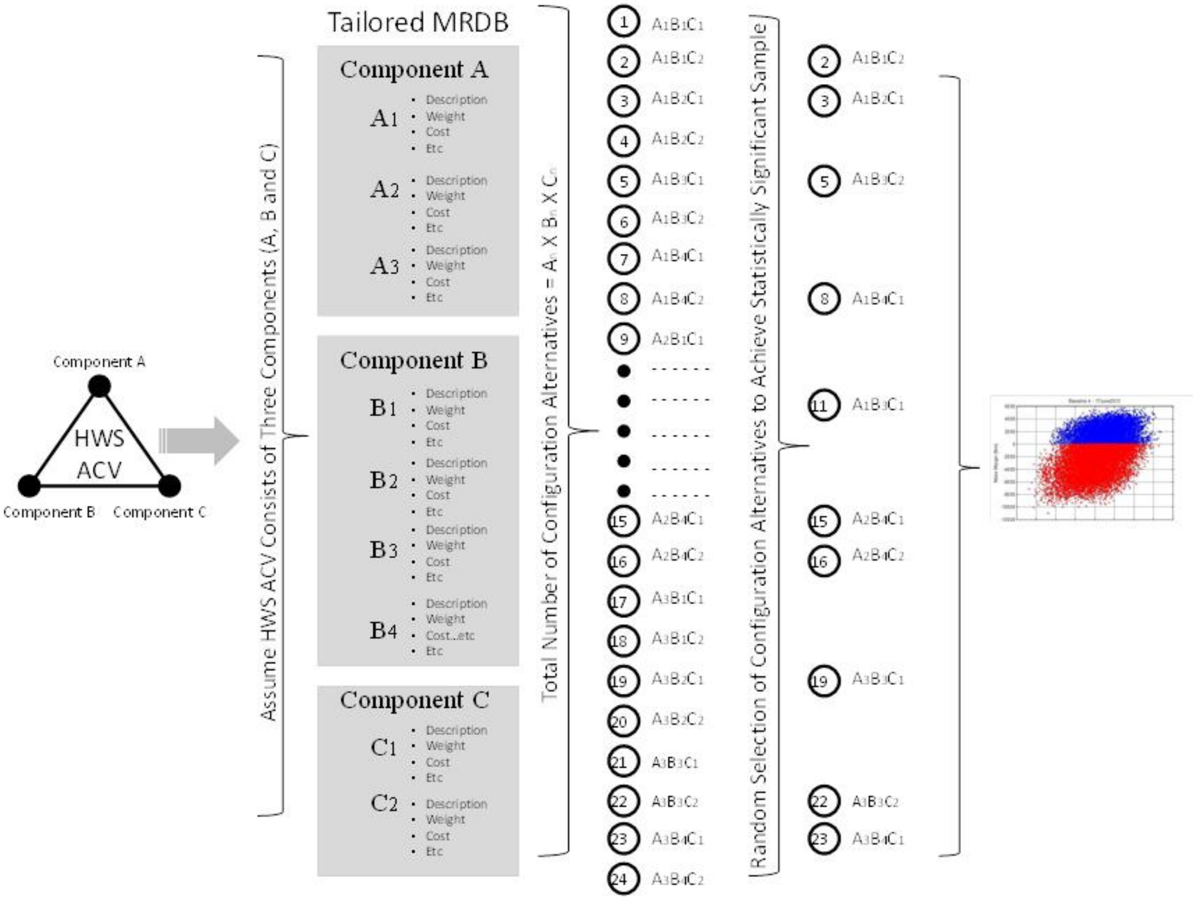


Figure 8: Development of Configurations for Capability Concepts

Figure 9 is an example visualization showing the cost vs. Mass Margin for 20,000 configurations for a single capability concept. The red points have a negative mass margin; these configurations are too heavy to achieve planing and are therefore not feasible. The blue points are deemed feasible. However, with the level of modeling fidelity employed, the technical viability of any one of the "blue dot" configurations cannot be determined to a high degree of confidence; additional design maturation and detailed analysis may prove a configuration deemed feasible as not viable. If the viability of all configurations were guaranteed, then the optimal solution (minimum cost) for each capability concept would be the feasible (blue) configuration corresponding to the lowest cost. However, since such confidence is not warranted, the trend of the data is more important than any specific point (configuration).

One of the challenges with using the Monte Carlo method is that while this method is good at generating mean values, it is not efficient in identifying extreme values. Within the context of this study, we seek to identify the extreme configurations that populate the region with a positive mass margin. To identify more points within this region, an optimizing algorithm was implemented to favor the selection of lighter components. Figure 10 plots additional points the optimization algorithm identified with a positive mass margin. The colors in Figure 10 represent a relative diversity metric which is an indicator of the number of components that have multiple alternatives within the set of configurations with a lower Average Procurement Unit Cost (APUC) and a higher mass margin. Points on the left of the scatter plot have low diversity in that if a given configuration proves unviable because of a problem with a specific component, there is not a high likelihood of being able to choose another configuration with a different component as a fallback that will not cost more or have a lower mass margin. At the lower right corner of the scatter plot, the configurations will have maximum diversity because there are in many cases multiple fall back options in case of the failure of a specific component. The diversity metric is a relative metric with points to the left or above the Pareto Frontier having a value of zero and points on the x-axis and to the right of the highest APUC having a value of 1.0. The diversity metric was used as a risk indicator in assigning a representative cost for a given capability concept.

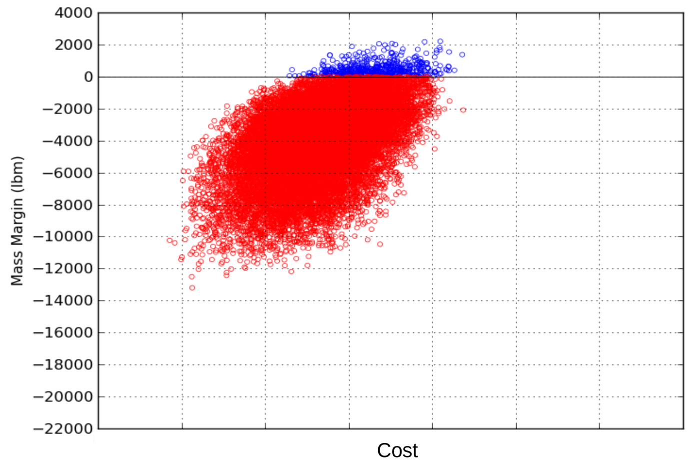


Figure 9: FACT Scatter Diagrams (20,000 point Monte Carlo Run)

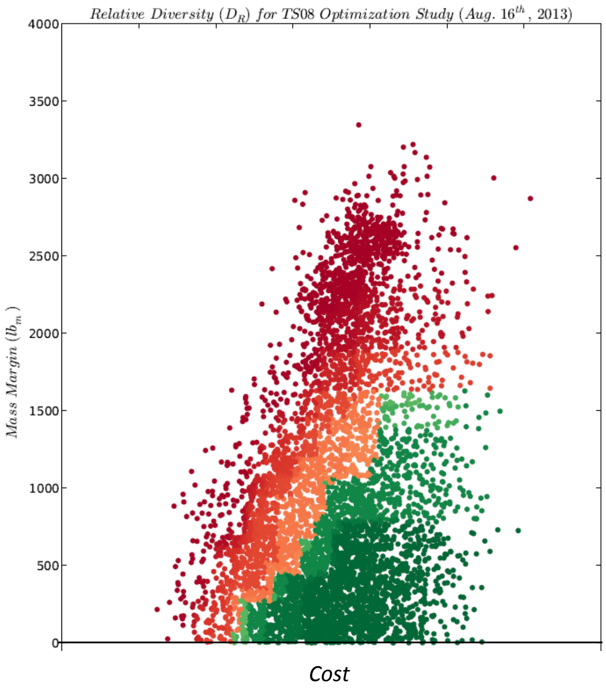


Figure 10: FACT Scatter Diagram showing Diversity Metric for points with positive mass margin (Generated using Optimizer)

Establishing a Representative Cost

In a traditional point-based concept study, a “representative” configuration would be created for a specific capability concept. The estimated cost of this representative configuration would also be considered the “representative cost” for the capability concept. The representative costs of different capability concepts could then be compared to utility for each capability concept to determine the best value capability concept. The difficulty with this construct is that there is little to show that the configuration produced is truly representative of the capability concept. What makes a configuration “representative?” How does one know that a configuration is “representative”?

In the set-based design approach used in the ACV concept exploration, a representative configuration is not selected. Instead a “representative cost” for a capability concept is based on a subset of the feasible configurations for that capability concept. If all the blue points in Figure 9 were viable, and an objective is to minimize cost, then a “representative cost” for the capability concept would correspond to the blue point with the lowest cost. In fact, because the Monte Carlo method is not efficient at finding extremes (minimums or maximums), other configurations likely exist that are even cheaper. However, since only feasibility and not viability can be determined at this stage of analysis, there is no assurance that the lowest cost feasible configuration will prove viable. Hence picking the blue point with the lowest cost as "representative" is not appropriate.

In selecting a representative cost for a capability concept based on a set of potentially feasible configurations as depicted in Figure 10, the following should be considered:

1. The risk of a configuration not being viable is greater when the estimated mass margin is lower. This is because the weight estimate does not account for integration risk or design risk.
2. The risk of achieving a given cost and mass margin is less if there are more configurations with a lower estimated cost and higher mass margin and a higher diversity of component utilization within this set of configurations. The diversity metric depicted in Figure 10 measures the amount of diversity among the configurations to the “left and above” the plotted point.
3. A source selection process favors less expensive configurations, hence a “representative cost” should de-emphasize high cost configurations over low cost configurations with the same level of risk.
4. Ideally, the “representative costs” of multiple capability concepts should correspond to the same general level of risk.

To address these issues in establishing a representative cost, the following common process (addresses consideration 4) was employed:

a. Only capability concepts with a peak mass margin greater than a specified higher feasibility limit (to account for weight uncertainty, integration risk and design risk) are considered feasible and have a representative cost established. (addresses consideration 1)

b. Remaining configurations are sorted by diversity metric.

c. The representative cost of the capability concept is established as the median value of all the points with a diversity metric greater than 80% of the peak diversity metric value. (addresses considerations 2 and 3).

To determine lower and upper cost estimates to capability concept, the modeling uncertainty of the Phase 1 Cost Model was applied to the representative cost. Hence the range of costs for a capability concept accounts for both technical risk and cost modeling uncertainty.

BASELINE STUDY

The baseline study provided a lower bound of what an acceptable ACV would cost and if this cost is too high, then the logical outcome is to either accept a low water speed ACV, or invest in developing and maturing technology to reduce the cost of high water speed amphibious combat vehicles.

The baseline study evaluated four "below-threshold" capability concepts. These four capability concepts maintained high water speed and under-blast protection level "C". As shown in Figure 5, the remaining major design features impacting cost and operational effectiveness re: Number of troops carried, weapon system, and direct fire protection level B. While variations of the four capability concepts were systematically improved, threshold performance was intentionally not achieved. The costs estimates generated by this baseline study, for these four concepts, provide insight as to the lower bound for cost for an acceptable ACV. In addition, this study generated a recommended "weight budget" for adding capability on the ACV.

In presenting the results of the baseline study to Marine Corps leadership, the costs were found within a range to warrant continuing the study. Hence the option to continue the study was exercised.

TRADE STUDY

The trade study followed the baseline study to fully explore the design space by systematically varying the number of troops carried (14 or 17), weapon system ("X", "Y", or "Z"), under-blast protection level ("C" or "D"), and direct fire protection ("A" or "B"). A total of twenty four capability concepts were developed. A Monte Carlo simulation consisting of 20,000 randomly generated configurations was developed for each capability concept. For those capability concepts that were projected to have configurations with a positive mass margin, additional configurations were generated using an optimization algorithm. Each capability concept was assigned a feasibility category of "Feasible," "High Risk Feasibility," or "Not Feasible" depending on the peak mass margin generated. The results for all 24 capability concepts are shown in Table 2.

Table 2: Feasibility Assessment of Trade Study Capability Concepts (Based on Ground Rules & Assumptions)

Capabilities	14 Troops; "A" Direct Fire Protection	14 Troops; "B" Direct Fire Protection	17 Troops; "A" Direct Fire Protection	17 Troops; "B" Direct Fire Protection
"C" Under-Blast Protection; Weapon "X"	**Feasible**	**Feasible**	**Feasible**	**High Risk Feasibility**
"C" Under-Blast Protection; Weapon "Y"	**Feasible**	**Feasible**	**Feasible**	**High Risk Feasibility**
"C" Under-Blast Protection; Weapon "Z"	**High Risk Feasibility**	**Not Feasible**	**Not Feasible**	**Not Feasible**
"D" Under-Blast Protection; Weapon "X"	**High Risk Feasibility**	**Not Feasible**	**Not Feasible**	**Not Feasible**
"D" Under-Blast Protection; Weapon "Y"	**High Risk Feasibility**	**Not Feasible**	**Not Feasible**	**Not Feasible**
"D" Under-Blast Protection; Weapon "Z"	**Not Feasible**	**Not Feasible**	**Not Feasible**	**Not Feasible**

The term "Feasible" was assigned to those capability concepts with a peak mass margin above the upper feasibility limit. Figure 11 includes example scatter plots for a "Feasible" capability concept. Note that while any one of the many configurations with a mass margin greater than zero may prove not viable when more detailed analysis is performed, the likelihood that all the configurations with a positive mass margin are not viable is low, assuming that they all do not suffer from a common failure mode.

Separately, a lower feasibility limit was established as an arbitrary but reasonable "margin" to account for integration and design maturity risks. Mass margin for any configuration above the lower feasibility limit accounts for weight estimation tolerances. The "Feasible" capability concepts have many configurations with a mass margin above the lower feasibility limit to account for weight estimation errors.

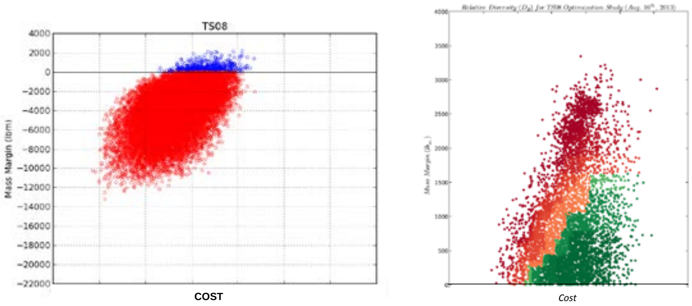


Figure 11: Scatter Diagrams for a "Feasible" Capability Concept

"High Risk Feasibility" was assigned to those capability concepts with a peak mass margin between the lower and upper feasibility limits. Figure 12 includes scatter plots for a "High Risk Feasibility" capability concept. Because the number of configurations with a mass margin above the lower feasibility limit is considerably less than for those capability concepts deemed "Feasible", the risk of not achieving a viable configuration is much greater.

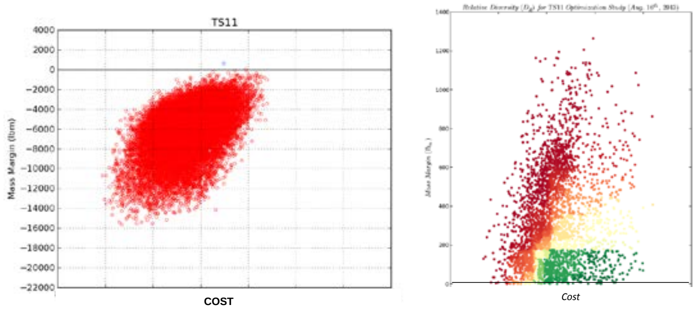


Figure 12: Scatter Diagrams for a "High Risk Feasibility" Capability Concept

"Not Feasible" was assigned to those capability concepts with a peak mass margin below the lower feasibility limit. Figure 13 is a scatter plots for a "Not Feasible" capability concept. Note that the designation "Not Feasible" is only appropriate under the conditions of the Ground Rules and Assumptions. For example, the maturing of new technologies could improve the feasibility of some capability concepts currently deemed "Not Feasible."

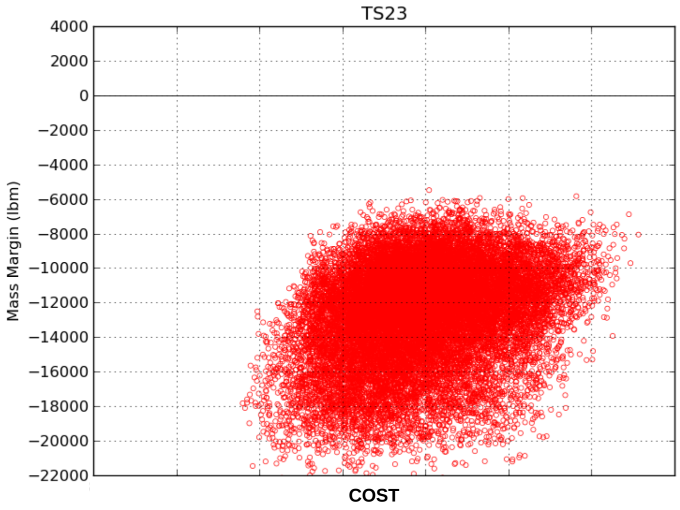


Figure 13: Scatter Diagram for a "Not Feasible" Capability Concept

One of the important insights from the scatter diagrams is shown in Figure 14. Should changes to the hydrodynamic (and hydrostatic) performance of the ACV increase the planing weight, then this additional weight capacity can be used to incorporate heavier, but less expensive components, or used to improve the capability of the ACV. For the scatter plots, increasing the planing weight shifts the Y-axis downwards and changes the top "red" points into "blue" points. Note that a High Water Speed ACV has two weight constraints: the maximum weight to achieve planing, and the maximum weight to provide a minimum acceptable reserve buoyancy.

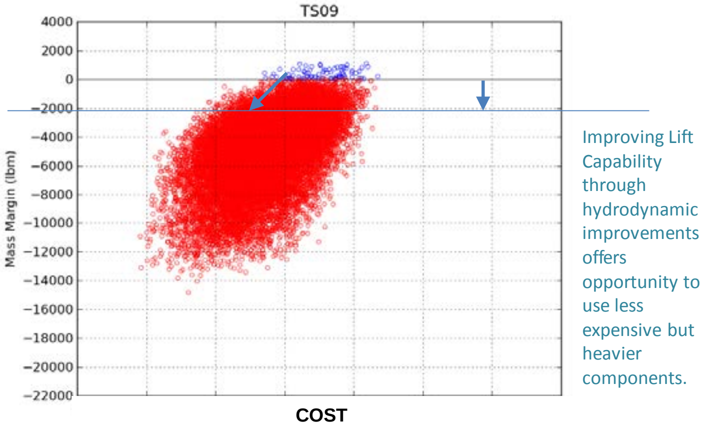


Figure 14: Impact of Hydrodynamic Improvements on Scatter Diagram

REQUIREMENTS ANALYSIS

The Requirements Study team used an ACV DOORS database to manage all requirements documents and to identify and document the technical, cost and operational impact of varying requirements within the CDD. The Requirements Study team closely collaborated with the Technical Modeling team and the Cost team to produce relevant data for each ACV concept configuration. Figure 15 provides a graphic overview of the workflow and general processes executed by the Requirements Study team. It illustrates how the DOORS database played a central role in managing and organizing all requirements documents, requirements configurations and many study artifacts for the ACV team.

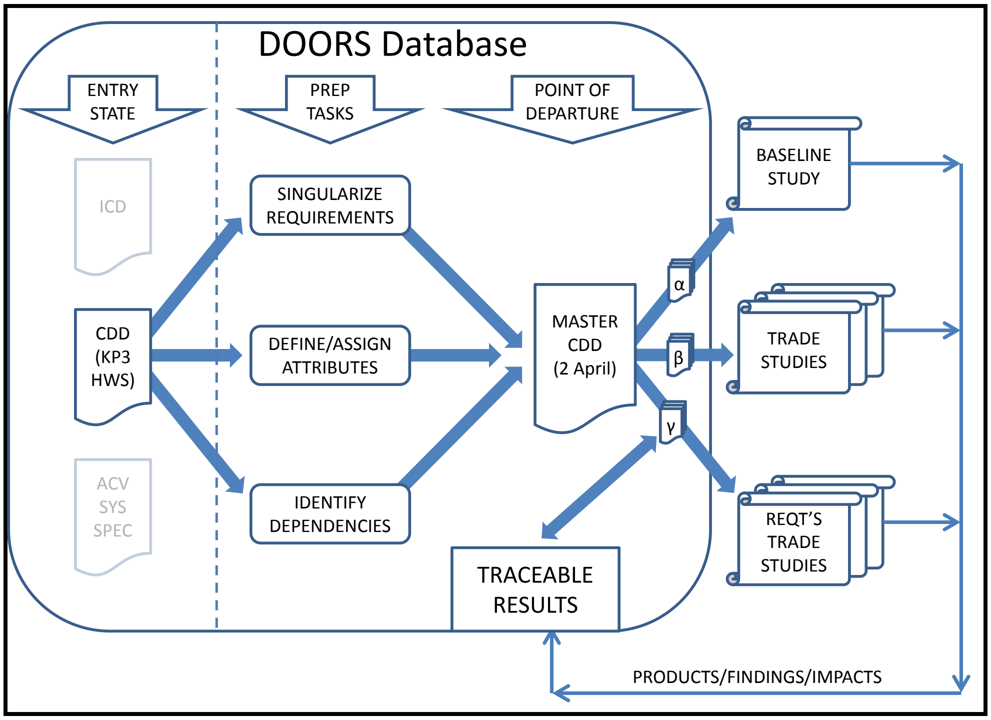


Figure 15: (U) Requirements study general workflow

Requirements Decomposition

The previously developed draft CDD for a HWS ACV was reviewed and assessed to identify operational capability levels that could be reduced or removed to accommodate the limited mass margin required to enable a HWS vehicle. As shown in Figure 16, each of the 198 draft HWS ACV CDD requirements were analyzed in detail to define amplifying attribute information; identify internal CDD dependencies and requirements coupling; assess potential impacts to cost, weight, and reliability; and determine capability tradeoff opportunities. The initial requirements analysis consisted of an impact assessment to determine cost, weight, and reliability implications to the overall HWS ACV capability concept. Impacts were estimated based on both the threshold requirements as written and excursions defined in the Baseline and Trade Study Capability Concepts (e.g. Weapon "X" vs Weapon "Y"). The results of the trade space analysis identified 40 requirements with tangible design and cost impacts to a HWS ACV and therefore identified as tradable. The tradable requirements were grouped by functionality and interdependency to provide 28 distinct capability trades. Each of the defined trades were further analyzed to determine measurable below threshold increments in capability with realized cost and weight savings, for some this included deletion of the capability.

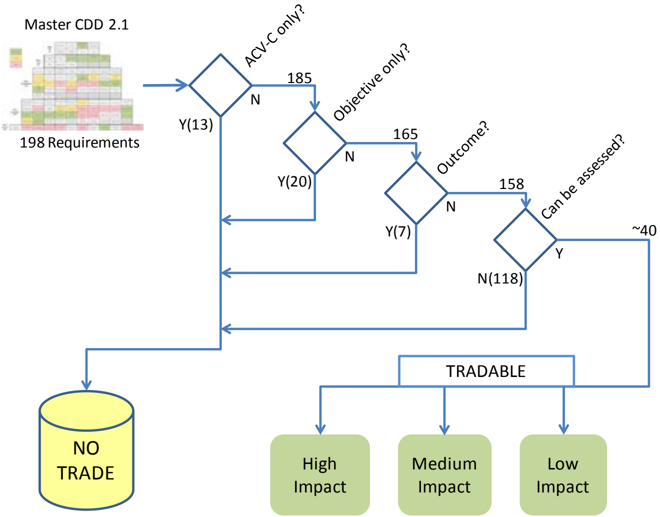


Figure 16: Identifying Tradable Requirements

Requirements Technical and Cost Impact Studies

For each of the 28 distinct capability trades identified in the Requirements Decomposition, a representative cost and weight impact was estimated based on the impacted WBS elements in the MRDB. For 26 of the capability trades, only a few alternatives were available for implementing each capability level. For these trades the cost and weight impact calculations were performed manually. For two of the trades, a large number of inter-dependent component choices precluded manual calculations; FACT was used to estimate the impact.

Operational User Feedback

To understand the operational utility, preference, and suitability of defined trades, a survey and user workshop were conducted by the ACV Team. The survey consisted of a series of questions requesting the respondent to rank four “big rock” capabilities (High Water Speed was assumed) from 1 to 4 in order of decreasing importance, as well as evaluate the tradable capabilities for operational importance to a HWS ACV. Tradable capabilities were assessed as Critical, Very Important, Important, Somewhat Important, or Not Very Important. The survey was available to Marines representing the Assault Amphibian, Infantry, and Operational Planner specialties in the three Marine Expeditionary Forces (MEFs) and in the National Capital Region (NCR). Over 250 Marines responded. Key takeaways from survey responses are:

- For the four “big rock” capabilities evaluated, users clearly emphasized the importance of offensive capability (lethality and troop capacity) over defensive capability (under-blast protection and direct fire protection).
- For the additional tradable capabilities, users valued enhancing the survivability and effectiveness of their offensive capability.
- Although there were differences in rankings based on specialty or organizational affiliation, users were consistent in their views on what constitutes the top principal capabilities.

The user workshop was conducted on 9-11 July 2013 at Ellis Hall, Marine Corps Base Quantico (Figure 17, official USMC photo). Twenty-four Marines (officers and enlisted) from all three MEFs and the NCR participated in the workshop. The workshop evaluated the tradable capabilities and determined their relative value given that cost and weight constraints would more than likely preclude all capabilities being accommodated in a HWS ACV.

Figure 17: Workshop conducted at Ellis Hall on 9-11 July 2013.

For additional operational perspective, a qualitative assessment of the benefits of HWS was conducted. Analysis focused on HWS contributions to operational flexibility, new mission alternatives and force protection. Data used in this analysis was collected through interviews with operational planners from the three MEFs, United States Marine Corps Forces Command (MARFORCOM) and Marine Forces Pacific (MARFORPAC).

EFFECTIVENESS ANALYSIS

The operational effectiveness analysis is the first analysis to attempt to isolate the benefit of high water speed during forcible entry operations to the Marine Air-Ground Task Force (MAGTF). The Operations Analysis Division, under the Deputy Commandant, Combat Development & Integration, conducted two analyses to examine the value of high water speed during forcible entry operations and measure the relative combat effectiveness of the trade study design alternatives: Value of High Water Speed Study and the Trade Study Operational Effectiveness Analysis.

Over the years, several benefits have been postulated for a high water speed vehicle. Primary among these are a reduction in enemy reaction time, improved survivability against shore-based threats, improved coastal reach, and the ability to employ reaction forces directly from the sea base. The Value of High Water Speed Study analyzed each proposed benefit to determine if it could be quantitatively supported.

The Trade Study Analysis quantified the operational impact of the different trade study capability concepts. The primary analytic tool used in the trade study analysis was COMBATXXI. COMBATXXI is a high-resolution combat simulation which models down to the individual Marine and vehicle. COMBATXXI represents the full range of MAGTF operations, including close air support and amphibious operations.

The trade study analysis used three diverse scenarios: the Platoon Security Patrol, Marine Expeditionary Unit (MEU) Ship-to-Objective Maneuver (STOM), and Surface Battalion Landing Team (BLT) Assault. These scenarios represent a mix of amphibious and non-amphibious operations and encompass multiple levels of MAGTF organization.

Three metrics are used to evaluate force effectiveness:

1) The System Force Exchange Ratio (FER) captures the percent of major red systems lost divided by the percent of major blue systems lost and includes tanks, Infantry Fighting Vehicles, ACV, anti-tank weapons, artillery, heavy mortars, and rockets;

2) The Personnel FER captures the percent of red personnel lost divided by the percent of blue personnel lost, accounting for

changes in the number of blue personnel due to changes in vehicle troop capacity;

3) The System Exchange Ratio (SER) measures the number of red systems lost due to ACV divided by the number of ACV lost.

LOW WATER SPEED TRADE STUDY

After the study began and the initial results for the high water speed trade study were produced, it became apparent that much had been learned since the previous low water speed concepts were developed. To enable a fair comparison of low water speed capability concepts with high water speed capability concepts, the scope of the study was increased to include developing 24 low water speed capability concepts to match the 24 high water speed capability concepts. All 24 low water speed capability concepts are feasible.

MODULARITY AND FLEXIBILITY

The trade study highlighted that the HWS ACV is weight critical. The other analyses showed the potential benefits of increased capability. The innovation team identified candidate technologies that still required maturation, but offered the opportunity to increase the carrying capacity of a HWS ACV and create different capability options. These technologies required full scale testing to confirm their predicted performance and sufficient mass margin exists to incorporate them. Modularity and flexibility are techniques for preserving these options.

Flexibility is defined for the ACV to mean that for a given requirement, the exact value for the requirement has not been established with certainty; the design must be able to affordably adapt to a specified range for the requirement's value. The exact value for the requirement will be established no later than a specified date. Flexibility enables deferring a decision on the requirement's value until more is known about the impact of the requirement on the design and on the utility of the vehicle. Flexibility is different than specifying a threshold and objective value in that in the former case the Government determines the performance of the vehicle while in the latter, industry determines the performance of the vehicle. In identifying requirements as flexible, the following categories were established:

- Short Term: Requirement will be determined prior to Milestone A
- Mid Term: Requirement will be determined within 1 year after Milestone A
- Far Term: Requirement will be determined prior to Milestone B

Modularity requirements within the ACV program are defined as the "Ability to inherently meet the current threshold and accept the modularity impacts in order to grow to the final desired capability." Modularity requirements are intended to produce a material solution at Initial Operational Capability (IOC) that gives Marine Corps leadership of today and the warfighters of tomorrow (post-IOC) the ability to swap equipment with no modification to hull, mechanical and electrical (HM&E) systems. These swaps could be done at the depot or in the field. The future modular upgrades can be removed, replaced, or enhanced by removal and/or replacement of a set of components/parts.

Variants are a form of design modularity. Variants must be defined at the time an ACV is contracted for, but the vehicles have high commonality with the other ACVs. Variants are not intended to be convertible to another variant type once the vehicle is in service; however the high commonality in design may make such a conversion feasible.

Modularity requirements specify the incorporation of modularity "hooks" into production vehicles to include the HM&E interfaces and space claims that will easily accept future capability upgrades. The intention is to preclude the need for any modification to the HM&E systems to accept a future upgrade capability. The modularity requirements do not specify or describe the actual future upgrade system or package. The modularity requirements do require structural and mechanical/automotive accommodation of potential future upgrade system weight but do not require accounting for that future weight within the IOC GVW.

For vehicles such as a HWS ACV where providing for all desired capabilities at the same time is probably not feasible, modularity enables optimizing the vehicle for a particular mission. Instead of deciding very early in the acquisition program as to a vehicles capability, the decision for what capabilities to incorporate is deferred to when the vehicle is in service. Modularity also enables purchasing a "base" vehicle during challenging fiscal environments and then selectively upgrading the vehicle in an affordable manner when funding constraints are less severe.

The modularity candidates (if selected) are intended to be documented in the CDD as requirements pairs. The first requirement specifies the threshold capability at vehicle IOC. The second requirement specifies the incorporation of any HM&E structures and interfaces along with space reservations needed to easily accept a potential future capability.

A review of the draft CDD resulted in the identification of 30 requirements that could be addressed by a combination of flexibility and/or modularity.

SUPPORT FOR FOLLOW-ON ACTIVITIES

In addition to the studies performed to enable a HWS vs LWS ACV decision, other activities were conducted to facilitate transition to the next stage of design and acquisition. These activities included:

Acquisition Planning
Innovation Team Tasking
Weapon System Open Architecture Interface Development
Analytic Framework Development
Common Cost Model Improvement
MRDB Improvement
Concept Design

Acquisition Planning developed multiple scenarios for a high level acquisition schedule with associated funding profiles and competition strategies. These acquisition scenarios were presented to a panel of acquisition experts from across the Department of Defense. Feedback from these experts was used to improve and iterate the acquisition plan.

The innovation team explored promising technologies that did not meet the GR&A criteria for inclusion into the MRDB. Promising technologies such as hydrodynamic lifting bodies and alternate engine configurations were studies for possible maturation and incorporation into the ACV design in future design stages.

The value of on open architecture interface for the ACV weapon system was recognized early during the study. Advantages include:

1. Ability to defer decision on the exact weapon system to be used until the weight capacity of the ACV was demonstrated with physical prototypes.
2. Ability to initially field a less expensive weapon system to keep procurement costs down, but with the ability to affordably upgrade to more capable weapons should the need develop.
3. Ability to develop and test one or more weapon systems prior to integration with the ACV; improve reliability estimates and if needed, implement a reliability growth program much earlier than would be possible if the weapon were tightly integrated into the ACV design.
4. Ability to affordably support a “mixed fleet” of ACVs with different weapons stations.
5. Ability to better pace threats with weapon system improvements over the ACV service life.

Consequently, an effort was initiated to begin the development of an open architecture interface for the ACV weapon system.

The Analytic Framework describes the tools, algorithms, and methods that are anticipated to be used to analyze follow-on ACV designs. The Analytic Framework was developed collaboratively with the two industry partners. The Analytic Framework is anticipated to help develop the system specification. It also is helping prioritize analytic tool development projects.

The Common Cost Model was developed collaboratively with industry to ensure cost estimates of configurations are consistent, comparable, and repeatable. The Phase 1 Cost model used as part of the trade studies was improved upon to support follow-on design studies.

The MRDB largely reflected the results of market surveys from the Government and industry partners. During this time period several MRDB augmentation contracts were initiated to identify more subsystem and component alternatives from non-traditional sources. Once their acceptability is verified, these alternatives will be incorporated into the MRDB for inclusion in future design configurations.

The purpose of the ACV Concept Design effort was for GDLS and BAE to develop, refine and assess initial concept designs to reduce technical and cost risk. The effort included concept design development and refinement, specific trade studies, and experimentation/test plans for Configuration Item (CI) alternatives. The concept designs developed by industry were consistent with the results developed through FACT.

CONCLUSION

The process and approach described in this paper for assessing the feasibility and cost of producing a HWS ACV was extremely effective and provided a high degree of confidence in the technical conclusions and risk assessments. Furthermore, the process and approach proved to be a highly responsive, effective and disciplined method for tackling extremely complex acquisition challenges. Key tenants included:

- A diverse team consisting of technical, operational and program management experts from across the naval acquisition, operational and technical communities, as well as industry and academia.
- The ability to address leadership questions with technical and analytical rigor that traditional approaches have not yet demonstrated an ability to do.
- The ability to develop in depth knowledge of the technical problem and potential solution set, a risk based understanding of what was feasible and infeasible, and high confidence cost estimates based on technical feasibility and diversity of solutions.

In turn, the team provided leadership with not just the knowledge and information they needed to make informed decisions, but also with a solid and defendable analytical basis to have confidence in the decisions they make.

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