Application of a DoDAF Total-Ship System Architecture in Building Naval Ship Operational Effectiveness Models

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 produce 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 process 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 continues with the description of a new methodology introduced by Kerns, Brown and Woodward for building a DRM and ultimately an OMOE using a total-ship system architecture and the DoD Architecture Framework (DoDAF 2.0). It describes the application of this DRM and architecture to develop related Operational Effectiveness Models (OEMs) and complete the new OMOE as an alternative to the current expert opinion-based OMOE.

OEMs are developed for multiple discrete event operational situations based on the DRM/OpSit framework developed in the operational domain of the ship system architecture. The scope of these OEMs is determined in the architecture. The complexity is determined primarily in the simulations themselves. Each mission may have multiple OpSits to describe the typical operations of that mission, but this paper considers only one OpSit per mission area for simplicity. Each mission has a measure of effectiveness (MOE) based on its OpSit measure results. The resulting mission area MOEs are combined to form the OMOE.

A US Coast Guard (USCG) Offshore Patrol Vessel (OPV) is used as a case study in our research. The ship design architecture and Design Reference Mission are based on the OPV mission requirements, and the Drug Interdiction OpSit is used as a specific example in this paper.

1. INTRODUCTION AND REVIEW

The objective of the research described in this paper [14][15] is to develop a method for building Operational Effectiveness Models (OEMs) and an Overall Measure of Effectiveness (OMOE) in a total ship system architecture using the DoD Architecture Framework (DoDAF 2.0), and to integrate this method with our current multi-objective optimization approach to perform naval ship Concept and Requirements Exploration (C&RE) [1][2][3][8][18][20][21].

Our new C&RE process is shown in Figure 1. 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), and ultimately an Overall Measure of Effectiveness (OMOE) Model. Our previous paper presented the architecture, Naval Mission...
Essential Task List (NMETL) and DRM development [15] after briefly describing Model-Based Systems Engineering (MBSE) [4], DoDAF 2.0 [9], the JCIDS process [5][6], Joint Capability Areas (JCAs), the Universal Joint Task List (UJTL), Universal Naval Task List (UNTL) [22] and the Naval Tactical Task List (NTTL) [16]. This paper continues with OEM development for a Drug Interdiction OpSit and its associated Measure of Effectiveness (MOE) as an example of the next step in our C&RE process. Figure 2 shows how these components relate to each other in a DoDAF 2.0 schema specifically adapted for our ship design system [7].

**Figure 1 - New Ship Concept and Requirements Exploration Process (C&RE)**

**Figure 2 - Ship Design System DoDAF Architecture (adapted from [7])**
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 2. CORE software is used to build this architecture. It identifies the individual parts of the architecture as classes including Capabilities, Functions, Components, Operational Tasks, etc. 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 [23].

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 [6]. This requires that for ship C&RD the ICD, JCAs and related UNTL tasks must provide the foundation for system (ship) architecture development [22].

The Design Reference Mission defines 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. It is 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 situations [19].

Figure 3 - Element Relationship View for Notional OPV ICD
Navy Mission Essential Tasks (NMETs) for a particular ship mission or ship design are selected from the UNTL in the architecture with associated measures of task performance and conditions under which the task could be accomplished. The collection of tasks is called a Naval Mission Essential Task List (NMETL), tailored for a particular design. 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 are combined to calculate an OMOE for a given ship design. This is accomplished in the context of the system architecture. Figure 3 shows the relationship of the OPV missions to the ICD document element. 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 the architecture 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 4 shows this traceability. Figure 4 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 4 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 4 - Traceability Diagram from JCA to NMET

Once the relationships are established connecting the JCAs to the NMETL, OpSit Functional Flow Block Diagrams (FFBDs) are built using the NMETs, and finally OEMs are built using the OpSit FFBDs. If this is managed in a disciplined way, all applicable JCAs are considered and all applicable NMETs are included in the NMETL and ultimately in the DRM and OEMs. This insures that the DRM has sufficient scope and the ship has the required capabilities to perform its required missions and fill the capability gaps specified in the ICD and by the JCIDS Capabilities-Based Assessment (CBA).
2. OPERATIONAL EFFECTIVENESS MODEL (OEM)

2.1 OPSIT Functional Flow Block Diagram (FFBD)

We use the Drug Interdiction (DRUG) mission as our example for building an OEM from an OpSit FFBD. USCG cutters are generally considered to be conducting their Port, Waterway and Coastal Security (PWCS) mission until specific incidents or tasking require the ship to shift to other mission OpSits, in this case the DRUG OpSit.

The EFFBD for the DRUG OpSit is shown in Figure 5. The DRUG OpSit begins after tasking and transit to the DRUG mission OpArea. NMET 1.4.8.2 Conduct Counter Drug Operations encompasses all of the activities that are 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 DRUG OpSit. Figure 6 is the property sheet for NMET 1.4.8.2 showing the associated measures and possible conditions to be applied.

Figure 5 has three parallel branches based on the ‘AND’ construct which means these activities are or can be conducted in parallel. The top branch depicts tasks for a helicopter to be launched, search the assigned area, and process the identified TOI. The center branch depicts tasks for the OPV to search and process targets within the assigned operational area. The bottom branch depicts the various tasks associated with the OPV intercepting a smuggling vessel and bringing it to a stop to conduct a boarding.

We describe OEM models for each of these FFBD branches, but first we describe the particular scenario, consistent with the DRUG OpSit, that is used for the OEM.
The Enhanced FFBD or EFFBD in Figure 5 displays the same view as an 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 a 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 this 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.

![Figure 6 - NMET 1.4.8.2 Conduct Maritime Counter Drug Operations Property Sheet](image)

### 2.2 Details and Assumptions for DRUG OpSit Scenario

The typical maritime-based modes of narcotic smuggling use small high-speed craft capable of carrying 1 to 2 tons of contraband, referred to as ‘go-fast’ vessels by the USCG. These craft can be commercially designed high-speed recreational boats or the Caribbean style wooden ‘yola’. Both of these types of vessels are characterized by multiple outboard engines and are 25 to 45 feet in length with relatively low freeboard and either an open bay or cabin area forward capable of carrying the contraband. The use of homemade submarines that dive only a few feet is beginning to emerge as a viable threat and...
slower moving yachts or coastal freighters are occasionally used as smuggling vehicles hoping to evade authorities by blending in with lawful maritime traffic. The go-fast remains the vehicle that challenges USCG vessel capabilities with a combination of high-speed, low radar cross-section (RCS), and shallow draft that allows the smuggler to operate in waters too shallow for larger USCG vessels.

The presence of vast shallow banks in the Caribbean off the southeastern coast of Florida provide the opportunity of leveraging the go-fast advantages while challenging the Coast Guard to detect and intercept these vessels before reaching shore. The Great Bahama Bank, Little Bahama Bank, and Cay Sal Bank range between 40 and 50 nm off the Florida coast. Our DRUG OpSit scenario is notionally based in the Cay Sal Bank area. The isolated nature of this bank provides a realistic setting for a single USCG OPV asset to be tested because it is somewhat remote and provides a narrower opportunity to the go-fast. As such the area is ideal for assigning a medium endurance Coast Guard asset like an OPV. This bank is farther from shore-based Coast Guard Air Stations and cutter homeports lending to the use of longer endurance assets that may be capable of deploying air assets. The Great and Little Bahama Banks are relatively close to Miami-based cutters and aircraft and these operational areas are better handled by a force lay-down of multiple patrol boats and craft coordinating with shore based aircraft for surveillance. Figure 7 is a Google Earth image of the Cay Sal Bank area.

The conditions included with the NMETs are general environmental and operational conditions. These include conditions like wind speed, sea state, and rules of engagement. The conditions for our DRUG OpSit are specified by choosing typical conditions in our chosen operational area that maximize the advantages of the go-fast vessel.

For our DRUG OpSit simulation the following environment conditions are assumed:

- Sea State: 4 (this would be varied probabilistically if ship seakeeping is considered)
• Water Depth (Cay Sal Bank): 1 - 9m, characterized by rocky outcroppings and coral reefs
• Water Depth (Surrounding Cay Sal Bank): 100 - 1000m
• Time Period: 12 hours corresponding generally to dusk until dawn

Sea State 4 corresponds to winds of 11-15 nautical miles per hour and wave heights from 1 - 2m. It is characterized by small breaking waves with some whitecaps. This sea state has little effect on the top speed of ‘go-fast’ vessels while masking the boat wake effect that creates a white trail of disturbed salt water. It is typically this white trail that is picked up visually from aircraft before the ‘go-fast’ itself is visible, and typically before a small helicopter radar can detect the vessel. Smuggling vessels mostly operate during nighttime hours which somewhat affects the ability to detect them visually, although modern infrared sensors and night vision equipment generally negates most of this advantage.

The OPV has launch envelopes for both small boats and aircraft that describe the limiting conditions for launching. A helicopter is also sensitive to relative wind speed which limits the helicopter launch window. A Sea State of 4 would have little effect on the ability to launch either helicopters or small boats.

Having a helicopter embarked is a function of the ship design. If the design includes a flight deck and hangar the vessel is considered to have an embarked helicopter. A vessel design with a flight deck, but without a hangar typically does not have an embarked helicopter, and is assumed to be without a helicopter. The advantage of the deployed helicopter to the OPV is as a deployable high-speed sensor for detection purposes.

For purposes of our current study, it is assumed that an embarked helicopter does not have the capability to conduct disabling or take downs of ‘go-fast’ vessels. This is a capability and tactic that is increasingly being employed in the Coast Guard, but it is a function of aircrew training and tactics based at specific air stations, therefore only a small portion of flight crews have this capability. Assuming that the helicopter is incapable of disabling tactics also places more emphasis on other OPV design characteristics such as the OPV sustained speed and small boat options.

We assume that OTH capable small boats have an imposed max range from the OPV of 55nm and that the OPV and small boats are capable of disabling go-fast vessels. Modern small boats are being designed with higher sustained speeds, longer range communications packages, and better safety and ergonomics to increase boat/crew endurance. A small boat with longer endurance ranges and long range communications that allows it to operate out of the OPV’s visual range is described as Over-The-Horizon capable and referred to as an OTH. However, these vessels typically still have a communications range limit and a commanding officer (CO) imposed range limit based on the CO’s comfort level. The CO range limit typically mirrors the communications limits, but may be adjusted by other considerations such as ocean and geographical conditions. One such consideration is operating on a vast shallow bank. If the small boat needs assistance, the deploying vessel may not be able to reach it. Our 55nm range limit may be beyond many COs comfort level, but the endurance range and communications capabilities of some OTHs could be well beyond this range so 55nm is used as a reasonable trade-off for simulation purposes.

The OPV and its small boats are considered to have disabling capabilities. This is a training requirement for cutter crews. For this simulation the assumption that the OPV and small boats have this training-based capability means that if the OPV and or small boat are capable of intercepting the go-fast based on course and speed then the interception task is considered complete or successful. This
assumption means that once the OPV or small boat intercepts the go-fast, the smuggling vessel is either compliant and voluntarily stops or the OPV/small boat conducts successful disabling fire. So interception equals a stopped go-fast 100% of the time.

A go-fast vessel is generated in the simulation model once for every 12 hour simulation event. The go-fast is generated based on a random uniform distribution between time zero and 10 hours. The remaining two hour window gives the simulated OPV the time to detect and attempt an intercept before the 12hr time limit expires. This assures that no simulation run results are based on expired time.

The one go-fast per 12 hour window tests the ability of the OPV to detect and intercept a smuggling vessel traveling through its assigned operational area. So the measure of effectiveness is probabilistic based on given opportunities. The simulation measures how often the mission objective-based measures are achieved. The measures are described later in the next section of the paper.

The threat vector in our simulation is limited to south to north, meaning all the go-fasts are generated at the very southern border of the geographical operational area traveling in a northerly direction because the drug producers are in the south and trying to smuggle their product to the US in the north. The go-fast course is generated by a random uniform distribution between 080 and 100 in the Cartesian coordinate system (true compass courses of 010T to 350T). The go-fast is assumed to maintain this course throughout the simulation. This assumption is based on the go-fast advantage of speed and the shortest distance to their goal being a straight line. Realistically the go-fasts may make some minor course changes but never typically anything extreme because their fuel is a limiting factor. The minor course changes result more often because the go-fast has to stop or slow down to reassess current position and course to destination. The dynamic movement of a go-fast vessel at high-speeds makes it difficult to read GPS screens or compasses to maintain a straight line track over long periods. If the go-fast has been unknowingly detected then slowing down or stopping to adjust course is an advantage for the Coast Guard. Even if they haven’t been detected the slowing down or stopping gives the Coast Guard more time to detect the go-fast. This simulation assumes they can and do maintain course and speed throughout or until intercepted. In most cases any evasive maneuvers by a go-fast after being detected just results in giving more Coast Guard assets time to get into position because their goal is understood. In these cases a straight line, high-speed assumption is to the go-fast advantage and is a reasonable assumption.

The go-fast is generated at the southern border of the area picture in Figure 7 with the initial x-position value being generated by a random uniform distribution between 20 and 80. The southern border of the area in Figure 7 is 100 nm long. The limitation of the x start position is to ensure the go-fast has to travel through some part of the operational area based on the random course generated. If the go-fast was generated at x-position 0 and the random course was any course west of true north then the go-fast would spend zero time in the operational area. The reciprocal is true of the eastern edge of the area.

Any suspicious vessel traffic detected by Coast Guard assets is referred to as a target of interest (TOI). The rest of this section refers to the go-fast threat as a TOI. TOI speed is based on a normal distribution with 45 as the mean and 5 as the standard deviation. The resulting slowest and highest speeds are approximately 27 knots and 64 knots respectively. This is based on personal experience that the vast majority of narcotics smuggling vessels are in the middle of a 40-50 knot range with occasional outliers for both slow and fast.

The final characteristic is the TOI RCS which is generated for each simulation run based on a random uniform distribution between 1m² and 16m². This RCS is used to calculate the range that the OPV radar
can detect the TOI. This RCS range is based on a study of X-band radar ability to detect small, fast moving vessels. The study was conducted in England and tested vessels ranging from small rigid-hull inflatable boats to larger military and fishing type craft comparable to larger center console fishing boats with multiple outboards that are often used as go-fast narcotics smuggling vessels. X-band radars are used on all Coast Guard cutters as their primary surface search radars [13].

TOI characteristics are summarized in Table 1. The final operational assumption is that if the TOI y-position reaches 150nm from the southern operational area border without being intercepted then the TOI is safe and the has OPV failed. This assumption is also made for the eastern border of the operational area because the Great Bahama Bank is to the east and the OPV would not be able to pursue. Although an OTH capable boat could possibly pursue to a certain point before exceeding communications or imposed ranges, for the purposes of this simulation this is a safe area for the TOI.

Realistically, additional force lay down to the north or even east by a patrol boat on the bank could be coordinated to intercept the TOI. The assumption that the TOI is safe in these areas applies reasonable constraints to the operating area to test the OPV’s ability to establish an intercept solution within that operating area. This stresses the intercept capability. The ability to detect the TOI is important because the overarching goal of the Coast Guard is to identify and interdict these vessels so the OPV could detect the TOI and track it long enough for other Coast Guard assets to get in place. The OpSit however is designed to just test the OPV and not the force lay down. The limit to the east is based on the Great Bahama Bank being an area the OPV could not reasonably operate in. The same safe limit is not established to the west because that area is navigable water until the Florida Keys. This allows the OPV some leeway in conducting the intercept in open water to the west.

<table>
<thead>
<tr>
<th>TOI Characteristic</th>
<th>Distribution</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>Normal</td>
<td>Mean 45knots, Std Dev 5 knots</td>
</tr>
<tr>
<td>Radar Cross Section</td>
<td>Uniform</td>
<td>1m² - 16m²</td>
</tr>
<tr>
<td>Course</td>
<td>Uniform</td>
<td>350T - 010T (80 - 100 deg)</td>
</tr>
</tbody>
</table>

2.3 Measures for DRUG OpSit Scenario

In the case of the DRUG OpSit the general mission objective with respect to a vessel at sea is to detect, identify, and interdict at sea, illegal narcotics attempting to be smuggled into the U.S. by conducting a vigilant search of the assigned operational area. The measures associated with the tasks to accomplish this objective must be identified. Naval Task 1.4.8.2 Conduct Maritime Counter Drug Operations and associated measures are directly related to this mission objective. This NMET’s measures are listed in Table 2. These measures must be analyzed to choose which measures to use for the OpSit MOE. Only those measures that are directly affected by ship design variables are considered.

M1 is an aggregate measure of the USCG and other agencies’ ability to conduct the counter narcotic mission, but not a good measure for the OPV design because the deployed vessel is only interested in the search, detection, and interception of smugglers. The crew and cutter immediately hand off responsibility of smuggling cases once the detection and interception are completed or failed. All investigation and measurable results are the responsibility of shore-based USCG investigators and partner agencies like the DEA and Customs.
M2 is a function of intercepting TOIs, but is dependent on the number of smugglers on the TOI crew and therefore is not a useful measure for ship design.

Table 2 - Measures for Conduct Maritime Counter Drug Operations NMET

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

M3 is a function of how much contraband intercepted vessels are carrying and therefore not a useful measure for OPV.

M4 is also not useful for OPV. Smuggling incidents depend on being in the right place at the right time and how often the smugglers decide to run.

M5 and M6 are basically the same measure but M5 is probabilistic. This measure is directly affected by the OPV’s ability to search its assigned area to detect and identify smuggling vessels. M5 is used as one of the OpSit measures.

M7 is a probabilistic measure based on the OPV’s ability to intercept smugglers given the number of opportunities. M7 is used as one of the OpSit measures.

M8 is not an appropriate measure because of the assumptions made in the OpSit simulation. In the simulation, TOIs either maintain course and speed to the end or they are intercepted. While a vessel may turn back because of the OPV’s ability to get into an intercept position, turning back is still a choice made by the TOI operator. In our OPV simulation, these vessels are just included in the number of vessels intercepted.

M9 is not a useful measure because the number of vessels seized would be 100% of the vessels intercepted.

M10 is directly related to how much area the OPV’s sensors can cover which is directly affected by OPV radar design variables (including radar height) and deployable sensors coverage like helicopters. The measure can be a time-weighted percentage of area covered during the 12hr simulations. It must be time-weighted because deployable sensors like helicopters are fuel or power limited and do not remain operational the entire time. M10 is used as one of the OpSit measures.

M11 and M12 both have aspects that are design dependent, but they are directly dependent on the tactical choices of the operators. These measures are much more useful in measuring the integration of
human abilities and system capabilities. This is more practical as a training measure than a design measure so they are not included in the OpSit MOE.

M13 is similar to M7 but does have an important difference. M13 is the percentage of TOIs intercepted based on the number of TOIs detected. This measures the rate at which the OPV can intercept the TOIs that it detects. M7 measures the percentage of TOIs intercepted based on total TOIs that enter the operational area whether the OPV knew they were there or not. This is an important distinction because being able to detect the TOI and being able to intercept the TOI are based on different ship design aspects. M13 and M7 are both useful measures to include in the OpSit MOE.

M14 is not a useful measure for the OpSit because 100% of the TOIs intercepted would be boarded so the result would be equal to M7 or M13 depending on how the total number of TOIs is defined.

The measures selected for the OpSit MOE are renumbered and listed in Table 3 with the equations for how the measures are calculated in the OpSit simulation.

### Table 3 - DRUG OpSit Measures

<table>
<thead>
<tr>
<th>Measure Number (Original)</th>
<th>Method</th>
<th>Description</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1 (M5)</td>
<td>Percent</td>
<td>Detection Rate</td>
<td>TOIs detected/total number of TOIs</td>
</tr>
<tr>
<td>M2 (M7)</td>
<td>Percent</td>
<td>Mission Success Rate</td>
<td>TOI interceptions/Total number of TOIs</td>
</tr>
<tr>
<td>M3 (M13)</td>
<td>Percent</td>
<td>Intercept Rate</td>
<td>TOI interceptions/number of detections</td>
</tr>
<tr>
<td>M4 (M10)</td>
<td>Percent</td>
<td>Surveillance area coverage</td>
<td>area covered/area assigned (time weighted)</td>
</tr>
</tbody>
</table>

### 2.4 Drug Interdiction (DRUG) OpSit FFBD (Center Branch) – OPV Navigation, Search and Process Targets

The center branch of the Drug Interdiction (DRUG) OpSit EFFBD in Figure 5 is enlarged in Figure 8, and models the OPV navigation, search and process target operation.

![Figure 8 - DRUG OpSit FFBD (Center Branch) - OPV Navigation, Search and Process Targets](image)

The OpArea assigned to the OPV within the Cay Sal Bank, Figure 7, is indicated in Figure 9 by the red box. The OPV vessel commander is responsible for TOIs in this OpArea and will employ tactics to exploit the area. This is a notional OpArea only. It is approximately 75nm wide and 60nm long for a total of 4500 nm². This is a large area to cover, but the navigable area is reduced significantly for the OPV by Cay Sal Bank. The search pattern to be employed is a bar pattern search north of the tip of the bank. The northern tip of the bank has some small rocky islands that would help obscure the OPV to TOI radar (if they have one) and block some light if the TOI has night vision. The bank also has small rocky islands all around the edges of the bank that smugglers typically like to skirt to be able to hide themselves. The bar pattern (short red line in Figure 9) is repeated at a speed of 10-15 knots and is positioned to be in the middle of TOIs running either extreme of the banks.
The OPV detection capability is based on the simplified radar equation in Equation (1) [24].

\[
r = \left\{ \frac{P_T G^2 \sigma \lambda}{(4\pi)^3 S} \right\}^{1/4}
\]  

Equation (1)

In this equation \( r \) is the detection range, \( P_T \) is the power transmitted by the radar, \( G \) is the radar Gain, \( S \) is the minimum detectable signal (MDS) for the radar, \( \lambda \) is the wavelength of the radar and \( \sigma \) is the radar cross section of the TOI. \( P_T, G, S \) and \( \lambda \) are determined by the radar selection. The RCS of the TOI is given in Table 1.

Figure 9 - OPV Op-Area and Search Patterns

A common surface search radar on U.S. Navy and Coast Guard vessels is the AN SPS-73. The AN SPS-73 \( P_T \) is 25,000kW on the X-Band which has a range of wavelengths of 2.5 - 4cm, 3cm is used. The gain and MDS are not available. A reasonable assumption for gain is 30-40db based on known radars and typical settings. MDS is calculated to be approximately 13kW using a known detection range and RCS for another vessel.

Due to refraction, radar waves are capable of reaching slightly beyond the visual horizon. To account for this an analytical approximation is commonly used called the four-thirds earth approximation. This approach assumes that the earth is four-thirds the size of its actual radius and that radar waves travel in a straight line. Equation (2) approximates the distance to the radar detection horizon based on the radar height on the ship [24]. Where \( r \) is the radius of the earth and \( h \) is the height of the radar.

\[
d \approx \sqrt{2rh}, \quad [r \gg h]
\]  

Equation (2)

Using Equation (2) with the radius of the earth in kilometers and radar and mast heights in meters gives Equation (3).

\[
d_{total} \approx 4.126(\sqrt{h_{OPV}} + \sqrt{h_{TOI}})
\]  

Equation (3)

The detection range of the OPV radar based on Equation (1) could still be over the radar horizon with a TOI RCS in the upper range given in Table 1. Both Equation (1) and Equation (3) are calculated simultaneously in the simulation and the minimum value is chosen.

Figure 10 shows the various components of the Drug OpSit simulation in ExtendSim. The upper left hand corner shows the various OPV navigation, search and process components. The block labeled ‘Initial OPV Status’ sets the initial course, speed, and position of the OPV. The navigation loop updates the current position based on course and speed every minute and includes a table of the OPV x and y-positions relative to the initial position based on the time and bar search pattern.
The updated OPV x and y-position are also sent to the red hierarchal block along with the current TOI position, and the distance between the two points is calculated. The distance to the TOI and the OPV detection range are used to determine if the distance to the TOI is less than or greater than the detection range. If the TOI is inside the OPV detection range the Ship Detect attribute is set to 1, otherwise it stays at 0. The Ship Detect along with the Helicopter Detect attributes are used to check detection and if the TOI is detected, the simulation sends the OPV to the Intercept Solution Loop, and records that the TOI was detected into the database to be used in the measure (M4) calculations.

In the TOI navigation loop, the TOI is generated by a random number from a uniform distribution between time 0 and time 10hrs. TOI attributes are provided by random number generators and include the TOI course, TOI x position, TOI speed, and the TOI RCS. The TOI enters the loop construct and waits one minute to allow for the position updates. The distance the TOI travels in one minute is calculated for both the x and y directions to get a dx and dy value. These values are entered into the TOI Position Update block to be used by the detection calculation blocks for both the OPV and helicopter. The next block is a decision block that sends the TOI out of the simulation if it has been intercepted or has exited the operational area and is considered safe and sends it back through the navigation loop if neither is true based on the TOI Path value. If the TOI is safe the result is recorded in the database.

### 2.5 Drug Interdiction (DRUG) OpSit FFBD – Helicopter Operations

The top branch of the Drug Interdiction (DRUG) OpSit FFBD is enlarged in Figure 11 and models the OPV helicopter operations. 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.

Figure 11 - DRUG OpSit FFBD (Upper Branch) - Helicopter Operations

Both of the current USCG helicopters (HH-60 and HH-65) use the same radar system. The available radar characteristics for these helicopters result in large detection ranges (30-60nm), and the radar horizon based on an altitude of 3000 feet results in horizons of hundreds of miles. After interviews with several current USCG helicopter pilots who have been involved in go-fast TOI searches it was determined that these numbers are unrealistic. The pilots claim that the radar does not work this well for small contacts unless the seas are absolutely flat and then detection ranges may be 10-12 nm. The radar system also has only a 120 degree view centered on the front of the helicopter. The pilots claim that the radar is mostly used for weather and air collision avoidance although they can pick up large vessels at around 100 nm and larger yachts, coastal freighters, and sports fishing vessels at 25-50 nm. The smaller go-fast type of craft is almost always detected visually first. Typically the pilots and crew can visually detect these kinds of vessels at approximately 10nm in calm seas. They primarily detect the white wake streak in the water before they see the boat. In Sea State 4 with a medium chop and whitecaps, the visual detection range drops to approximately 5-7 nm, 3-6nm at night. Based on this input, the helicopter detection range in the model is generated by a random number based on a normal distribution with a mean of 5 nm and standard deviation equal to 1 nm.

The helicopter type in our model is assumed to be the HH-65 because it is a smaller short range helicopter designed for smaller Coast Guard vessels like the OPV. The HH-65 conducts its search based on the orange pattern shown in Figure 9. The HH-65 is assumed to maintain a speed of 130 knots to complete the pattern in approximately 1hr 45 minutes. This speed is slightly above designed cruising speed, but the pilots state that they average about 130 knots when on search patterns. The 1hr 45mins is based on the average HH-65 flight with considerations for fuel. If there is one helicopter the pattern is repeated 3 times during the 12 hour simulation with a 2hr stand down time between flights. These are both based on experience when the operational tempo is not being influenced by intelligence reports of specific smuggling events. In the case of directed intelligence the flight crew would likely fly more often and with less stand-down time. Our scenario assumes a standard operational tempo.

The Helicopter Navigation Loop simulation shown in Figure 10 starts with the helicopter generator which uses an internal schedule to generate the helicopter flights at the designated times. Once the helicopter flight is generated the first block immediately assigns the detection attribute to the helicopter. If the TOI is detected before the final two helicopter flights they are also routed through the first decision block to the early exit block. The helicopter position is also updated in one minute intervals. The
helicopter position is based on a table look up like the OPV because its search pattern is a constant. The calculation time is also used to check how long the helicopter has been in the air and when the time check variable reaches 106 minutes the helicopter is exited via a recover helicopter exit block. Otherwise the helicopter continues the loop.

The next helicopter block inputs the distance to the TOI from the helicopter. This block also inputs the helicopter detection range generated by a random number generator block using a normal distribution. This block checks the difference and if the TOI is within detection range it sets the helicopter detect attribute to 1 to indicate to the OPV to start the intercept loop. If the helicopter detects the TOI the HeloDetect decision block routes the helicopter to the HeloDetect exit block so it can be recorded in the database. Otherwise the helicopter continues through the loop. The next block checks to see if the OPV detected the TOI and if it has, routes the helicopter to the Helo-Recovered exit. Otherwise the helicopter continues the loop. Additional considerations to be added to this simulation include launch and recovery events that are dependent on the sea state and the OPV seakeeping characteristics.

2.6 Drug Interdiction (DRUG) OpSit FFBD Lower Branch – Intercept and Boarding

The maneuvering/intercept/boarding branch of the OpSit, enlarged in Figure 12, 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 the 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 requests 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. The Transport Personnel activity refers to transporting the Boarding Team to the TOI. If the intercept is possible either the OPV itself or the OTH small boat conducts this intercept and transport. 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 disabling and take-down. 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.

Figure 12 - DRUG OpSit FFBD (Lower Branch) - TOI Intercept and Boarding
Once the OPV or helicopter detects the TOI in the simulation the OPV will increase to maximum sustained speed and attempt to intercept the TOI. Intercept implies a zero distance to the TOI, but depending on its small boat capabilities the OPV may not have to close the entire distance. This logic will be a function of the OPV small boat selection in the ship synthesis model.

Calculations of the intercept solution, illustrated in Figure 13, are based on the U.S. Navy maneuvering board method of solving for intercepts. This method uses a compass-based plot to simultaneously use vectors and relative motion plots to solve for a variety of maneuvering solutions. This process is done in the Cartesian coordinate system based on a reference frame with the OPV always at the origin.

A capable OTH allows the OPV to launch its boat from relatively far away and the OTH to conduct the intercept. The OPV must be able to approach within a minimum range before it is safe to launch the boat. So instead of solving for an intercept solution we solve for a maximum closest point of approach (CPA) to launch the small boat to finish the intercept. This CPA range is a function of the small boat capabilities (speed and range) and some logical assumptions.

Figure 10, Intercept Loop Solution, begins when the OPV commences the intercept loop if the TOI is detected by either the OPV or helicopter. This first equation block is important because it controls all the calculations for the intercept solution. This block inputs all the variable values needed to calculate the intercept. The next equation blocks output the OPV maximum speed and the calculated intercept course. These are used to calculate the change in the x and y-position for every minute just as was done for the TOI. The resulting dx and dy values are used to update the OPV x and y-position attributes and to calculate the current distance to the TOI which is checked versus the required intercept CPA distance. If the TOI is inside the intercept CPA distance the intercept is assumed to be complete. In the cases where there is no possible solution for a successful intercept based on the OPV max speed vector being unable to reach the relative motion line, the simulation will stop and the OPV will never intercept the TOI.

Figure 14 shows the interface designed for the DRUG OpSit model with all inputs required to run the model collected in a single notebook window.
2.7 OEM Demonstration

To demonstrate the DRUG OpSit functionality, four simulation cases were run. Table 4 lists the inputs entered for each case. Each case was run 1000 times in the simulation model and data was collected into a spreadsheet that calculated the measures in Table 3.

Table 4 - Ship Design based Variables for the OpSit Simulation for each Run

<table>
<thead>
<tr>
<th>Model Input</th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPV $V_s$ (kts)</td>
<td>28</td>
<td>32</td>
<td>22</td>
<td>28</td>
</tr>
<tr>
<td>Bridge Height (m)</td>
<td>11.1</td>
<td>10</td>
<td>12</td>
<td>11.1</td>
</tr>
<tr>
<td>Radar Height (m)</td>
<td>20</td>
<td>15</td>
<td>22</td>
<td>20</td>
</tr>
<tr>
<td>OTH Capable (1=Yes, 0=No)</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Small Boat Endurance @ Vs (hr)</td>
<td>9.2</td>
<td>2</td>
<td>5</td>
<td>9.2</td>
</tr>
<tr>
<td>Small Boat $V_s$ (kts)</td>
<td>45</td>
<td>35</td>
<td>38</td>
<td>45</td>
</tr>
<tr>
<td>Radar Power Transmitted (kW)</td>
<td>25000</td>
<td>30000</td>
<td>25000</td>
<td>25000</td>
</tr>
<tr>
<td>Gain (dB)</td>
<td>31</td>
<td>40</td>
<td>31</td>
<td>31</td>
</tr>
<tr>
<td>Wavelength (cm)</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Assumed TOI Height (m)</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Helicopter Capable (1=Yes, 0=No)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Number of Helicopters</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

The results for each case are shown in Table 5. Case 2 indicates that radar height has a noticeable impact on detection, but Case 4 indicates that a design with no helicopter has the most significant impact on detection. Even with its limited detection range, the speed and search range of the helicopter covers a large area and greatly increases detection probability.

Table 5 - Simulation Case Results

<table>
<thead>
<tr>
<th>OPV Characteristics</th>
<th>Detection Rate M1</th>
<th>Mission Success Rate M2</th>
<th>Intercept Rate M3</th>
<th>Area Coverage M4</th>
<th>Result Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Helo and OTH</td>
<td>0.736</td>
<td>0.629</td>
<td>0.855</td>
<td>0.065</td>
<td>Best overall</td>
</tr>
<tr>
<td>2. Helo, no OTH, low radar height</td>
<td>0.709</td>
<td>0.124</td>
<td>0.175</td>
<td>0.058</td>
<td>Worst overall</td>
</tr>
<tr>
<td>3. Helo and min OTH</td>
<td>0.759</td>
<td>0.249</td>
<td>0.328</td>
<td>0.067</td>
<td>Low success and intercept</td>
</tr>
<tr>
<td>4. OTH and no Helo</td>
<td>0.429</td>
<td>0.393</td>
<td>0.916</td>
<td>0.064</td>
<td>Low detection, high intercept</td>
</tr>
</tbody>
</table>
The Mission Success rate given by M2 shows the impact of small boat capabilities on the ability to intercept high speed TOIs. Case 2 has no OTH capabilities while Case 3 has OTH capability, but with a limited top speed and endurance time. Even though Case 4 was without a helicopter, which severely limited its detection capability, its Intercept Rate per TOI detected was the highest with its capable OTH.

This limited data set shows that an OpSit simulation can provide rational measures of design effectiveness. Similar results may be produced using the current OMOE method and expert opinion-based calculations, but using an OEM removes possible bias as long as the OpSit is developed through a logical, rational, and traceable method like the OPV ship design architecture.

Several assumptions made for building the DRUG OpSit model as described in this section could be removed in a more complex simulation model. The assumption that the TOI maintains its course and speed also means that the interactions between the OPV, OTH and helicopter do not have to be modeled. If the helicopter has to return for fuel before the interception is complete, the information on the TOI course and speed cannot be updated to ensure an intercept. This greatly decreases the probabilities of over the horizon intercepts if the OPV itself does not have radar contact. This change would also put more stress on the helicopter characteristics. The model could then also allow choices for larger helicopters with longer endurance such as the HH-60.

Running the model over longer time period to include transit distance and time to the closest supply point would be useful in placing some stress on the endurance capabilities of the OPV. This can be further stressed by adding occasional suspect TOIs that may still require interception to determine whether or not they are actual smugglers. This burns more fuel and stresses the OPV endurance more in the OpSit and is a routine occurrence for vessels involved in these missions.

The USCG is stressing increased C4ISR capabilities for their new cutters to be able to interact with DOD forces and share a common operating picture. The ability to share current data over communication links with more capable DOD surveillance assets increases the OPV’s ability to intercept TOIs because the DOD assets can detect and track TOIs at greater distances. These capabilities can be modeled in the simulation by including Navy or Air Force surveillance flights that can update the entire operational surface picture for the OPV.

3. OVERALL EFFECTIVENESS MODEL (OMOE)

After OpSit OEMs for each mission area have been simulated, the resulting measures must be combined into a single MOE value per OpSit. Giving each measure an equal weight is not a rational method because the measures could have different levels of importance to the mission. Above this, mission MOEs must be combined into a single OMOE, again with individual mission areas having different importance to the overall OPV mission. The USCG, for example, distinguishes SAR as its most important mission, and will call off other missions as necessary to save life and property, even though OPV would have limited time conducting SAR over its life cycle. A possible solution to the weighing of measures is to use AHP [17] and expert opinion as in our current method to determine appropriate measure and mission weights. A possible OEM-based OMOE hierarchy for the OPV (with Defense Readiness not expanded for readability purposes) is shown in Figure 15, created using the system architecture in CORE. Measures for each mission area would be calculated using OEMs, but above this expert opinion based weight would be used.
4. OBSERVATIONS AND CONCLUSIONS

Our research objectives are to build and assess OEMs in the context of a DoDAF total-ship system architecture, to determine the influence of OEM scope and complexity on OEM results, and to compare this method for determining effectiveness to the expert opinion-based method currently used in our ship design process. OEMs provide rational measures of effectiveness (MOEs) based on realistic operational situations. The basis of these OEMs, as developed in our architecture, is the DRM. By defining a DRM for a given ship design, the foundation is laid for using OEMs in the effectiveness model. If a total-ship architecture approach is adopted as a standard requirement for the ship design process, then OEMs become a natural choice to measure effectiveness.

The DoDAF architecture provides an ideal method for developing a 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 is time consuming and only one OpSit OEM model was completely developed for this paper. This OEM development shows how the DRM can successfully be used to build a rational and viable scenario and produce rational measures of effectiveness.

More research is required to understand the impact of OpSit scope and complexity on the MOE results. The combination of multiple OpSit measures into mission MOEs, and multiple mission area MOEs into a single OMOE will likely require expert opinion to determine weights and complete an OEM-based OMOE function. 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 and before the impact of OpSit scope and complexity can be determined. This is our future work.

5. REFERENCES

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