Application of a DoDAF Total-Ship System Architecture in Building a Design Reference Mission for Assessing Naval Ship Operational Effectiveness

By

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ABSTRACT

The Naval Ship Design Concept and Requirements Exploration (C&RE) process used at Virginia Tech is based on a Multi-Objective Optimization approach that explores the design space to identify a Non-Dominated set of ship design solutions ranked by cost, risk, and effectiveness. The current method of calculating an Overall Measure of Effectiveness (OMOE) used in this approach is based on expert opinion and pairwise comparison. Despite the good results obtained using expert opinion, more direct physics-based Operational Effectiveness Models (OEMs) starting with a detailed Design Reference Mission (DRM) including mission Operational Situations (OpSits), conditions, and measures may provide greater confidence in the validity of the results and a perception that results are more unbiased and rational.

This paper describes a method for building a Design Reference Mission (DRM) composed of multiple Operational Situations (OpSits) required by the ship's mission. The DRM is defined using a Model Based Systems Engineering (MBSE) approach and a Total-Ship System Architecture to define and understand the relationships between various aspects of the ship design and their relationship to operational effectiveness. The system architecture is based on the DoD Architecture Framework (DoDAF 2.0). It includes the DRM and enables the development of Operational Effectiveness Models (OEMs) as an alternative to an expert opinion-based OMOE.

A notional US Coast Guard (USCG) Offshore Patrol Vessel (OPV) is used as an example in this paper. The ship design architecture and Design Reference Mission are based on the OPV mission requirement specified in a notional Initial Capabilities Document (ICD).

1. MOTIVATION AND BACKGROUND

The traditional approach to ship design is largely an 'ad hoc' process. Experience, design lanes, rules of thumb, preference, and imagination guide selection of design concepts for assessment. Often, objective attributes are not adequately quantified or presented to support efficient and effective decisions. This is particularly true for mission effectiveness. Requirements and design characteristics cannot be rationally specified without a thorough understanding of their impact on total ship cost, risk and effectiveness [3][8][19][20].

Over the last fifteen years at Virginia Tech and MIT, a total system approach to the ship design process has been developed, including an efficient search of the design space for non-dominated designs based on the multi-objective considerations of effectiveness, cost and risk [2][3][4][16][17][23][25]. This approach addresses the Analysis of Alternatives phases (Pre-AOA and AOA) of the US Department of Defense acquisition process. The current method of calculating an Overall Measure of Effectiveness

(OMOE) used in this approach is based on expert opinion and pairwise comparison. During this time, systems engineering (SE) has also been evolving to include new Model-Based Systems Engineering (MBSE) approaches [5], Enterprise Architectures including new Department of Defense (DoD) architectures [12], and Naval Systems Analysis and effectiveness-modeling methods [13][14].

The objective of our research is to develop a methodology for building Operational Effectiveness Models (OEMs) and an Overall Measure of Effectiveness (OMOE) as an alternative to an expert opinion-based OMOE, and to integrate this methodology with our current multi-objective optimization approach to perform naval ship Concept and Requirements Exploration (C&RE). This paper describes the first part of this methodology, building a Design Reference Mission (DRM) composed of multiple Operational Situations (OpSits) with conditions and measures that can be used for building the Operational Effectiveness Models (OEMs). The DRM is defined using a Model Based Systems Engineering (MBSE) approach and a Total-Ship System Architecture to define and understand the relationships between various aspects of the ship design and their relationships to operational effectiveness.

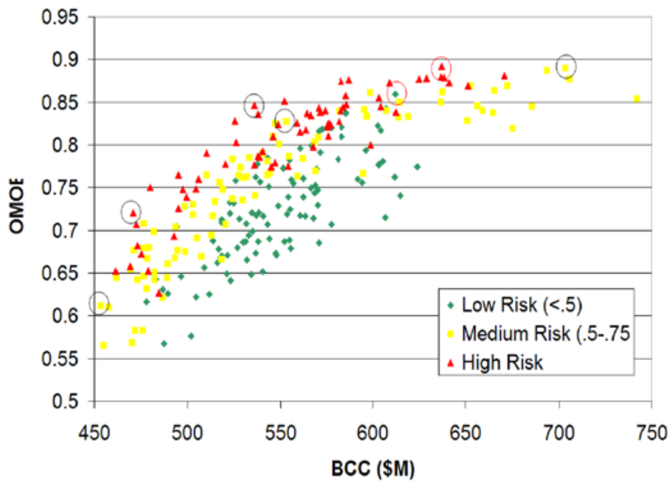


Figure 1 - Non-Dominated Frontier [25]

A non-dominated solution for cost, risk and effectiveness, for a given problem and constraints, is a feasible solution for which no other feasible solution exists which is better in one objective attribute and at least as good in all others [3][4]. Non-dominated concepts are typically presented in a multi-dimensional plot of cost, risk, and effectiveness where each point in the plot represents a feasible ship design. Figure 1 is a typical 2D representation of non-dominated results with the color/shape of each design point representing the risk, with cost on the x-axis, and effectiveness on the y-axis. All the designs represented in this plot are feasible and non-dominated. The preferred design should always be a non-dominated design. The non-dominated surface with a full range of cost-risk-effectiveness possibilities can be presented to decision-makers, “knees in the curve” can be seen graphically, trade-off decisions can be made, and specific design concepts can be chosen for further analysis [3].

Our new C&RE process is shown in Figure 2. This process will be discussed more completely later in this paper, but the first steps in this process must develop a clear and precise mission definition including mission essential tasks, Design Reference Mission (DRM) with Operational Situations (OpSits), Operational Effectiveness Models (OEMs), Required Operational Capabilities (ROCs), and ultimately an Overall Effectiveness Model. The development of these important system elements is the primary focus of this paper.

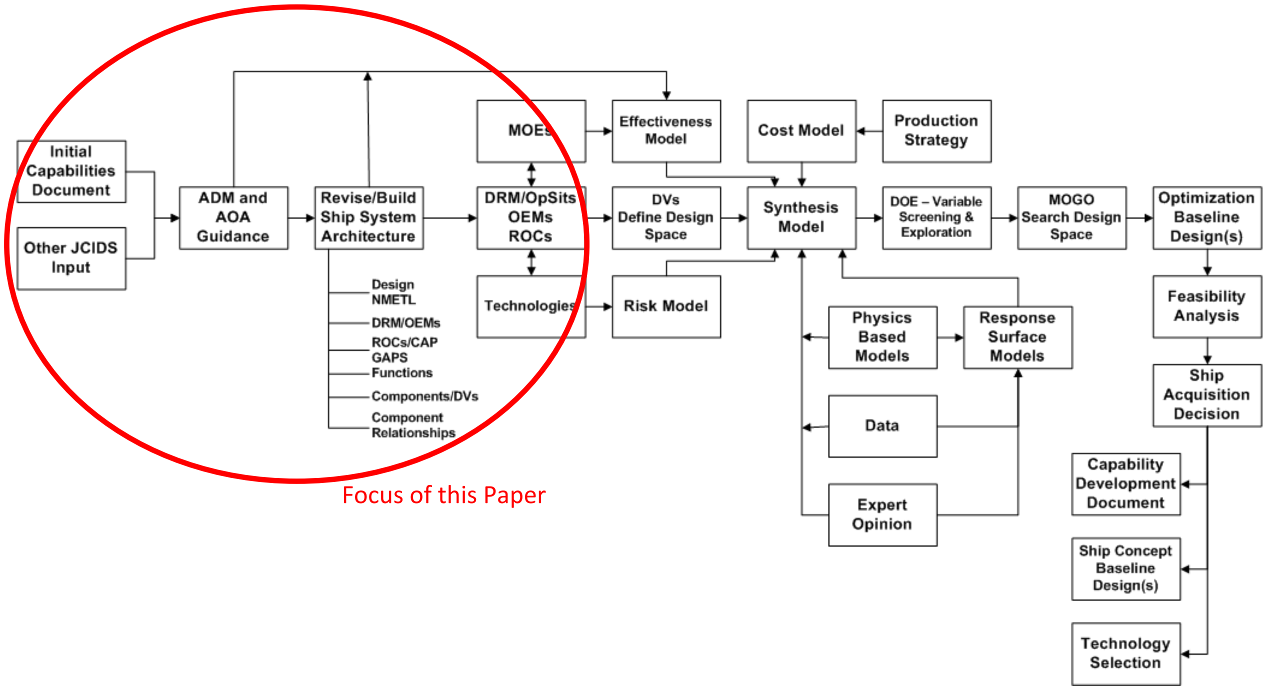


Figure 2 -New Ship Concept and Requirements Exploration Process (C&RE)

1.1 Model-Based Systems Engineering (MBSE)

Systems Engineering (SE) addresses both engineering and management processes. It begins with a clear statement and understanding of the problem, must resolve competing trade-offs, must identify system boundaries, and perhaps most important, it must manage complexity. A critical tool to a successful SE approach is an effective system architecture and data model. A systems model serves as a "repository" to document important characteristics, data and relationships, from customer requirements to function to system architecture to validation and verification. Complex Systems-of-Systems (SoS) are too large to manage without a system model. [5]

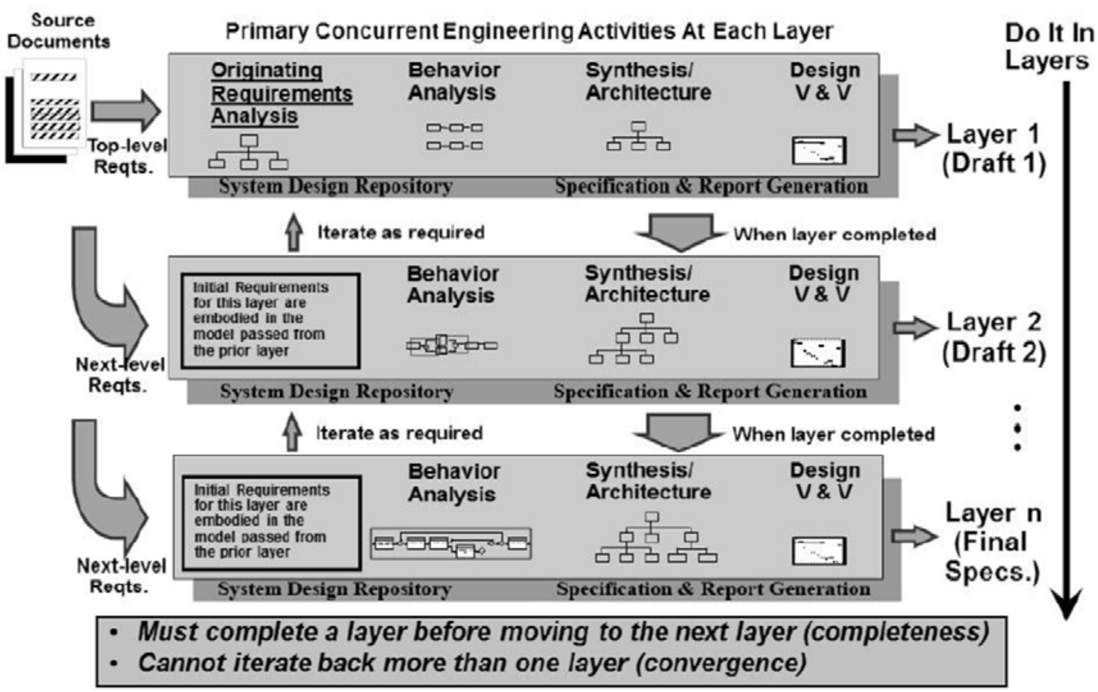


Figure 3 - Model-Based Systems Engineering (MBSE) [5]

Figure 3 illustrates the MBSE process and architecture as a series of layers. Each layer involves the four activities of Requirements Analysis, Behavior or Functional Analysis, Synthesis/Architecture, and Validation and Verification. Concept and Requirements Exploration deals significantly with Requirements, defining requirements in terms of missions, operational tasks, and operational scenarios, and translating them into cost-effective capabilities, system functions, components and interfaces. This is represented by Layer 1 in Figure 3.

Our research uses CORE software developed by the Vitech Corporation to build our ship system architecture [28]. CORE was designed as a tool for MBSE. CORE allows users to build a system design repository and work simultaneously in all four of these activities at various levels. MBSE requires unambiguous language to provide a structured and universal framework for system models. The SDL (System Definition Language) is used by CORE [5]. SDL evolved primarily from SysML. It is a formal Element-Relationship-Attribute (ERA) language augmented by graphical structures with semantic meaning to define or specify a system. SDL is based on the following primitive language concepts:

- *Elements* (i.e., entities) correspond to nouns in English. Elements define objects and serve as the basic units in the system repository. Grouped into one of several classes (e.g., Component, Function, etc.).
- *Relationships* are similar to verbs. Define a link between two elements - corresponds to the mathematical definition of a binary relation. Relationships are not commutative, each relationship having a definite subject and object. However, for each relationship, there is a complementary relationship that defines the link from the object to the subject.
- *Attributes* further describe elements much like adjectives modify nouns. The attributes of an element serve to define critical properties of elements. For instance, attributes of a component would include the component number and component type.
- *Attributed-Relationships* correspond to adverbs in English. The attributes of a relationship serve to define critical properties of the relationship.
- *Structures* provide specification of semantically explicit system control constructs (Concurrency, Iteration, Loop, Multiple Exit, Replication, Selection, and Sequence).

The system model data base consists of elements that are modified by attributes and related to other elements. This structure corresponds to an object-oriented approach. Elements are represented as objects with the attributes stored as data within the objects. The relationships then define the interaction between objects.

1.2 Defense Acquisition, JCIDS and the Unified Navy Task List (UNTL)

The US Navy and USCG ship and system acquisition process (Figure 4) begins with an Initial Capabilities Document (ICD) which is developed and issued by the Joint Capabilities Integration and Development System (JCIDS) [10][11]. There are three key processes in the DoD that must work together to deliver the capabilities required for national defense: the requirements process (JCIDS); the acquisition process (DoD 5000); and the Planning, Programming, Budget, and Execution (PPBE) process. In ship design, we are directly involved with all of these, and in this paper we address the first.

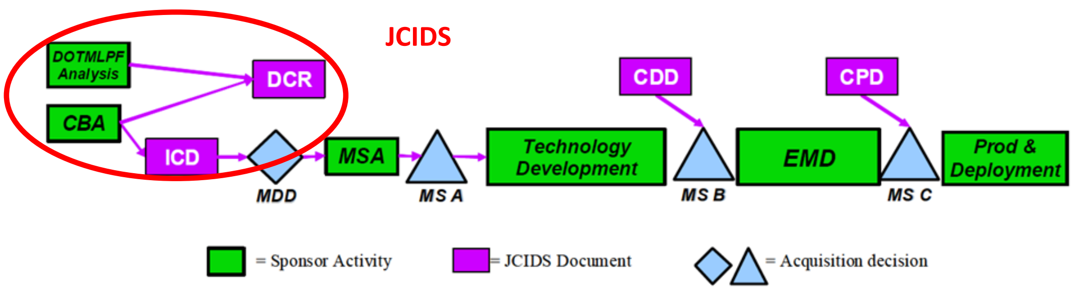


Figure 4 - DoD 5000 Acquisition Process Starts with JCIDS [6]

JCIDS plays a key role in identifying the capabilities required to support the National Defense Strategy, the National Military Strategy, and the National Strategy for Homeland Defense. JCIDS supports the acquisition process by identifying and assessing capability needs and associated performance criteria to be used as a basis for acquiring the right capabilities, including the right systems. These capability-needs then serve as the basis for the development and production of systems to fill those needs.

The JCIDS process is initiated through the execution of a Capabilities-Based Assessment (CBA), Figure 5, in the context of the DoD Architecture Framework (DoDAF) [12]. The objective of the CBA is to validate capability gap(s) by providing:

- identification of the mission
- capabilities required and their associated operational characteristics and attributes
- capability gaps and associated operational risks
- assessment of the viability of non-materiel solutions
- recommendations on type of solutions (transformational, evolutionary, or information technology) to be pursued.

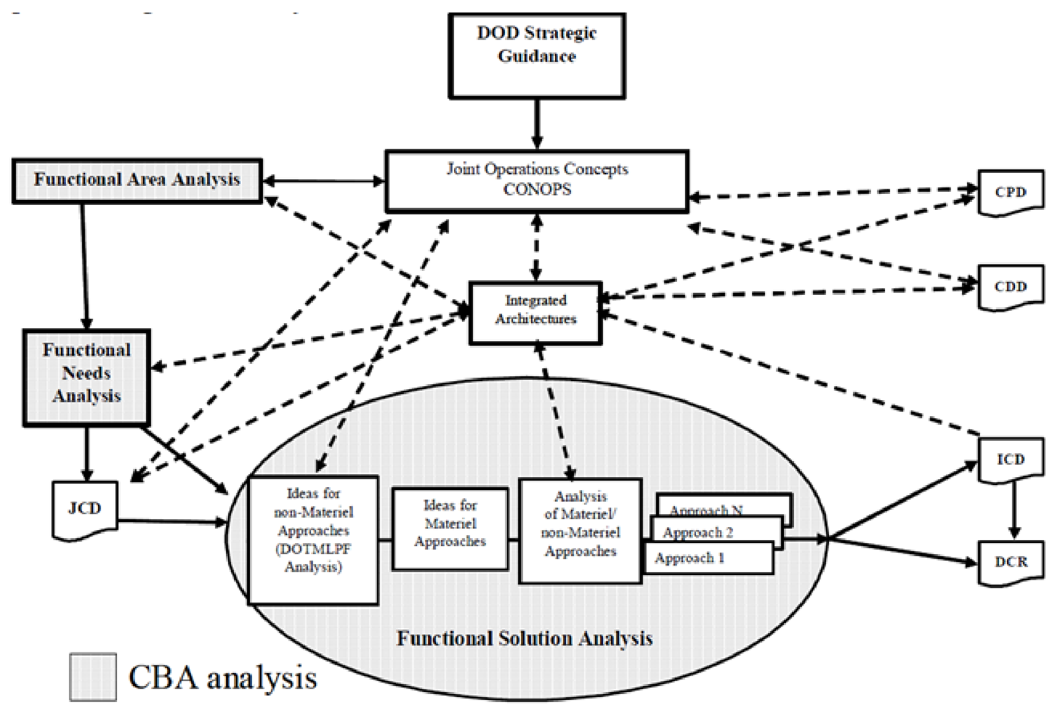


Figure 5 - Capabilities-Based Assessment (CBA) [7]

The results of the CBA are documented in one of two documents. If materiel solutions are to be pursued, an Initial Capabilities Document (ICD) is produced.

JCIDS uses Joint Capability Areas (JCAs) at the first four levels (tiers) of its integrated architecture (Tier 1 = Force Support, Battlespace Awareness, Force Application, Logistics, Command and Control, Net-Centric, Protection, Building Partnerships, Corporate Management and Support). JCAs are collections of like-DOD capabilities functionally grouped to support capability analysis, strategy development, investment decision making, capability portfolio management, and capabilities-based force development and operational planning. The Functional Capabilities Boards (FCBs) are organized around the Tier 1 JCAs, and the JCIDS documents link the capabilities identified to the applicable JCAs. The JCA's are where we start to define the capability gaps and other required capabilities of our ship or ship system.

The mission area or military problem considered by the CBA must have an operational context that is both relevant to the problem and the needs of the defense strategy. Scenarios must be chosen in such a way that the full spectrum of operational situations relevant to the defense strategy will be examined and impact calculated effectiveness. The military objectives of these scenarios provide a source for developing the list of capabilities to be examined. These capabilities, coupled with the scenarios, are further refined using the Universal Joint Task List (UJTL), Universal Naval Task List (UNTL) and the Naval Tactical Task List (NTTL). At this point in the assessment, the emphasis is on describing how the objectives would be achieved with the programmed force. The task representation, however, must also be able to account for the proposed Concept of Operations or CONOPs, so some flexibility is required. Operational conditions are part of the scenarios, and tasks are derived from capabilities needed to achieve the military objectives of the scenarios.

1.3 DoD Architecture Framework (DoDAF 2.0)

The Institute of Electrical and Electronics Engineers (IEEE) Standard 1471 (2000) defines architecture as: "The fundamental organization of a system embodied in its components, their relationships to each other, and to the environment, and the principles guiding its design and evolution."

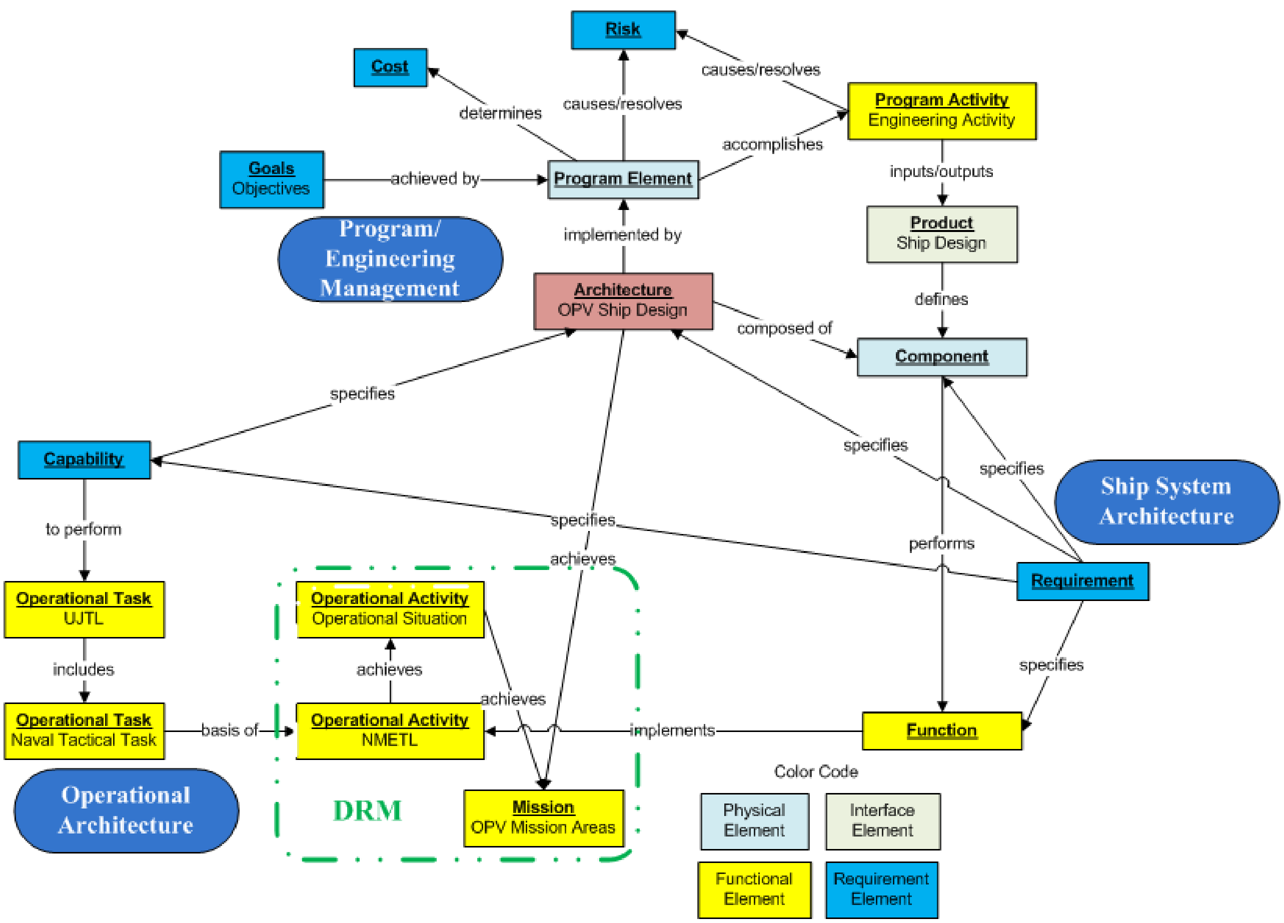


Figure 6 - Ship Design System DoDAF Architecture (adapted from [8])

The Department of Defense Architecture Framework (DoDAF 2.0) is the overarching, comprehensive framework and conceptual model enabling the development of architectures to facilitate Department of Defense (DoD) managers at all levels to make key decisions more effectively through organized information sharing across the Joint Capability Areas (JCAs), Mission, Component, and Program boundaries [8]. In the context of a system engineering model, a DoDAF 2.0 schema can be represented as shown in Figure 6, specifically adapted for our ship design system.

Our DoDAF ship system architecture includes three domains: Operational Architecture, Ship System Architecture and Program/Engineering Management Domains with classes and relationships as shown in Figure 6. CORE identifies the individual parts of the architecture as classes including Capabilities, Functions, Components, Operational Tasks, etc. Each class contains elements of that class. So the ship would be a component and then it would be broken down into its many physical parts with each being captured as a component system or subsystem.

The Operational Architecture Domain provides necessary classes, attributes and relationships to capture the initial operational requirements, guidance, mission, and required capabilities. The Capability class defines the qualities, abilities, features, etc., of the entire architecture that can be used or developed to achieve action goals. The Mission element is the mission(s) the overall architecture was designed to achieve. The Operational Task element is an action to be performed in support of a mission. An Operational Activity is an action or process needed to fulfill a mission, task, or role. The Operational Item element class is the data or physical entity that is required for the flow between operational activities and, thereby, between the performers [28].

The Ship System Architecture Domain includes Component elements, the system or system of systems with their interfaces. It includes Function elements and ultimately Requirement elements, standards and specifications. The Components are the physical or logical elements that perform a specific function or functions. The Function elements define the functions of the components. The Requirement elements can be either an originating requirement extracted from a source document, a refinement of a higher-level requirement, a derived characteristic of the system or one if its subcomponents, or a design decision [28].

The Joint Chiefs of Staff (JCS) requires that system architects and associated processes must have clear and consistent relationships with the JCIDS architects and processes [7]. This requires that for ship C&RD the ICD, JCAs and related UNTL tasks must provide the foundation for system (ship) architecture development [27].

1.4 Operational Effectiveness Models and Design Reference Missions (DRMs)

An Overall Measure of Effectiveness (OMOE) model or function is an essential prerequisite for optimization and design trade-off. Our prior work with mission effectiveness models has used multi-attribute value theory (MAVT) and the analytical hierarchy process (AHP) with expert opinion to integrate many diverse inputs, and assess the value or utility of ship performance in an OMOE function [1][3][4][9][22]. The benefit and efficiency of this approach has been partially demonstrated in a study revisiting the DDG-51 design [26], and in a simple experimental study comparing results obtained using a commercial war-gaming tool to expert opinion results [9].

Despite the results obtained using expert opinion, more direct physics-based Operational Effectiveness Models (OEMs) starting with a detailed Design Reference Mission (DRM) may provide greater confidence in the validity of the results and a perception that results are unbiased and rational.

Design Reference Mission(s) define the specific projected threat and operating environment baseline for a given force element, which may range from a single-purpose weapon system to a multi-mission platform to a multi-system, multi-platform system of systems. They are primarily an engineering design tool to support systems engineering activities by identifying significant design-driving operational elements and characterizing them to the level of detail necessary to assess design impact. A DRM also includes detailed characterizations of the threat, background traffic, weather, and other factors required to assess system performance and overall platform effectiveness. OpSits are developed as part of the DRM to feature selected operational characteristics, or combinations thereof, in operationally viable combat environments [24].

1.5 Navy Mission Essential Task (NMET) Development

In the CBA capabilities are grouped by the JCAs which are in turn refined by the UJTL, and the NTTL in the case of a ship design, to identify the tasks that the required capabilities enable. The capabilities are those required by the ship design to meet the mission objectives. The tasks that are enabled by the required capabilities are the basic elements for accomplishing the mission or mission objective. Figure 7 illustrates these relationships.

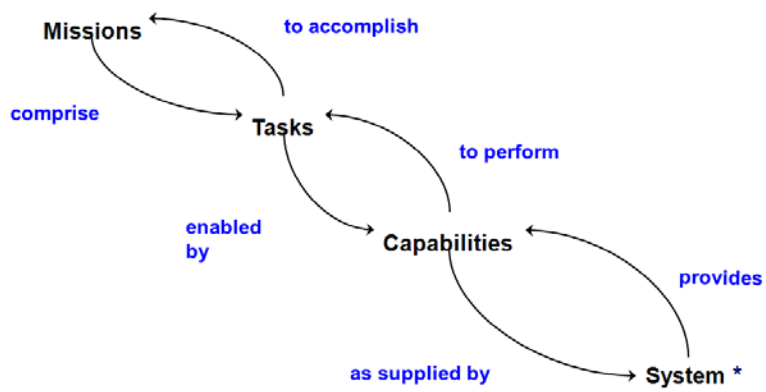


Figure 7 - Ship Design to Mission Accomplishment Relationships [21]

Navy Mission Essential Tasks (NMETs) for a particular ship mission or ship design are selected from the UNTL with associated measures of task performance and conditions under which the task could be accomplished. The final collection of tasks is called a Naval Mission Essential Task List (NMETL), tailored for a particular design. The Universal Navy Task List (UNTL) is a combined Navy, Marine Corps, and Coast Guard document that includes tasks from the UJTL and NTTL. The UNTL also includes measures for each task and possible conditions to assign to task. The conditions list is thorough but not necessarily comprehensive. The NMETs, properly sequenced, form a scenario that includes its own measures and conditions. The scenarios built from NMETs become the OpSits that make up the DRM. These OpSits can be translated into a discrete-event simulation that considers the conditions and uses the identified measures of task performance to calculate a specific measure of effectiveness for a ship design in that OpSit. The family of OpSit simulations that fully encompass the mission set of the ship can be combined to calculate an OMOE for a given ship design. This is accomplished in the context of the system enterprise architecture, and is the basis of the process described in this paper.

2. THE CONCEPT AND REQUIREMENTS EXPLORATION (C&RE) PROCESS

Next we consider the initial steps of our new C&RE Process presented in Figure 2. Given the JCIDS input, ICD, ADM and AoA Guidance, the process begins by building or adapting a total-ship system enterprise architecture. This is followed by further development of the Design Reference Mission (DRM) with Operational Situations (OpSits), Operational Effectiveness Models (OEMs), Required Operational Capabilities (ROCs), and finally an Overall Effectiveness Model.

2.1 Build/Adapt Ship System Enterprise Architecture

The processes described so far including JCIDS, DRM development, OEM development, NTTL, NMET and the ship design/synthesis model become very complex without a method for building a system architecture that recognizes all the elements of the complex system and their relationships. The architecture can also be a single source repository for all the information required for or produced by the ship design process, and a useful tool for understanding individual roles in the design process and how those roles are affected and related to other roles. This includes understanding the impacts of design decisions or changes on the physical design, but also on other aspects of the architecture like cost, risk, function, capabilities, and how it affects other engineers responsible for different parts of the design process.

JCIDS is already organized according to DoDAF 2.0 architecture requirements. The Operational Architecture Domain is defined by the same data the JCIDS process uses in the CBA introduced in Section 1.2. JCAs that encompass general required capabilities of the current ship design are identified and captured as Capability class elements in the architecture illustrated in Figure 6. The JCAs are mapped to their related UJTL tasks which are refined into their related NTTL tasks. The UJTL and NTTL tasks are captured as Operational Tasks in Figure 6. The NTTL tasks are used as a shopping list to identify which tasks are mission essential and therefore required to be accomplished in a given scenario. The mission essential tasks are Navy Mission Essential Tasks (NMETs) and are captured as Operational Activities in the architecture and collectively become the NEMTL. The NMETs are sequenced in such a way to define operational scenarios for the required missions. The scenarios or Operational Situations (OpSits) are captured as overarching Operational Activities in the architecture. The OpSits are assigned to specified missions, which are captured as Mission class elements in the architecture. The resulting combination of the NMETs, OpSits, and Missions comprise a Design Reference Mission (DRM) for a given ship design

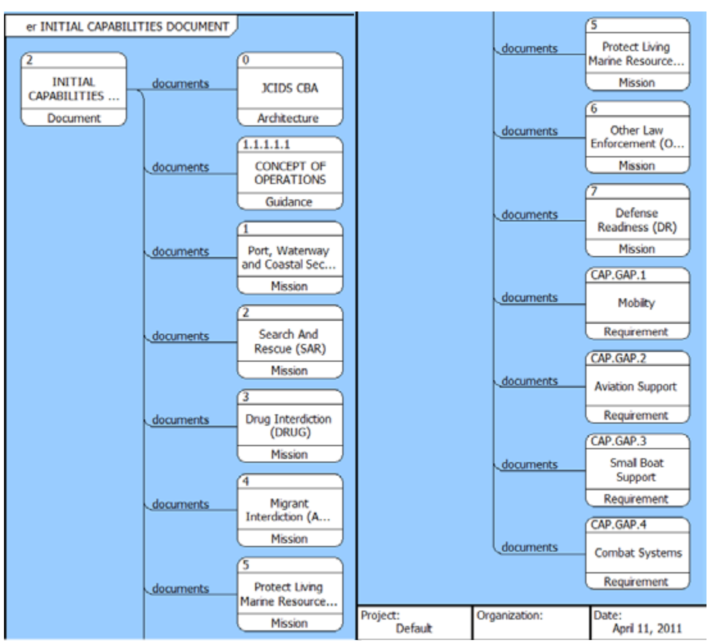


Figure 8 - Element Relationship View for Notional OPV ICD

CORE also has classes for Documents and Guidance. The other classes in the architecture can be related to these two classes as ‘guided by’ or ‘documented by’. As an example, the ICD is entered as a document and from the ICD the CONOPs is extracted to become a guidance element, the missions are extracted to become Mission class elements, and the capability gaps are saved separately as Requirements class elements with attributes set to capability. All of these however are related to the ICD by ‘documented by’. CORE can upload certain types of document files directly into its user interface and allow the user to select and copy text directly into element property sheets. In CORE this tool is called the element extractor and was used to load the ICD and produce the missions and requirements (capability gaps) elements. Figure 8 is a view from CORE called the Element Relationship view that shows all the relationships to the ICD document element.

Other documents identified in our CORE ship system repository are the JCA Framework Lexicon and the UNTL. Other guidance includes the Coast Guard Strategy (for the OPV) and the Joint Operations Concepts. The JCIDS manual is also saved as a document and the JCIDS CBA process is captured as a Guidance element for building the architecture.

2.1.1 Capturing Capabilities and Tasks from the JCAs and UNTL

The next step is to begin the process of defining the DRM in terms of OpSits and NMETL tasks. We will use our notional OPV to illustrate this process. The missions of the OPV have already been defined by extracting them from the ICD. For the purpose of this example OpSits are limited to one per mission area. The required number, scope and complexity of OpSits will be addressed in future work. The mission objectives are described on each mission element property sheet as the element description. Figure 9 shows the Port, Waterway and Coastal Security (PWCS) mission element property sheet with the mission description.

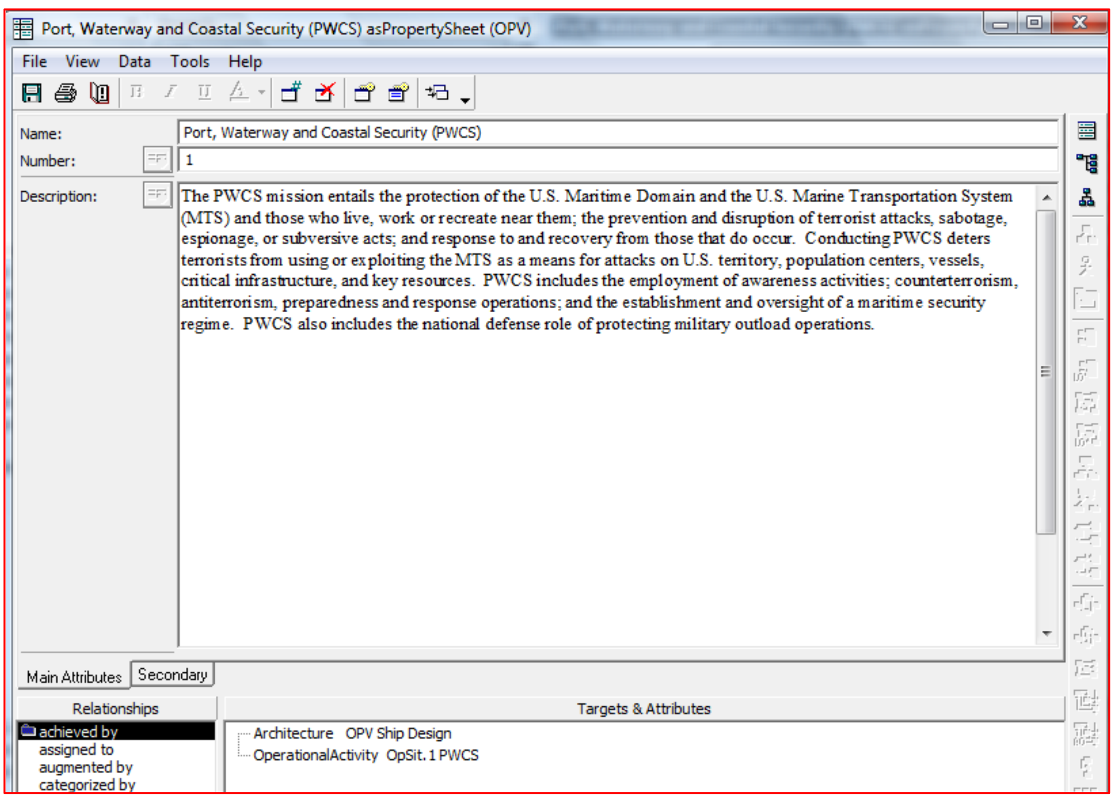


Figure 9 - PWCS Mission Element Property Sheet

The capabilities required to meet mission objectives are defined using the JCA lexicon. In the case of the OPV, the Coast Guard command would likely establish a set of JCAs related to the Coast Guard mission set. In our research the full list of possible JCAs was studied and any that had some relevance to the OPV mission were selected as possibilities. Each JCA was captured in CORE as individual elements of the capability class with their numbers and descriptions recorded. A total of 65 JCAs were identified. Figure 10 is a snapshot of a table view of a portion of the JCAs that includes the number, name and description of each JCA.

	Number	Name	Description
20	JCA.2.2.4	Exploit, Ocean Environment	The ability to provide relevant meteorological, oceanographic and space environmental information for integration into operational activities.
21	JCA.3.1	Maneuver	The ability to move to a position of advantage in all environments in order to generate or enable the generation of effects in all domains and the information environment.
22	JCA.3.1.1.4	Maritime, engage	The ability to maneuver to engage on the surface of the sea.
23	JCA.3.1.3.4	Maritime, influence	The ability to maneuver to influence on the exterior or upper boundary of the sea.
24	JCA.3.1.4	Maneuver to Secure (MTS)	The ability to control or deny (destroy, remove, contaminate, or block with obstacles) significant areas, with or without force, in the operational area whose possession or control provides either side an operational advantage.
25	JCA.3.1.4.1	Air (MTS)	The ability to secure the region beginning at the upper boundary of the land or water and extending upward to the lower boundary of the Earth's ionosphere
26	JCA.3.1.4.4	Maritime, MTS	The Ability to secure the surface of the sea
27	JCA.3.2	Engagement	The ability to use kinetic and non-kinetic means in all environments to generate the desired lethal and/or non-lethal effects from all domains and the information environment.
28	JCA.3.2.1	Kinetic Means	The ability to create effects that rely on explosives or physical momentum (i.e., of, relating to, or produced by motion).
29	JCA.3.2.1.3.1	Air (EKM)	The ability to kinetically engage moving targets in the region beginning at the upper boundary of the land or water and extending upward to the lower boundary of the Earth's ionosphere (approximately 50 KMs).
30	JCA.3.2.1.3.3	Surface (EKM)	The ability to kinetically engage moving targets on land or water. 31.
31	JCA.3.2.2	Non Kinectic Means	The ability to create effects that do not rely on explosives or physical momentum (e.g., directed energy, computer viruses/hacking, chemical, and biological)

Figure 10 - Table of JCAs in CORE

The next step in the process is to identify the tasks that must be completed to accomplish the mission and support the JCAs. The UNTL is a combination of the UJTL and NTTL with measures for the tasks to provide a single document to identify tasks and define the NMETs. A database for mapping between JCAs and UJTLs was developed by the JCS. This database is a valuable resource for identifying the UJTLs to capture in the CORE architecture model. The UJTLs were entered in CORE as individual elements of the Operational Task class. The NTTL containing all the Navy Tasks, referred to in the UNTL instruction as NTAs, is formatted to match the UJTL. The NTA numbers and descriptions correspond closely to the UJTL task level of war but with some variations due to the specific nature of the NTAs. The NTTL is a subset and refinement of the Universal Joint Tasks into Navy, Coast Guard, and Marine Corps specific tasks. There are also some logical relationships to the operational level of the UJTL so these relationships were included. The NTAs are also saved as Operational Task elements in CORE and their relationship to the UJTLs is defined as 'refines'. The NTAs 'refine' the UJTL level tasks. Finally, NTA's required for the notional OPV mission are collected as an OPV NMETL list under the Operational Activity class.

2.1.2 Defining the DRM and Building the OpSits

The DRM is defined by Missions, OpSits, and NMETs including their measures and conditions. Our notional OPV DRM is defined by 11 OpSits, one for each mission including the sub-missions under Defense Readiness. Each OpSit is represented as an Operational Activity element. The relationship in CORE is that the OpSit Operational Activities 'achieve' a Mission.

By maintaining the direct relationship between the Navy tasks in the Operational Task class and the NMETs in the Operational Activity class the NMETs are still traceable back to the JCAs. Figure 11 shows how traceability diagrams can be customized in CORE so that the NMET Operational Activities are traceable back to the JCAs. Figure 11 starts with a single JCA at the top which in this case is JCA 4.7.2.1.1 Law Enforcement. This JCA requires the capabilities to perform the UJTL level tasks below the JCA. The UJTL is then refined by all the possible NTAs that could relate to that UJTL. Then those NTAs chosen to be the NMETs in the OpSits have the NMET Operational Activity element added below in the hierarchy. The NTAs are also captured in the architecture in a hierarchy so that some NTAs could be refined by other NTAs. In Figure 11 for example the NTA 1.4.8 Conduct Maritime Law Enforcement, is refined by NTAs 1.4.8.1 Conduct Alien Migrant Interdiction and 1.4.8.2 Conduct Maritime Counter Drug Operations. All three of these NTAs have associated NMETs as shown in the hierarchy.

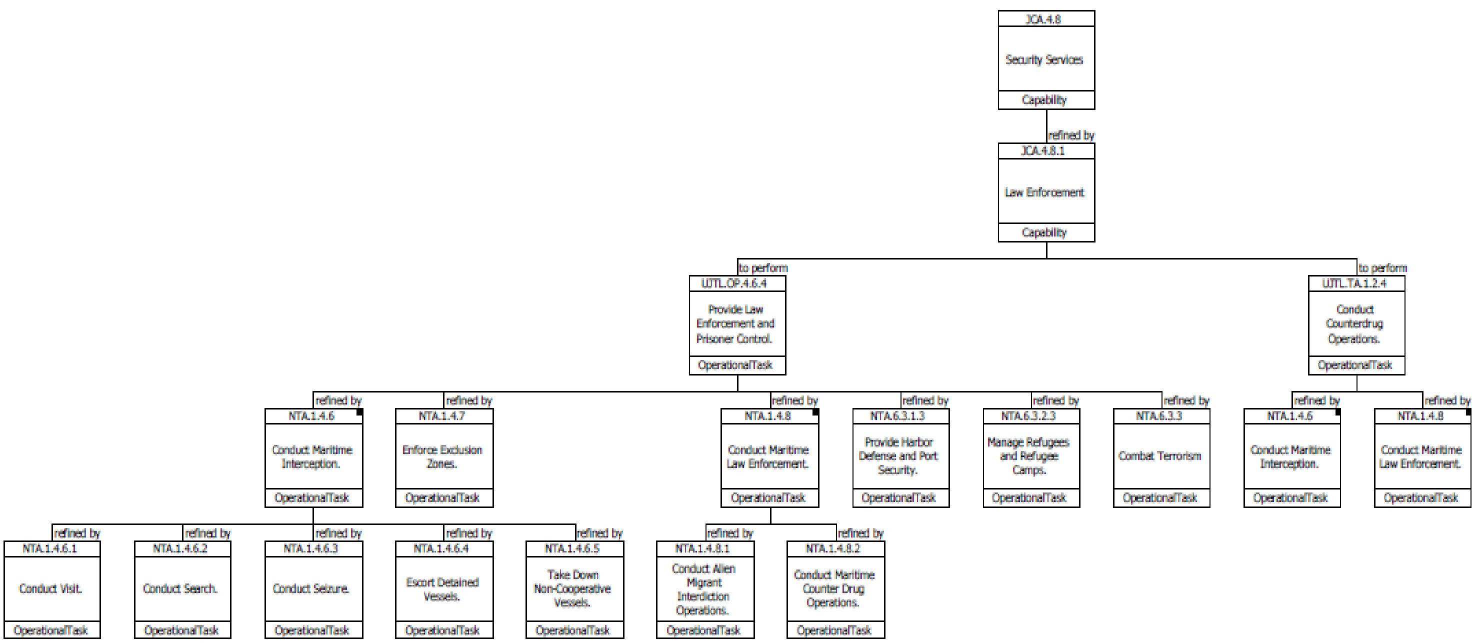


Figure 11 - Traceability Diagram from JCA to NMET

Once the relationships have been established to connect JCAs to the NMETs, OpSit Functional Flow Block Diagrams (FFBDs) can be built. When complete, OpSit elements can be expanded to show the sequenced NMETs that make up the OpSit.

First it is important to understand the nature of the Coast Guard missions for the OPV. Coast Guard cutters are generally considered to be always conducting the PWCS mission until specific incidents or task direction require the ship to shift to other mission objectives. This means that as soon as a cutter gets underway from a mooring it is immediately considered to be patrolling waterways and conducting coastal security because this mission defines the general purpose of the Coast Guard. There are specific mission scenarios that would be considered PWCS such as protecting assets from maritime terrorist attacks or defending U.S. shores against any foreign attacks as much as the Coast Guard is capable. For planning purposes this means that even if the OPV is conducting a patrol in or near known drug smuggling routes the mission of the ship is PWCS until a drug smuggling vessel is identified. At that point the OPV would shift to the Drug Interdiction mission. For the OpSits developed in CORE all the other OpSits are initiated from the PWCS OpSit.

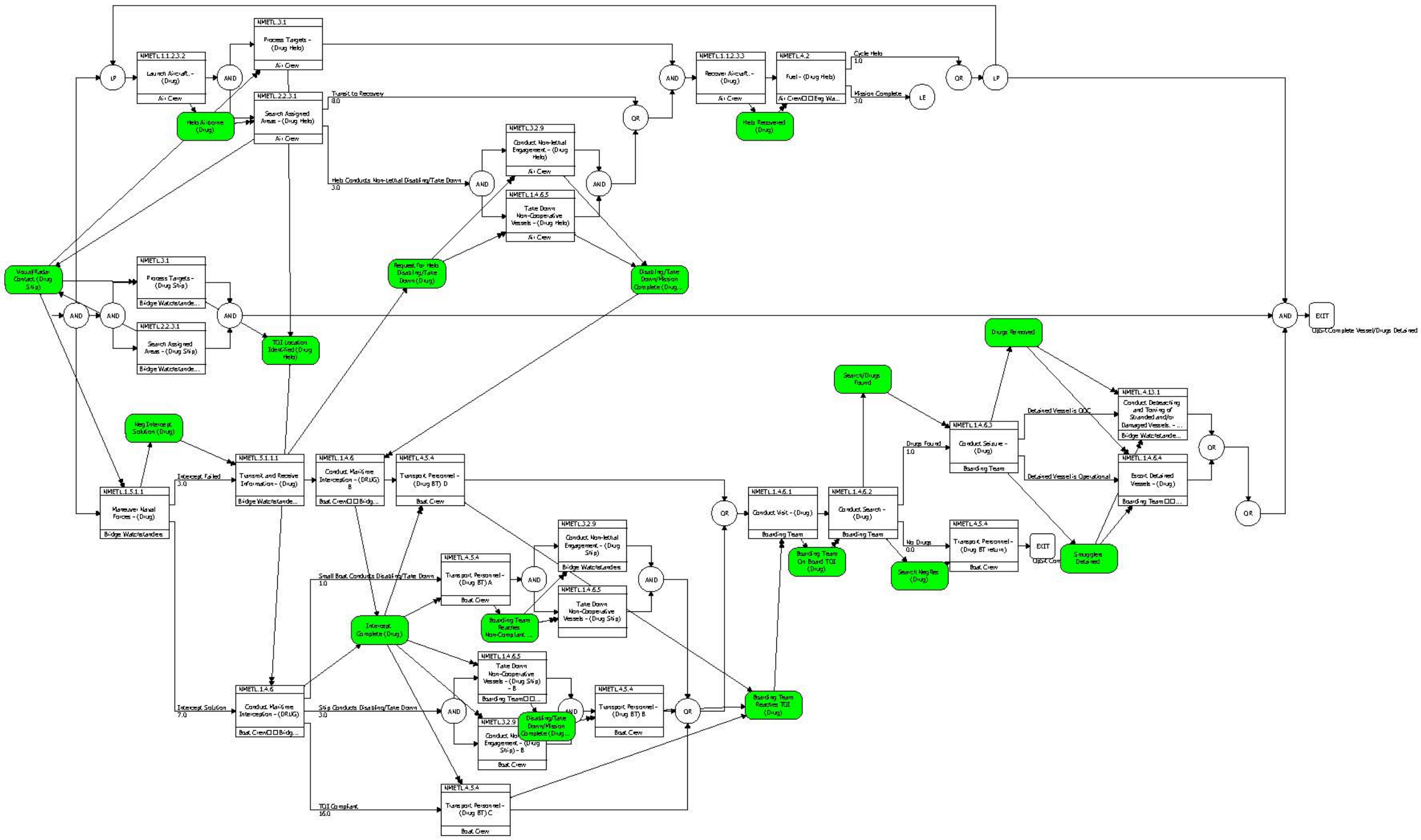
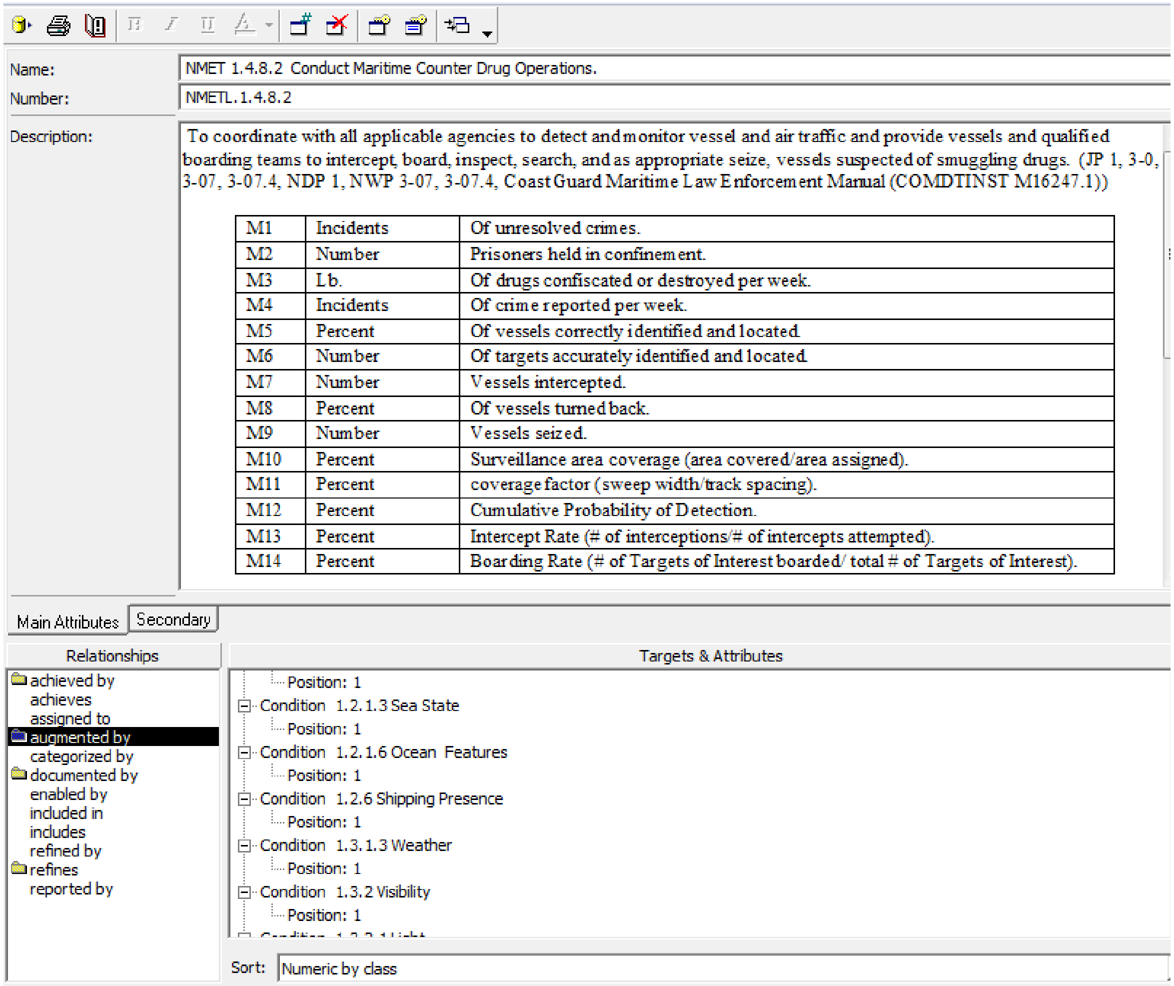


Figure 12 - Drug Interdiction (DRUG) OpSit Enhanced FFBD (EFFBD)

The DRUG Interdiction (DRUG) OpSit is used here as an example. The DRUG OpSit begins after tasks in the PWCS OpSit of searching assigned operating areas by both the ship and possibly a helicopter have identified a Target Of Interest (TOI) assumed to be a drug smuggler. The EFFBD of the Drug OpSit is shown in Figure 12.

NMET 1.4.8.2 Conduct Counter Drug Operations encompasses all of the activities that will be included in the Drug OpSit (although more than one OpSit could be used for this NMET), therefore this NMET's measures and conditions define the measures and conditions for the entire OpSit. Figure 13 is the property sheet for NMET 1.4.8.2 showing the associated measures and some of the possible conditions to be applied. This is also true for Migrant Interdiction for which the OpSit is entirely encompassed by NMET 1.4.8.1 Conduct Alien Migrant Interdiction Operations.



Name: NMET 1.4.8.2 Conduct Maritime Counter Drug Operations.

Number: NMETL.1.4.8.2

Description: To coordinate with all applicable agencies to detect and monitor vessel and air traffic and provide vessels and qualified boarding teams to intercept, board, inspect, search, and as appropriate seize, vessels suspected of smuggling drugs. (JP 1, 3-0, 3-07, 3-07.4, NDP 1, NWP 3-07, 3-07.4, Coast Guard Maritime Law Enforcement Manual (COMDTINST M16247.1))

M1	Incidents	Of unresolved crimes.
M2	Number	Prisoners held in confinement.
M3	Lb.	Of drugs confiscated or destroyed per week.
M4	Incidents	Of crime reported per week.
M5	Percent	Of vessels correctly identified and located.
M6	Number	Of targets accurately identified and located.
M7	Number	Vessels intercepted.
M8	Percent	Of vessels turned back.
M9	Number	Vessels seized.
M10	Percent	Surveillance area coverage (area covered/area assigned).
M11	Percent	coverage factor (sweep width/track spacing).
M12	Percent	Cumulative Probability of Detection.
M13	Percent	Intercept Rate (# of interceptions/# of intercepts attempted).
M14	Percent	Boarding Rate (# of Targets of Interest boarded/ total # of Targets of Interest).

Main Attributes | Secondary

Relationships: achieved by, achieves, assigned to, augmented by, categorized by, documented by, enabled by, included in, includes, refined by, refines, reported by

Targets & Attributes:
Position: 1
Condition 1.2.1.3 Sea State
Position: 1
Condition 1.2.1.6 Ocean Features
Position: 1
Condition 1.2.6 Shipping Presence
Position: 1
Condition 1.3.1.3 Weather
Position: 1
Condition 1.3.2 Visibility
Position: 1

Sort: Numeric by class

Figure 13 - NMET 1.4.8.2 Conduct Maritime Counter Drug Operations Property Sheet

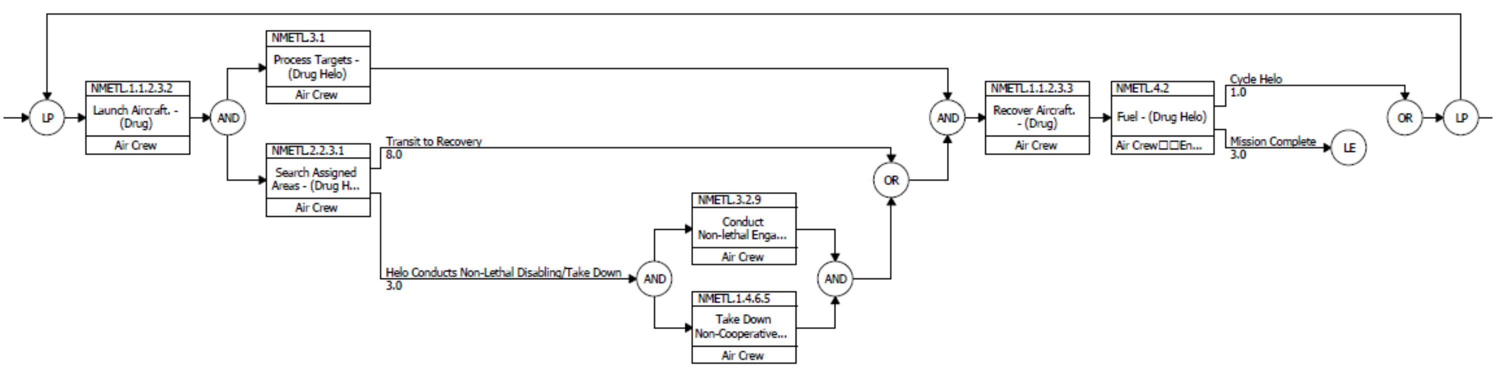


Figure 14 - Drug Interdiction (DRUG) OpSit FFBD – Upper Branch

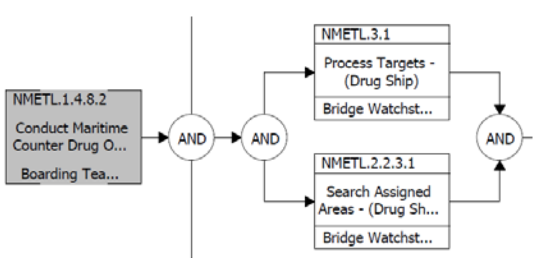


Figure 15 - Drug Interdiction (DRUG) OpSit FFBD – Middle Branch

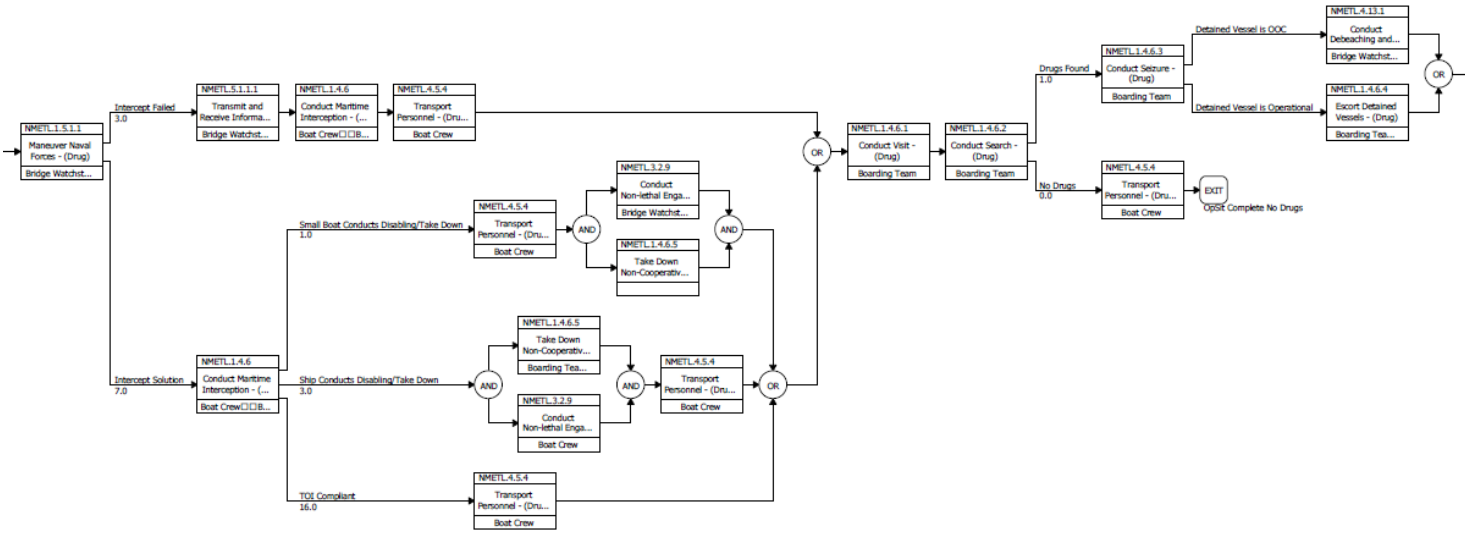


Figure 16 - Drug Interdiction (DRUG) OpSit FFBD – Lower Branch

Figure 12 has three parallel branches based on the 'AND' construct which means these activities are or can be conducted in parallel. The top branch, enlarged in Figure 14, depicts the tasks for a helicopter to be launched, search the assigned area and process the identified TOI. Typically the helicopter conducts search and escalating levels of disabling non-lethal tactics before using firearms to disable engines. Finally, the helicopter is recovered based on a completed mission or required refueling. The exits from the Fueling activity show that the helicopter can be cycled back to the launch activity if required via a loop or exit the loop via the mission complete branch so that the OpSit can be completed. The middle branch, enlarged in Figure 15, depicts the tasks for OPV to continue to search and process targets within the assigned operational area. The bottom branch, enlarged in Figure 16, depicts the various possible actions associated with intercepting a smuggling vessel and bringing it to a stop to conduct a boarding. The maneuvering/intercept/boarding branch of the OpSit starts with the Maneuvering NMET to represent the OPV attempting to move into an intercept position while still assessing whether intercept is possible either by the ship or OTH capable small boat. The Maneuver activity exits based on whether intercept is possible or not. If the intercept solution fails, which is the top branch, the OPV would request the helicopter take-down the non-compliant vessel via the Transmit and Receive Information activity and then conduct the interception once the TOI is stopped. From here the Transport Personnel refers to transporting the Boarding Team to the TOI. If the intercept is possible either the OPV itself or the OTH small boat conducts the interception. There are three possible exits from this Conduct Maritime Interception which depend on whether the TOI is compliant. If the TOI is not compliant either the OPV or OTH small boat conducts the disabling and take-down as described for the helicopter. In all cases, the result is the TOI is ready to be boarded. After the TOI has stopped, either voluntarily or forcefully, the Boarding Team conducts the boarding which includes the Visit, Search, and Seizure activities. However, if no contraband is discovered the Boarding Team may return to the OPV via the transport personnel activity. If contraband is discovered the vessel, crew, and contraband will seized and the vessel will either be escorted or towed to port depending on whether the vessel was disabled.

The Enhanced FFBD or EFFBD in Figure 12 displays the same view as the FFBD, but with the information and or material required to pass between the activities as inputs and outputs from activities. These inputs and outputs are collected in the class called Operational Items in the DoDAF schema. An example of the use of Operational Items in the EFFBD is that the Maneuver Naval Forces task outputs

'Neg Intercept Solution' meaning the OPV is unable to intercept and this output triggers the Transmit and Receive Activity which outputs the request for the helicopter to conduct the disabling. This in turn triggers the helicopter to conduct the non-lethal engagement and take-down activities which when complete outputs that the activity is complete. This triggers the OPV to conduct the intercept on the stopped vessel and upon completion triggers the Transport Personnel activity to take the Boarding Team to the TOI.

CORE also has the capability to conduct discrete event simulation of the FFBD. This is useful for identifying mistakes in the functional flow sequence of activities. This discrete event simulation is only capable of testing the FFBD flow logic, and does not have the capability to incorporate the mathematical modeling required to build the OpSit into an OEM simulation model. This is accomplished using discrete-event simulation modeling software.

Once all the OpSits are completed the collection of OpSits for all missions define the scope of the OPV DRM. The OpSits, and therefore the DRM, are traceable to the JCAs through the NMETs and Operational Tasks. The OpSits are directly related to the OPV Missions based on the 'achieves' relationship and are therefore traceable to the ICD which in turn means they are traceable to the guidance, such as the Joint and Coast Guard Strategy, that goes into the JCIDS process to develop the ICD for the OPV. The next step is to make the OpSits traceable to the ship design itself to show that the ability to successfully complete the mission objectives is ultimately based on the functionality and design of the components of a given ship design.

2.1.3 System Architecture

The focus of our paper thus far has been the Operational Architecture Domain, defined through Capabilities, Operational Tasks, Operational Activities, Operational Items, Performers and Missions. To continue the architecture and establish the relationship between the OpSits and the ship design the System Architecture Domain must be constructed. This work is in progress, but we have added a temporary framework for it that is discussed briefly in this section.

The first step is to build the Component class based on the components for our notional OPV. The top level component (System of Systems) is the Offshore Patrol Vessel, and it is broken down in a hierarchical framework based on the relationship 'built from'. We use the traditional ESWBS for this hierarchy as shown in Figure 17 and Figure 18. The characteristics of these components reflect the possible DV selections from the MOGO, and subsequent selection of the baseline design(s). This will be accomplished in a number of levels interactively with the architecture and discussed in a later paper.

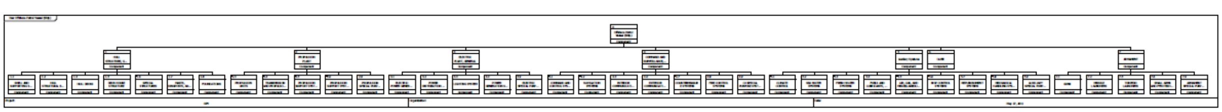


Figure 17 - OPV Component (SWBS) Hierarchy

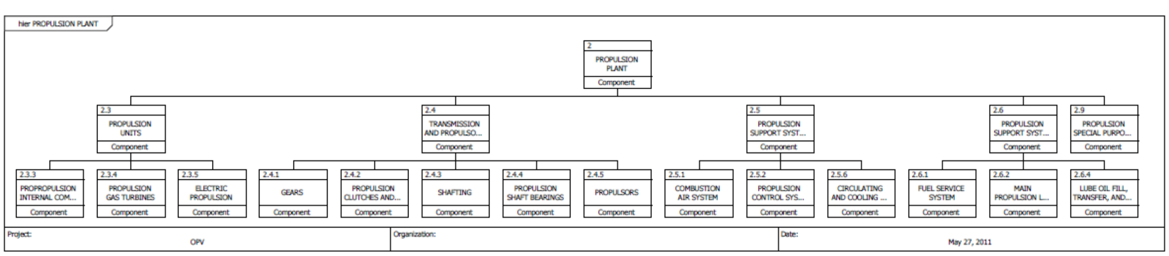


Figure 18 – OPV Propulsion Machinery Plant (SWBS 200) Component Hierarchy

The functions for each component are entered into CORE in the Function class based on the 'performs' relationship with a particular component. The functions can also be viewed hierarchically with respect to other functions based on the 'decomposed by' relationship. The top level function, directly related to the top level component, Offshore Patrol Vessel, is the function "perform CG Missions".

Figure 19 is a hierarchical view of "perform CG Missions" with the Provide and Support Operational Requirements function expanded along with the sub-functions of Anti-Surface Warfare and Provide Tactical Transfer of Personnel.

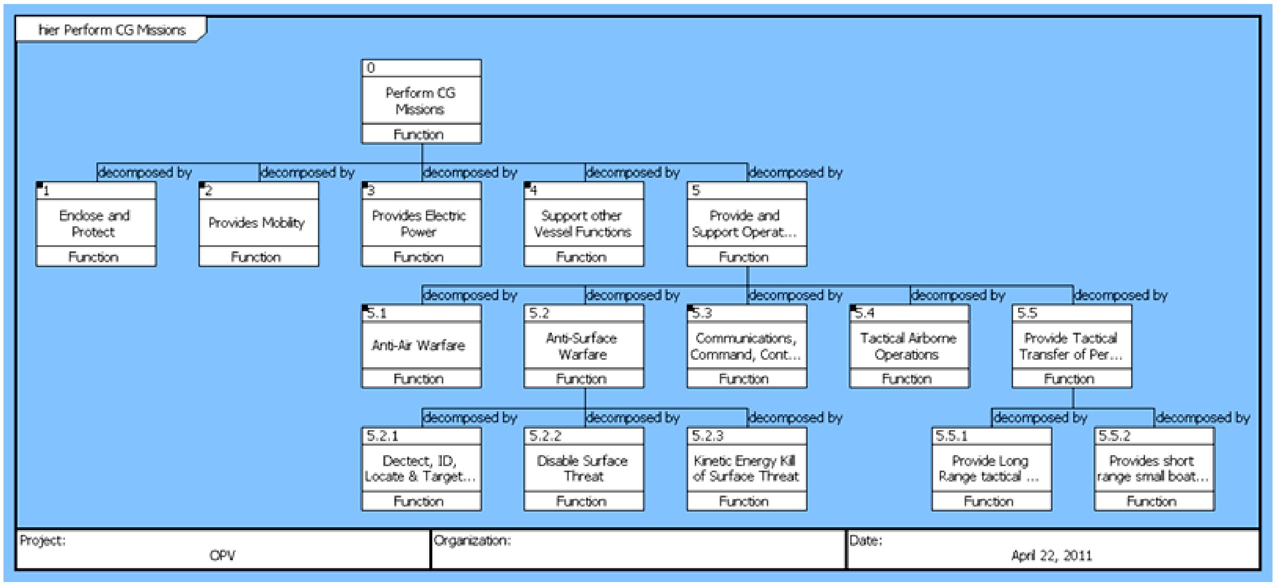


Figure 19 - OPV Function Hierarchical View

The OPV functions are then related to the NMET level Operational Activities by the relationship 'implements'. The Components are also related to Performers by the same relationship. Functions are also related to the Requirement class, which includes the capability gaps, by the 'specifies' relationship.

With these additions, the OPV ship design DoDAF architecture has traceability between the Operational and Systems domains. The OpSits and the activities they are composed of are traceable through the Operational Architecture Domain and through the Systems Architecture Domain. The NMETs used to build and define the OpSits are traceable to the JCAs. The NMETs are sequenced via the OpSit scenario to accomplish the mission objectives as defined by the ICD and thus the CBA from the JCIDS process. The NMETs are also traceable to the design variables of the OPV via the component functions. The functions are specified by the capability gaps from the ICD and the components must provide the functionality to perform the NMETs and achieve mission objectives.

OEMs can now be developed using simulation software for multiple discrete event operational situations based on the OpSit framework developed in CORE. These simulations depend explicitly on ship design variable values. The scope of these OEMs is determined by the CORE framework. The complexity is determined primarily in the simulation software. Each mission has a measure of effectiveness (MOE) based on the measure results from its' OpSit(s) simulations. A Response Surface Model (RSM) is built in a Design of Experiments (DOE) for each MOE as a function of Design Variable (DV) values. The resulting MOE RSMs are combined to form the OMOE.

2.2 Effectiveness Model (OMOE)

Our next task is to combine the mission OpSit RSMs into a single OMOE. Weighing the missions evenly or by the amount of time typically spent conducting them may ignore the importance of individual missions. The US Coast Guard, for example, identifies SAR as their most important mission, and will leave other missions as necessary to save life and property. The OPV will likely spend only limited time conducting SAR over its life cycle but SAR is their most important mission. Likewise the OPV is always assumed to be conducting PWCS unless called off on another mission and OPVs will spend a great deal of time at this mission. This could skew the weighing of the OMOE to the PWCS mission even though the possible PWCS OpSits, such as a maritime terrorist attack, would have less of a chance of occurrence than a SAR mission.

A possible solution to the weighing of individual MOEs is to use the AHP as in our current expert opinion process. The difference between the current OMOE function and the new one based on the OEMs is that the MOEs are built from viable, mission-based, probabilistic scenarios using physics and the design variables directly. The OMOE hierarchy for the OPV (with Defense Readiness not expanded for readability purposes) is given in Figure 20, created directly using the system architecture in CORE. It simply requires mission pair-wise comparison to calculate the weights.

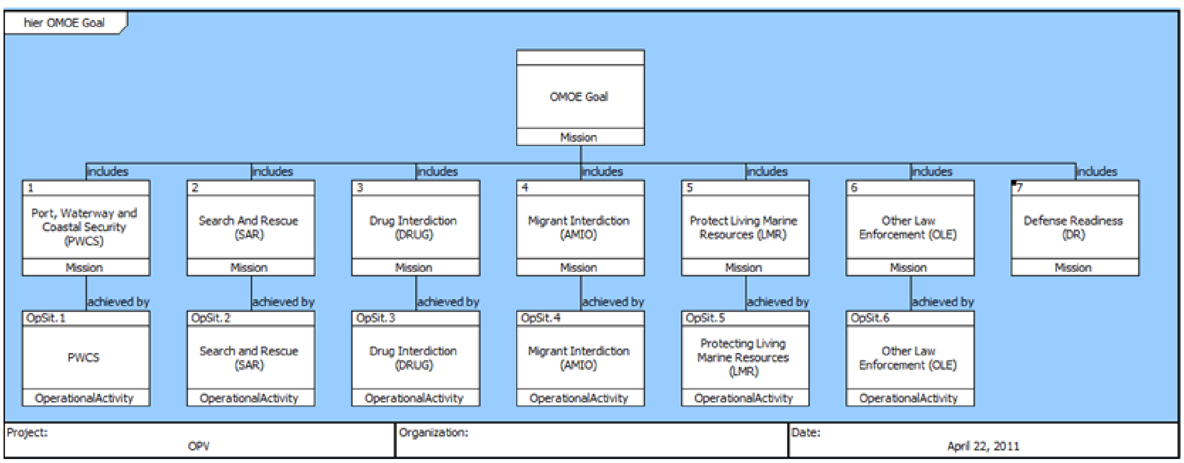


Figure 20 - Proposed OPV OEM-based OMOE Hierarchy

3. OBSERVATIONS AND CONCLUSIONS

Our system architecture development focused on developing the Operational Architecture Domain to rationally define a DRM and its OpSits. The ability of the architecture to act as a single source repository for all data, guidance, design characteristics, functions, processes, cost, risk, effectiveness, and capture all of the relationships between these aspects makes it a potentially powerful tool.

The DoDAF provides the general architecture guidance to ensure all parties are working within the same lexicon and producing the same required documentation. We have seen that while the DoDAF guidance is useful, system architectures for specific purposes may require some different relationship distinctions within the architecture. Our architecture has added a relationship between Capability and Operational Task to capture the development of the NMETs (Operational Activities) from JCAs (capability class) through the UJTL and NTTL (Operational Tasks).

The DRM provides rational measures of effectiveness (MOEs) based on realistic operational situations and the NMETL. The DRM is developed as an integral part of the Total-Ship System

Architecture. By defining a DRM for a given ship design, the foundation is laid for using OEMs in the effectiveness model. If the Total-Ship System Architecture approach is adopted as a standard requirement for the ship design process, then OEMs become a natural choice to measure effectiveness and evolve directly from the architecture.

It takes significant effort to build the simulation models, and it will take more effort to build the RSMs from these models to use in the synthesis model. Integrating the OEMs into an OMOE may also require expert opinion to mission and OpSit weights. The OEM process will require more research to determine if the desire to limit expert opinion in the process outweighs the simplicity of the current expert opinion-based OMOE function. This research will include comparing the results of both methods to attempt to determine which is better or more valid.

Figure 2 shows how the C&RE process can be modified to include the MBSE architecture and tools. After receiving JCIDS input and AOA guidance, an existing ship design architecture similar to that for proposed design could be modified for a new design. This includes the NMETL, DRM, OEMs, ROCs, components and component relationships. This saves having to develop architectures from scratch for every new design.

The first steps in the concept explorations process should follow the six architecture steps presented in DoDAF 2.0 [12]:

1. Consider the use and objectives of the architecture – In our application, the architecture will be used as a data repository for the ship design system and design process and to produce various views of the process necessary for a disciplined complex System of Systems design. This could include:

    - ICD and other AoA guidance documents and data
    - Applicable components of the National Defense Strategy, the National Military Strategy, and/or the National Strategy for Homeland Defense
    - Complete JCA architecture including UJTL, NTTL and their relationships
    - Specific ship design NMETL
    - Design DRM and OpSits with Operational Activity FFBDs
    - ROCs and capability gaps specified as requirements
    - Specific ship design Risk Register
    - Design goal - OMOE
    - Collection of Acquisition and Ownership Costs
    - Design components, functions and views that capture their relationships
    - Design activities
    - Design products

2. Determine the scope of the architecture - Level 1 of the MBSE levels (Figure 3) with:

    - Operational Domain - Select/edit from a full JCA/UJTL/NTTL list to specify the NMETL for a particular design.
    - System Domain - Define ship Components to at least two digit SWBS groups consistent with and including all DVs by editing full SWBS list. Determine Functions necessary to 'implement' NMETL and address in DVs. Level 2 would extend this to 3-digit SWBS. Specify requirements (CDD with KPPs and Level 1 system requirements) after MOGO and selection from Non-Dominated designs. Continue to update requirements in successive architecture levels.

- Program/Engineering Management Domain – Specify design activities and products for Concept Development. Level 2 would extend this through Preliminary Design.

3. Determine the data required - collect all documents and data required to conduct steps 1. and 2.
4. Collect, organize, correlate and store the data - build the architecture and store all data in a single repository (CORE)
5. Conduct analysis in support of architecture objectives. This could be done by operating on/updating the data in the ship system architecture using external tools to perform necessary analyses, calculations and optimization including:
    - OEM
    - OpSit Simulation Models & RSMs
    - AHP/OMOE Calculation
    - Synthesis Model
    - Cost and Risk Calculation
    - Optimization
    - Various engineering analyses
    - Design process definition, optimization and planning
6. Present results in a view/form to support the decision-maker
    - Architecture views and reports
    - Non-Dominated Frontier

An important objective of our research thus far was to assess the value and potential contribution of the new MBSE approaches and other System Engineering tools to improve and update the Multi-Objective Optimization approach to the ship design process. We were able to research the potential contribution of these approaches and determine that these approaches and tools are very useful for organizing and understanding the C&RE and ship synthesis process. However, this research proved to be only a preliminary step in determining the overall value of these approaches and tools to the complete ship design process. These approaches and tools required an extensive amount of input and setup before beginning actual ship design processes. More research is required to better determine if these efforts add value to the ship design process.

Another objective was to assess and improve OEMs in the context of DoDAF 2.0 architecture and the OEMs integration with the ship synthesis models including the influence of scope and complexity on OEM results, and compare this method to the expert opinion-based method currently used. The DoDAF architecture provides an ideal method for developing the DRM and capturing the relationships from required capabilities to the mission essential tasks that define the OpSit. These tools provide the means to build rational and viable OEMs that are traceable through the architecture to the ship design and to the strategic guidance. The effort to develop the initial architecture was time consuming. More research will be required to understand the impact of scope and complexity of the OpSit on the MOE results. A complete set of OpSits must be developed into an OEM-based OMOE function before this method can be properly compared to the current expert opinion-based method.

A final objective was to evaluate the contribution of the Systems Engineering approach to the C&RE process. Our research was able to use the MBSE architecture to capture the C&RE process into a single repository to better understand the complex nature of this process. To properly understand and assess the value of this approach to the C&RE process, the new C&RE process presented in Figure 2 must be evaluated in multiple ship design case studies. Building the Ship Design System Architecture and using the OEM as an effectiveness model both require significant effort. More research is required to determine if these tools add sufficient value and/or efficiency to the overall process to warrant their use.

4. ACKNOWLEDGMENT

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