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SYSTEMS ENGINEERING CAPSTONE REPORT

**MODELING AND SIMULATION TO IDENTIFY
OFFENSIVE DENIAL MINING KEY PERFORMANCE
DRIVERS AND BEHAVIORAL RESPONSES**

by

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June 2021

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MINING KEY PERFORMANCE DRIVERS AND BEHAVIORAL RESPONSES**

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ABSTRACT

The United States Navy has kept only a few varieties of maritime mines in its inventory for the last several decades and has let its mining tactical doctrine stagnate in order to prioritize its mine countermeasure capabilities. This thesis looks at mine warfare (MIW) through a modern lens using modeling and simulation (M&S) to capture a broader set of factors around the mining operational environment beyond mine performance characteristics and employment parameters to also include probabilistic enemy responses measured against updated mission success criteria. This thesis explores three generic and unclassified experiment scenarios to draw broad conclusions about the factors that most affect mining success and lays the groundwork for future exercises to explore specific mining use cases to inform the next generation of mines and their employment. Analysis indicates that air delivery strategies generally outperform surface, submarine, or UUV delivery with regard to affecting enemy behavioral outcomes. Note that the UUV delivery is associated with a lower overall quantity of mines, the impact of which can be mitigated through UUV movement speed and individual mine probability of detection and engagement.

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LIST OF ACRONYMS AND ABBREVIATIONS

AoR	area of responsibility
ASW	anti-submarine warfare
bCM	bEastcoast Miners (capstone team name)
CNO	Chief of Naval Operations
CONOPS	concept of operations
DOE	design of experiments
BLU	bomb live unit (vs. BDU, bomb dummy unit)
GICHD	Geneva International Centre for Humanitarian Demining
GP	general purpose
GUI	graphical user interface
IPR	interim progress review
JCS	Joint Chiefs of Staff
JDAM	joint direct attack munition
JP	joint publication
lat/long	latitude and longitude
LCS	littoral combat ship
LITMUS	LCS integrated toolkit for mission engineering using simulation
LMW	littoral and mine warfare
M&S	modeling and simulation
MAST	Modeling and Simulation Toolbox
MBSE	model-based systems engineering
MCM	mine countermeasure
MIW	mine warfare
MK	mark (type)
MOE	measure of effectiveness
MOP	measure of performance
NAVAIR	Naval Air Systems Command
nm	nautical miles

NPS	Naval Postgraduate School
NSWCDD	Naval Surface Warfare Center Dahlgren Division
ODM	offensive denial mining
OSM	Orchestrated Simulation through Modeling
PEO	program executive office(r)
QS-ER	Quickstrike extended range (mine)
SE	systems engineering
sec	second(s)
SCG	security classification guide
SLMM	submarine launched mobile mine
SME	subject matter expert
SoS	systems of systems
SW	software
UUV	unmanned underwater vehicle
V&V	verification and validation
VBA	Visual Basics for Applications
WP	waypoint
XLUUV	extra-large unmanned underwater vehicle

EXECUTIVE SUMMARY

There are numerous historical examples that demonstrate the value of maritime mining and victory achieved through mine warfare (MIW). The lethal efficacy of naval mines is illustrated in the U.S. Navy's significant investment in its mine countermeasure (MCM) community. However, current expenditures for offensive mining capabilities is dwarfed by investments in these defensive efforts. Offensive mining doctrine, proficiency, and employment has stagnated, regressed, or even been ignored until a conflict is imminent or already begun. Recently, there has been a rejuvenated interest in exploiting the cost effective and force multiplying characteristics of mines. The U.S. Navy is refocusing its mission priorities to include these potential benefits, especially as it relates to advancements in unmanned underwater vehicle (UUV) capabilities, detection sensor technologies, and practical viability of autonomy, semi-autonomy, and programmability of future mines.

This project sought a better understanding of the key performance drivers that can be leveraged within different operational mine warfare frameworks to maximize minefield effectiveness. A new offensive mining mindset, called offensive denial mining (ODM), was defined based on traditional offensive mining measures of effectiveness (MOE) and adding four mission centric MOEs of turn, block, fix, and disrupt defined in Edwards (2019). ODM can integrate with modern warfare kill chains, providing strategic deterrence of unwanted maritime traffic, and in doing so also passively free up critical naval resources that would otherwise be supporting strategic objectives. This project was focused on defining, modeling, and analyzing ODM using a probabilistic behavioral simulation to compare minefield effectiveness under these updated MOEs.

The Naval Surface Warfare Center, Dahlgren Division has been developing the Orchestrated Simulation through Modeling (OSM) framework over the past decade. The current iteration of the JAVA GUI software that leverages the OSM framework is called MAST, short for modeling and simulation toolkit, and was created specifically for this type of operational research and mission engineering analysis of naval systems. The team developed three experimental scenarios defined to explore the relationships between ODM

considerations on an unclassified level. These scenarios were designated air, vessel, and UUV delivery, respectively, in which blue were friendly forces and red were hostile forces. To facilitate comparison and approximate the operational considerations associated with these alternatives, each scenario was generally characterized by the speed of the delivery platform, mine deployment capacity, number of drop sites utilized, and relative capability of the deployed mines. The air delivery experiment is a high speed, medium capacity vehicle deploying at a single site with less capable mines. The vessel delivery experiment is a medium speed, high capacity vehicle deploying at multiple sites with an average mine. And the UUV delivery experiment models a slow speed, low capacity vehicle that is able to employ highly capable mines, as shown in Table 1.

Table 1. Baseline Experiment Scenario Assumptions

Blue Parameters	Speed	Capacity	Drop Sites	Mine Capability
Air	High	Med	1	Low
Vessel	Med	High	2	Med
UUV	Low	Low	2	High

All simulation excursions utilized minefield drop sites randomly assigned within a 50 x 50 nautical mile minefield region with an objective of influencing two red vessels transiting from set starting positions east of the deployment area to a desired waypoint to the west, as seen in Figure 1. Red vessel logic implemented probabilistic behavioral decisions to simulate enemy responses to mines it detected, either changing its course, fixing in place, or continuing on its path, and communicating the danger with a “flee” message.

Five MOEs were developed to assess operational importance. The primary MOE, termed Red Impact, captured the ability of the minefield to impact a red vessel’s transit to its intended waypoint. If neither of the Red vessels decided to turn or fix, Red Impact was zero for that excursion. If both red vessels were inhibited, Red Impact was two; and Red Impact was 1 if only one of the vessels was affected. Agent death was designated a

secondary MOE and used to capture legacy mindset MOEs, and last mine deployed was designated a secondary MOE to better inform a decision point across experiments. The MOE table is shown in Table 2.

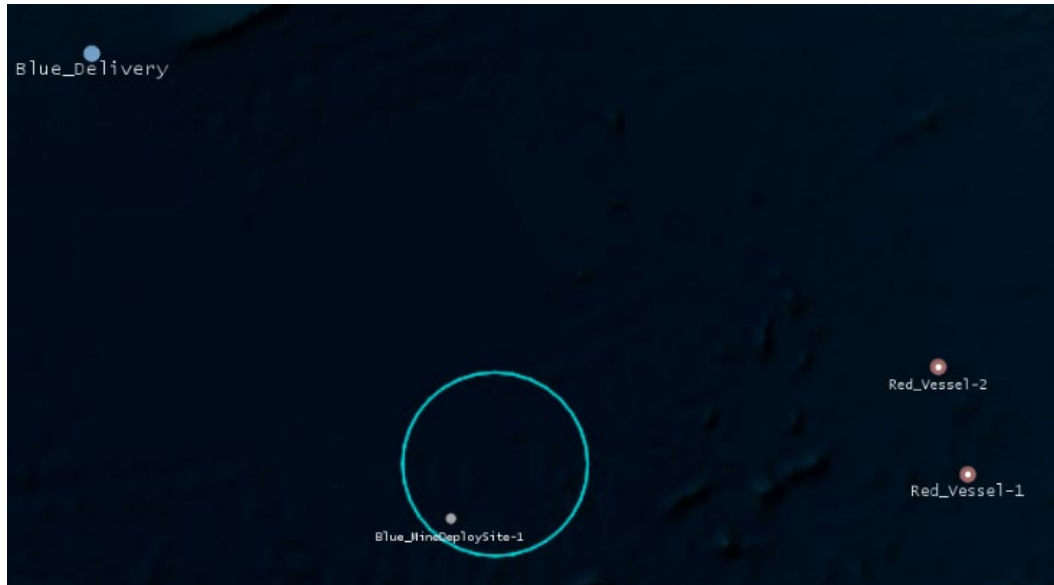


Figure 1. ODM Excursion Scenarios (MAST)

Table 2. ODM MOEs

MOE	Alternate Nomenclature	min	max	units	category
red impact	number impacted	0	2	vessels	Primary MOE
last mine deployed	time to deploy	0	∞	seconds	Secondary MOE
agent death	number red vessels kill	0	2	vessels	Secondary MOE
agent hit	-	0	total mines	hit	derived MOE
total mines	number deployed	0	as defined	mines	derived MOE

Input variables were defined to examine the impact of changes to blue force operations, blue force system design characteristics, and red force behavioral logic. 21 variables were defined for the air experiment and 25 variables were defined for the vessel and UUV experiments. A nearly orthogonal Latin hypercube design of experiments (DOE) was run across all three scenarios. The 21 variables identified for the air experiment resulted in 128 unique excursion runs, and the 25 variables identified for vessel and UUV resulted in 256 excursions each. These DOEs were then replicated utilizing the Hamming

super computer in collaborations with the NPS SEED Center to generate 3,780 excursions for air and 5,000 excursions for both vessel and UUV for analysis. The team found that variables associated with the probabilistic decision logic for the red vessels were generally more influential than those with physical values like velocity, range, or quantity of mines. This was true of the primary MOE of Red Impact across all three scenarios.

To reduce the relative importance of red behavior in the model, a refined analysis was conducted to specifically focus on the blue configuration characteristics that had the largest impact on operational effectiveness. The results for the primary MOE (Red Impact), legacy MOE (agent death), and secondary MOE (time to deploy) are shown in Figure 2. Although all three experiments seem to indicate similar primary MOE results, the outcome differences are statistically significant in the model. The air delivery is most effective in terms of Red Impact and is considerably faster to deploy than either vessel or UUV delivery. This is particularly important because under a legacy mindset focused exclusively on red agent death, the air delivery single site seeding would have been classified least effective. Likewise, the slow but capable UUV mine delivery would have fared only marginally more effective using agent death, but has the second highest rating just under air using the ODM Red Impact MOE.

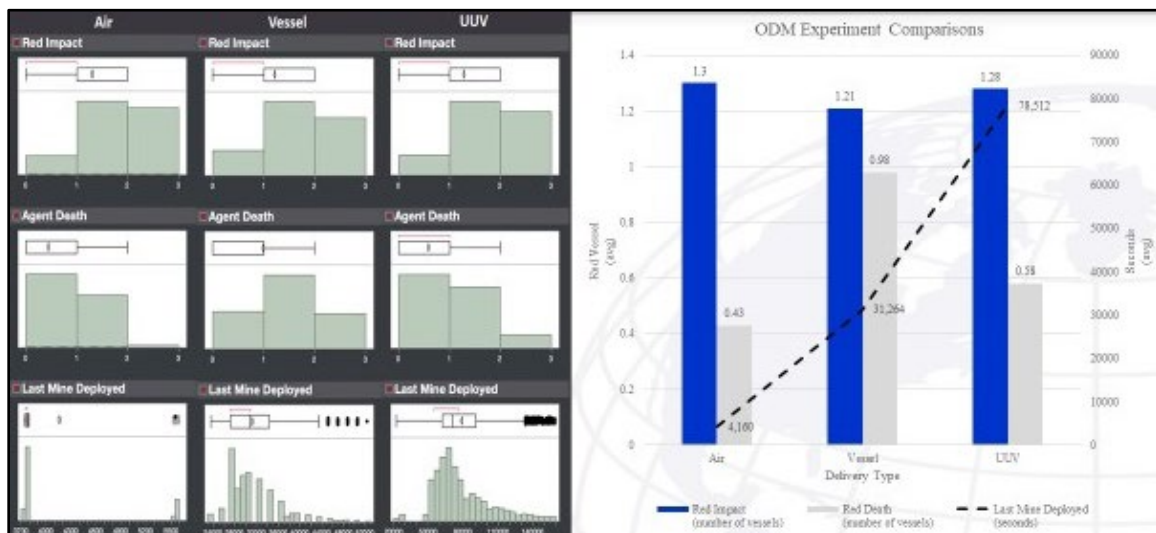


Figure 2. ODM Scenario Results

The model provides a starting point for operational analysis of ODM. While the systems modeled in the simulation were intentionally generic to avoid classification, the model is designed to allow for rapid introduction of specific system data. Future work could more fully implement mission objective (Edwards 2019) MOEs or increase the complexities of red force decision logic. However, even at this higher level and early maturation stage, the implications of applying ODM concepts in this project can be applied to focus development and acquisition efforts and better inform employment strategies of the future battlespace.

References

Edwards, Joshua. 2019. "Preparing Today for the Mines of Tomorrow." *Naval War College Review*. Accessed October 7, 2020. <https://digital-commons.usnwc.edu/nwc-review/vol72/iss3/5>.

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To our families, we give everything, including this.

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I. INTRODUCTION

A. BACKGROUND

There are numerous historical examples that demonstrate the value of maritime mining and victory achieved through mine warfare (MIW). The lethal efficacy of naval mines is illustrated in the U.S. Navy's significant investment in its mine countermeasure (MCM) community. However, investment in defensive efforts dwarfs current expenditures in future offensive mining capabilities or what the National Research Council terms Offensive Denial Mining (ODM) (2000). Historically, Offensive Mining doctrine, proficiency, and employment has stagnated, regressed, or even been ignored until a conflict is imminent or already begun.

Recently, there has been a rejuvenated interest in exploiting the cost effective and force multiplying characteristics of mines. The U.S. Navy is refocusing its mission priorities to include these potential benefits, especially as it relates to advancements in unmanned underwater vehicle (UUV) capabilities, detection sensor technologies, and practical viability of autonomy, semi-autonomy, and programmability of future mines. ODM is a natural choice to contribute to the Chief of Naval Operations (CNO) project *Overmatch* challenge to "support the operational ... environment that will enable our sustained maritime dominance" by "delivering synchronized lethal and non-lethal effects" (2020). The tenets necessary to achieve the CNO's goal to build a Naval Operational Architecture of the Future Force are to be built by "an integrated any-sensor/any-shooter kill chain" as defined in his October 2020 *A Novel Force* memorandum. ODM is capable of enhancing this goal by actively participating in those kill chains, providing strategic deterrence of unwanted maritime traffic, and in doing so also passively freeing up critical naval resources that would otherwise be supporting those strategic objectives.

B. PROJECT OBJECTIVES

Offensive mining in general and ODM specifically are domains that could provide an asymmetric strategic advantage but have been under-studied, and therefore, under-exploited. This presents an opportunity. Current ODM doctrine and tactics need to be

analyzed through modern measures of effectiveness (MOE) to quantify both the protective (blue water) and offensive (within twelve miles of hostile coastline) potential mining environments and identify any shortfalls (Edwards 2019). Expanding on previous studies that have “focused on isolated examination of minefield deployment and characteristics, this research ... examine[s] alternative unmanned and manned systems of systems capable of deploying and supporting minefields as an integrated part of joint offensive operations ... [by] consider[ing] multiple candidate operating areas and alternative delivery platforms” (Beery 2020). Specific tasking given to the team to explore are:

1. Define a candidate offensive mine warfare concept of operations (CONOPS)
2. Define a systems architecture of operational activities and related systems that can be examined to determine their impact on minefield deployment effectiveness
3. Develop and analyze an operational simulation in order to:
 - a. Identify key performance drivers
 - b. Inform comparison of operational frameworks(Beery 2020)

C. PROCESS

To accomplish these broad project objectives, the team developed a project waterfall methodology to define major gates and milestones, as shown in Figure 1, starting with a literature review to get familiarized with MIW, its subordinate elements, and related subject matter. Current MIW analysts, operators, and experts were identified who helped frame the bounds of the review and shed light on some of the history surrounding it. The team collaborated with advisors to identify applicable resources and additional experts in the field of MIW. The inputs from the project sponsor and advisor corps were leveraged to inform group planning and contribute professional expertise to ensure that team’s output provided value to the Navy. The initial literature review discovered materials covering MIW CONOPS and technical reports analyzing MIW operations, but it failed to produce a generally available practical guide to ODM. To fill the gap in the existing literature, the project efforts were focused on developing an operational simulation, which could be utilized to identify key performance drivers and ultimately make recommendations on how to maximize minefield deployment effectiveness.

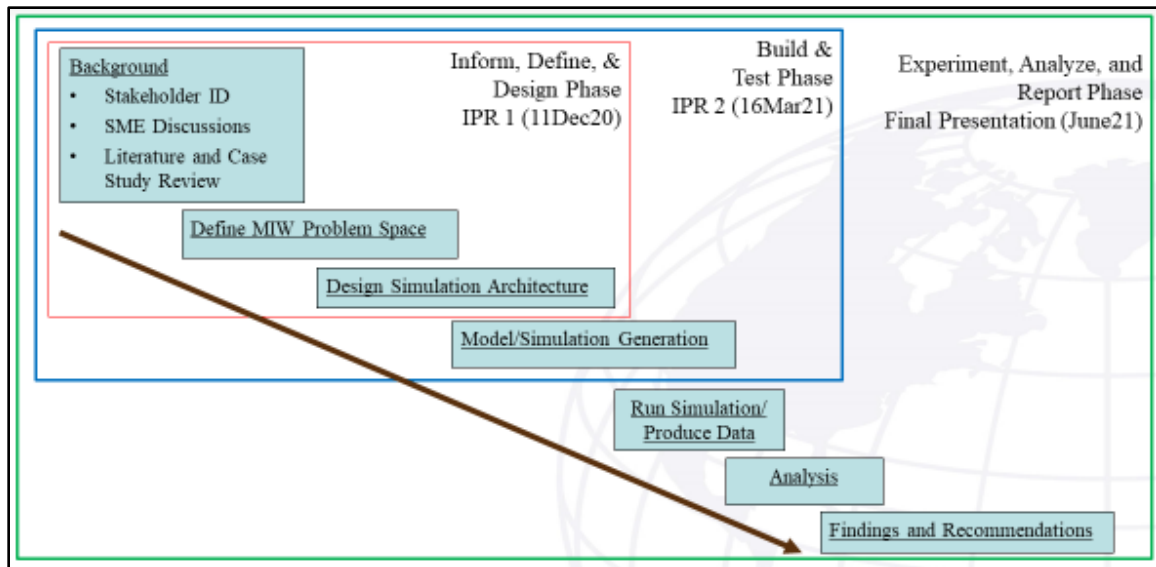


Figure 1. bCM Thesis Project Methodology

To develop the operational simulation model to be used, the team followed the top-down systems engineering (SE) approach captured in the modified Software Engineering Vee seen in Figure 2. By decomposing the generalized high level MIW CONOPS into their component system requirements, the team designed a simulation model which produced data mapped to those requirements as seen on the left-hand side of the modified Vee approach. The model output data was collected and analyzed, verifying its appropriate mapping back to system design requirements, and recommendations validated to satisfy the comparison of operational frameworks.

Additionally, on a quarterly basis the team presented status to community stakeholders and interested NPS faculty to solicit additional input from all interested parties as well as provide the opportunity for a collaborative forum. Ultimate findings and recommendations were formally published in this report and presented in a progress review prior to graduation.

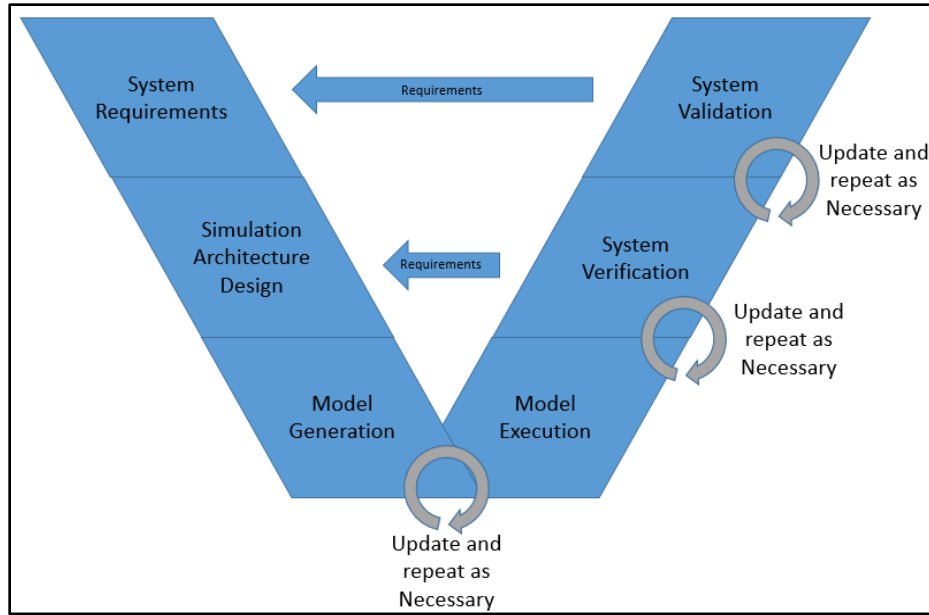


Figure 2. bCM Modified Vee Approach. Adapted from Buede (2009).

D. TEAM ORGANIZATION

The team members were assigned responsibilities to ensure an equitable division of labor and adequate consideration of both technical proficiency and administrative logistics. Though all team members were active contributors during each phase and helped ensure SE principles were followed through each step, the designated lead reserved a tie-breaking vote with respect to their topic domain execution.

- Lead Programmer and Software Developer. Responsible for the model design architecture, simulation development, and liaison with software (SW) developers and SW program subject matter experts (SMEs) external to the team.
- Maritime Environmental Expert and UUV Community Liaison. Responsible for the identification and incorporation of environmental variables and considerations into the model validated by UUV community contacts and personal experience in UUV testing.

- Fleet Liaison and Security Manager. Responsible for interacting with U.S. Navy operators and community managers to ensure adequate incorporation of CONOPS and technical specifications at the appropriate classification level are applied throughout the model development, data production, and analysis reporting.
- Lead Editor and Data Analyst. Responsible for the final review, formatting, and submittal of all team deliverables. Holds the final determination on report formatting and content inclusion decisions.

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II. LITERATURE REVIEW

A. REVIEW OF PRIOR WORK METHODOLOGY

The team conducted a review of existing MIW literature and historical naval mining case studies to inform the ODM mission set. As offered by the sponsor initially and confirmed within this review of work, MIW needs an updated paradigm that incorporates the novel application of both manned and unmanned systems. The team started with historical MIW documents and expanded into MIW employment-alternative discussions; they then expanded into doctrine manuals, tactical scenario articles, and technical reports, and finished with an overall SE review to support the administrative logistics necessary in executing the capstone project. The team recognized very early in the process that efforts and deliverables could have been shifted to restricted or classified realms. The team was deliberate in following the MIW Security Classification Guide (SCG) to ensure that the data, information, reports and analysis contained in this project were intentionally constrained to unclassified sources to allow for the widest distribution practicable.

After obtaining a basic understanding of naval mines, warfare strategies, objectives, and technology, the team began to develop questions and realize the scope of the problem space being explored in this project for the Navy. The Navy has been pushing to modernize and reinvest in offensive mining by taking advantage of the low-cost characteristics of mines and associated technologies for warfare commanders to affect enemy combatants. This explicitly includes a push to include the submarine community in the future of offensive mine development but starts with an understanding of the current doctrine, inventory, and development efforts.

B. OFFENSIVE MINING SYNOPSIS

Naval MIW is divided into two efforts, MCM whose goal is to eliminate naval mines and mining which is focused on the placement of the mines themselves. This traditional hierarchy further breaks down mining operations into either offensive, defensive, or protective mining, with the main difference being how close they are to friendly or enemy waters (Joint Chiefs of Staff [JCS] 2011). Figure 3 illustrates this

hierarchy from the Joint Publication (JP) 3-15 but is shown here in modified form with Offensive Mining highlighted. Those specific definitions are:

- Offensive – laid in enemy territorial water or waters under enemy control
- Defensive – laid in international waters or international straits with the declared intention of controlling shipping in defense of sea communications
- Protective – laid in friendly territorial waters to protect ports, harbors, anchorages, coasts and coastal routes (JCS 2011)

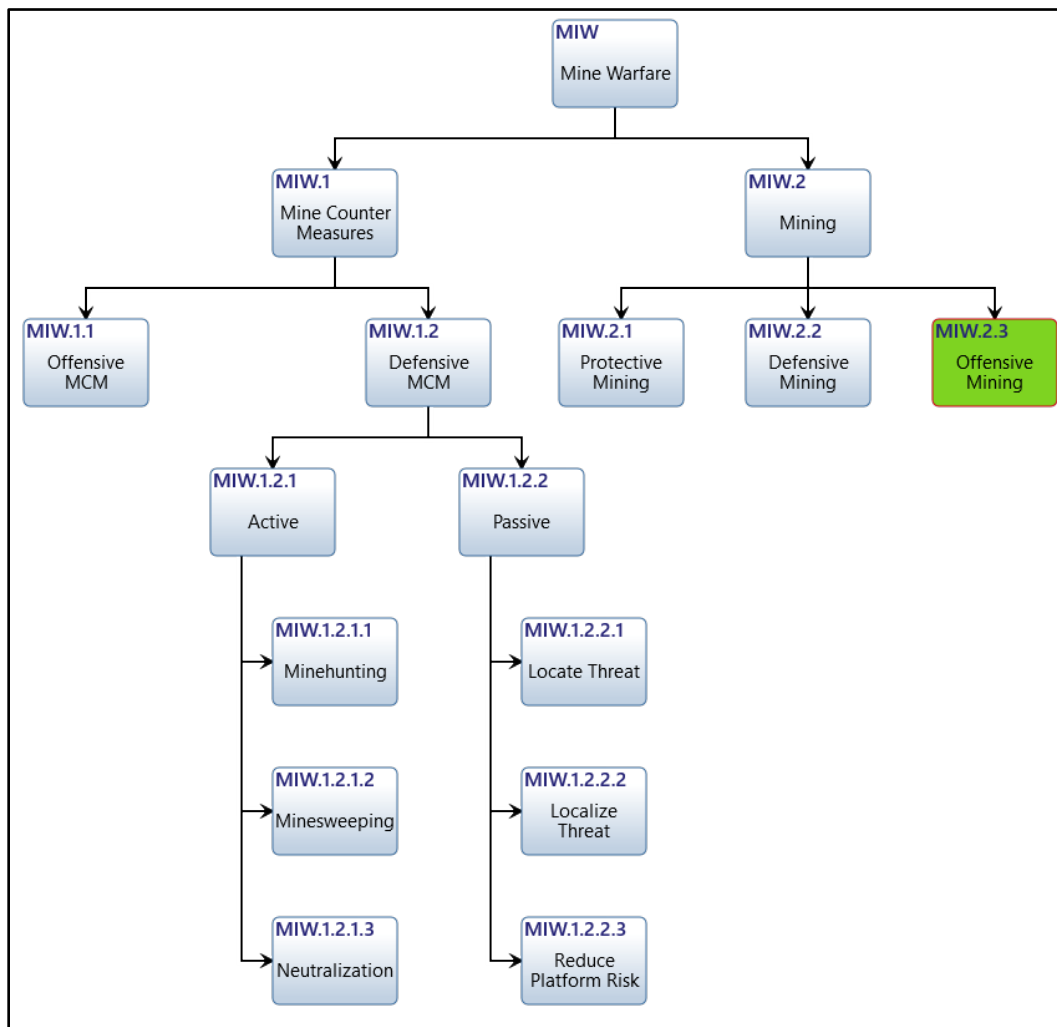


Figure 3. Elements of Mine Warfare. Adapted from JCS (2011).

Offensive mining can be used to limit enemy economic and war sustainment efforts, as well as make it more difficult maneuver or achieve strategic objectives (JCS 2011). The offensive mining operational concept is further illustrated in Traditional Offensive Mining Operational Concept Diagram presented as Figure 4. Major components identified in the Operational Concept Diagram are friendly surface vehicles, submarines, UUVs and air vehicles which can all deploy mines. Additionally, enemy combatants, neutral shipping, and biologic traffic are real life considerations. Finally, there are a variety of mines, including potentially “smart mines” in development, which may utilize established or future communication networks (Edwards 2019).



Figure 4. Offensive Mining Operational Concept Diagram

The deployment vehicles used for mining can be aircraft, surface ships, or subsurface vessels like submarines or UUVs. All the vehicles can be used for offensive mining, although each one presents unique advantages and disadvantages. For example, aircraft are able to penetrate and deploy minefields in locations potentially inaccessible by ships or submarines; however, mine placement accuracy is traditionally lower than when using surface ships (JCS 2011).

Figure 4 presents a graphical representation of multiple types of mines, which are characterized by their final position in the water. Those position categories are defined by the JP 3-15 (2011) as:

- Bottom Mines – non-buoyant weapons held in place by its own weight
- Moored Mines – held in place above a seabed by a cable or chain attached to an anchor
- Moving Mines – mines that move based on external factors
 - Drifting Mines – buoyant or neutrally buoyant mine that is free to move based on external factors
 - Oscillating Mines – hydrostatically controlled mine which oscillates at or near a preset water depth

Examples of actual applications of mining are discussed in Appendix A. The examples emphasized how successful minefields are defined by both ships destroyed, as well as the additional difficulty to operate in the area of minefields. Furthermore, the examples illustrate the importance of deploying a variety of mines in each minefield.

C. U.S. OFFENSIVE MINING INVENTORY AND DELIVERY SYSTEMS

Of the three general types of naval mines—bottom, moored, and moving—the U.S. military inventory is best described when sorted by delivery method, either by aircraft or by ships. Although mine laying can be done by surface vessels, the U.S. inventories currently only allow for subsurface deployment, and so the latter category is labeled “clandestinely” delivered mines, as seen in Figure 5.

1. Quickstrike Mines

The Quickstrike family of mines are bottom type naval mines called the Mark (MK) 62, MK 63, and MK 65 as shown in the top right quadrant of Figure 5. These unguided, free-fall mines are built upon the general purpose (GP) iron bombs of various yields, specifically the 500 pound BLU-111/MK 82, the 1,000 pound BLU-110/MK 83, and the 2,000 pound BLU-117/MK 84 bombs, respectively (Naval Air Systems Command [NAVAIR] n.d.). GP bombs are “dumb” or free-fall munitions that are widely used across Joint and Coalition forces because they provide a good balance of blast and fragmentation effects for their payload and they provide a platform that can be modified with an

assortment of capability upgrade kits (Geneva International Centre for Humanitarian Demining [GICHHD] 2017).

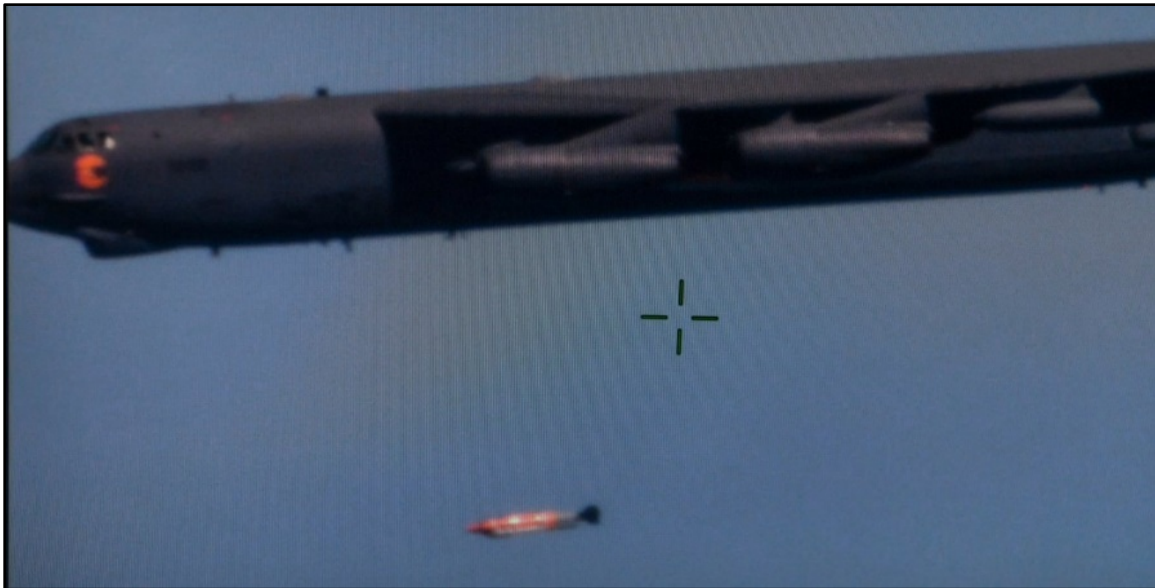


Figure 5. U.S. Military Maritime Mines. Source: Eckstein (2020).

A Quickstrike Mine is “made” when the appropriate kit is installed similar to how a GP bomb graduates to become a JDAM (Joint Direct Attack Munition) with the addition of a guidance kit. In the Quickstrike case, though, adjustments are made to the fusing or other operational settings turning a bomb – that use impact to trigger activation – into a mine –that will lay in wait for the appropriate arming criteria to be met. These upgrades are not mutually exclusive, and the Navy is currently developing both Quickstrike JDAM and Quickstrike Extended Range variants shown in the top left quadrant of Figure 5.

With the roots of the Quickstrike “family tree” tracing back to JDAM and GP bombs, the compatibility of Quickstrike mines with any coalition aircraft is all but assured. However, the required testing to authorize these munitions to be fielded and employed has been limited to the Navy’s strike fighter and maritime patrol aircraft and the Air Force’s bombers (e.g., the B-52 shown testing the Quickstrike Extended Range [QS-ER] in Figure

6 from 2019.) Along with the B-52's 70,000 pound payload capacity and the B-1's 75,000 pound capacity, the Air Force's heavy bomber wings provide the ability to deliver a significant number of these mines quickly (Boeing n.d.). Likewise, the B-2's ability to support over 40,000 pounds in a sortie gives the added benefit of stealth insertion while only making a slight trade-off to capacity (Northrop Grumman n.d.).



U.S. Navy Photo: A B-52 Stratofortress, assigned to the 49th Test and Evaluation Squadron from Barksdale Air Force Base, La., conducts an operational demonstration of the Quickstrike-ER (QS-ER) Naval mine project in the Pacific Ocean, May 30, 2019 [sic]

Figure 6. QS-ER Deployment Test. Source: Eckstein (2019).

For more tactical execution, the Navy relies on its forward deployed assets in Carrier Air Wings and Maritime Patrol detachments in the form of the F/A-18 Hornets and P-8 Poseidon, respectively. At only a fraction of an Air Force heavy bomber load outs, the P-8's 20,000 pound capacity still brings a significant mine deployment opportunity to the area of responsibility (AoR) or theater of operations (Boeing n.d.). In contrast, with no bomb bay storage on its significantly smaller airframe, the F/A-18 variants place all weapons stores off wing mounted pylons and payload capacities are even further reduced when at-sea carrier launch weight restrictions come into play. But those comparatively lighter mine-carrying cargos per platform are overcome with operational strategies like

deploying in two to four ship sorties or assembling significant multi-ship strike packages. Considerations, no doubt, that will transfer over to the F-35 Joint Strike Fighter (*Lightning II*) as it comes online just as the recent transition from the P-3 Orion was successful into the P-8 (NAVAIR n.d.). See an example of a MK 62 Quickstrike mine being dropped from a P-3 in Figure 7.



U.S. Navy Photo: MK 62 Quickstrike Mine Deployed From a P-3C Orion aircraft in 2004.

Figure 7. MK 62 Quickstrike Deployment. Source: Pietrucha (2016).

2. Submarine Launched Mobile Mines

The MK 67 Submarine Launched Mobile Mine (SLMM) is the sole vessel-launched mine currently in use by the U.S. Navy, as shown in the lower right quadrant of Figure 5 and Figure 8. It is a converted MK 37 Torpedo with modified arming triggers (National Research Council 2001).

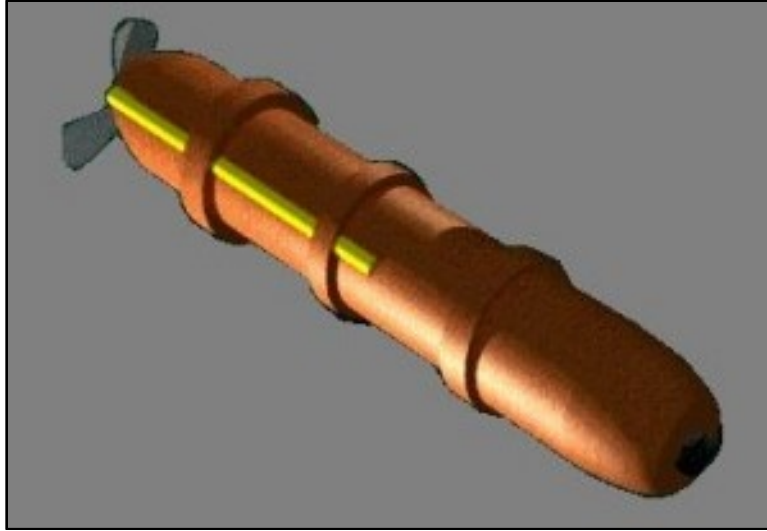


Figure 8. MK 67 Submarine Launched Mobile Mine. Source: Truver (2015).

With a capacity of approximately 25 on board a Virginia-class fast attack submarine (Congressional Research Service 2021), the mine-laying implications are formidable especially considering that SLMMs are clandestinely delivered and the placement is assured and precise through operator inputs. However, just like the Quickstrike family of mines, SLMMs are stationary bottom mines once placed.

3. Hammerhead Mines

The Hammerhead mine is still in development but hopes to field as a key component to subsurface mine deployment in the near future. Its notional construction, based off the MK 54 with a mooring module, is shown in the lower left of the U.S. Military Mining Portfolio figure and in Figure 9. This mine is designed to be delivered by submarine or UUV and then loiter in critical choke points (McLeary 2020). The Hammerhead mine procurement is being fast-tracked by the Navy, underlying its importance to the Navy's future considerations (Hambling 2020).

The Hammerhead development explores updates across three novel employment capabilities. First, Hammerhead promises to bring communications and processing capability to the U.S. mine arsenal for the first time. This addition opens the door to “legalizing” their use during peacetime in ways the conventional mines failed to comply,

or at least operated in some gray areas, of international maritime norms. Second, it plans to add innovative sensor capabilities to allow for a minefield to be netted over a much wider area with the single moored Hammerhead lying in wait for the correct target to be identified and targeted. Lastly, the intent of Hammerhead is to be delivered by UUV almost exclusively ensuring hostile forces are completely unaware of their laying.

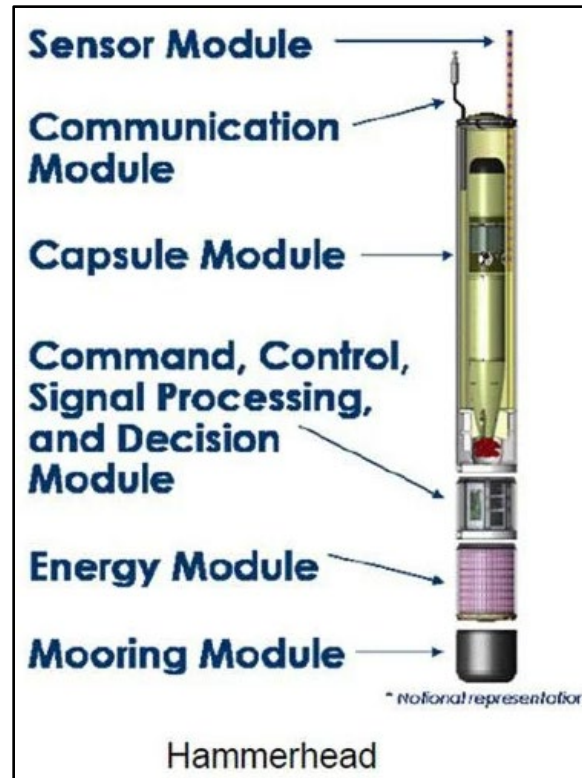


Figure 9. Notional Hammerhead Representation. Source: Hambling (2020).

D. OFFENSIVE DENIAL MINING

The literature review presented the MIW paradigm of past, present, and future mine construction and shed light on the complexities of MIW operations. It revealed that specific mine parameters will be affected by external forces and specific environmental factors. The team found that previous MIW effectiveness studies focused primarily on minefield composition and arrangement but failed to emphasize the desired strategic impact and the delivery system. The more directed focus of those studies creates an opportunity for this

project. There is potentially significant value to be gained by focusing on the broader integrated mine system: starting with mining mission objectives, then considering the type, size, geometry, delivery, sustainment, and deactivation of the minefield to be employed. While exercising this more holistic approach to mining, the team identified a disconnect trying to resolve the traditional definitions and legacy ideas surrounding offensive mining with the new mining mechanisms, technology, and doctrine being employed. The team remapped the legacy minefield defined by Protective and Offensive Mining breakouts shown in Figure 3 to a new concept termed Offensive Denial Mining (ODM) with considerations independent of employment region but sensitive to mission objectives defined by Edwards (2019). The top-level breakdown of the ODM problem space that the team developed is shown in Figure 10.

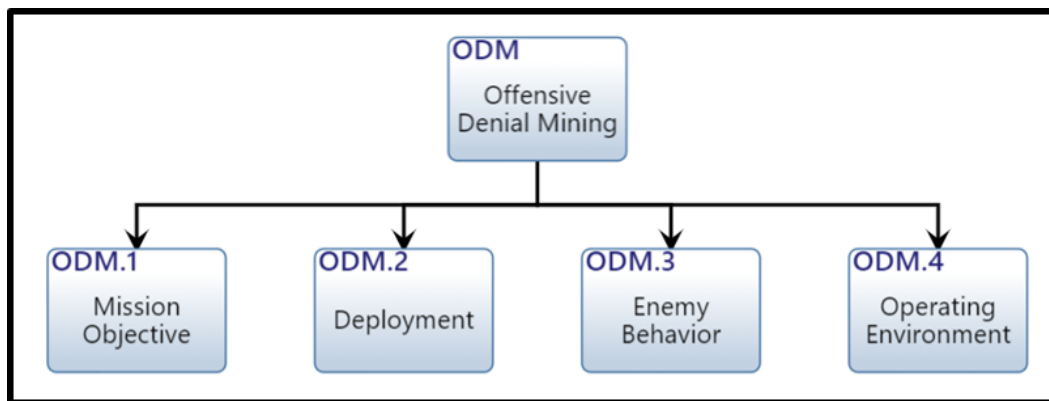


Figure 10. High-Level Offensive Denial Mining Considerations

1. Mission Objective

Much of the initial problem space was shaped by looking at offensive mining through the lens of mining mission objectives. Edwards (2019) identified and defined four unique objectives for mining as:

- Turn – divert enemy formations from intended transit
- Block – stop maritime traffic along a specific avenue of approach
- Fix – slow or stop targets to create a target rich environment for friendly forces

- Disrupt – alter enemy formations and tempo, interrupt enemy timetables, and/or cause the enemy to begin mine countermeasure operations

Notice that these objectives are independent of geographical location as defined under the legacy system as offensive, defensive, or protective. For example, blocking mining could be achieved to keep an enemy confined to their own ports, keep an enemy from entering a friendly port, or keep an enemy away from an area being primed for some other operational purpose be it a neutral coastline or a blue water AoR. Ultimately, when exploring ODM, the team uses mission objective to answer the question, “What is the minefield trying to make the enemy do?” and then uses that to define the appropriate MOE.

2. Deployment

When learning about the ways mines can be laid, the team broke out the delivery mechanisms into three main groups: air, manned vessels (surface or submarine), and UUVs as shown in Figure 11. By keeping the categories of deployment vehicles more broad, the team was able to explore the interactions of generic concepts across these domains and analyze how the different choices within them affect outcome. In doing so, the work done within this project could remain both insightful and unclassified, while still providing a useful tool and template for more specific research in the future.

Although each of these groups has similarly titled considerations—*number of mines, mine type, time to deploy, and geometry of minefield*—each category’s answers are vastly different and particular. One would expect significant tradeoffs would need to be weighed when determining whether to use a B-52 *Stratofortress* to lay a field of *Quickstrike* bottom mines or sending in the USS Virginia to lay a field of SLMMs. The particulars of those scenarios though interesting are classified and are outside of the scope of this project.

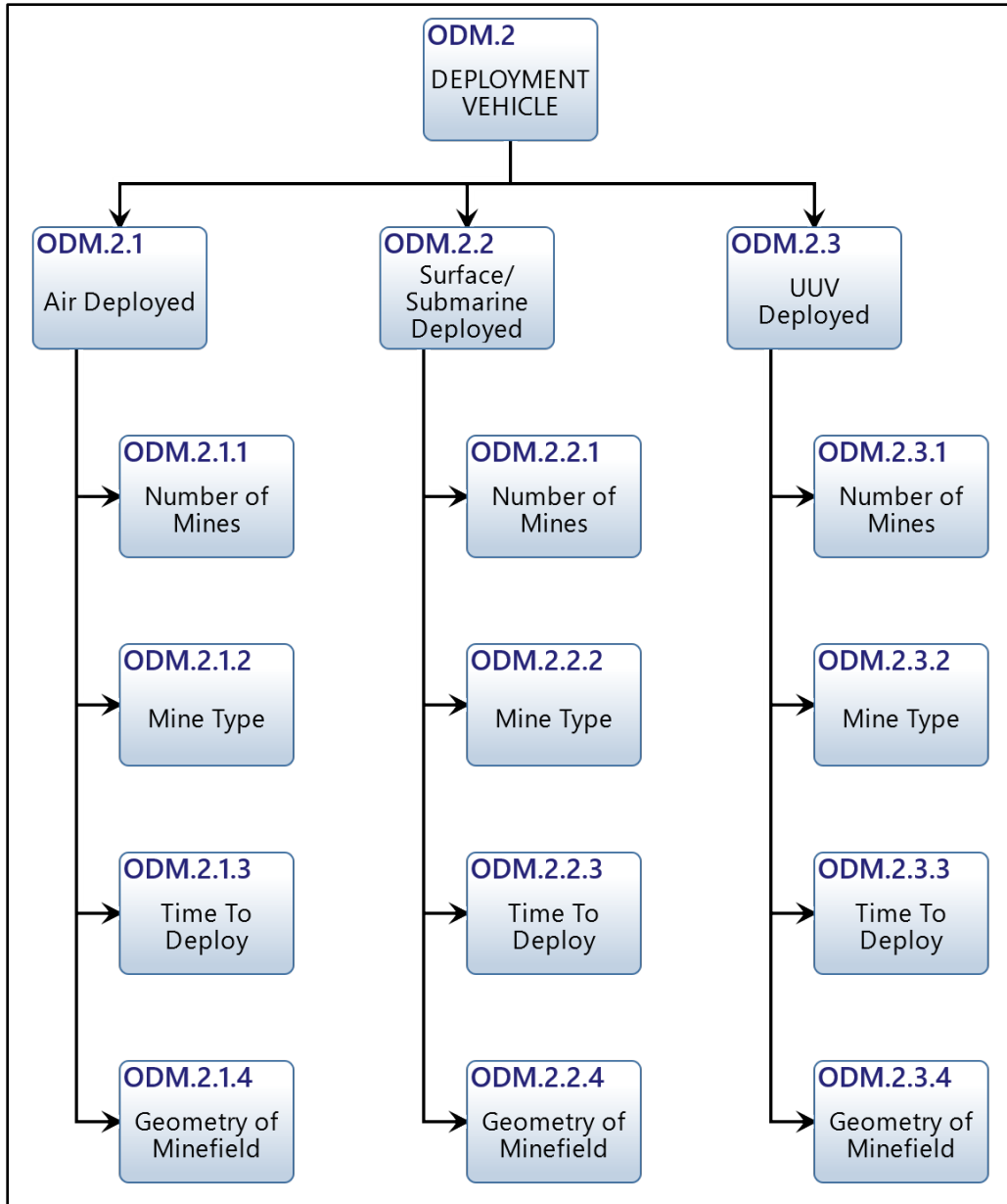


Figure 11. ODM Deployment Vehicle

First is the quantity of mines that can be delivered from UUVs, which have little room for extra payloads. The second limitation is the time required for minefield deployed. UUVs are required to conserve energy, with most designed to be capitalize on max efficiency at 2–4 knots, with faster speeds detracting from time the UUV can spend underway. Though some UUVs have a “sprint” capability, this directly impacts the third limitation, the range of the UUVs. By accepting deployed time and speed tradeoffs, UUVs

could deploy large amounts of mines but would need a mothership nearby to work effectively within that limited range. Extra Large UUVs (XLUUV), such as Boeing's *Orca*, as shown in Figure 12, may have the ability to fundamentally change mine deployment by UUVs by increasing range, speed, and autonomy, but that is outside the scope of current U.S. Navy capabilities (Baker 2019).



Boeing's Orca design is based on its previously developed Echo Voyager XLUUV, which can perform duties at sea for months at a time.

Figure 12. XLUUV Concept. Source: Husseini (2019).

3. Enemy Behavior

Minefields, both land and maritime, have a unique quality in that their effectiveness is dependent on the adversary's awareness to the general mine danger area (the overarching area declared by the mining force under international law). In a best-case mining scenario, an adversary's inability or unwillingness to attempt detection or MCM operations could be leveraged to deter them from transiting a declared mine danger area without actually laying munitions. On the other hand, the sinking of friendly, neutral, or even adversarial commercial traffic ignorant or indifferent to the threat and trying to transit the minefield

could be lost before divulging their fate to the intended targets. To capture this dichotomy, the team split enemy response into two general categories, basic mine detection and MCM capabilities, as seen in Figure 13.

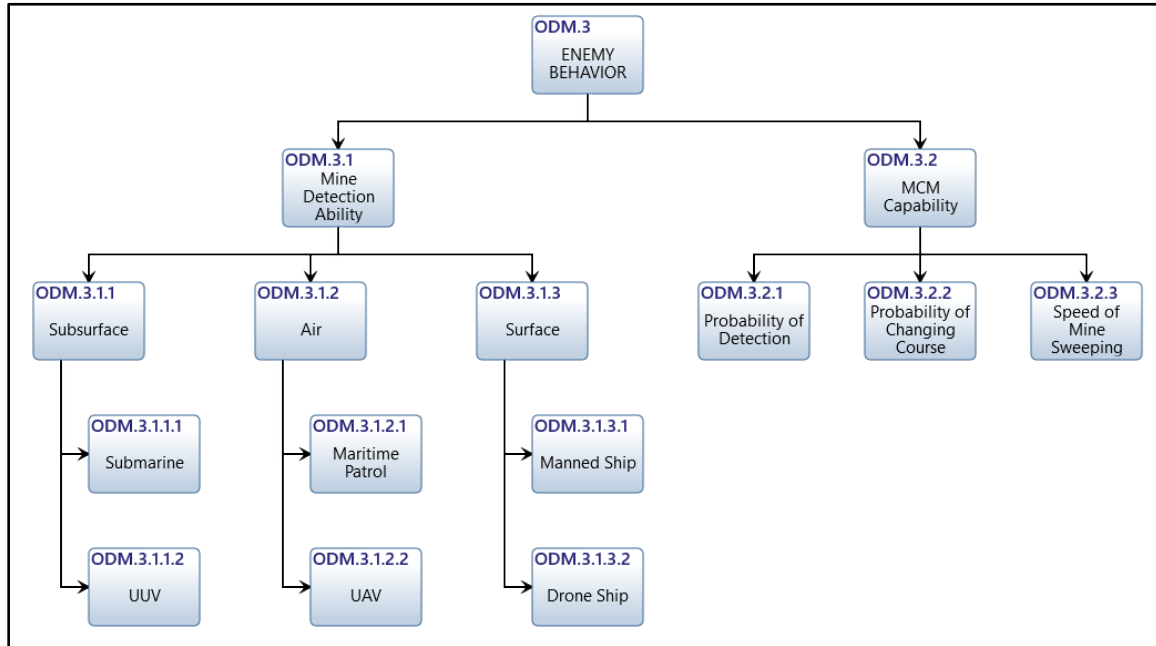


Figure 13. Enemy Behaviors Affecting ODM Employment

4. Operating Environment

The minefield operating environment category of ODM frames mining around the answers to the question, “How does where a mine field is located affect its effectiveness?” Like with mission objective, the minefield environment is unique in every circumstance. Hypothetical scenarios like cutting off traffic into the hostile port of San Francisco would require different considerations than if defending the scenic Bay of Monterey, as would efforts to control shipping traffic off the cliffs of Point Loma. These considerations, broken out in Figure 14 describe multiple elements of minefield definition that are not addressed through the definition of the mission objective, deployment vehicle, or enemy behavior.

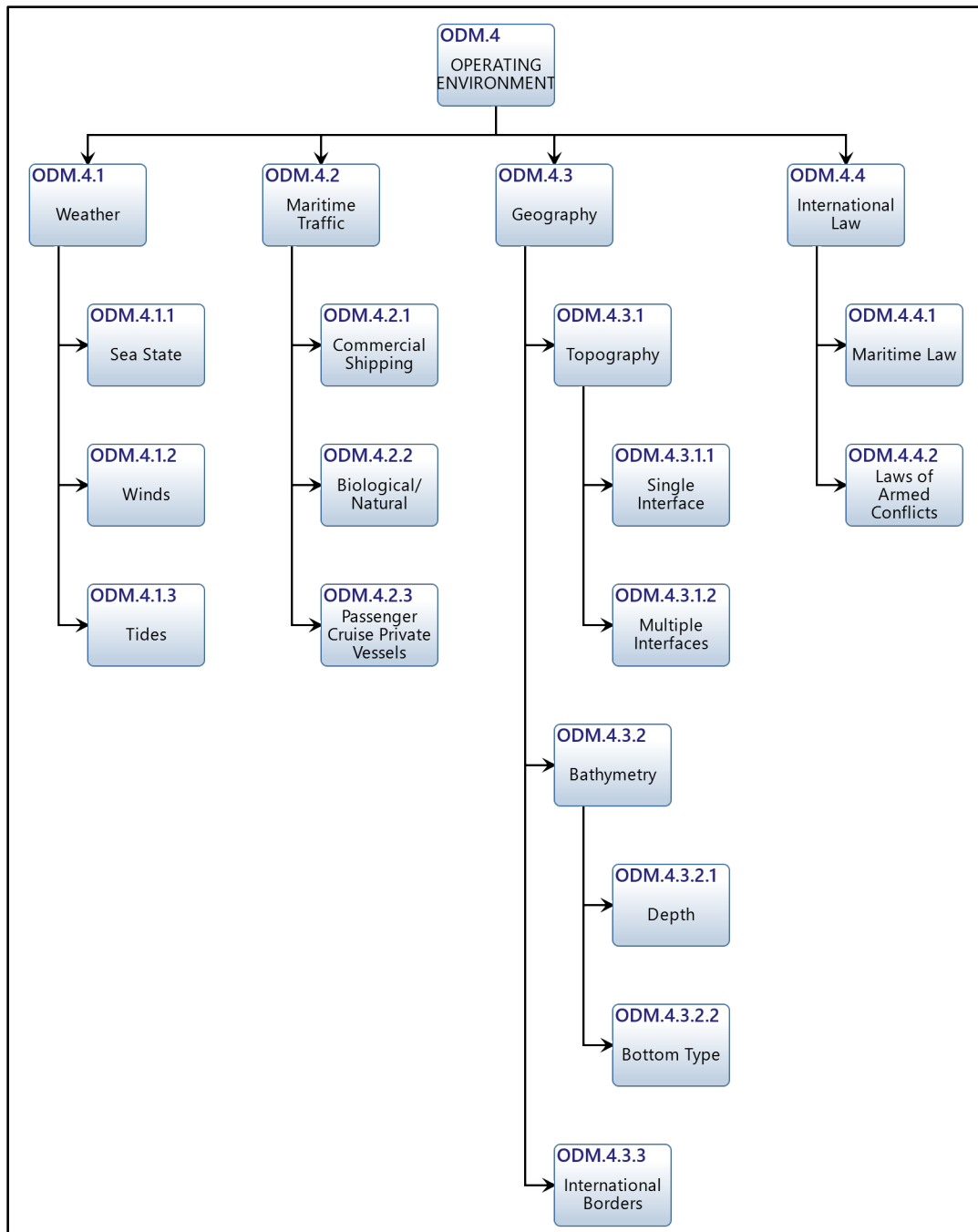


Figure 14. ODM Operating Environment

Likewise, the real-life considerations affecting mining include the size of the minefield, water depth, bottom type, presence of debris (floating or suspended), and local weather and sea states can also affect the employment. Employment must also be limited

when considering neutral or friendly vessels that could potentially be transiting the areas, as well as balancing potential impacts on the biological ecosystem.

III. ODM MODELING

A. MODEL SOFTWARE PROGRAM SELECTION

Based on the architecture developed in the previous chapter, the team established boundaries for the ODM modeling effort. Figure 15 presents a description of each of the elements of the ODM operation that the team considered for inclusion in an operational simulation model. To develop and capture the architectural framework that defined ODM, the team chose the Innoslate online SW suite, version 4.4.0.1.

In addition to the administrative software, the team desired to find an agent based program to support M&S work. To accurately represent the variable systems, environment, and decision logic associated with ODM, the team pursued an agent-based simulation that was able to handle a design of experiments and produce data suitable for operational analysis. M&S tools that met all these criteria, were widely available, and any already in use within the community of stakeholders were prioritized. The team looked for a program that would check off all these features finding a prime candidate called Littoral Combat Ship Integrated Toolkit for Mission Engineering Using Simulation (LITMUS). It had been used in recent NPS operational research assessing tactical anti-submarine warfare (ASW) scenarios the team had examined during the literature review. LITMUS was a Java coded program that used a GUI that ran on top of the Orchestrated Simulation through Modeling (OSM) framework developed by Naval Surface Warfare Center, Dahlgren Division (NSWCDD) (Tilus 2018). From its initial development in 2014, OSM has realized its goal to model systems of systems (SoS) which do not require model changes when new systems are introduced, removed, altered, or replaced (Winfrey, et al. 2014). OSM and LITMUS were tools extending collaborative efforts between NSWCDD and NAVAIR (Wallace and Cummings 2015) presenting them as the logical choice to use through the modeling of ODM.

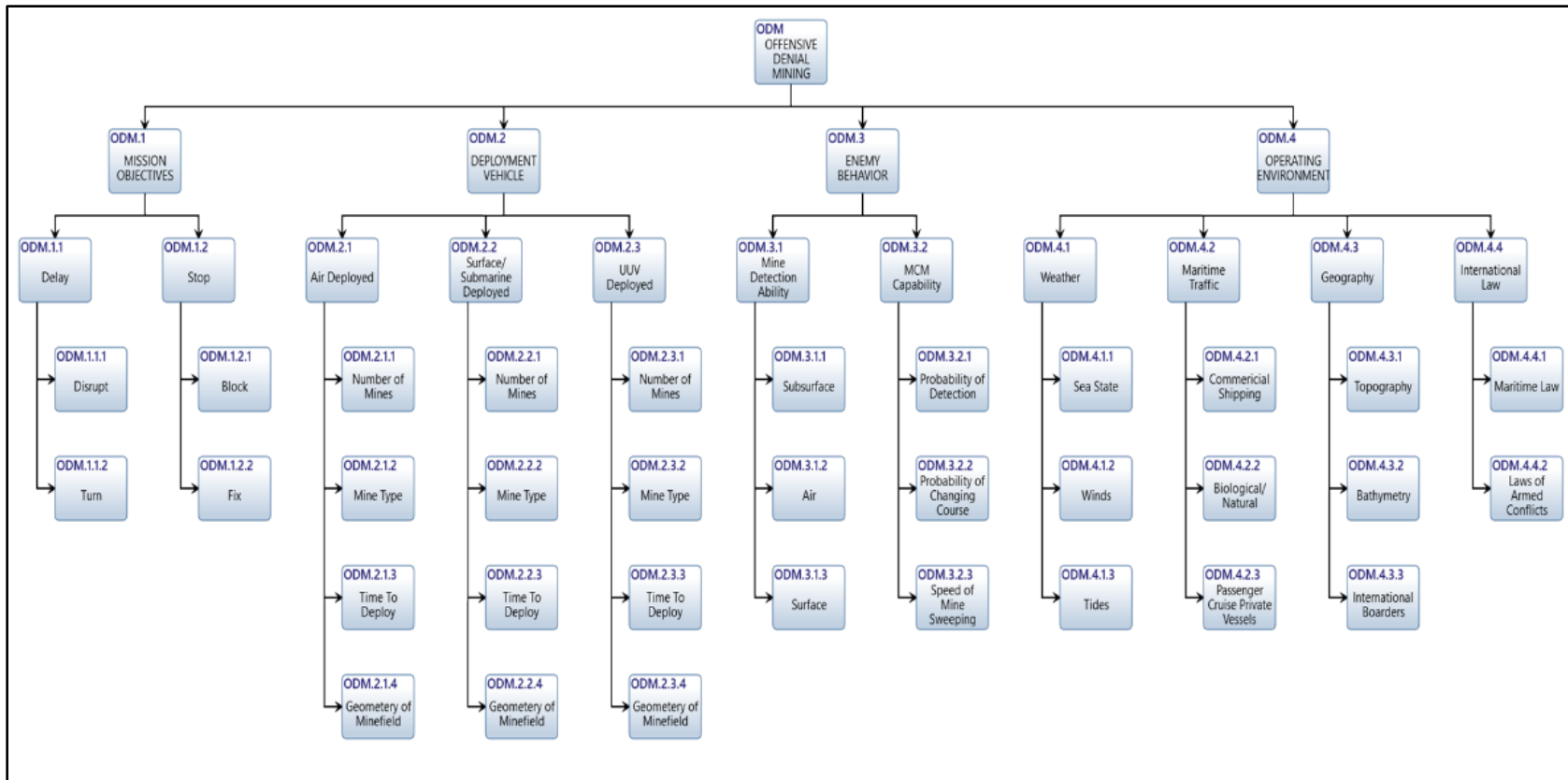


Figure 15. Decomposition of Offensive Denial Mining Considerations

Under its existing iteration, the LITMUS program has been rebranded and is known currently as the Modeling and Simulation Toolbox (MAST). MAST is built as a behavior-based modeling and simulation tool for warfare analysis (MAST User's Guide) and was ultimately selected because it would allow the team to explore the wide range of user defined agents, parameters, and interactions surrounding ODM thereby adding a new dimension to Surface, Subsurface, and Air Warfare communities it was already representing.

B. MODELING AND SIMULATION TOOLBOX (MAST)

1. MAST Overview

NSWCDD (M31) controls development of MAST and granted the team access to version 2.9, still in beta pre-release testing, for use in this project. The software program itself is limited distribution to U.S. Government only, and the default interface can be seen in Figure 16.

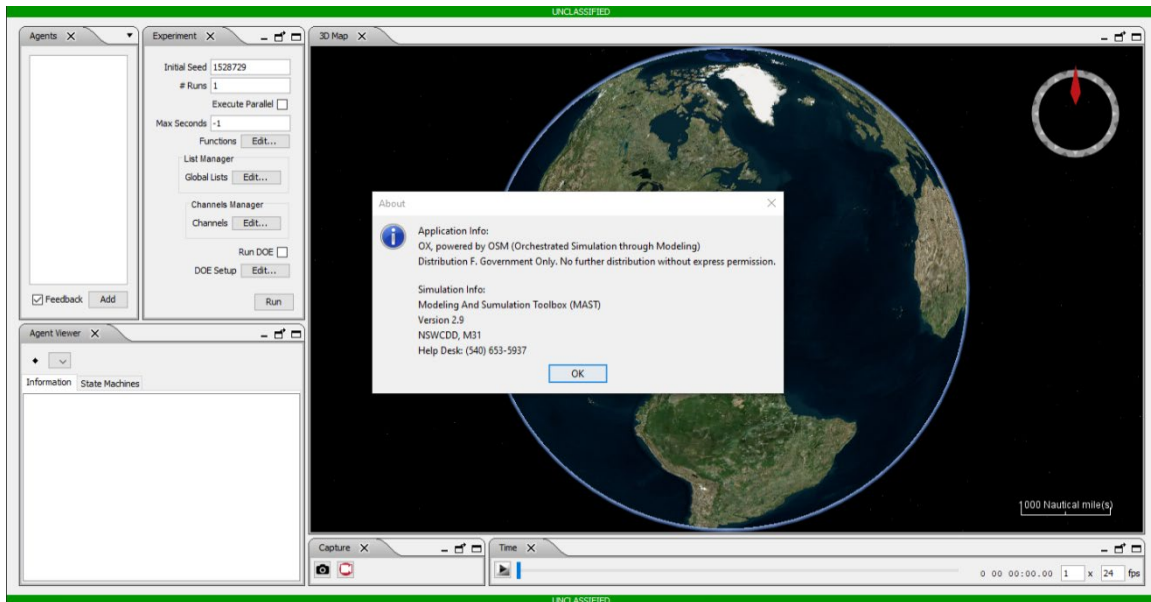


Figure 16. MAST Desktop and SW Information

MAST is designed to support surface and air warfare concepts and even has pre-defined agents representing the USS Freedom (LCS 1) and USS Independence (LCS 2) available for user selection. However, all labels are purely cosmetic and item characteristics can be defined or manipulated to the user's will as technique and necessity dictate. Agents are composed of the platform, subsystems, and state machines. The user defines the agent's name, assigns team affiliation and adversarial factions, labels the platform (physical representation), delineates the characteristics of any allocated subsystems (e.g., sensors, communications, and weapon systems), and develops the state machines through MAST GUIs, all of which dictate the resulting agent behavior when the model is run. An example of the GUI for defining these attributes can be seen in Figure 17. MAST allows for the definition of geographic agents which are used to establish visual cues for the user or can interact or trigger behaviors in other agents.

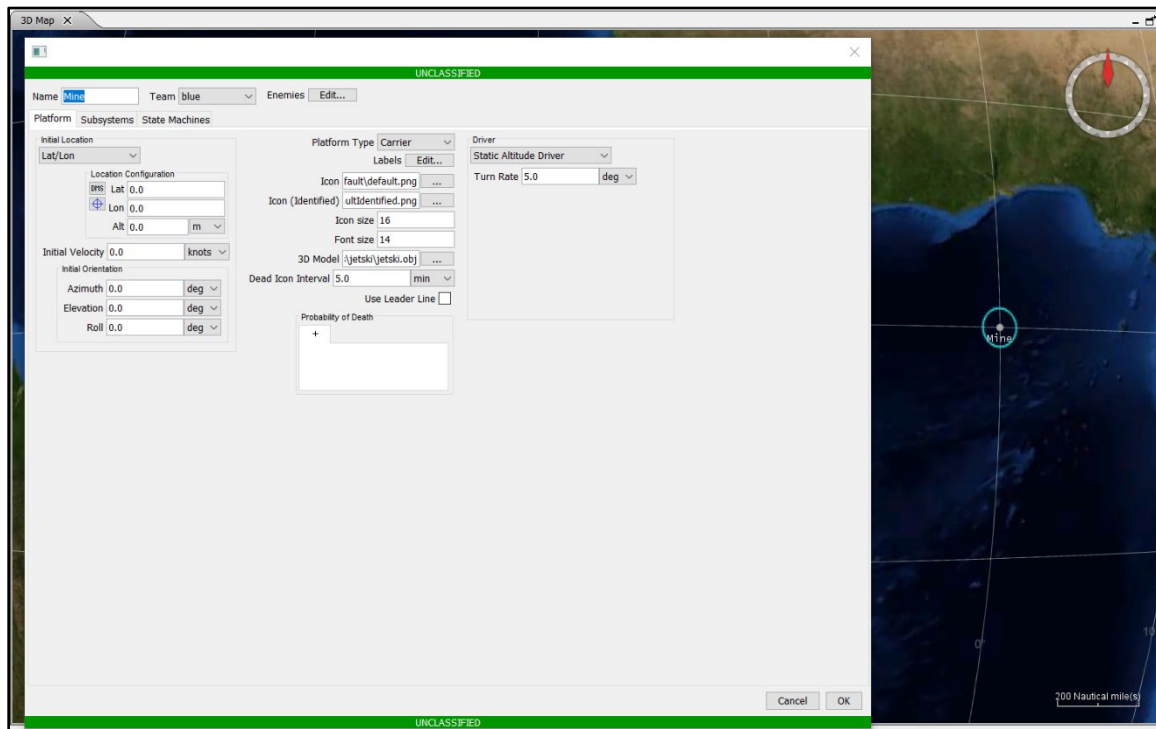


Figure 17. MAST Agent Definition GUI

2. MAST Model Boundaries

a. *Exclusions and Limitations*

Although the MAST GUI offers a very friendly user experience, allowing quick navigation anywhere in the world, the team chose to keep all project scenarios centered around the intersection of the Equator and Prime Meridian at the point 0° North latitude and 0° East longitude in the Gulf of Guinea, which MAST defaults to as the starting location. A standard 50 by 50 nautical mile (nm) geography circle was used throughout the project experiments as a default minefield region within this AoR. The standard minefield region is shown as a light blue circle illustrated on the right side of the 3D Map window in Figure 17 (halo around the gray mine agent labeled “Mine”) and exemplified in Figure 18 around the “Blue_MineDeploySite” point.



Figure 18. General AoR Laydown

In doing this, the team limited the model operating environment to be free of many of the sub-characteristics that would be important to real-world ODM operations but also removed any unintentional bias, political implications, or reference to specific locations that would unduly elevate the classification of this report. Future ventures would be free to leverage MAST’s point flexibility to be any latitude, any longitude, any altitude or any

depth. Agents modeled within the program do not interact with the environment GUI layers, only other agents built within the simulation. An aircraft will not crash, a ship will not run aground, and more relevantly for ODM, a mine will not alter its effects based on the bathymetry. Like topography, bathymetry, and bottom type, weather conditions within MAST are not a selectable feature.

Although MAST can support the development of other maritime traffic agents within the operating environment, the team de-prioritized the development of commercial and private shipping as well as any biological interactions. All of the experiment scenarios were built on a zero altitude-zero depth layer with agents acting under default MAST physical space dimensions pre-programmed thus effectively acting as point masses. All agent-to-agent interactions occurred through distance triggers of different types, which precluded any agent collisions or direct exchanges. Under these parameters, no red air or subsurface vessels were modeled. From an enemy behavior model standpoint, only basic transit functionality was modeled to support runs and evaluation.

b. Included Behaviors and Model Assumptions

Three agent types make up the foundational experiment: a blue delivery vehicle, a blue mine, and a red vessel. Across all simulation experiments the general flow of events are as follows:

1. A blue delivery vehicle within the AoR starts to the Northeast of the desired minefield area (50 x 50 nm circle centered at 0°N/0°W)
2. Specific deploy sites are randomly generated within the blue minefield area
3. The blue delivery vehicle transits to the deploy site(s), deploys its payload of mines, and then exit back towards West-Northwest
4. Red vessels within the AoR start to the East of the minefield area, hold for a set amount of time, and then transit to a destination waypoint (WP) West-Southwest of the minefield area

To begin modeling, the team started by reading the user's guide provided by MAST, walking through tutorials provided in MAST, and following guided video

demonstrations recorded by the NPS SEED (Simulation Experiments and Efficient Designs) Center for Data Farming lead MAST developer. From there, the team constructed simple use cases, iteratively building the complexities of agents and interactions. These early foundational experiments used fixed variables that were eventually varied during the DOE analysis stages of the project.

Due to complexity, MAST limitations, or project scope limitations many characteristics which make up ODM had to be excluded from the modeling effort. The team was able to capture many of the important ODM considerations, and these can be seen in the green colored boxes in Figure 19.

3. MAST Foundational Model Parameters

Based on the ODM behaviors that the team chose to model, a foundational experiment consisting of three major agents was developed and matured over the course of this project. The foundational experiment agents included: blue delivery parameters, mine parameters, and red vessel parameters.

a. Blue Delivery Agent Parameters

For the ODM deployment vehicle, the team was able to develop three types of blue delivery agents. Each blue delivery agent is made up of a platform, subsystems, and state machines. The first platform is representative of an air delivery vehicle, the second platform is representative of a surface or subsurface (referred to as “vessel” throughout the paper) delivery vehicle, and the third platform is representative of a mothership vessel that deploys a UUV delivery vehicle. It is important to note that each system must be configured to fully develop the platform of choice. However, it is important that platforms are named and typed, so that they can be identified by other agents in the experiment. Each blue delivery agent has a mine subsystem. Each blue delivery agent has three general state machines that tell it to go to the deploy site(s) located within the blue minefield area, launch the mine subsystem agents, and then follow waypoints to egress the AoR. Air delivery has a single deploy site, vessel has two deploy sites, and UUV has two deploy sites. The high-level action diagram for the blue delivery agents is depicted in Figure 20.

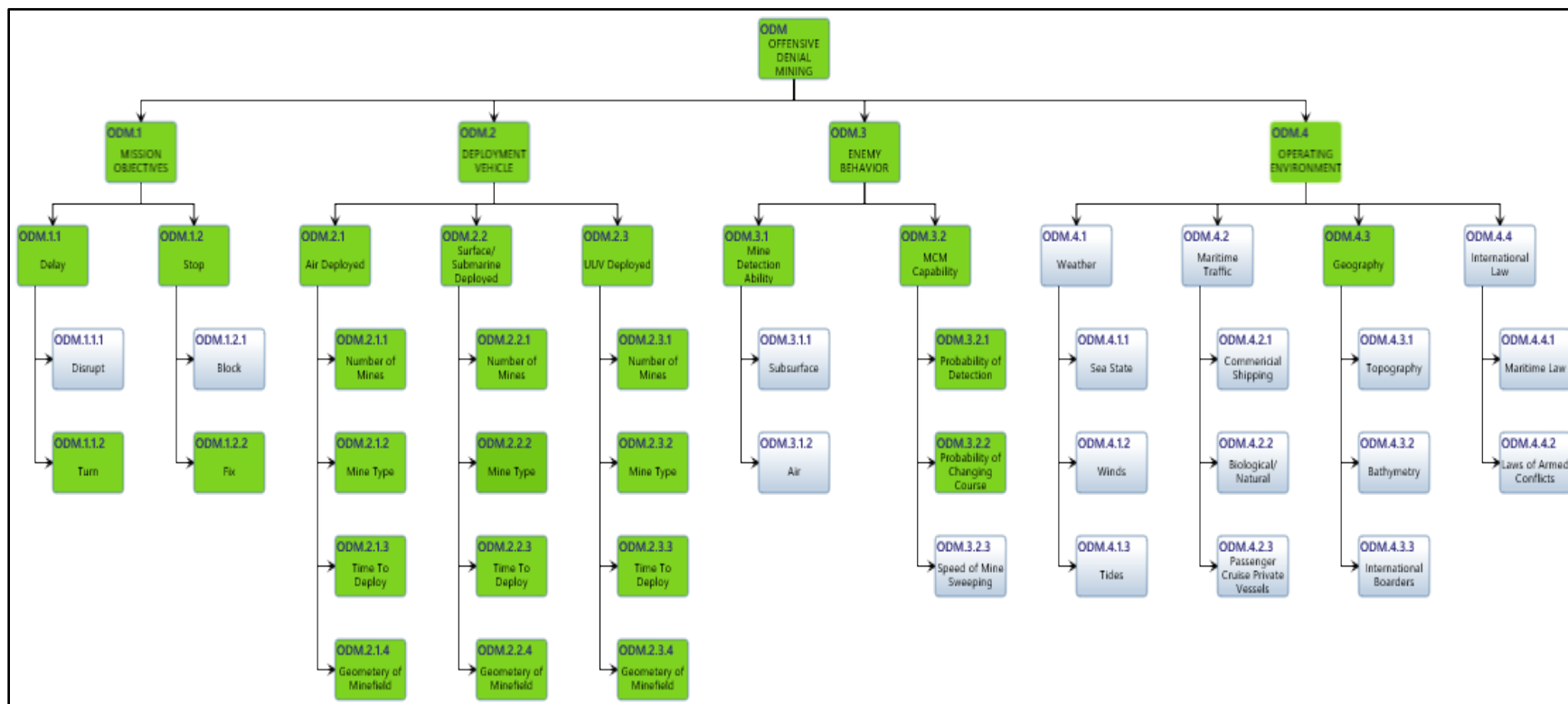


Figure 19. ODM Considerations Modeled in MAST

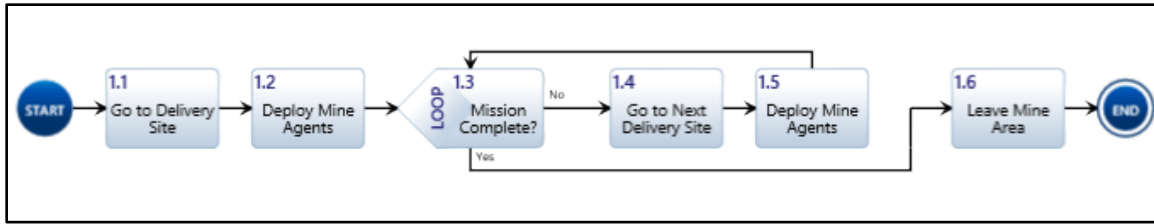


Figure 20. Blue Delivery State Logic

MAST does not have any pre-built mine agents. As such, a mine subsystem agent was created as a subsidiary of the delivery platform. As a child, it is not initialized until the parent agent enters its “deploy” state. The mine is representative of an explosive that has a sensor and detonates upon identifying its target. The mine is modeled with its own “sensor” and single-fire “gun” subsystems. Additionally, it can switch between two states during the simulation, either “manage tracks” or “suicide.” The mine waits in the “manage tracks” state until its sensor subsystem detects and identifies an enemy, which triggers its gun subsystem to fire, causing it to change to the explosive “suicide” state.

b. Mine Agent Parameters

For the mine model, the platform name is “Mine” with a type designation of UUV. It is a part of team blue and its enemies are red. Its subsystems are a sensor and a gun. The sensor subsystem is configured to have an identification range of 60 nm, an envelope-based detector of 60 nm, and targets platforms of type “destroyer” with a probability of detection of 1.0. The gun subsystem is configured to have a probability of death of 1.0 and also targets platforms of type “destroyer” with a probability of hit of 1.0. The mine stays in its “manage tracks” state until triggered to change to its “weapons” state. The manage tracks state maintains the location of the mine once deployed. The weapons state transitions the gun subsystem (and thus the whole mine) to suicide after being triggered and firing its single shot at a target. Figure 21 shows a screenshot from MAST detailing the agent subsystem configuration menu where mines are instantiated as children of a delivery platform.

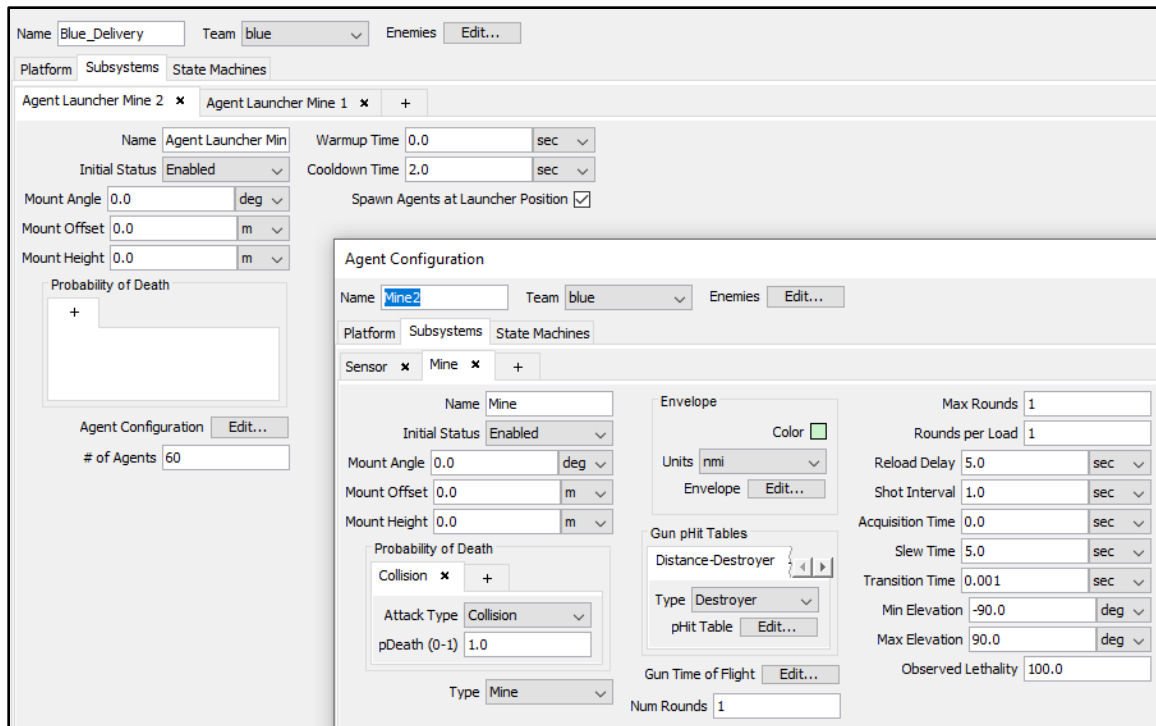


Figure 21. Blue Delivery Subsystem and Mine Configuration GUI

MAST does not have the ability to randomly distribute agents around a point or within a region. The team had to find a surrogate solution for developing the minefields themselves. When the delivery vehicle arrives at its intended deployment point it enters a deploy state and triggers its agent launcher subsystems. Based on the user defined parameters, the mine agents are created or initialized as though they are being “shot” out of a deployment system. The default cycle times in MAST are captured in seconds and can be defined by the user, however the default times for launch cycle, shown on the right of Figure 21, were used in the foundational experiments and throughout. The team selected the mine agents’ initial state machine to “Follow Patrol Waypoint” which allows the agent to calculate its own random waypoint within a specified variance from a specified location. The mine(s) then navigates to its calculated waypoint achieving a pseudo-random distribution around the specified user-defined location (NSWCDD, M31 n.d.). After a random time interval between one and two minutes from the time that the mine enters the “Follow Patrol Waypoint” state, the mines transition out of the patrol state and into a “manage tracks” state with a stationary position and their detection sensors active

simulating that the mine is armed and the minefield is activated and the mines begin actively waiting to detect targets. An example of random mine distribution can be seen in Figure 22.



Figure 22. MAST Mine Distribution Example

After transitioning out of the follow patrol state the mine enters a manage track state, which keeps it in its relative position. During this period, the mine will be searching for any vessels that enter its sensor radius. Once a vessel is detected, and within range, the mine will fire a shot at the target. The mine agents can fire a single shot, after which they enter a suicide state, and are removed from the simulation. Figure 23 presents an action diagram from Innoslate that graphically depicts the state dependent logic for mine behavior implemented in the MAST model. The summary of the mine agent parameters is displayed in Table 1.

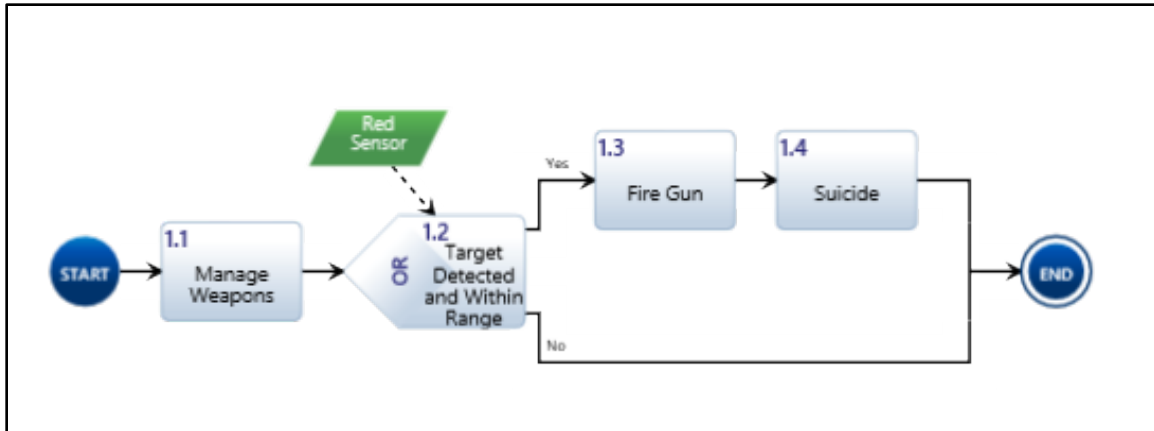


Figure 23. Mine Activation Logic

Table 1. Mine Agent Setup Parameters

Platform	Subsystems	State Machines
Name: Mine	Sensor: 60 nm; Envelope-based Detector: 60 nm; pDetect: Destroyer; Sensor pDetect: 1.0	Tracks: Follow Patrol Points <i>transition to Manage Tracks</i>
Type: UUV	Mine: pDeath: 1.0; Gun pHit Tables Type: Destroyer; Gun pHit Table: 1.0	Weapons: Manage Weapons <i>transition to Shots Fired At</i> Target <i>transition to Suicide</i>
Team: Blue		
Enemies: Red		

c. Red Vessel Parameters

The red vessel agents begin the simulation in a fixed position and attempt to follow a set of waypoints towards a destination point that requires them to move towards the minefield. For the red vessel, the platform name is “Red_Vessel” with a type designation of destroyer. Note that a type designation is required in MAST and does not assume that the red vessel is a specific class of destroyer. It is a part of team red and its enemies are blue. It is configured to sense mine agents, communicate with other red vessels, and navigate to a destination with the ability to change course of fix position upon detecting a mine. Therefore, its subsystems are a sensor, transmitter, and receiver. The sensor has an identification range of 100 nm, an envelope-based detector of 60 nm, detects platform types

of UUV, with a probability of detection of 1.0. The transmitter and receiver subsystems both have a communication range of 10,000 nm and are set to the default channel “Channel.” In addition, the receiver listens for messages of type “Command.” The red vessel state machines include navigation, tracks, and communications. The navigation state machines are hold position and follow waypoints. The red vessel holds position in the simulation to ensure blue delivery vehicle has time to lay the mine field before the red begins its mission. The red follows waypoints at 50 knots to its end point unless it is triggered by proximity to a mine agent or receiving a command from another red vessel to “Flee From” the general area. At this point, the red vessel makes a probability based decision to fix position, change course, or continue on its path. The tracks state machines manages the red vessels tracks. The communications state machine has a communications manager state and send command state. The communications manager is set to listen for message types of “Command” and set to the default channel “Channel.” The send command state sends a command of type “Flee From” to the other red vessels.

If the Red Vessel detects a mine, it can proceed in a variety of ways. These behaviors are probability-based decisions, which the agent decides in the order in which they are programmed. Upon detection of a potential mine, the red agent will choose to perform an action or continue on towards its waypoint. The actions the agent can choose are to change course or to fix position. The agent will then choose to send a command directing the other Red Vessel agent to either change course or fix position.

If at any time, the agent receives a command from another Red agent the receiving agent will make a probabilistic decision to change course, fix position, or maintain course. An example of the MAST simulation with the Red Vessel agents can be seen in Figure 24. A summary of Red Vessel parameters is displayed in Table 2. The action diagram for the Red Vessel agents is depicted in Figure 25. Figure 26 depicts the Red Vessel agents holding position after detecting a mine, and Figure 27 depicts the Red Vessel agents changing course after detecting a mine. Note that the sensor circles in the MAST graphics correlate to the number of mines that are deployed in the scenario. Therefore, the green circles shown in a UUV graphic will be lighter than the green circles shown in in an Air or Vessel graphic.

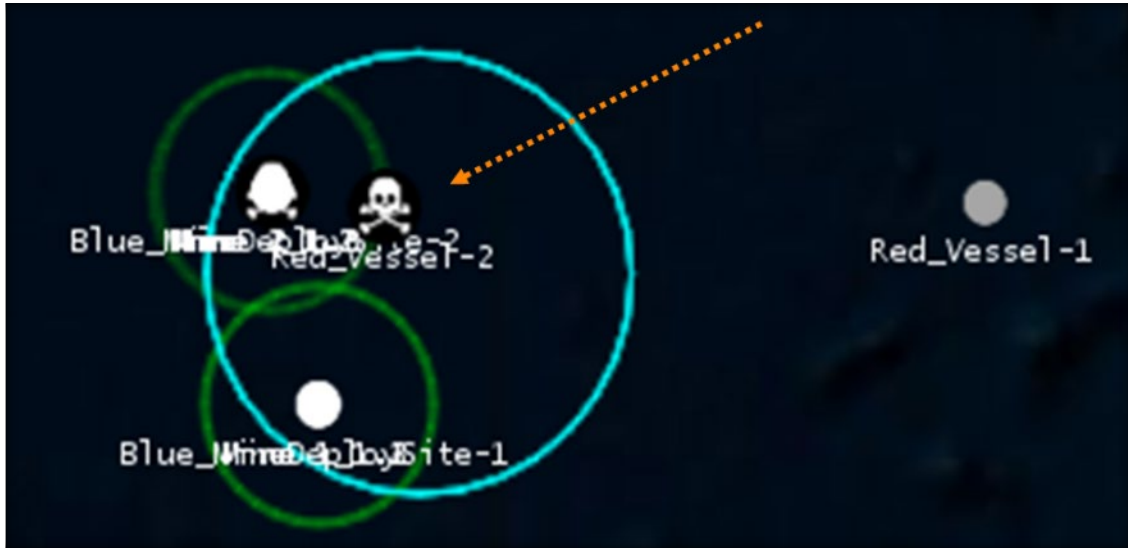


Figure 24. MAST Simulation Example

Table 2. Red Vessel Setup Parameters

Platform	Subsystems	State Machines
Name: Red_Vessel	Sensor: 100.0 nmi; Envelope-based Detector: 60.0 nmi; pDetect: UUV; Sensor pDetect: 1.0	Red Navigation
Type: Destroyer	Transmitter: Communication Range: 10000.0 nmi; Channel Names: Channel	Hold Position
Team: Red	Receiver: Communication Range: 10000.0 nmi; Channel Names: Channel; Message Type: Command	Follow Wapoints: 50 knots <i>until triggered by Command Received or Proximity to Mine</i>
Enemies: Blue		Fix for 20.0 hours
Probability of Death Attack Type: Mine		Change Course at 180.0 degrees
pDeath: 1.0		Follow Wapoints: 50 knots
		Tracks
		Manage Tracks
		Blue Communications
		Communications Manager: Message Types: Command; Channel Names: Channel
		Send Command: Flee From

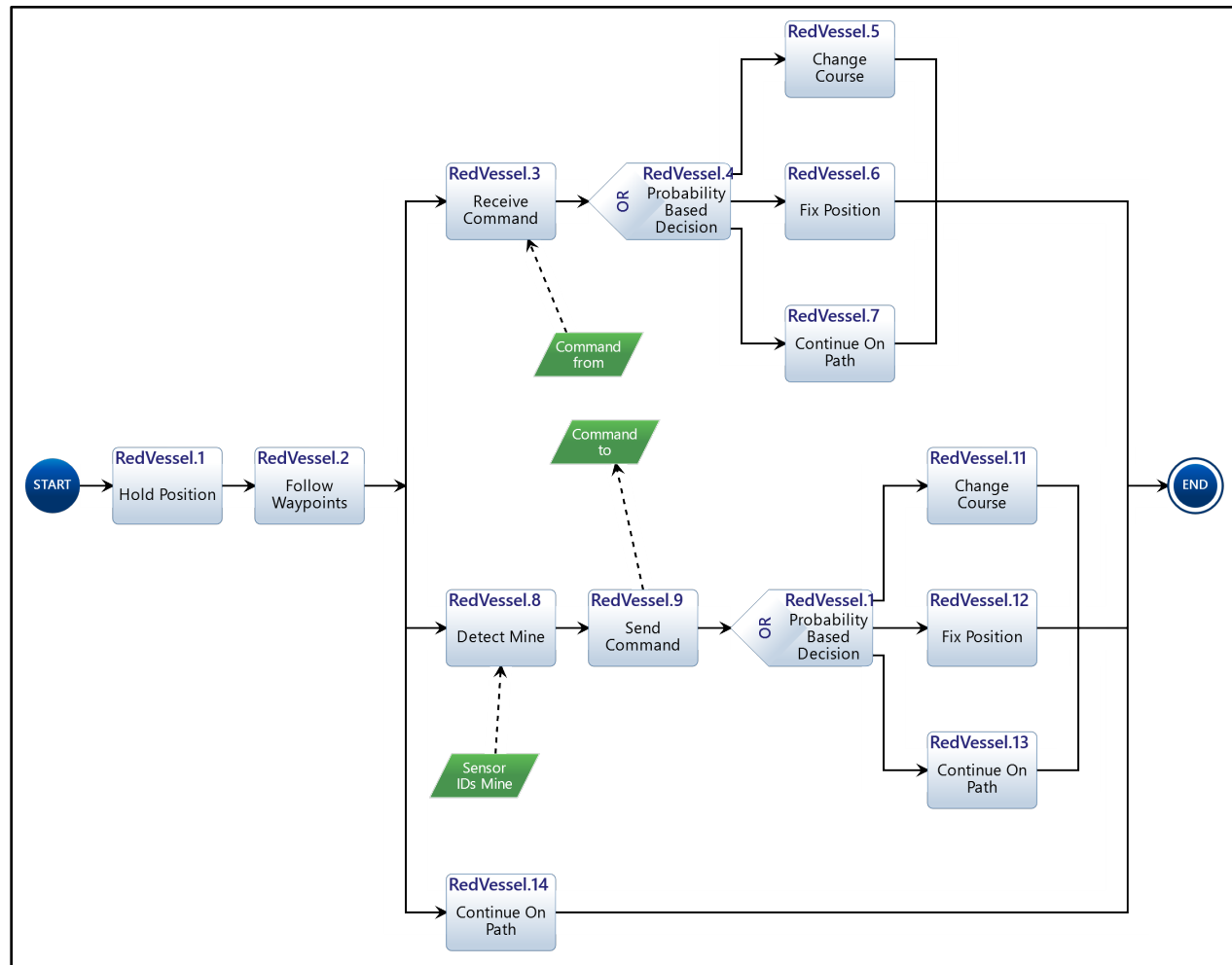


Figure 25. Red Vessel Transit Logic

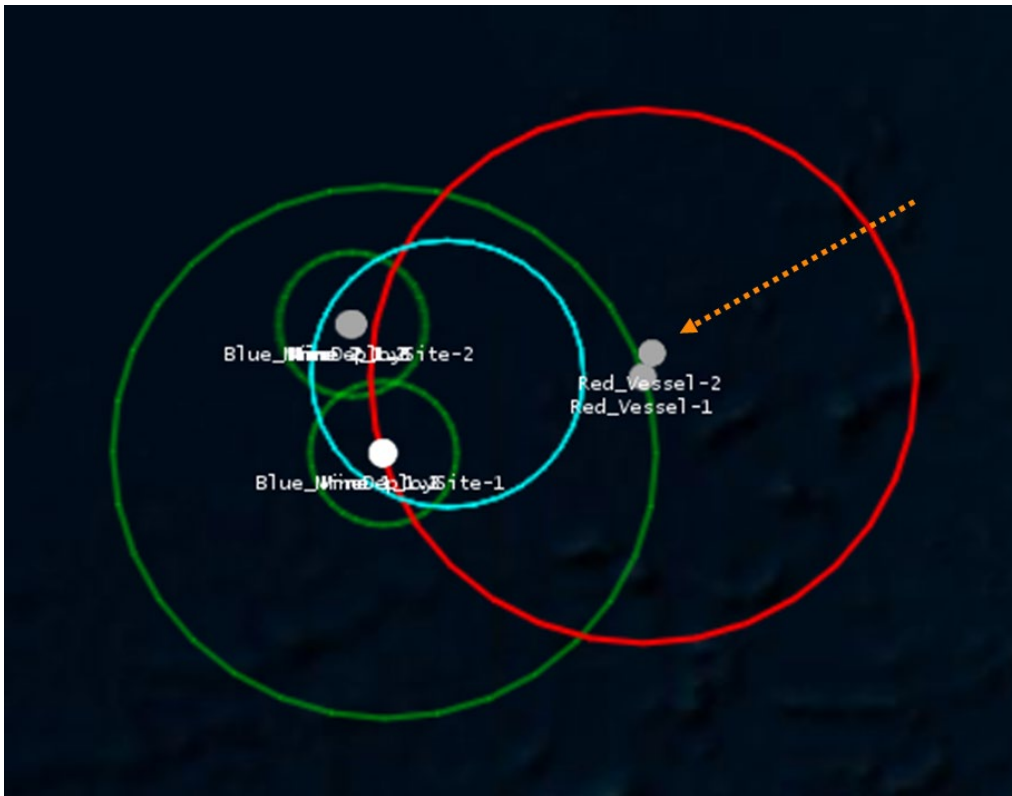


Figure 26. Red Vessel Detecting Mine/Holding Position



Figure 27. Red Vessel Changing Course

4. ODM Baseline Experiment Scenarios

The iterative development of the model enabled the team to define three experiment scenarios for final analysis and reporting. The team prioritized unclassified conceptual characteristics to capture the higher level takeaways from the ODM experiment scenarios through standardization across experiments over modeling actual weapon attributes. Table 3 presents a description of the three experiments, corresponding to air delivery, vessel delivery, and UUV delivery.

Table 3. Baseline Experiment Scenario Assumptions

Blue Parameters	Speed	Capacity	Drop Sites	Mine Capability
Air	High	Med	1	Low
Vessel	Med	High	2	Med
UUV	Low	Low	2	High

a. Air Delivery Experiment

The air delivery method is characterized by a single fast moving deployment agent which could deploy a “medium” number of mines at a single delivery location.

For the air delivery model, the platform name is “Air” with a type designation of carrier. It is a part of team blue and its enemies are red. It only goes to a single deploy site, so its only subsystem is an agent launcher. The agent launcher subsystem is responsible for configuring and launching sub-agents, in this case: mines. The air delivery state machines are transiting to the deploy site, launching agents, and following waypoints to egress out of the AoR. The air delivery agent begins its transit to the area of operations at 240 knots. Upon reaching the deployment site, the agent deploys 40 mines. The air delivery agent then proceeds to an exit waypoint. Table 4 presents an overview of the blue air delivery agent characteristics, subsystems, and state machines. Figure 28 shows an example case where the blue air delivery agent transits to the minefield location and immediately deploys its mine, where the blue and green circles represent the detection envelopes of the mines.

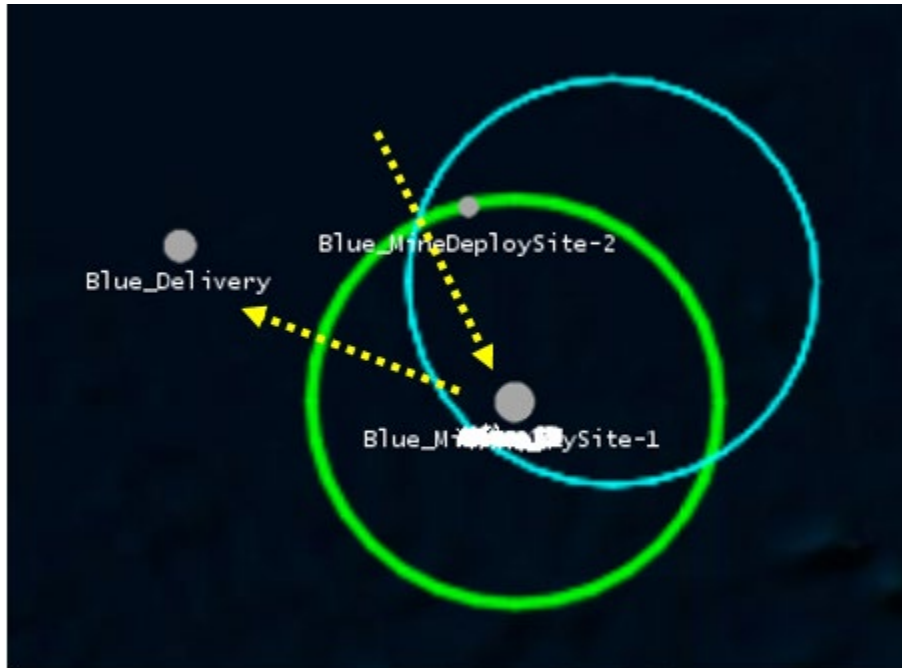


Figure 28. Air Minefield Deployment

Table 4. Air Delivery Agent Setup Parameters

Platform	Subsystems	State Machines
Name: Air	Agent Launcher; # of Agents: 40	Go to Deploy Site: 240 knots
Type: Carrier		Launch Agent
Team: Blue		Follow Waypoints: 240 knots
Enemies: Red		

b. Vessel Delivery Experiment

The surface delivery method is characterized by a single delivery vehicle moving at medium speed, deploying a large quantity of mines at two different mine deployment locations, and then progressing to an egress point.

For the vessel model, the platform name is “Blue_Delivery” with a type designation of carrier. It is a part of team blue and its enemies are red. It goes to two deploy sites, so it has two subsystems that are both agent launchers. The agent launcher subsystem is responsible for configuring and launching sub-agents, in this case: mines. The vessel

delivery state machines are transiting to the deploy site, launching agents, and following waypoints to egress out of the AoR. The vessel delivery agent begins its transit to the area of operations at 50 knots. Upon reaching the first deployment site the agent deploys 60 mines. It then transits to the second deployment site, where it deploys 60 mines. The vessel delivery agent then proceeds to an exit waypoint. Figure 29 shows an example case where the blue vessel delivery agent transits to the minefield location and immediately deploys a large quantity of mines. The blue vessel delivery agent then transits to the second deploy site, and deploys another quantity of mines. The blue and green circles represent the detection envelopes of the mines. Table 5 presents an overview of the blue surface vessel characteristics, subsystems, and state machines.

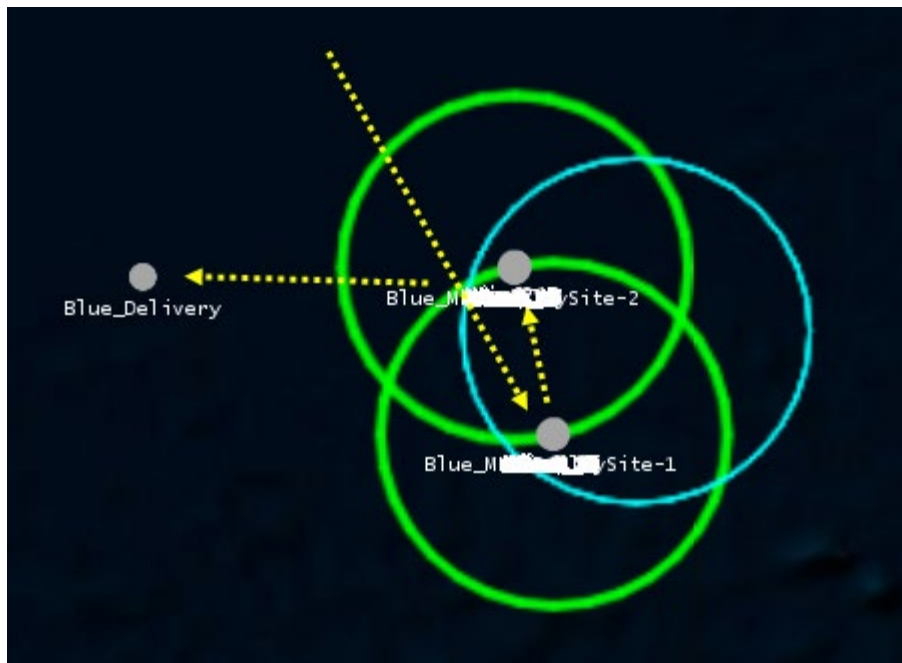


Figure 29. Vessel Minefield Deployment

Table 5. Vessel Delivery Agent Setup Parameters

Platform	Subsystems	State Machines
Name: Blue_Delivery	Agent Launcher Mine 1; # of Agents: 60	Go to Deploy Site 2: 50 knots
Type: Carrier	Agent Launcher Mine 2; # of Agents: 60	Launch Agent
Team: Blue		Go to Deploy Site 1: 50 knots
Enemies: Red		Launch Agent
		Follow Waypoints: 50 knots

c. UUV Delivery Experiment

The UUV deployment is characterized by a mothership that deploys a UUV to perform mine laying operations. The mothership moves into the area and deploys a UUV vehicle, and then maintains station outside of the deployment envelope. The UUV vehicle travels to the first deployment site and deploys a payload of mines. It then returns to the mothership and waits for a rearming period. After this delay, it repeats the deployment at the second mine site. The UUV vehicle then returns to the mothership and the mothership egresses to an egress point.

For the UUV model, the platform name is “DeliveryMothership” with a type designation of carrier. It is a part of team blue and its enemies are red. It is configured to launch a UUV and communicate with the UUV. Therefore, its subsystems are an agent launcher, transmitter, and receiver. The agent launcher subsystem is responsible for configuring and launching sub-agents, in this case: UUVs. The transmitter and receiver subsystems both have a communication range of 100,000 nm and are set to channel “DeployChannel.” Note that the 100,000 nm communication range is not intended to represent currently fielded systems, rather it is a modeling choice to avoid minefield deployment failures that occur in MAST when the delivery system transits out of range of its children systems. The mothership state machines include navigation and communications. The navigation state machines are transiting to the deploy site, launching agents, holding position, and following waypoints to egress out of the AoR. The mothership delivery agent begins its transit to the area of operations at 50 knots. Upon

reaching the first deployment site the agent deploys a single UUV agent and then maintains station outside of the deployment envelope until it receives a message from the UUV that it has completed its mission. Upon receiving the mission complete message, the mothership delivery agent then proceeds to an exit waypoint at 50 knots. The communications only has one state machine that is a communications manager. The communications manager is set to listen for “Message A” on channel “DeployChannel.” Table 6 presents an overview of the UUV delivery agent characteristics, subsystems, and state machines.

Table 6. UUV Delivery Agent Setup Parameters

Platform	Subsystems	State Machines
Name: DeliveryMothership	Agent Launcher - UUV; # of Agents: 1	Blue Navigation
Type: Carrier	Transmitter: Communication Range: 100000 nm; Channel Names: DeployChannel	Go to Deploy Site: 50 knots
Team: Blue	Receiver: Communication Range: 100000 nm; Channel Names: DeployChannel	Launch Agent
Enemies: Red		Hold Position <i>until triggered by Message A received</i>
		Follow Wapoints: 50 knots
		Blue Communications
		Communications Manager: Message Types: Message A; Channel Names: DeployChannel

For the UUV subsystem, the platform name is “UUV” with a type designation of UUV. It is a part of team blue and its enemies are red. It is configured to launch mine agents and communicate with the mothership. Therefore, its subsystems are two agent launchers, transmitter, and receiver. The agent launcher subsystem is responsible for configuring and launching sub-agents, in this case: mines. The transmitter and receiver subsystems both have a communication range of 100,000 nm and are set to channel “DeployChannel.” The UUV state machines include navigation and communications. The navigation state machines are transiting to the deploy site, launching agents, resupplying at the mothership, returning to the mothership, and sending a message to the mothership that it has completed its mission. The UUV subsystem agent begins its transit to the area of operations at 50 knots. Upon reaching the first deployment site, the agent deploys 10 mines. It then returns

to the mothership at 50 knots to receive another payload of mines. It then transits to the second deployment site at 50 knots, where it deploys 10 mines. The UUV vessel delivery agent then returns to the mothership and sends the message that it has completed its mission, at which point the two vessels proceed to an exit waypoint at 50 knots. The communications only has one state machine that is a communications manager. The communications manager is set to listen for “Message A” on channel “DeployChannel.”

Figure 30 shows an example case where the blue UUV transits to the minefield location, deploys a single sortie, waits for a variable period, transits to a second deployment location and deploys a second sortie and subsequently exits the minefield. Table 7 presents an overview of the UUV subsystem characteristics, subsystems, and state machines.

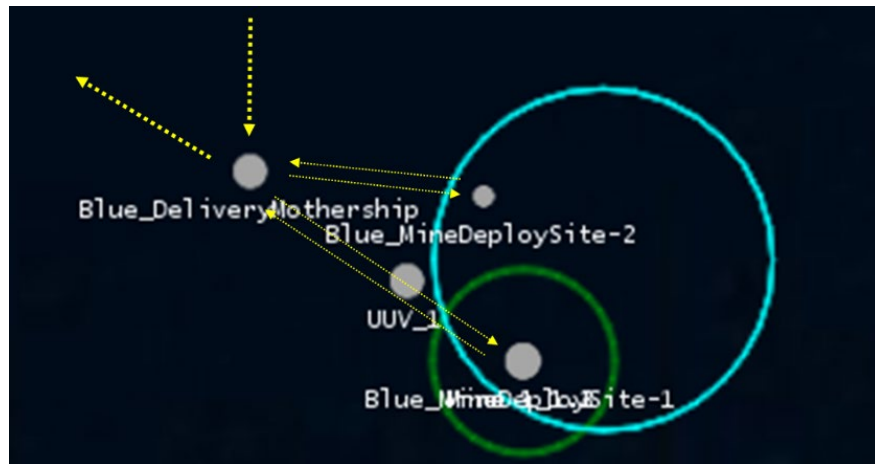


Figure 30. Mothership and UUV Minefield Deployment Route

Table 7. UUV Delivery Agent Setup Parameters

Platform	Subsystems	State Machines
Name: UUV	Agent Launcher - Mine 1; # of Agents: 10	Blue Navigation
Type: UUV	Transmitter: Communication Range: 100000 nm; Channel Names: DeployChannel	Go to Deploy Site 1: 50 knots
Team: Blue	Receiver: Communication Range: 100000 nm; Channel Names: DeployChannel	Launch Agent
Enemies: Red	Agent Launcher - Mine 2; # of Agents: 10	Resupply: 50 knots
		Resupply Delay: 3 min
		Go to Deploy Site 2: 50 knots
		Launch Agent
		Return to Mothership: 50 knots
		Send Message
		Follow Waypoints: 50 knots
		Blue Communications
		Communications Manager: Message Types: Message A; Channel Names: DeployChannel

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IV. ODM SIMULATION

Using the foundational MAST model, the team developed a strategy to determine which operational and system design considerations had the largest impact on operational effectiveness. The first step in the assessment process was the definition of appropriate MOEs. The U.S. Navy defines performance and effectiveness measures for mining through its Program Executive Officer (PEO) for Littoral and Mine Warfare (LMW) Instruction (PEOLMWINST) 3370.1A. The mining framework is focused on characterization of the mine, its employment and sustainment, in terms of minefield threat over time (PEOLMW 2008). On the other hand, the team wanted to look beyond these predefined measures with the understanding that:

1. These types of analysis have already been done, a wide breadth of equations, considerations, and tools are already available and in use by operators, planners, and developers.
2. The parameters for a given system, whether already developed or still in conception, would still need to go through these standardized measures of performance (MOPs) and MOE wickets.
3. The defined models the team used assumed these MOPs and MOEs could be plugged into future models to produce (classified) results capturing real life characterization or help define the necessary MOP or MOE of mines or mining systems being developed.
4. The MOEs utilized for assessment of the MAST model are appropriate for analysis of the operational scenario proposed in this project, but necessarily do not characterize the “true discriminator...the successful completion of the particular mission” (PEOLMW 2008). Similarly, while the MOEs have applicability for a single operational scenario, there are additional strategic planning factors that may influence resource management within an AoR.

A. PRIMARY MOE DEFINITION

ODM is built upon the “true [mine effectiveness] discriminator” (PEOLMW 2008) mission objectives. Edwards (2019) defines four objectives, but the team classified those four into just two for this project:

- Delay – the hostile agent decides to adjust its original itinerary by changing course, speed, or route but still intends to be able to achieve its intended waypoint. Edwards’ turn and disrupt missions are included in ODM’s delay mission objective. The terms delay and change course (CC) were used interchangeably throughout the project as this concept was developed, M&S efforts were progressed, and data management matured.
- Stop – the hostile agent abandons its attempt to achieve its intended waypoint. Edwards’ block and fix mission objectives are included in ODM’s delay mission objective. The terms stop and fix were used interchangeably throughout the project as the concept was developed M&S efforts were progressed, and data management matured.

To facilitate analysis, the MAST modeled captured metrics for both the quantity of red vessels delayed and stopped independently. Those metrics were combined into an operationally focused MOE termed Red Impact. Red Impact is counted (1) if the red agent chooses to execute either of these two objectives and is not counted (0) if it chooses to maintain its initial follow waypoints state. The MOE for the run is the arithmetic sum of all red vessels in the excursion that qualify. The number Red Impact is a discrete output as low as zero (if all red vessels, when faced with a decision to proceed into a known minefield, choose to proceed) and as high as the number of red vessels modeled in the simulation (if all red vessels, when faced with a decision to proceed into a known minefield, choose not to proceed, i.e., change course or fix in place instead.) For this project, each experiment was run against two red vessels, so the range of Red Impact is between zero and two, inclusive [0,2]. Though the number of red vessels impacted is a discrete variable in a given MAST excursion, Red Impact was averaged over multiple probabilistic MAST

experiment runs allowing it to be analyzed using mean and confidence interval to compare across experiment scenarios.

In analyzing the comparison of alternative across the different defined MAST experiments using Red Impact the team can address both the true discriminator of mining effectiveness and help better inform strategic decision makers in how to best utilize their available resources to achieve the desired outcome or at least understand some of the tradeoffs that are available to them.

B. SECONDARY MOES AND ANALYSIS PARAMETERS

To ensure the operational impact of this report and to differentiate this analysis from previous studies the Red Impact MOE is the primary focus of analysis. However, verifying the model operated as intended through supportive output data and then validating that data against real world expectations would need to use additional or secondary MOEs. Secondary MOEs are categorized by those that directly support defining the ODM trade spaces (implicit) and those used for model V&V, troubleshooting, debugging, and/or interest to the team or to inform future efforts.

1. Implicit

a. Time to Deploy

Collection of the time it takes the blue delivery vehicle to finish laying the minefield is a powerful secondary MOE because it broadens the trade space around ODM to an analysis of alternatives (AOA) at the strategic level rather than the tactical level. A given delivery platform is limited to only specific types and payloads of certain ordnance, either from a platform constraint or by availability of the number of mines to be loaded. Traditional examination would likely assess a small number of those variations to determine their effects on the resultant minefield threat calculation. It is cumbersome and time consuming to subsequently add system characteristics such as speed of deployment for each of the alternative platforms. Instead, theater resource are first chosen and then used to achieve the desired threat. ODM modeling, however, not only captures and expands the traditional analysis space, it facilitates the wider range of platform AOA. The team

simplifies the nomenclature of the experiment scenarios to reflect the obvious difference in transiting speeds between aircraft, vessels, and UUVs.

Time to deploy is captured in the MAST experiments by collecting the time tag on the last mine agent to be launched at the last deploy site the delivery vehicle visits. The terms time to deploy and last mine deployed are used interchangeably throughout the project as the concept was developed, M&S efforts were progressed, and data management matured. Time to deploy (last mine deployed) is a continuous variable greater than zero and is reported in seconds.

b. Agent Death

Collection of the number of red agents killed (agent death) was important on several levels. First, it is a simple statistic that facilitates the comparison of alternatives across experiment scenarios. Second, due to the model logic red vessels are in one of four transit states: follow waypoint, change course, fix, or dead. By collecting the primary MOE (Red Impact) and death, the team can infer red vessels that continue in follow WP effectively unmolested. Lastly, it captures effectiveness using a traditional MIW metric, adversary casualties, which eases model V&V and positions ODM using a commonly accepted frame of reference. As with the Primary MOE, Agent death is a discrete variable between zero and two, inclusive [0,2].

2. Derived

a. Agent Hit

Collecting the total number of hits a red agent sustained in a given MAST excursion was important because it would be expected that not every mine that is triggered will destroy an enemy. The number of red agents hit (agent hit) is defined as the sum of all hits received by any red vessel over the course of the excursion. Agent hit is a discrete variable and has a range between zero and the total number of mines deployed in each MAST excursion (total mines), inclusive [0, total mines]. While it is possible for a single mine to simultaneously hit multiple targets, the MAST implementation of mine engagement limits the number of agents hit by a mine to one.

b. Total Mines

The total mines MOE is captured in the MAST experiments by adding the number of mines deployed (N_minesDeploy) at each deployment site together. This addresses the number of mine effects across experiment scenarios per the assumptions in Table 3 to reflect the upper limit of deployment capacity.

A summary of all the MOEs explored during this project is shown in Table 8.

Table 8. ODM MOE Summary

M O E	Alternate Nomenclature	min	max	units	category
red impact	number impacted	0	2	vessels	Primary MOE
last mine deployed	time to deploy	0	∞	seconds	Secondary MOE
agent death	number red vessels kill	0	2	vessels	Secondary MOE
agent hit	-	0	total mines	hit	derived MOE
total mines	number deployed	0	as defined	mines	derived MOE

C. DESIGN OF EXPERIMENTS

1. Defining DOE Input Variables

In order to capture the MOEs, the team had to isolate the list of factors from the various agent behavioral criteria available and decide over what ranges those parameters would need to be exercised. Although the experiment files use air, vessel, and UUV nomenclature, the team was very deliberate in setting up these scenarios as to not model any real life platforms, weapon systems, or stockpiles. Across the DOE, each baseline had to capture a more general category of parameters. Table 3 shows the summary parameters across experiments the team compared in the DOE. To capture these high-level experiment assumptions individual MAST agent parameters corresponding to general concepts. Those parameters fall into three major categories: blue agent characteristics, red agent characteristics, and red agent behaviors.

a. Blue Capability DOE

(1) Blue Delivery Speed

To capture the time to deploy MOE, blue delivery platform speed (V_mineDeploy) was varied as it transits to a deployment site. V_mineDeploy for air was run between 250 and 500 knots as a fast delivery platform per Table 3. For vessel V_mineDeploy, the ingress and egress speeds were held constant at 50 knots and the transit speed between deployment sites within the minefield was varied between 10 and 35 knots

(2) Blue Payload Capacity

The number of mines the blue delivery agent will deploy was varied based on platform and repeated for each deployment site. A range for the air delivery platform to drop at its sole deployment site was set between 20 and 40 of relatively low yield mines per Table 3. The number of mines deployed (N_minesDeploy) for the other experiment files was defined the same way across all deploy sites. As the platform describing the highest capacity of mines (Table 3), the vessel DOE ranged between 20 and 40 moderately effective mines per site. As the smallest delivery payload capable platform, UUV was only limited to between 1 and 10 mines per site but lay highly capable mines.

(3) Blue Mine Capability

To avoid classification issues specific mine characteristics were not used in the MAST model. Rather, the performance parameters for the mines were varied based on the delivery platform. The differences across platforms can be summarized by saying that the air agent can quickly deploy a moderate amount of less effective mines, the vessel can deliver a large payload of moderately capable mines, and the UUV delivers a limited number of highly capable mines. Capability, or relative effectiveness, of a mine was modeled using three MOPs: the range (R_ID) at which it could detect (or identify [ID]), the likelihood (P_Det) of which it would detect (or ID), and the likelihood (P_hit) that it would properly engage a target.

Within each excursion, mines dropped at the same site share the same characteristics, however, the MAST model architecture designated mines at different

deployment locations as different agents subject to different parameters. Administrative designation of the actual values assigned to the mines of a site were not able to be linked as a global variable and therefore processed differently in the DOE. Although the simulation made that distinction, adding an additional set of mine parameters for each additional deployment site, the site designator(s) are left out of the description here to minimize redundancy because the DOE parameters were equivalent.

Probability of detection (P_{Det}) is an MOP widely used across almost any sensor. It usually is defined in terms of likelihood as a function of distance from the sensor. The models do not incorporate range dependent probabilities of detection, but instead uses randomly assigned maximum range and a probability randomizer to determine if an enemy ship is detected. In the first round of simulation runs, the entire spectrum of probability was used, from zero to one, to minimize any user defined bias for mine performance. Like detection probability, the probability of proper engagement triggers were also explored over the maximum variation of zero to one. The only input was to define a more capable mine (UUV delivery experiment) as having a larger range of detection than the moderately capable mines (vessel delivery experiment) which was higher than lowest (air delivery experiment). DOE ranges are summarized for all five blue characteristics in Table 9.

Table 9. Blue Characteristics DOE Summary

Blue Capability DOE	V_mineDeploy (knots)		N_minesDeploy (number)		Mine P_Det (probability)		Mine R_ID (nautical miles)		Mine P_hit (probability)	
	<u>min</u>	<u>max</u>	<u>min</u>	<u>max</u>	<u>min</u>	<u>max</u>	<u>min</u>	<u>max</u>	<u>min</u>	<u>max</u>
Air	250	500	20	40	0	1	15	30	0	1
Vessel	10	35	40	60	0	1	30	45	0	1
UUV	3.5	20	1	10	0	1	45	60	0	1

b. Red Agent Characteristics

(1) Red Transit Speed

The variables assigned to each red vessel were unique and independent from the other red vessels but assigned in the same way. The range of possible red vessel transit speed (V_{followWP}) was randomized in each excursion to be between 5 and 50 knots, inclusive.

(2) Red Equipment

Once a red vessel transitioned out of their initialization hold and started steaming towards its intended destination, all modeled sensors are activated and looking for mines. Two red characteristics were modeled to capture an enemy's capabilities, their ability to detect blue mines, and their ability to share information and coordinate. To minimize unintentional bias, the entire probability spectrum from zero to one was explored when capturing both the likelihood of a red vessel being able to communicate (P_{tx}) and the chance (Red P_{Det}) that it would be able to find a mine within its sensor range. Through the initial DOE, the range (R_{mineID}) of detection (ID) was explored from a very incapable zero nautical mile (no sensors on board, relying on the other vessel to communicate danger) to a completely unrealistic 100 nm (leaving the chance of discovery to the probability randomizer.)

(3) Red Survivability

The last red capability modeled was the idea that even though the mine could execute its engagement exactly as planned the damage the red vessel would receive may not be consistent for all vessels. A third red probability was introduced to capture the likelihood that the vessel would be lost (P_{Death}) given it was hit by the mine. As with all first round DOE ranges, the entire spectrum was explored.

The DOE ranges for all five of the red vessels capability parameters are summarized in Table 10.

Table 10. Red Characteristics DOE Summary

Red Capability DOE	Red V_followWP (knots)		Red P_Det (probability)		Red R_mineID (nautical miles)		Red P_tx (probability)		Red P_Death (probability)	
	min	max	min	max	min	max	min	max	min	max
Air	5	50	0	1	0	100	0	1	0	1
Vessel	5	50	0	1	0	100	0	1	0	1
UUV	5	50	0	1	0	100	0	1	0	1

c. Red Agent Behaviors

The MAST model also incorporated randomized state change logic presented to the red vessels when they are made aware of the presence of a mine (either through onboard sensor detection or via a warning command transmitted from the other vessel that detected the mine.) A vessel decides to either disregard the information completely, continue on its way but execute a different route (change course), or give up (fix) on achieving its intended waypoint. The probability that a vessel will decide to transition off its original planned itinerary is independently assigned to each vessel, modeling more cautious adversaries (fix) and those who would be more cavalier (change course).

(1) Fix Position

The cautious adversary is represented by a vessel with a high probability to fix (P_fix) in place. The ODM experiments simplified Edwards' fix and block objectives (2019) into the stop function (sometimes labeled fix or hold in the software). The concept is agnostic to whether the enemy flees or holds, the operative goal of preventing arrival at its destination is achieved.

(2) Change Course

The model also captures the adversary who will not be denied and is willing to alter its course, even by retreating slightly, before carrying on. This behavior is captured across two factors, first the probability (P_cc) that an enemy is willing to change course and alter its route to its destination and the extent to which that route will be altered (Angle_cc.) When deciding to change course, a vessel can take up to a 120° turn in either direction. The DOE defines these parameters and no bias is given to alter path into or away from further danger. This was done to represent the possibility that a red vessel that decides to change course may alter its course towards another mine in the minefield. As with all other initial DOE probability ranges, probability of fixing and probability of changing course were allowed through the entire spectrum.

The summary of ranges for red behavior tendencies are shown in Table 11.

Table 11. Red Behavior DOE Summary

Red Behavior DOE	Red P_fix (probability)		Red P_cc (probability)		Red Angle_cc (degrees)	
	min	max	min	max	min	max
Air	0	1	0	1	-120	120
Vessel	0	1	0	1	-120	120
UUV	0	1	0	1	-120	120

2. DOE Analysis Type

MAST includes a native experimental design feature to facilitate analysis. MAST specifically implements nearly orthogonal Latin hypercube (NOLH) designs, which are well suited to operational simulations due to their space filling properties (Sanchez 2011). The DOE feature allows a user DOEs of up to 7, 11, 16, 22, or 29 different variables. Because the number of deploy sites is different across experiments, the air delivery experiment was able to use the 22-point NOHL setup to capture its 21 variables, but the

larger 29-point NOLH designs were needed to capture vessel and UUV's 25 variables. The 22-design point NOLH defined 129 design points. Similarly, the 29-design point NOLH is defined by 257 design points. The table showing the output of the calculated OLH files for air are shown in Table 12.

3. MAST DOE Setup

Although MAST features an integrated NOLH design size selection, all of the defined variables and ranges needed to be entered in the “Variables” section of the “DOE Setup” dialog, shown in Figure 31. The team utilized “Number” variables to allow minimum and maximum values to be entered. Note that the variables GUI only displays a tab and a half of variables and was not adjustable despite displaying a significant amount of data. Also, the variable nomenclature, labeled “ID,” uses a string file path construction based on the agent name and progressing down the subcategorization breakdown. Proper selection was deliberate and methodical yet still required tedious scrutiny to produce the right output. The manual process of designation, selection, and definition was done for all 21 times for Air and 25 times for each UUV and Vessel DOE parameters not accounting for mis-selections, rework, and verification during troubleshooting.

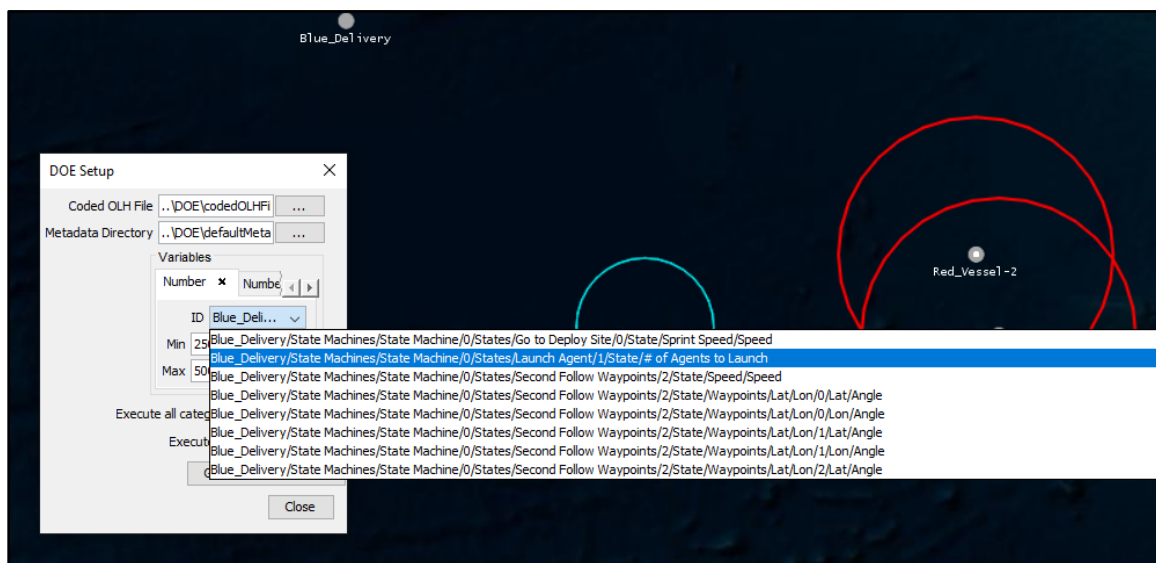


Figure 31. DOE Setup GUI

Table 12. Air Input Variable Correlation Matrix

	V_mineD eplpy	Mine1 P_Det	Mine1 R_ID	Mine1 P_hit	Red1 P_tx	Red1 V_follow WP	Red1 p_death	Red1 P_Det	Red1 R_mineID	Red1 P_cc	Red1 P_fix	Red1 angle_cc	Red2 P_tx	Red2 V_follow WP	Red2 P_Death	Red2 P_det	Red2 R_mineID	Red2 P_cc	Red2 P_fix	Red2 angle_cc
V_mineDeploy	1.0000	0.0000	0.0000	0.0000	0.0010	-0.0043	0.0019	0.0008	-0.0043	0.0008	-0.0021	0.0000	-0.0011	-0.0006	-0.0020	0.0002	-0.0029	0.0011	-0.0024	0.0000
Mine1 P_Det	0.0000	1.0000	0.0000	0.0001	0.0006	0.0016	-0.0009	-0.0052	-0.0011	0.0032	-0.0026	-0.0011	0.0005	-0.0001	0.0008	0.0034	0.0028	-0.0049	-0.0022	0.0001
Mine1 R_ID	0.0000	0.0000	1.0000	0.0000	0.0009	-0.0016	0.0006	0.0025	0.0001	-0.0044	0.0036	-0.0028	-0.0019	0.0013	-0.0017	-0.0010	0.0027	0.0006	-0.0035	0.0000
Mine1 P_hit	0.0000	0.0001	0.0000	1.0000	0.0052	-0.0031	-0.0040	0.0006	0.0001	-0.0037	0.0023	0.0005	0.0035	-0.0019	0.0006	-0.0035	0.0013	-0.0024	0.0002	0.0000
Red1 P_tx	0.0010	0.0006	0.0009	0.0052	1.0000	0.0028	0.0032	-0.0009	-0.0006	-0.0008	0.0025	-0.0002	-0.0014	0.0074	0.0007	-0.0007	-0.0029	-0.0023	-0.0025	-0.0023
Red1 V_followWP	-0.0043	0.0016	-0.0016	-0.0031	0.0028	1.0000	-0.0031	0.0000	-0.0044	-0.0012	-0.0008	0.0008	0.0010	-0.0021	-0.0043	0.0000	-0.0004	-0.0025	0.0043	0.0017
Red1 p_death	0.0019	-0.0009	0.0006	-0.0040	0.0032	-0.0031	1.0000	0.0038	0.0055	0.0000	0.0033	0.0014	-0.0023	0.0013	0.0003	0.0028	0.0036	-0.0027	-0.0048	-0.0018
Red1 P_Det	0.0008	-0.0052	0.0025	0.0006	-0.0009	0.0000	0.0038	1.0000	0.0007	-0.0009	-0.0011	0.0043	0.0021	-0.0004	-0.0011	0.0042	-0.0013	0.0029	0.0037	0.0013
Red1 R_mineID	-0.0043	-0.0011	0.0001	0.0001	-0.0006	-0.0044	0.0055	0.0007	1.0000	0.0049	-0.0017	0.0027	0.0044	-0.0033	0.0000	0.0004	0.0021	-0.0023	-0.0024	0.0044
Red1 P_cc	0.0008	0.0032	-0.0044	-0.0037	-0.0008	-0.0012	0.0000	-0.0009	0.0049	1.0000	-0.0001	0.0032	0.0045	0.0044	-0.0028	-0.0017	-0.0045	0.0005	0.0008	0.0019
Red1 P_fix	-0.0021	-0.0026	0.0036	0.0023	0.0025	-0.0008	0.0033	-0.0011	-0.0017	-0.0001	1.0000	-0.0028	-0.0012	0.0004	0.0027	0.0013	-0.0024	-0.0015	0.0028	0.0065
Red1 angle_cc	0.0000	-0.0011	-0.0028	0.0005	-0.0002	0.0008	0.0014	0.0043	0.0027	0.0032	-0.0028	1.0000	-0.0015	0.0052	-0.0023	0.0035	0.0018	0.0039	-0.0023	-0.0003
Red2 P_tx	-0.0011	0.0005	-0.0019	0.0035	-0.0014	0.0010	-0.0023	0.0021	0.0044	0.0045	-0.0012	-0.0015	1.0000	-0.0013	0.0050	0.0031	-0.0033	-0.0021	-0.0033	0.0003
Red2 V_followWP	-0.0006	-0.0001	0.0013	-0.0019	0.0074	-0.0021	0.0013	-0.0004	-0.0033	0.0044	0.0004	0.0052	-0.0013	1.0000	-0.0003	-0.0016	0.0005	-0.0029	0.0007	-0.0034
Red2 P_Death	-0.0020	0.0008	-0.0017	0.0006	0.0007	-0.0043	0.0003	-0.0011	0.0000	-0.0028	0.0027	-0.0023	0.0050	-0.0003	1.0000	-0.0026	0.0002	0.0013	0.0028	0.0000
Red2 P_det	0.0002	0.0034	-0.0010	-0.0035	-0.0007	0.0000	0.0028	0.0042	0.0004	-0.0017	0.0013	0.0035	0.0031	-0.0016	-0.0026	1.0000	0.0003	-0.0027	0.0049	-0.0019
Red2 R_mineID	-0.0029	0.0028	0.0027	0.0013	-0.0029	-0.0004	0.0036	-0.0013	0.0021	-0.0045	-0.0024	0.0018	-0.0033	0.0005	0.0002	0.0003	1.0000	0.0006	-0.0012	-0.0004
Red2 P_cc	0.0011	-0.0049	0.0006	-0.0024	-0.0023	-0.0025	-0.0027	0.0029	-0.0023	0.0005	-0.0015	0.0039	-0.0021	-0.0029	0.0013	-0.0027	0.0006	1.0000	0.0023	0.0002
Red2 P_fix	-0.0024	-0.0022	-0.0035	0.0002	-0.0025	0.0043	-0.0048	0.0037	-0.0024	0.0008	0.0028	-0.0023	-0.0033	0.0007	0.0028	0.0049	-0.0012	0.0023	1.0000	0.0035
Red2 angle_cc	0.0000	0.0001	0.0000	0.0000	-0.0023	0.0017	-0.0018	0.0013	0.0044	0.0019	0.0065	-0.0003	0.0003	-0.0034	0.0000	-0.0019	-0.0004	0.0002	0.0035	1.0000

Once all the factors, minimum and maximum values were manually entered, data collection had to be set up defining which event parameters to capture in the excursion log and where to output those files. Under “Data Options,” the team selected only the five data points shown in Figure 32. Note that data deselection or conservative inclusion to only important events is key to file output size and proved pivotal in leveraging the team’s organic computing capabilities. Outputs were originally limited to “Agent enters or leaves a state,” “Waypoint achieved,” “Scenario ends” and “Summary at end,” and “Agent is hit” and “Agent death.”

Detailed Log X

Output Directory:

Data Options

Agents

- ☐ Agent initialization
- ☐ Geometry initialization
- ☐ Agent launched
- ☐ Positions and velocities for: Check every: sec
- ☒ Agent enters or leaves a state
- ☐ Agent enters or leaves a wake. Check every: sec
- ☐ Agent enters or leaves a geometry/crosses a geometry line. Check every: sec
- ☒ Waypoint achieved
- ☐ Resources transferred

Sensors

- ☐ Initial detection
- ☐ Updated detection
- ☐ Passive detection
- ☐ Sensor identification
- ☐ Agent receives a detection/track/identification from another source
- ☐ Track dropped on an agent
- ☐ Jamming ends on an agent
- ☐ Electronic attack used

Orders

- ☐ Agent sends an order
- ☐ Agent receives an order
- ☐ Agent responds to an order

Scenario

- ☒ Scenario ends
- ☒ Summary at end

Attacks

- ☒ Agent is hit
- ☒ Agent death
- ☐ Agent fires a gun
- ☐ Gun burst intercepted target
- ☐ Agent fires a missile or torpedo
- ☐ Fire on bearing
- ☐ Missile seeker turns on
- ☐ Missile think rate
- ☐ Missile seeker detects a target
- ☐ Missile seeker acquires a new target
- ☐ Missile intercepts a target
- ☐ Missile dies/is removed from simulation
- ☐ Illumination ends on a target
- ☐ Laser fire
- ☐ Kill assessment results returned
- ☐ Disengage notice
- ☐ Point Defense

Figure 32. MAST Detailed Log Selections

4. Running the DOE

Although the team experienced relative success in early developmental efforts and DOE runs across smaller sampling output and even the final air delivery scenario, computing power on the teams’ government furnished equipment (GFE) proved inadequate to

complete even a single 29-point NOLH and necessary data output collection. A search for other resources available for the team to leverage led the team to utilize the Simulation Experiments and Efficient Designs (SEED) Center for Data Farming's Hamming High Performance Computing (HPC) machines. The Hamming HPC machines were configured to run MAST experiments. Note that the SEED Center for Data Farming's Hamming HPC configuration is a custom design which required close collaboration with the lead MAST developer to produce the MAST 2.9 style outputs. No longer technologically constrained, each scenario was run across 30 independent DOEs.

5. Data Formatting Process

The output data from MAST is formatted as a comma separated text file, which for a limited amount of desired data returned approximately 200 lines of data for each run of the DOE. Each MAST data point corresponded to a sensor detection, state change, or engagement status correlated to the time which it occurred in the model. Due to the quantity of data and the iterative troubleshooting which took place once the macro data was available a data extraction mechanism had to be designed and refined for use. It was determined that Visual Basic for Applications (VBA) to augment Microsoft Excel's data presentation ability would be most useful due to group knowledge, and the precise and repetitive nature of the MAST output files. As with the initial DOE execution, the 30 runs of the 22-point NOLH air deployment experiments (3870 excursions) was processed without incident. However, collation of the 30-run 29-point NOLH for both the vessel and the UUV experiments was limited to include only 5000 excursions, the equivalent to just over 19 runs.

The VBA code was utilized to summarize each run in a tab of an excel file, which was then summarized and integrated with the DOE generated using the SEED NOLH design spreadsheet (Sanchez 2011). For the initial data set, statistics were processed using Minitab to generate a high-level relative importance summary. JMP Pro (version 15.1) statistical software was utilized to conduct operational analysis per the strategy presented in MacCalman, Beery, and Paulo (2016). That analysis is presented in Chapter V and Appendix B.

V. MODEL DATA PRESENTATION AND ANALYSIS

A. PRELIMINARY RESULTS

Based on the initially assigned variables from the DOE, the simulation data and data extraction were examined to assess whether or not the model was executing appropriately. The checklist to confirm responses includes:

- Red vessel change course – return value is (0,1,2)
- Red vessel fix –return value is (0,1,2)
- Red vessel achieve final waypoint – return value is (0,1,2)
- Red vessel death – return value is (0,1,2)

Additionally, on a spot-check basis the order of events was confirmed in the data sets themselves as defined in Chapter III.

A summary level, relative importance analysis was performed for the two main MOEs: Red Impact and red agent death. The relative importance is based on a partition tree model, but summarized to describe which variable has the most influence throughout the dataset, and the proportional impact of all other variables based on the most influential variable. The objective of the relative importance analysis was to determine how to better refine DOE variables without utilizing real world data.

The red vessel death relative importance charts are shown in Figure 33 and the red vessel impact relative importance charts are shown in Figure 34.

One recurring trend from the relative importance of variables to death in Figure 33 is that the probability of red vessels changing course or fixing position are significantly more influential on the results than other variables. Additionally, variables represented as probabilities were generally more influential than those with physical values (i.e., velocities, ranges, quantity). That trend also carries through to the relative importance of variables to Red Impact in Figure 34. Of the six total relative importance charts, five of them

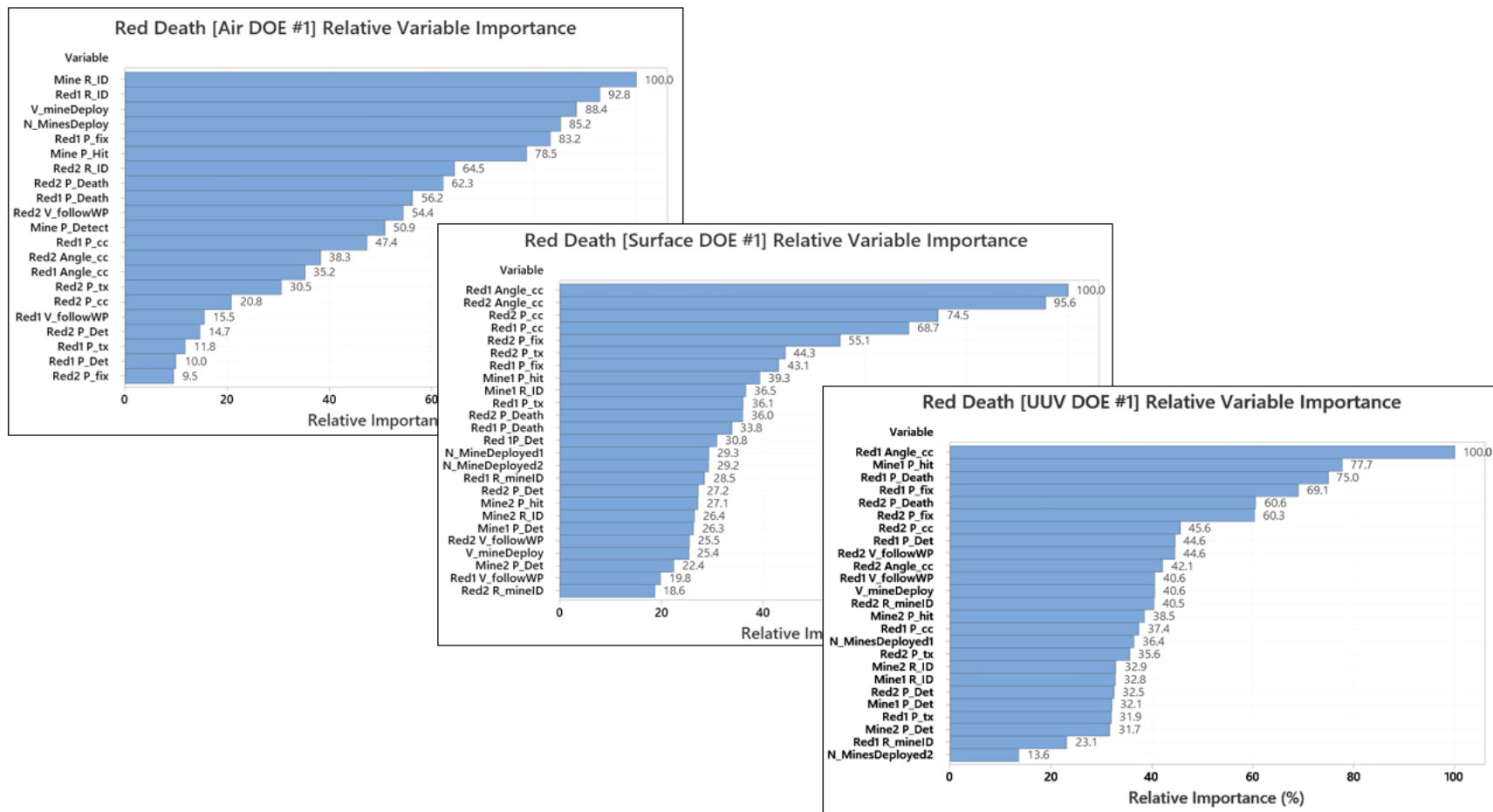


Figure 33. Agent Death Relative Variable Importance Chart

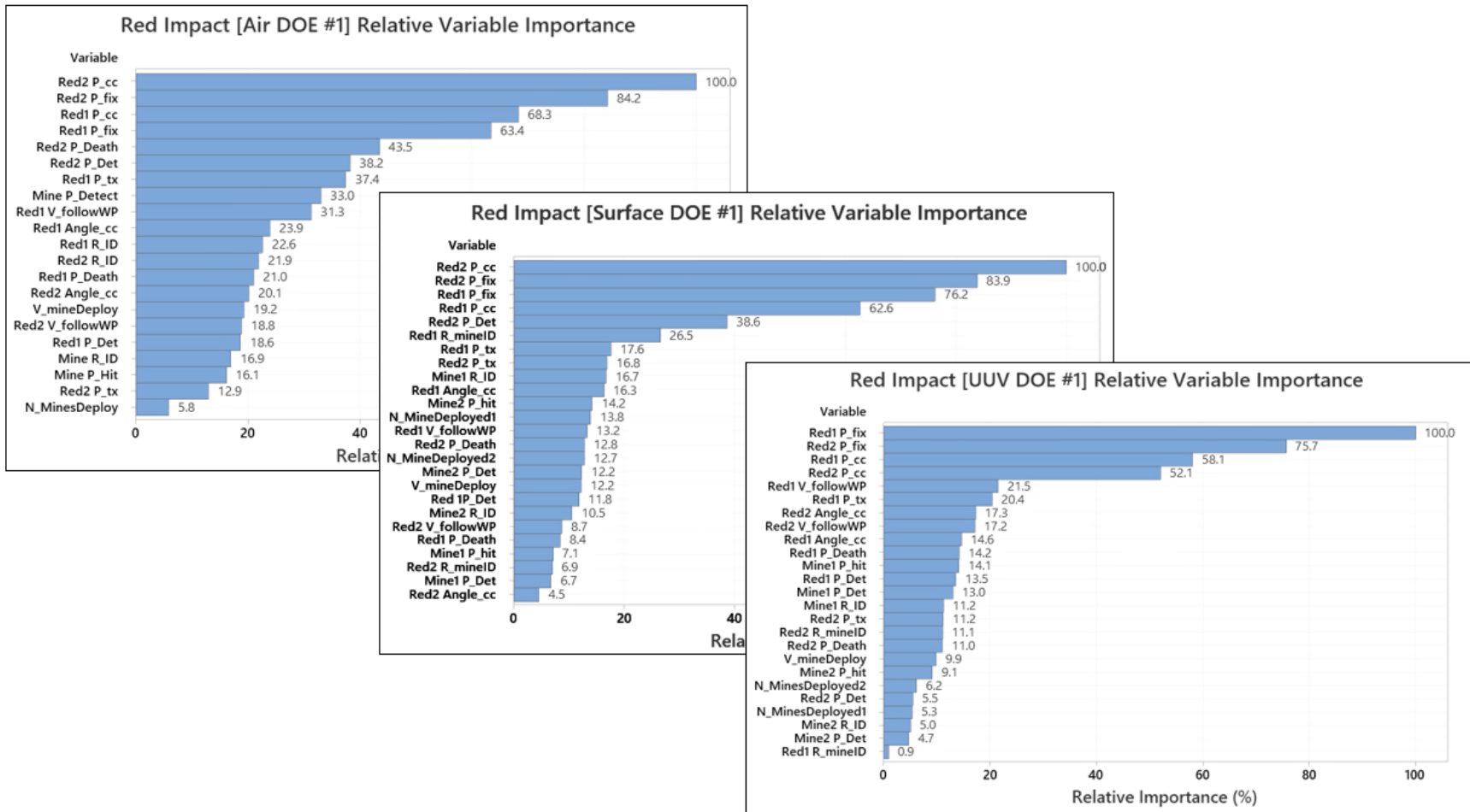


Figure 34. Red Impact Relative Variable Importance Charts

indicated the significance of probability of fix and change course had a larger impact on performance than any other variables. The exception is the red death relative variable importance when air delivery is utilized, in which the mine and red vessel radius of detection are the most important variables.

As a result of this preliminary data analysis, the conclusions were that the desired relationships in the simulation are valid. Additionally, probabilities of fix and change course were dominating the scenarios. Finally, probabilities overall had a relatively large impact overall compared to the physical values. This suggests that, when the probability of each enemy decision is varied from 0 to 1, changing those behaviors will have the largest impact on operational performance. While interesting, this does not result in actionable recommendations regarding minefield deployment or system development. Based on those conclusions, the team decided to refine many of the variables used in the DOE and run a 2nd iteration of NOLH DOE prior to final data analysis. Those specific updates are shown in Table 13, Table 14, and Table 15 with the red variables indicating changes from DOE #1 inputs.

Table 13. Mine Parameters and Capabilities DOE #2

	V_mineD eplay (knots)		N_mines Deploy (number)		Mine P_Det (probabili ty)		Mine R_ID (nautical miles)		Mine P_hit (probabili ty)	
	min	max	min	max	min	max	min	max	min	max
Air	250	500	20	40	0.6	0.9	15	30	0.6	0.9
Vessel	10	35	80	120	0.6	0.9	30	45	0.6	0.9
UUV	3.5	20	2	20	0.6	0.9	45	60	0.6	0.9

Table 14. Red Parameters and Capabilities DOE #2

	Red V_follow WP (knots)		Red P_Det (probability)		Red R_minelD (nautical miles)		Red P_tx (probability)		Red P_Death (probability)	
	min	max	min	max	min	max	min	max	min	max
Air	5	50	0.3	0.7	0	100	0.3	0.7	0.3	0.7
Vessel	5	50	0.3	0.7	0	100	0.3	0.7	0.3	0.7
UUV	5	50	0.3	0.7	0	100	0.3	0.7	0.3	0.7

Table 15. Red Behavior DOE #2

	Red P_fix (probability)		Red P_cc (probability)		Red Angle_cc (degrees)	
	min	max	min	max	min	max
Air	0.1	0.5	0.1	0.5	-120	120
Vessel	0.1	0.5	0.1	0.5	-120	120
UUV	0.1	0.5	0.1	0.5	-120	120

B. RECALIBRATION RUNS AND RESULTS

The updated DOE was similarly run through the NOHL process, once again resulting in 3870 or 5000 runs of data depending on the deployment vehicle scenario.

As shown in Figure 35 and Table 16 the Red Impact across each scenario is similar, however the deployment time varied greatly with air deployment being quickest to accomplish, and the UUV being the slowest. The vessel scenario also had the highest rate of red vessel death, while UUV and air were comparable. A notable intricacy of Figure 35 is that the air scenario “Last Mine Deployed” is clustered around two main points (approximately 3700 seconds and 5500 seconds), which is partially due to the rapid deployment in the air scenario which makes it appear more segmented than the vessel and UUV scenario.

These scenarios were further analyzed to determine which input variables had the greatest impact on results of each scenario. Categories of variables used for analysis were

leveraged from ODM Baseline Experiment Scenarios (specifically blue mine parameters and capability, red parameters and capability, and red behavioral decisions).



Figure 35. MOE Statistical Overview Histograms and Bar Chart

Table 16. MOE Statistical Overview (Average and Standard Deviation)

		Air	Vessel	UUV
Red Impact (Number of Vessels)	Mean	1.30	1.21	1.28
	Std. Dev.	0.66	0.69	0.67
Red Death (Number of Vessels)	Mean	0.43	0.98	0.58
	Std. Dev.	0.52	0.70	0.64
Last Mine Deployed (seconds)	Mean	4,160	31,264	78,512
	Std. Dev.	745	4,597	24,535

These scenarios were further analyzed to determine which input variables had the greatest impact on results of each scenario. Categories of variables used for analysis were leveraged from ODM Baseline Experiment Scenarios (specifically blue mine parameters and capability, red parameters and capability, and red behavioral decisions).

1. Blue Mine Parameters and Capability

Prior to discussing the specific blue mine parameters and capabilities, please note that for the figures in this section the X-axis encompasses the entire range of the input variable which is distinct between scenarios in multiple cases. Recall that the ranges for each of the input variables are presented in Table 13 through Table 15. Based on the operational concept modeled in MAST, the total number of mines is centered in a single location for air delivery and two locations for UUV and vessel deployment.

The most impactful blue parameter was the total number of mines, as seen in Figure 36. The relationship between the total number of mines delivered and both Red Impact and Agent Death varies based on the deployment method but is statistically significant in all cases. Note that in the UUV configurations, where the total number of mines is lower than in the air or vessel configurations, the impact of the total number of mines delivered is magnified (shown on the right side of Figure 36). With greater than or equal to 10 mines, the UUV scenario on average had 0.72 red vessel deaths, while less than 10 mines resulted in on average 0.42 red vessel deaths. At a relatively high number of mines as with the vessel scenario, the greater quantity of mines corresponded with a decrease in the probability of red vessel death but a corresponding increase in the probability of Red Impact. This is likely a result of more opportunities for the red vessels to identify the mines, which results in more opportunities to be impacted and avoid the minefield.

Amongst other mine parameters, the probability that a mine hits its target also consistently corresponds to an increased probability of red vessel death across all scenarios, shown in Figure 37. The impact of probability of mine hit on the Red Impact is less clear. For the air deployment scenario, a rising probability of hit results in a decreased Red Impact, that is also the case with the vessel deployment. However, for UUV the probability of hit either slightly increases or maintains the mean Red Impact. This is likely a factor of

the number of mines deployed, specifically with a large quantity of mines (like air or vessel scenarios) being more likely to be hit by a mine is results in more deaths and detracts from future possibilities to change course. For fewer mines (like UUV scenario), the greater probability of hit is less influential because of fewer opportunities for engagements.

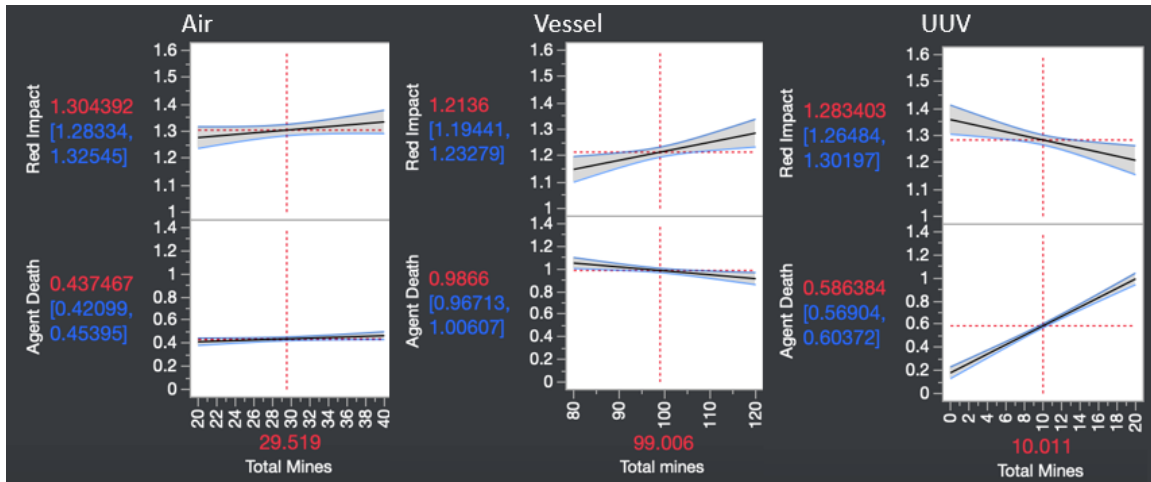


Figure 36. Total Mines Prediction Profiles

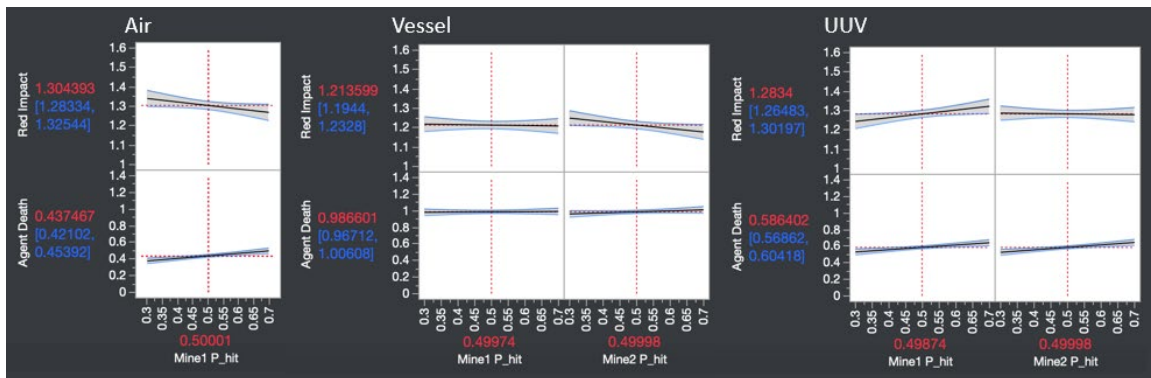


Figure 37. Mine Hit Probability Prediction Profiles

The other mine parameters and capabilities did not have consistent impacts across scenarios. The only remaining mine parameter that has a statistically significant impact is the velocity of the deploying vehicle for the UUV scenario. Figure 38 presents the relationship between the MOEs and the velocity of the deployment vehicle, with the UUV configurations shown on the right. This suggests that changes to the speed of the blue

surface and airborne delivery vessels, which already move at relatively high speeds, do not have a significant impact on operational performance. However, the UUV, which moves at a relatively slower speeds, experiences an increase in operational performance related to an increase in delivery speed.

Prediction profilers for the mine identification range and mine probability of detection are included in the Appendix B, note that neither variable is statistically significant for any of the deployment methods.

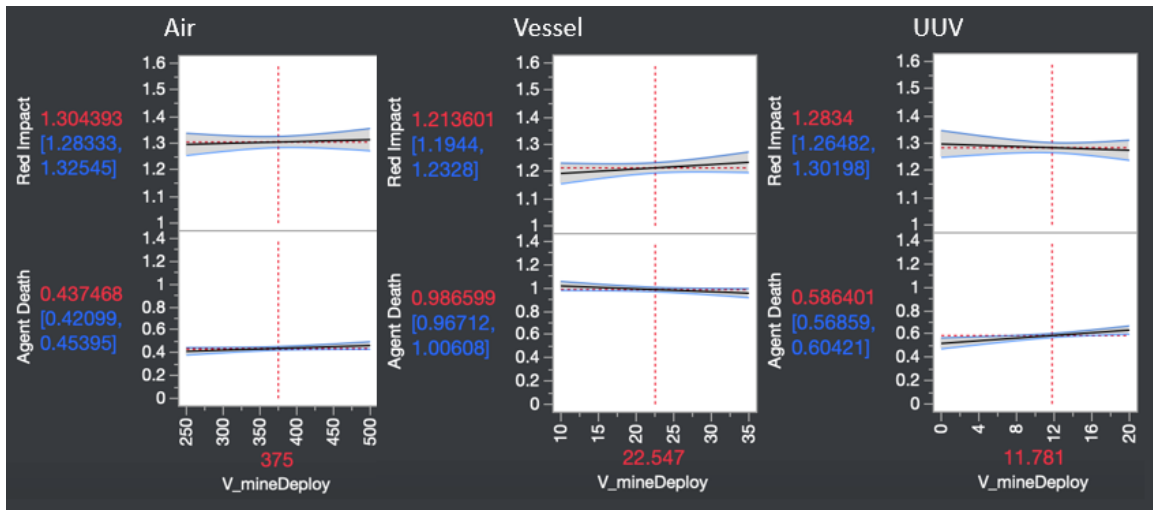


Figure 38. Blue Delivery Vehicle Speed Prediction Profiles

2. Red Parameters and Capability

Even though red parameters and capabilities are outside of the minefield planner's control, the model assesses relationships between those variables and platform performance. Red parameters and capability are a significant driver of the system results, especially when looking outside of the conventional MOEs and examining the impact on red platforms aside from just hitting or destroying them. Note in all figures in this section, design of experiments variables were selected for both red vessel 1 and red vessel 2 in each scenario.

The capability of red communications (denoted as probability of transmission) consistently improved the impact to red platforms, but also similarly decreased the

likelihood of red deaths. That trend is shown across all scenarios in Figure 39. This is unsurprising and suggests that permitting an adversary to communicate awareness of a minefield increases the chance that the adversary will alter their behavior and remain fixed or delayed by the minefield.

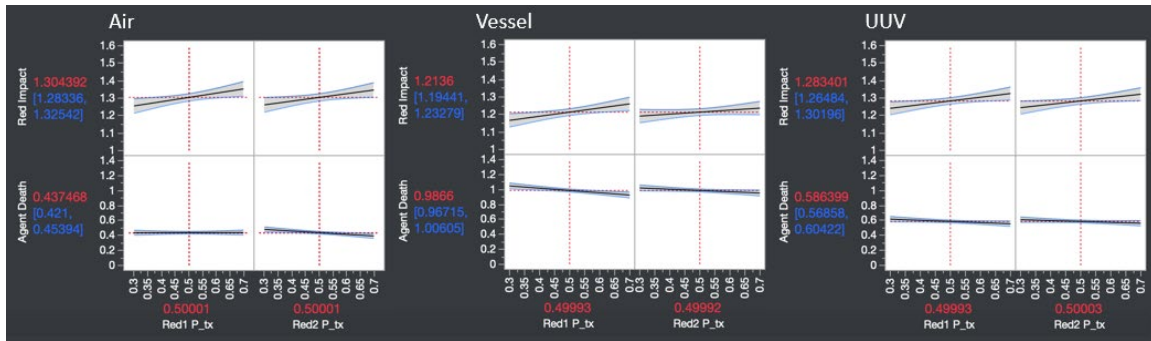


Figure 39. Red Communications Probability Prediction Profiles

Aside from the red communication, there were no variables that had a similar impact across scenarios but there were several variables that had a statistically significant impact in individual scenarios. The radius of red identifying opposition mines decreased the likelihood that the red vessels in the air scenario would take action. This reaction is unique to the air scenario and it is unclear what the driver is, as the radius of identification seemed to have little influence in the UUV and vessel scenarios seen in Figure 40. It is possible that the air deployment areas (single minefield area as opposed to two minefield areas in UUV and vessel) has a unique interaction with the red vessel transit paths compared to the other scenarios.

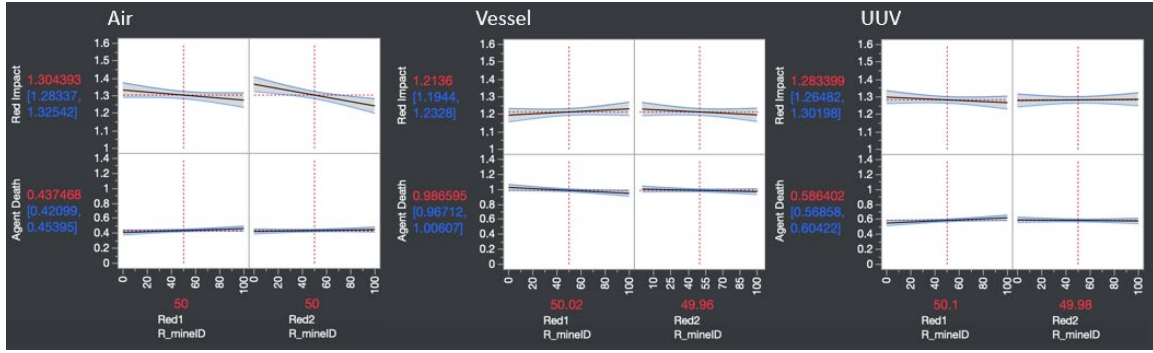


Figure 40. Red Detection Range Prediction Profiles

For the UUV scenario, which had the lowest quantity of mines deployed, the probability of red vessel death per mine hit tended to increase the probability of death as seen in Figure 41. That relationship was mitigated in the other scenarios where greater amounts of mines were deployed. This suggests that the performance characteristics of individual mines have a significant impact on operational performance as the size of the minefield is decreased. Recall that the UUV scenario utilized between 2–20 mines, while the air scenario and vessel scenario deployed between 20–40 and 80–120 mines, respectively. This suggests that, for similar operational scenarios, the probability of successful engagement for individual mines is only likely to have a statistically significant impact when the total number of mines deployed is under 20.

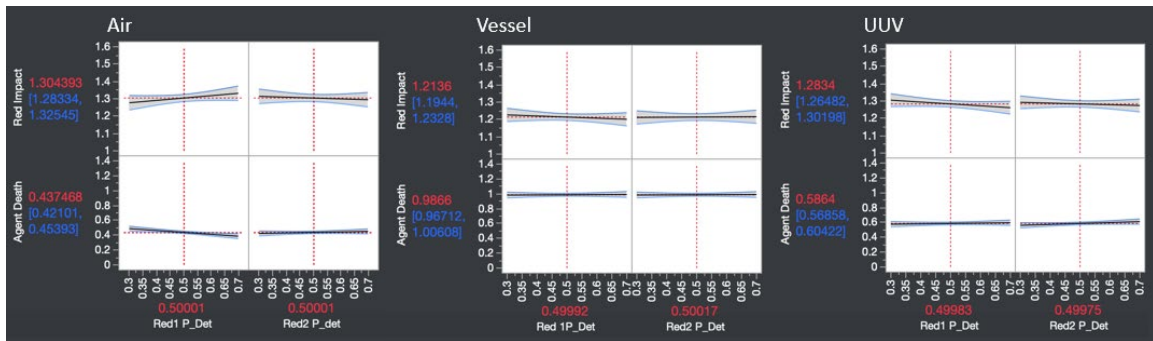


Figure 41. Probability of Death Prediction Profiles

Prediction profilers for the red vessel speed and red probability of detection are included in Appendix B, note that neither variable is statistically significant for any of the deployment methods.

3. Red Behavioral Decisions

As mentioned previously, the red decision logic has the largest impact on operational performance. The corresponding prediction profilers highlight the specific changes that can be expected in terms of Red Impact and red death based on the anticipated adversary behavior. Even though red behavior does not directly prevent red vessel death, it has a negative correlation because Red Impact makes it less likely the red vessel will be destroyed. Those relationships are visible in Figure 42 and Figure 43.

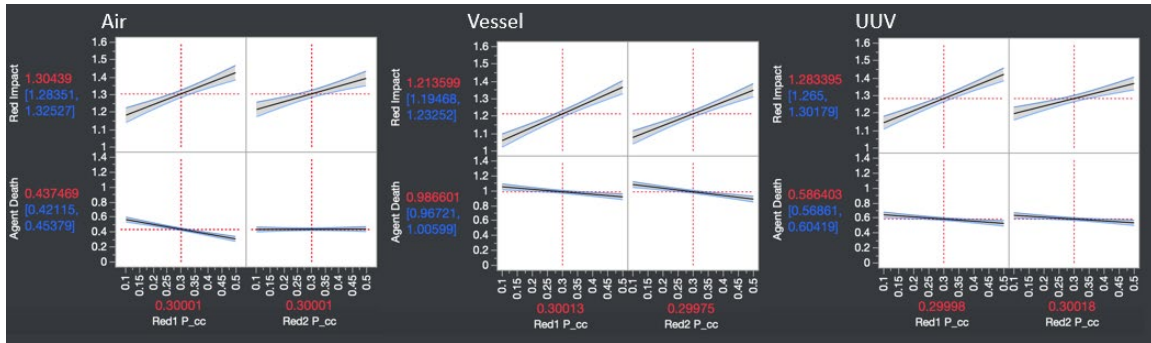


Figure 42. Change Course Probability Prediction Profiles

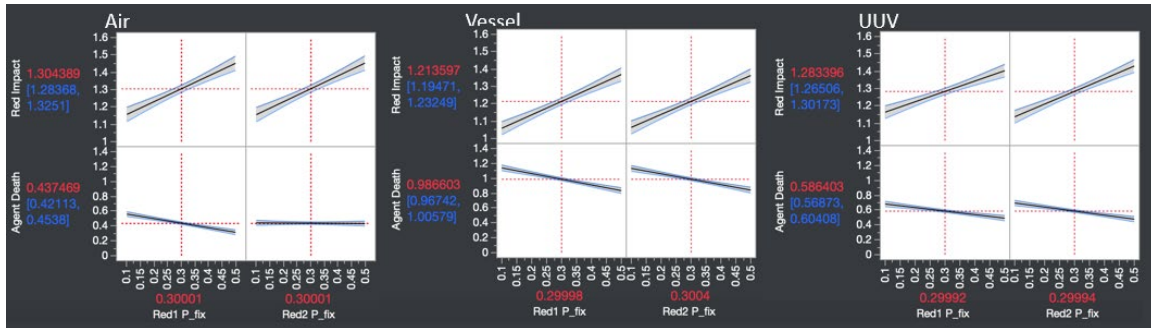


Figure 43. Fix Position Probability Prediction Profiles

While red behaviors make death less likely there were scenarios runs where the red vessel changes course, but the angle of course change is not severe enough to prevent it from transiting the minefield. The impact of the angle of change course depends on the original path of the red vessel and will also vary depending on the random mine dispersion. The relationship between angle of change course and impact and death are shown in Figure 44.

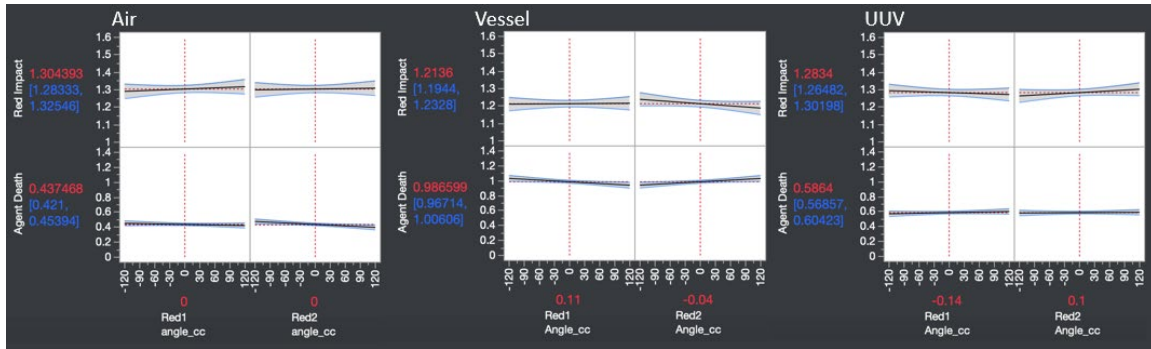


Figure 44. Change Course Angle of Turn Prediction Profiles

4. Partition Tree Analysis

To conduct analysis beyond the prediction profilers, which allowed the team to examine the isolated impact of each design characteristic, the team utilized predictive partition trees to highlight the relative importance of each design characteristic. One prediction profiler is included in the body of the report as Figure 50, the remainder of the prediction profilers are included as Appendix B. As with the partition tree analysis, red behaviors were consistently identified as having the largest impact on operational performance. While this behavior was expected to be significant, it did make in depth analysis of the minefield design characteristics difficult, so it was removed from additional analyses. For all scenarios the red vessel probability and radius of identification were amongst the most influential variables for both red vessel death and impact. Figure 50 presents a partition tree analysis which identifies the variables that have the largest impact on red agent death for UUV configurations. As expected, the number of mines correlated to higher rates of red vessel death and impact. The partition tree highlights the variables

that have the largest impact for under ten total mines on the left of Figure 50 and for over 10 total mines on the right of Figure 50. Note that when 10 or more mines are deployed red behaviors such as probability of fix and angle of changing course have the largest impact on performance. When 10 or fewer mines are deployed the probability that mines are identified as well as the probability that each mine hits its target have the largest impact on performance. This is consistent with the larger conclusion developed from the comparison of the UUV, vessel, and air deployment scenarios. The total number of mines has the largest impact on performance, even when the total number of mines is restricted to 2–20 in the UUV configuration. When the total number of mines is fixed at a low value, the characteristics of the individual mines begins to have an impact. This suggests that improvements to mine delivery capacity are likely to have a larger operational impact than improvements to individual mine performance characteristics.

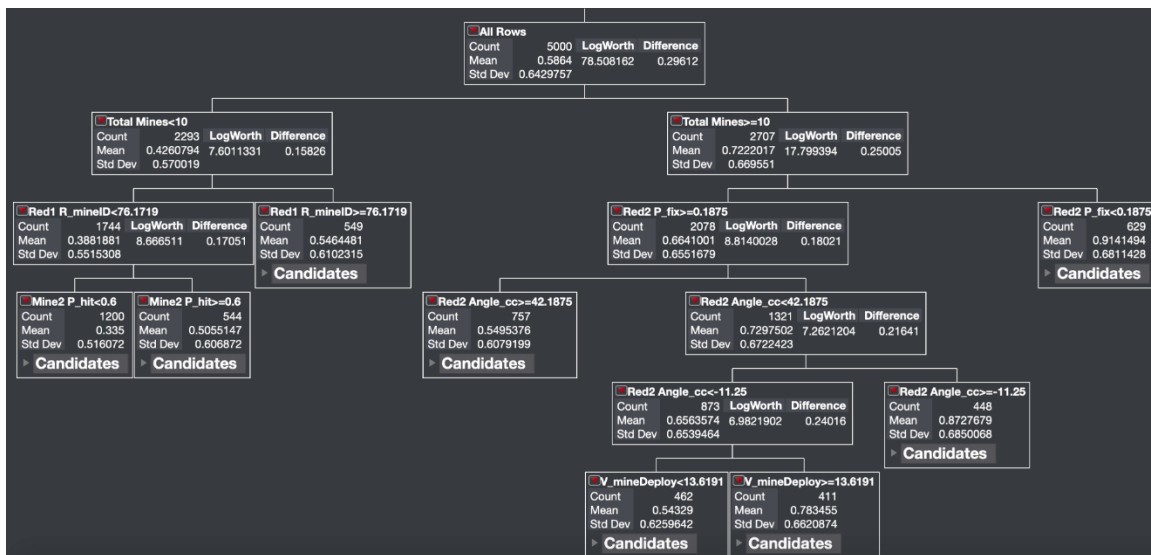


Figure 45. UUV Agent Death Partition Tree (All Variables)

VI. RECOMMENDATIONS AND CONCLUSIONS

A. SUMMARY OF ANALYSIS

Naval mines are an effective method of accomplishing objectives, manipulating and dictating enemy movements, and projecting power while lowering overall operations risks and costs by removing other naval assets from high-risk areas. Historically, offensive mining employment and research has not been a focus until conflict is imminent or in progress. This provides an opportunity for analysis by simulation to provide additional context on employment strategies, opponent behaviors, and potentially future mine attributes.

To support the evolving mission priorities of the U.S. Navy, the team analyzed ODM capabilities and relationships, specifically focusing on strategic deterrence of the enemy forces and the measured success of minefield deployment attributes based on projected red capabilities and behavior. Based on current mining literature, the team created a simulation model to assess the capability of a minefield to turn or fix an enemy. The simulation was setup to encompass three total experiments, one for each deployment mechanism, specifically air, surface vessel, and UUV. The simulation was then iteratively developed and tested to achieve realistic interactions between the minefield environment, deployment assets, and enemy vessels. The end goal of the simulation was to enable future use with classified or limited distribution data to realistically represent the utility of different mine capabilities or deployments.

The simulation utilized a NOLH DOE to assess the impact that changes to minefield characteristics and deployment strategies had on operational performance. This initial DOE was also analyzed with a relative importance analysis to determine if input variables could have their ranges restricted to develop generally applicable recommendations and guide more focused analysis. This unbounded analysis found that red behavior and decision logic dominated the results, these behaviors were subsequently constrained and a second NOLH DOE was developed, with the output data being statistically evaluated to determine how each deployment mechanism performed. Additionally, for each individual deployment

mechanism the output data was analyzed to elaborate on which variables had the most significant impact on the results.

1. Primary MOE: Red Impact

Regarding red vessel impact the primary driver was the red behavioral tendencies, specifically the tendency to change course or fix position. The ultimate driver is the predisposition for those red vessels towards risk acceptance or aversion with respects to their probability of continuing through the minefield or performing an impacted action. The next most significant drivers were the red mine detection and identification capabilities. If the red vessels were unable to avoid the minefields, their death or survival tended to be driven by the quantity of mines deployed, although the number of mines was more significant in smaller minefields (for example in the UUV scenario with at most 20 mines, having even a few additional mines had a much greater influence than in either the air or vessel deployment scenarios, which utilized between 20–40 and 80–120 mines, respectively).

2. Secondary MOE: Time to Deploy

The time to deploy for each scenario was generally dependent on the speed of the deployment vehicle and the number of mines to be deployed. The fastest scenario was deploying by air, while UUV was the slowest. UUV also had the greatest standard deviation in its deployment time, both overall and proportionally to the mean.

3. Other Conclusions

While some of the conclusions drawn from this analysis are logical even without the use of simulation, these results verify that the simulation can be used to develop operational relevant conclusions without the use of limited distribution information. Future work in this field leveraging the model development which has already taken place can closer align to reality or future capabilities, providing a clearer understanding of offensive denial mining's utility.

B. RECOMMENDED ODM ANALYSIS EXPANSIONS

1. Recommended MAST Expansions and Implementations

Over the course of the model developments several areas were deemed as areas which MAST improvements could benefit ODM modeling, and areas of the model where future developers could target to improve but were out of scope for this effort.

The ability to turn agents on or off would be an invaluable tool for MAST development efforts. Currently, if an agent is created in a MAST experiment, the agent is active for the simulation and experiments. If the ability to turn off agents existed, multiple scenarios or iterations of a model could exist within one MAST file. This would have allowed for the creation of one file for the three different delivery methods investigated in this report.

Some further development on agent distribution would also benefit ODM modeling within the MAST environment. In order to achieve a random distribution a work around was developed using the follow patrol points state. The ability to predetermine agent distribution would allow for more complex minefield shapes and distributions to be modeled. In order to achieve specific mine field shapes or distributions a developer would need to manually place each mine.

A dedicated mine agent or agents would allow for more in depth mine parameters and a deeper investigation into the effects of those parameters in specific mine field scenarios which future users may have interest in modeling. This would also increase the efficiency of future ODM model development efforts.

A final improvement for MAST would be the addition of water depth considerations, and bathymetric data. The inclusion of this data would allow for a more robust 3D model scenario and would allow for the inclusion of more specific considerations which effect mine deployment and effectiveness. For example, certain mines are designed to operate at specific depth ranges, bathymetric features could increase or decrease mine field effectiveness, different bottom types can influence red vessel mine detection probabilities, and many other potential factors which could be explored.

2. Focus for Continued ODM Study

Along with the potential for MAST improvements, future work can be conducted by future NPS cohorts or the Navy itself to expand upon the MAST models developed within this project in scope or fidelity. Due to time limits certain elements of the developed model were unable to be explored to their fullest extent. For example, mining is defined by four desired red vessel outcomes, however this model concentrated on just two. Future work could more fully implement the block and disrupt behaviors into the models or increase the complexities of red force decision logic in order to make them a fully capture Edwards' (2019) intent.

Future work could also focus on more subjective aspects of mine deployment. For example, subsurface deployment using a UUV is significantly more clandestine than a surface ship deploying a large quantity of mines. This is an aspect that can be investigated further in order to bring more real-world tactical considerations into the model.

This modeling effort utilized generic mines with a limited number of varied characteristics. Future development could focus on the development of different mine types. This includes smart mines, mines of varying effectiveness and ranges, and mines which can communicate and redeploy to allow for an agile mine field environment. This will bring new tools to mine field developers for specific use cases or future mine development efforts.

Future work could also allow interested parties to test specific use cases and scenarios. The model was developed to be site agnostic, and able to be altered for use in any scenario a modeler would be interested in. As such, future work could alter the minefield model to allow the use of specific information for mine quantities, mine deployment site size, mine deployment geometries, and mine spacing.

C. CONCLUSIONS

Naval mines are an effective method of influencing enemy movements through an autonomous projection of power thereby lowering operational risk and overall cost by removing traditional naval assets from high-hazard areas. This project developed a simulation model and conducted statistical analysis to identify the operational and design

considerations that had the largest impact on ODM performance. The analysis utilized the NOLH DOE to statistically vary mine capabilities and deployment as well as the red vessel capabilities and behaviors. The results suggest that red vessel detection and behavior are the most significant drivers of engagement results. The randomly generated minefields in the team's experiments were effective at destroying the enemy but were even more effective at deterring opposition transit. In fact, this study suggested that low quantities of mines can be comparably effective as high quantities at forcing the opponent to either change course or fix position, depending on red detection of those mines.

This study provides a platform for assessing naval mine deployment strategies and overall operational effectiveness, while also enabling better definition of future technologies which will allow the Navy to accomplish its mission. With the inclusion of actual capability, performance and behavioral information, this simulation can be further refined to augment mine deployment strategies future requirements. The simulation tool and generated experiments, as well as lessons learned and recommendations can be utilized as an operational analytic foundation for future developers to create mine warfare mission planning tools.

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APPENDIX A: CASE STUDIES

Historical examples of minefield laying and configuration were leveraged to inform unclassified input variables into simulation efforts. Particular variables of interest were number of mines, area, variety of mines, deployment mechanism, and any variables which can be used as measures of effectiveness.

The first historical example is the port of Hungnam during the Korean War. Although Hungnam represents a defensive minefield, the geometry and mine types can still be noted. As seen in Figure 46 the minelines were designed to prevent approach to a port. A total of 135 mines (all of which were moored, contact mines) were reported in the approximately 12 square Nm area surrounding the main port facility (Menarchik 2010).

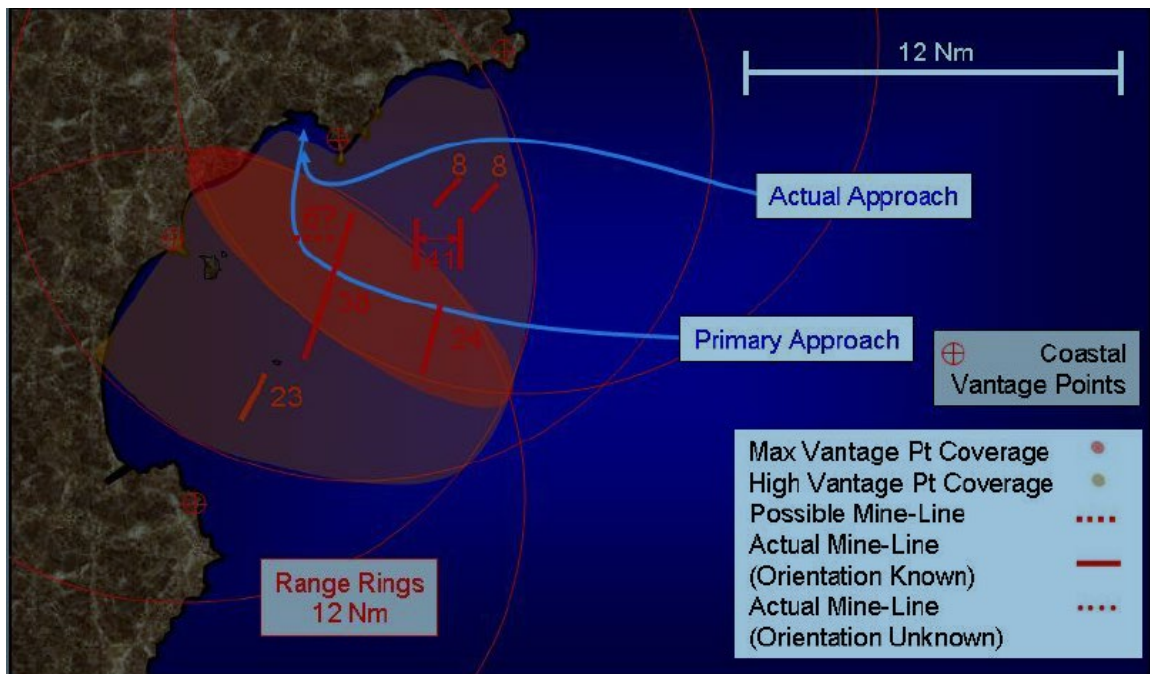


Figure 46. Hungnam Minefield Distribution. Source: Menarchik (2010).

Another significant example of minefield disposition is Wonsan, also from the Korean War. A combination of moored and moving mines were used for the defense of Wonsan port as shown in Figure 47. Although the minefields surrounding Wonsan were

reseeded throughout the war, estimates for between 500–4000 mines would be laid in the surrounding waters, although 403 mines were actually swept implying the number is on the lower end (Menarchik 2010).

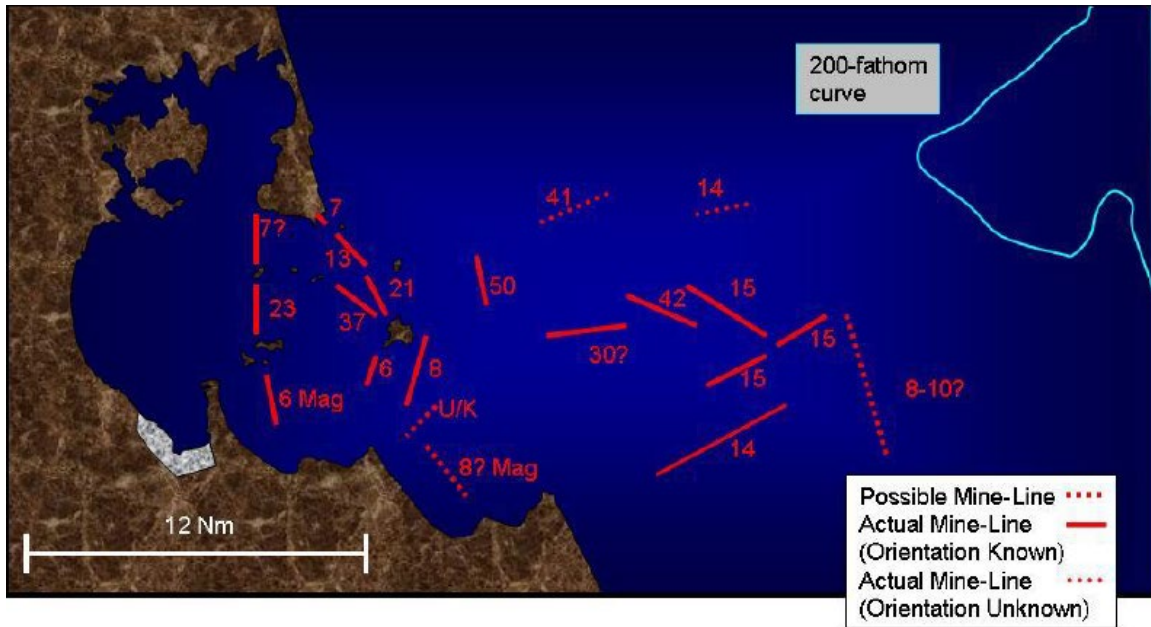


Figure 47. Wonsan Reconstructed Mine-Lines. Source: Menarchik (2010).

APPENDIX B: ODM PARTITION TREES

For a detailed analysis of each variable's significance across the model, partition trees were generated based on the second set of DOE inputs. Rules for generation were that no split could go to less than 5% of the total sample size, and that the partition trees would start with all variables before potentially being filtered if they are potentially masking other relationships.

A. AIR PARTITION TREES

The initial partition tree for air, based on the end result of death is shown in Figure 48.

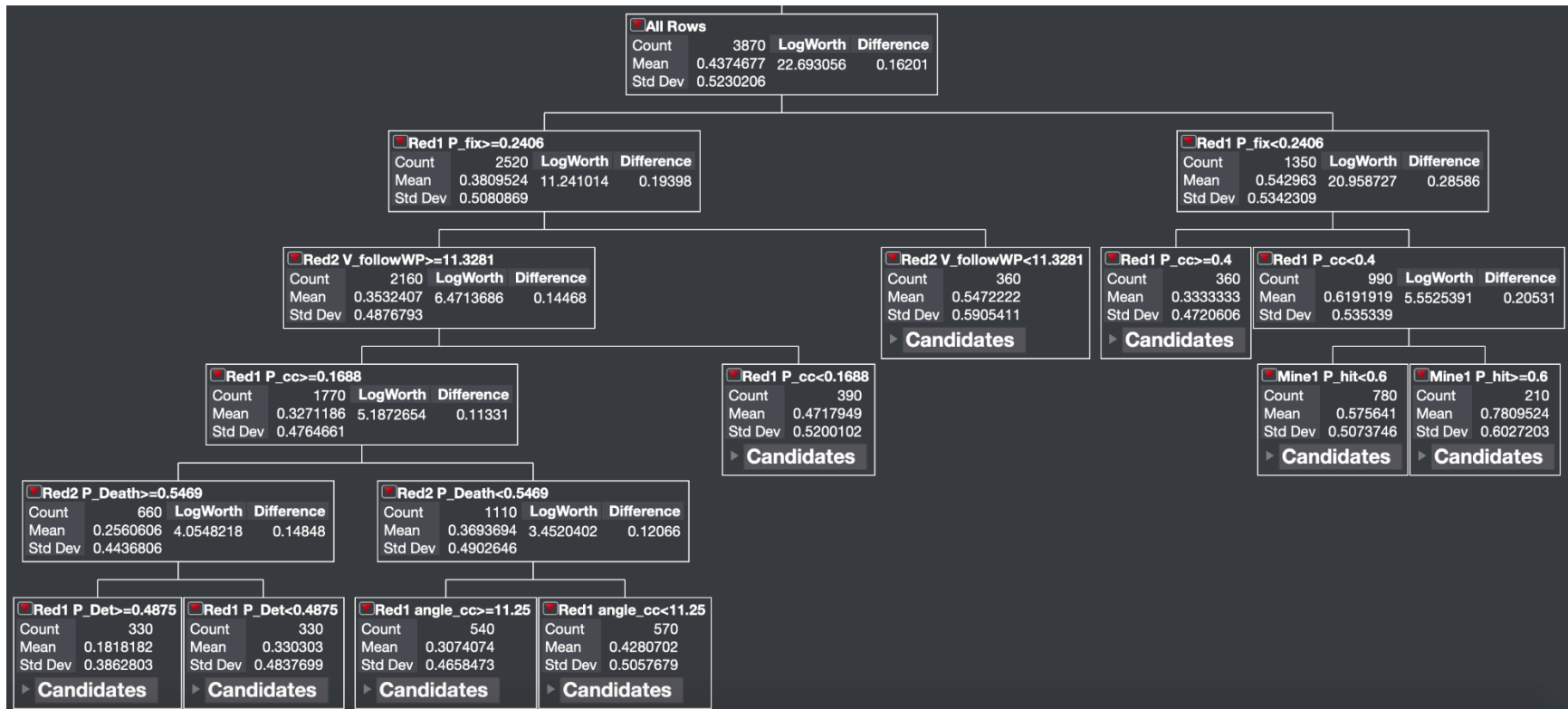


Figure 48. Air Agent Death Partition Tree (All Variables)

Based on the prevalence of red behaviors, the probability of change course, fix, and angle of course change were removed for the red death partition tree shown in Figure 49.

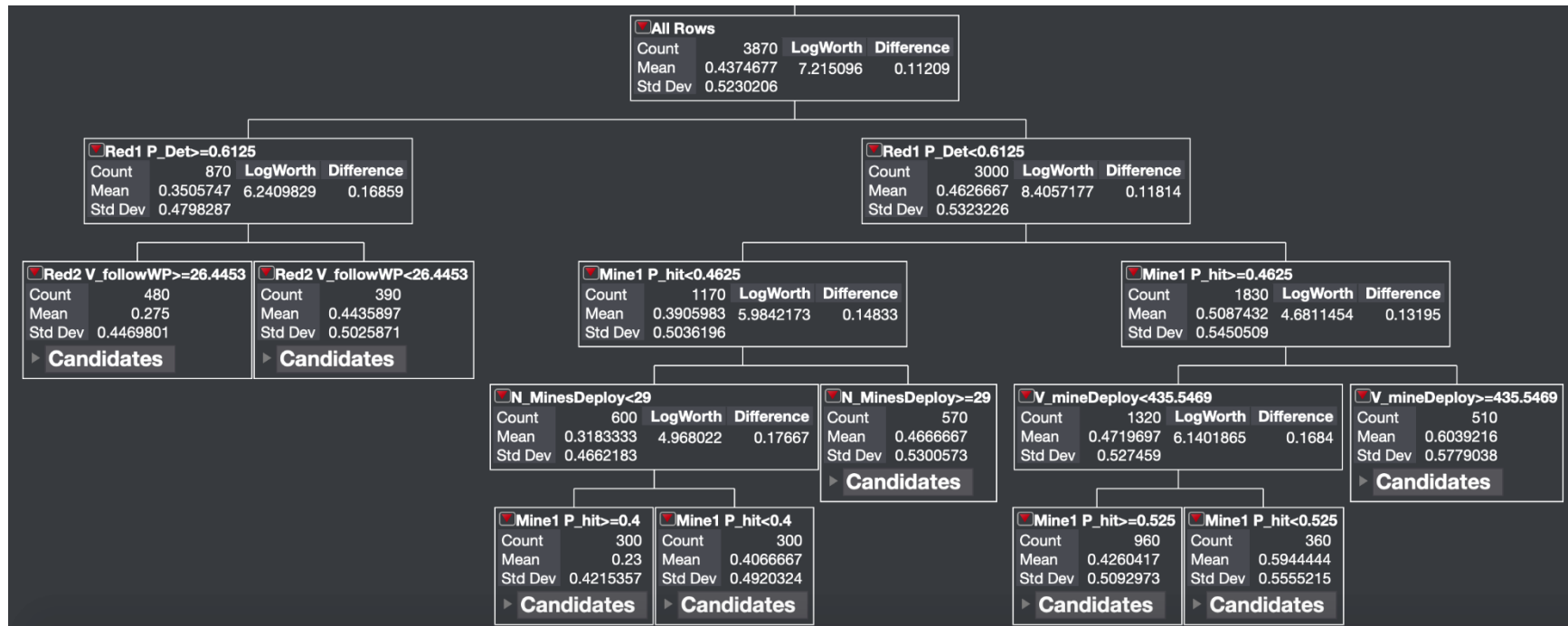


Figure 49. Air Agent Death Partition Tree (Less CC and Fix)

Similar to the partition tree for death, a partition tree for impact including all variables is shown in Figure 50.

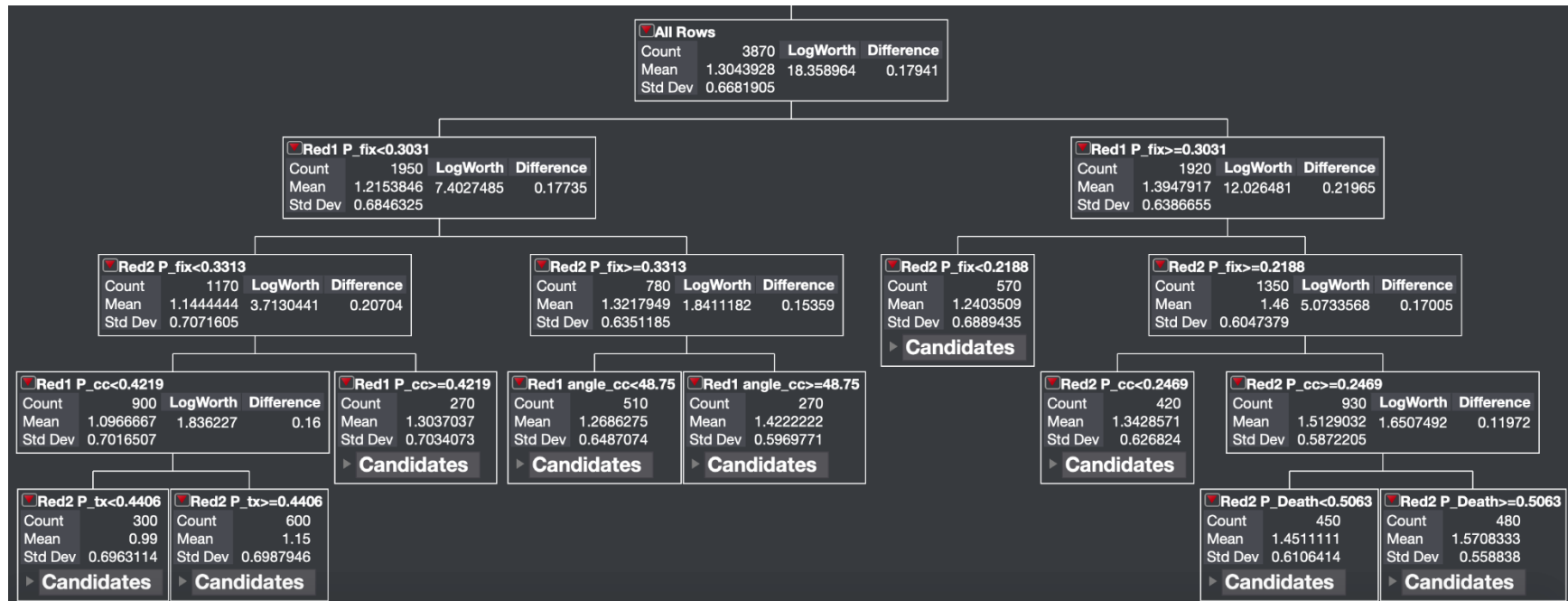


Figure 50. Air Red Impact Partition Tree (All Variables)

Once again, the probability of fix and change course is overriding other variables, so they were removed in the next iteration of the partition tree.

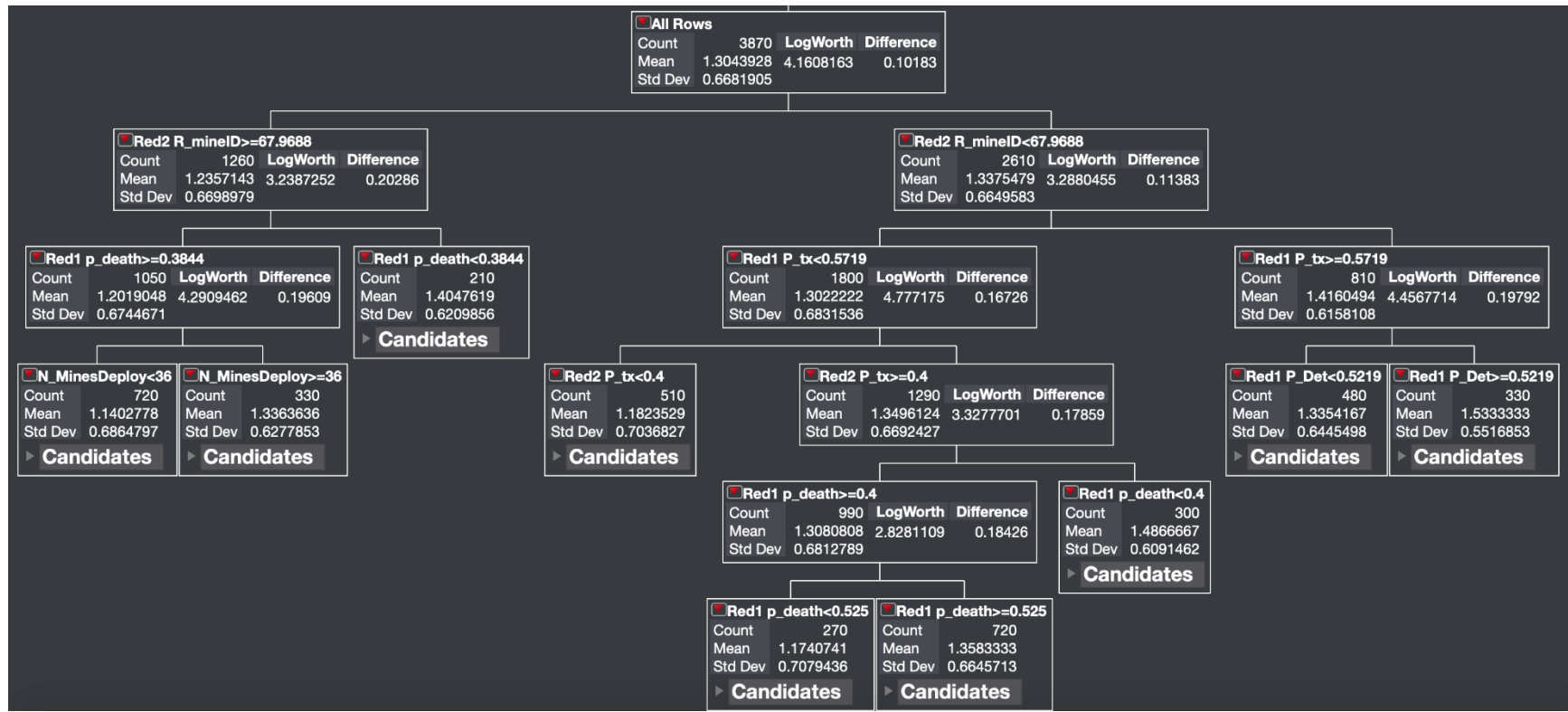


Figure 51. Air Red Impact Partition Tree (Less CC and Fix)

For a final iteration of the air partition tree all red variables were removed to see which minefield variables have a significant impact.

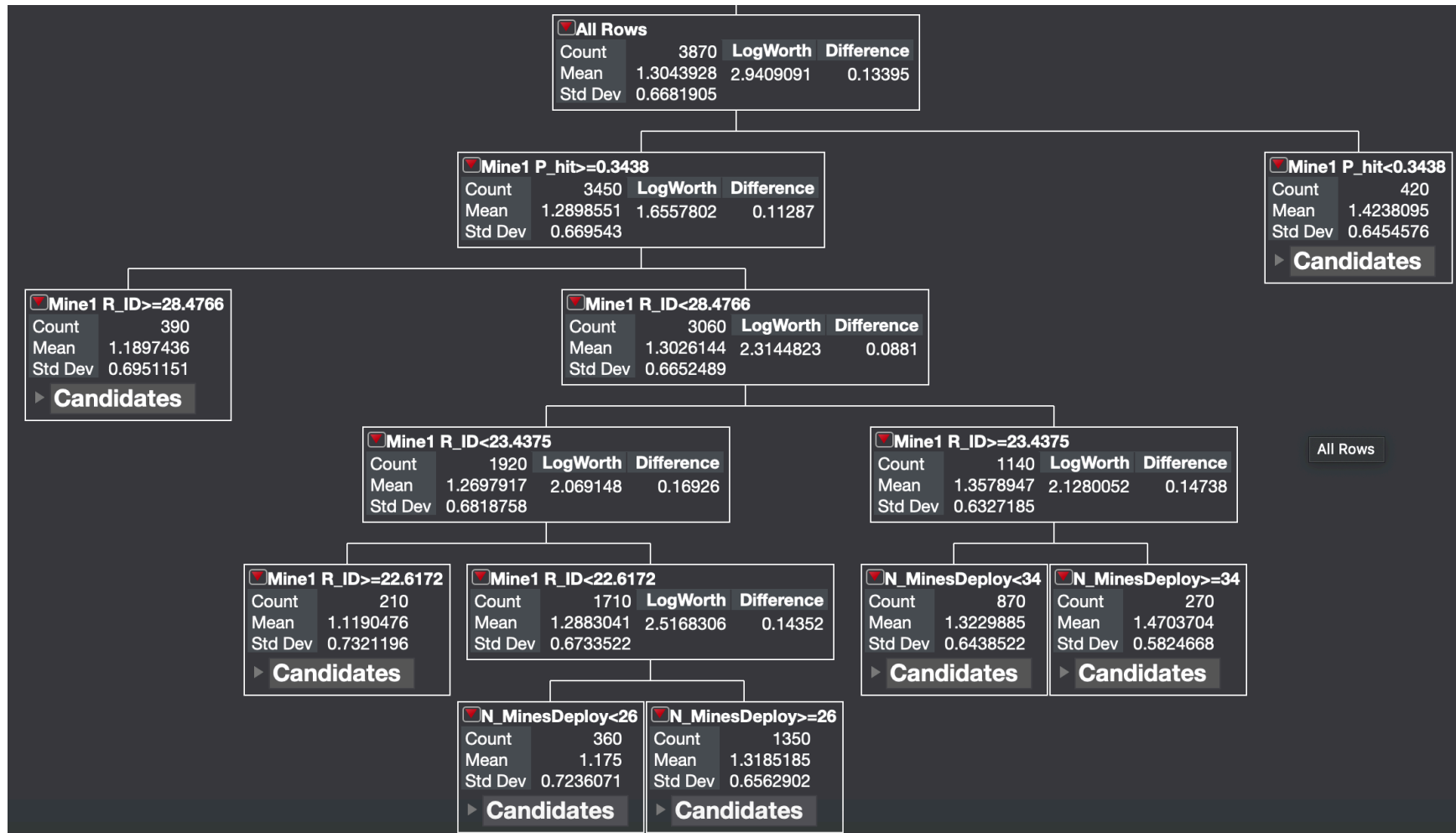


Figure 52. Air Red Impact Partition Tree (Less CC and Fix)

B. VESSEL PARTITION TREES

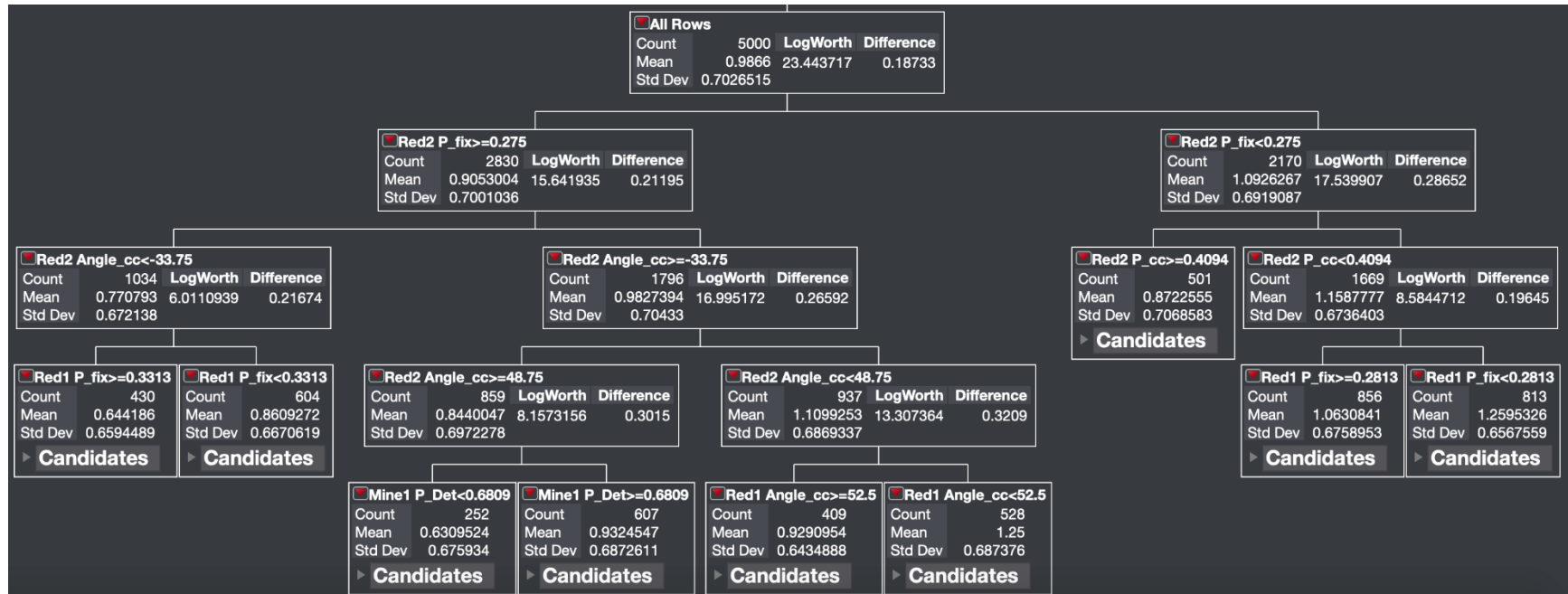
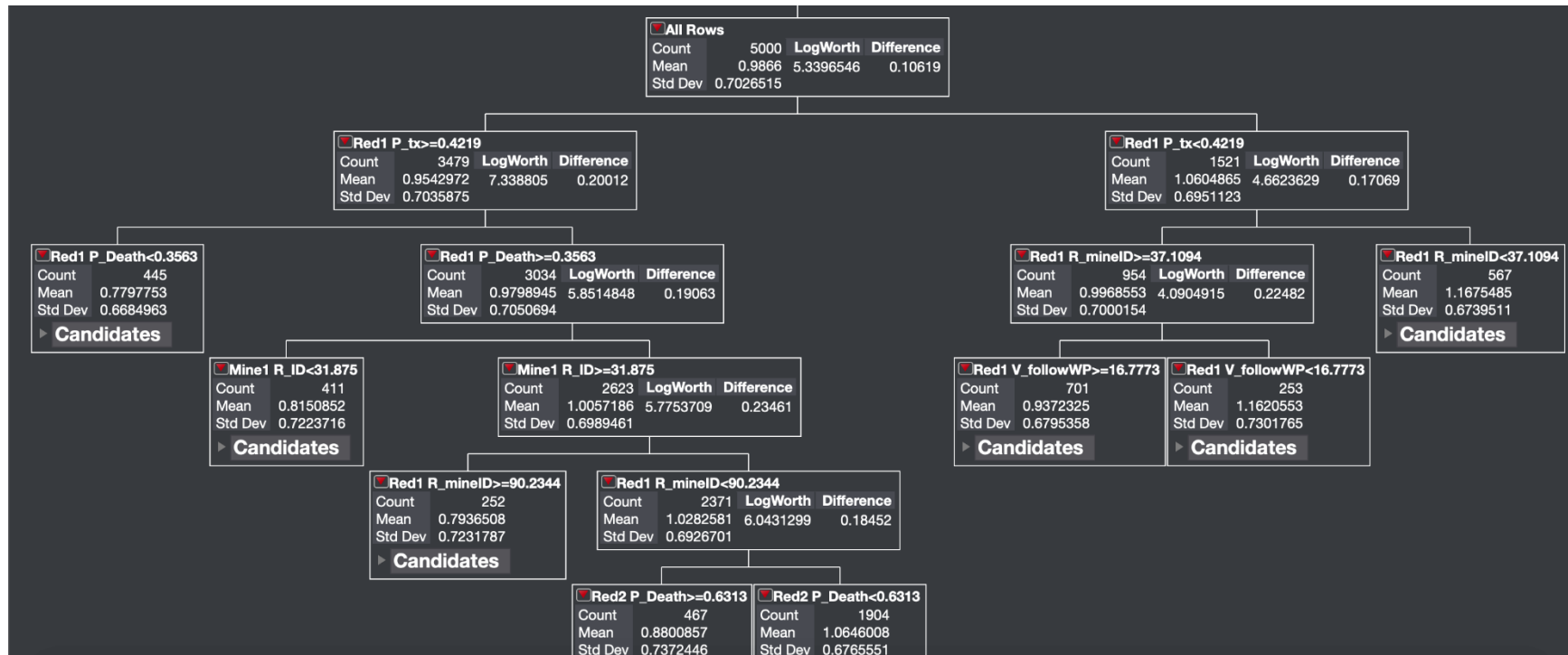


Figure 53. Vessel Death Partition Tree (All variables)

Similar to the air scenario, the probability of fix and change course were the driving force in the partition tree shown in Figure 53. Those were removed in Figure 54.



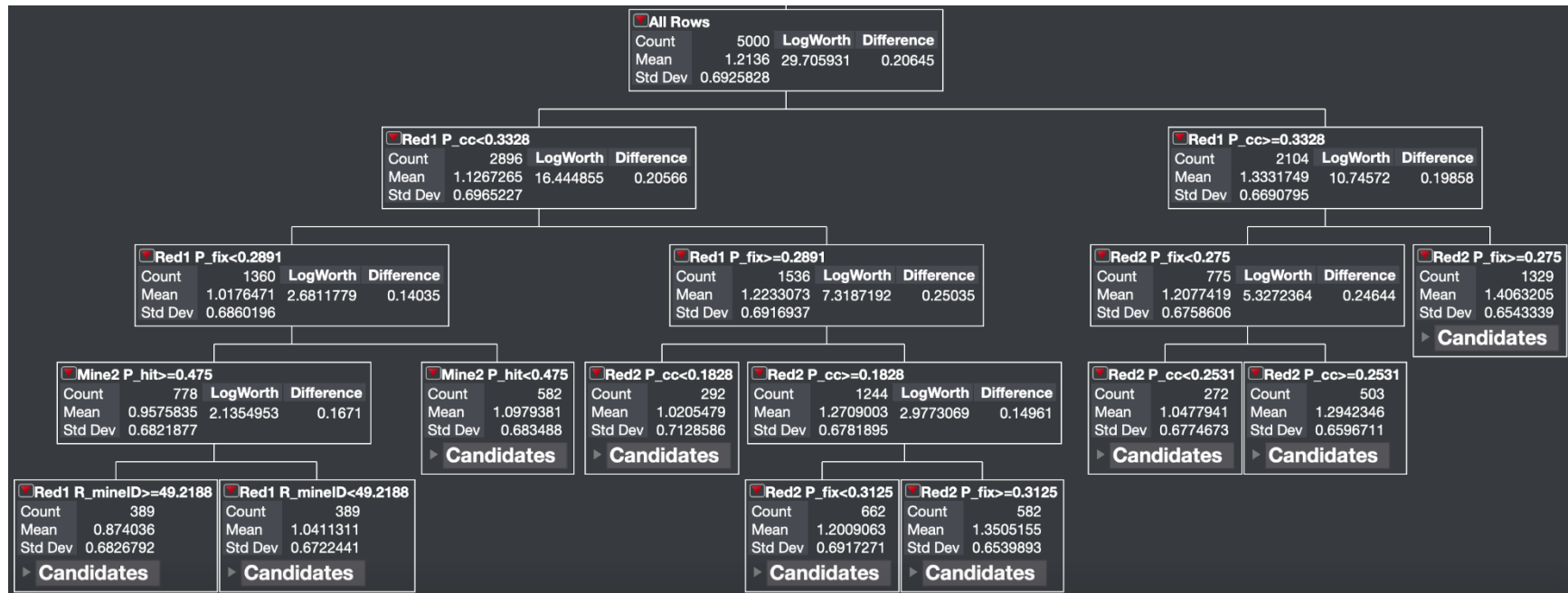


Figure 55. Vessel Red Impact Partition Tree (All Variables)

Similar to other partition trees the probability of change course and fix were noted to be overriding all other variables in Figure 55. Those were removed in Figure 56.

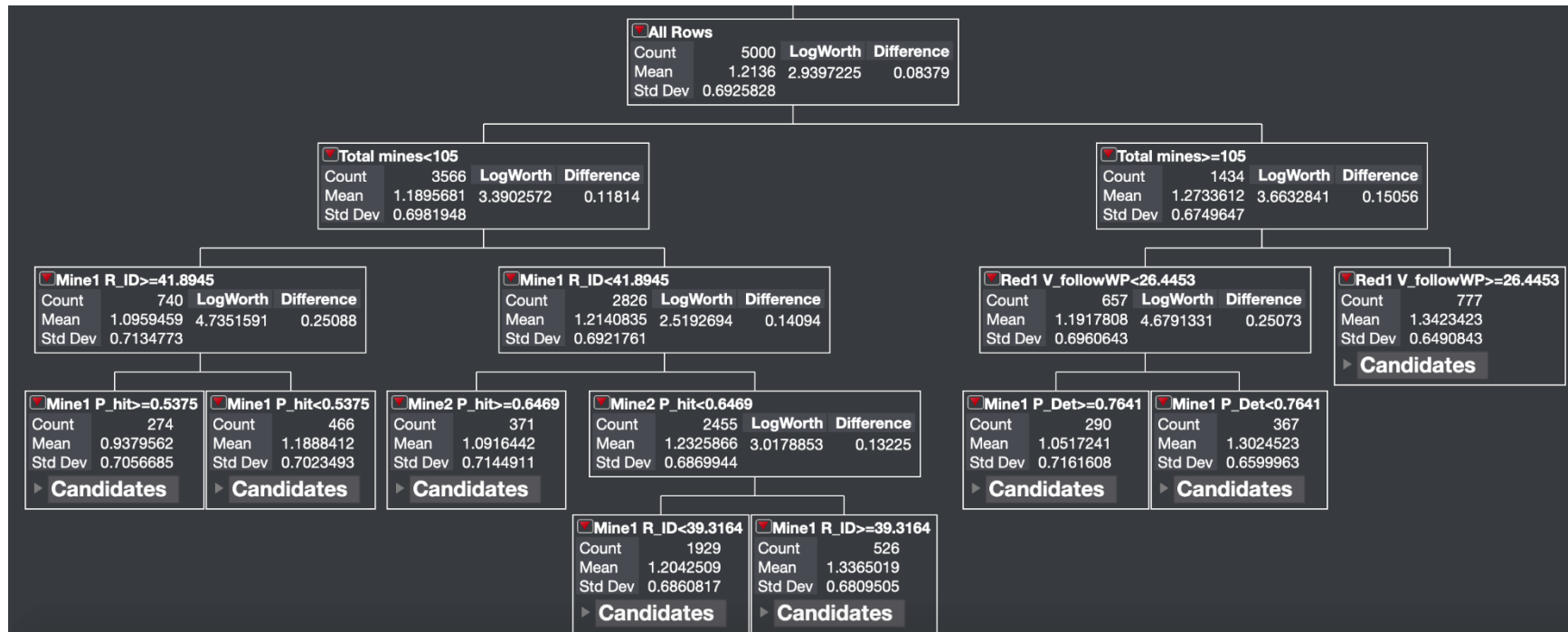


Figure 56. Vessel Red Impact Partition Tree (Less CC and Fix)

C. UUV PARTITION TREES

Please note the top level UUV partition tree is shown in the main body of the report as Figure 45.

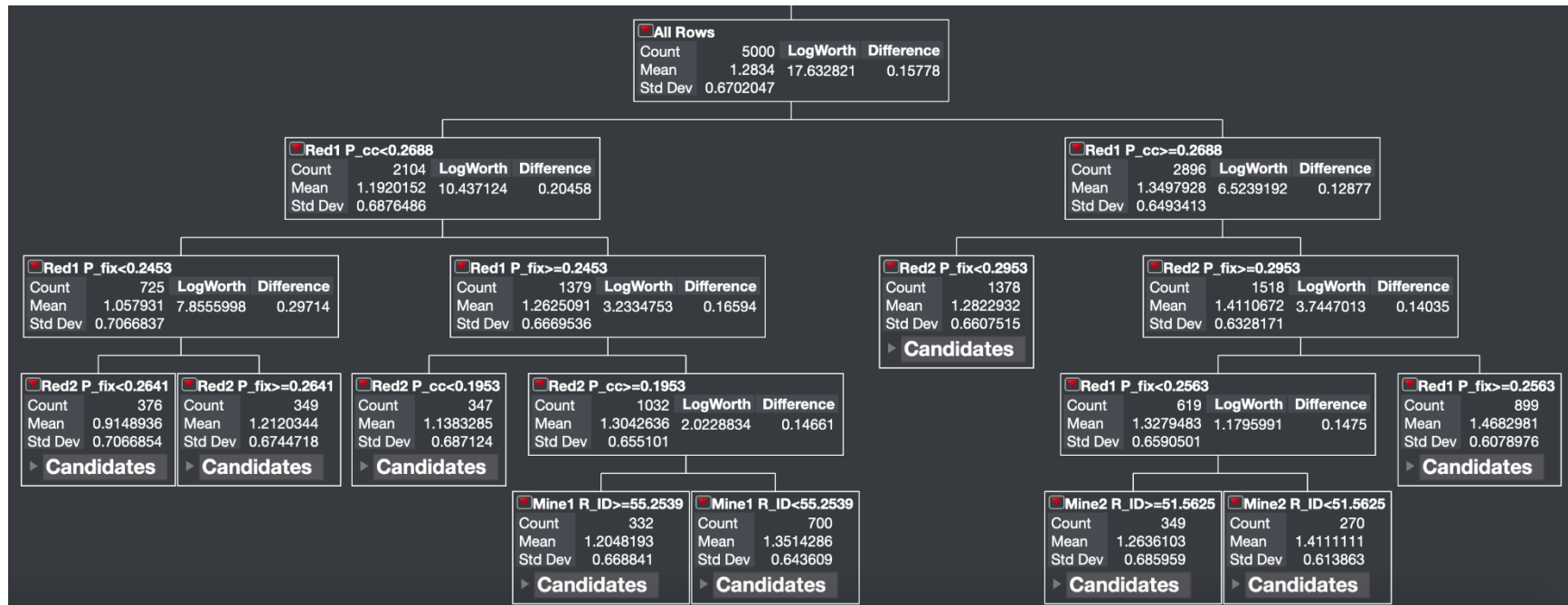


Figure 57. UUV Red Impact Partition Tree (All Variables)

Similar to previous partition trees, the probability of change course and fix dominate throughout the UUV impact in Figure 57 and were removed in Figure 58.

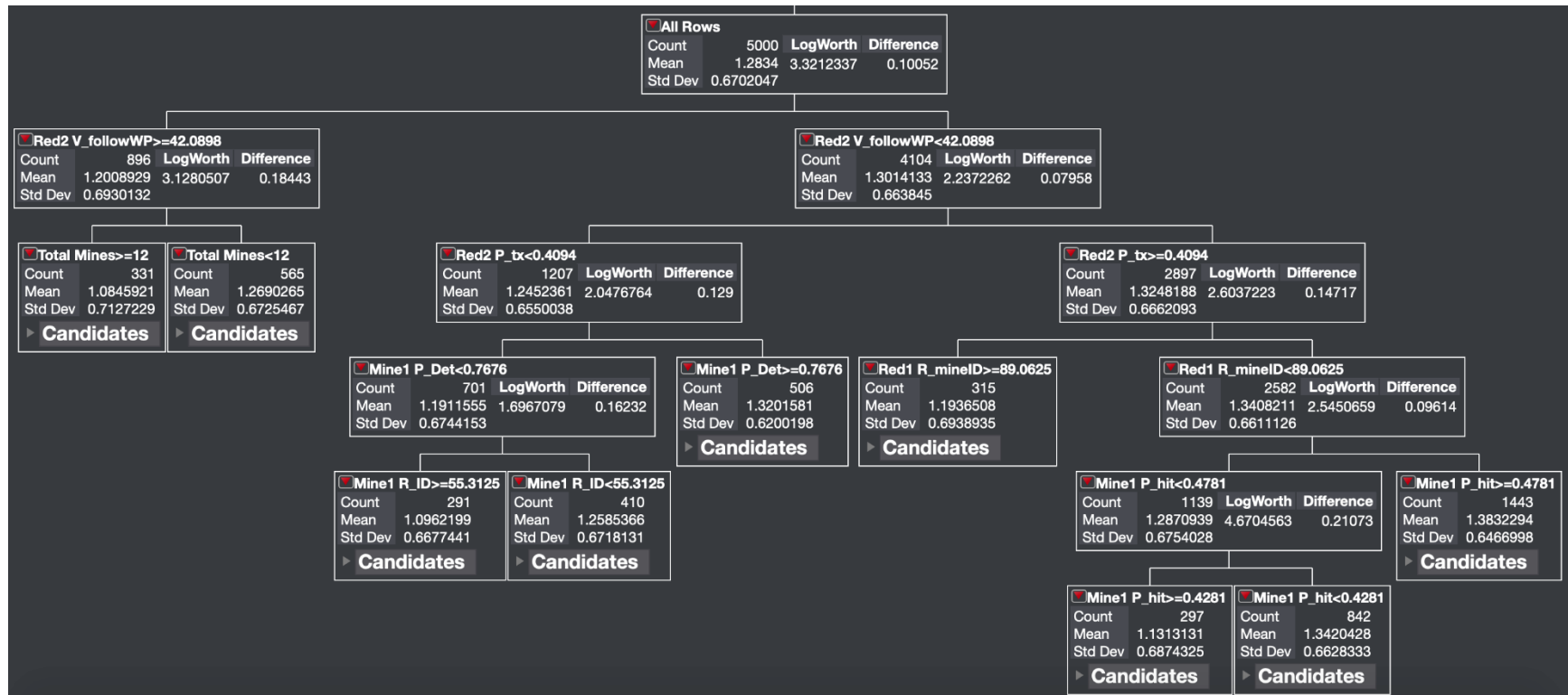


Figure 58. UUV Red Impact Partition Tree (Less CC and Fix)

D. PREDICTION PROFILES

In Figure 59 the radius of identification for the mines do not appear to have a significant or consistent impact across any of the scenarios.

Finally, the mine probability of detection also is not a significant driver of the Red Impact or red death as shown in Figure 60

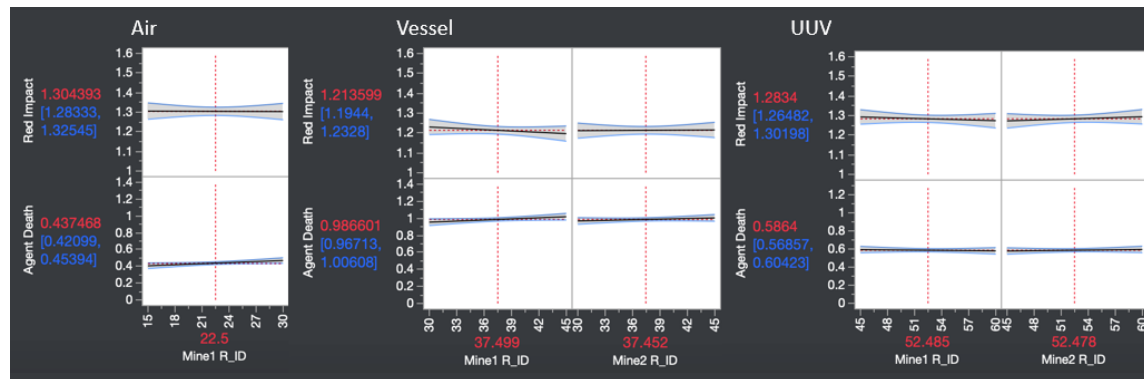


Figure 59. Mine Identification Range Prediction Profiles

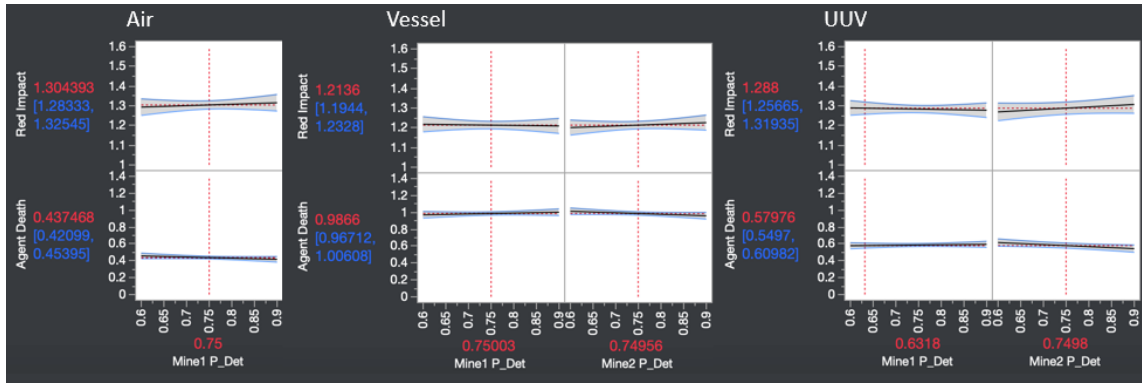


Figure 60. Mine Probability of Detection Prediction Profiles

In Figure 61 the impact of red vessel velocity does not appear to have any consistent trends across different scenarios.

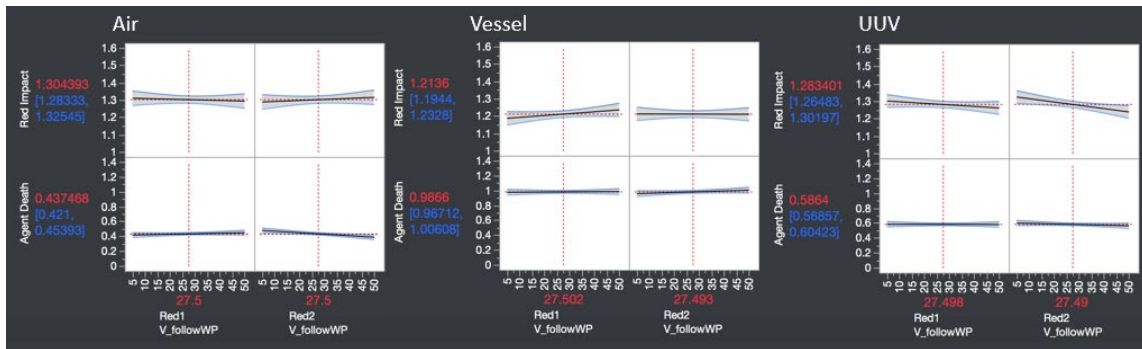


Figure 61. Red Vessel Speed Prediction Profiles

Finally, the red probability of detection does not have any variation outside the degree of uncertainty as seen in Figure 62.

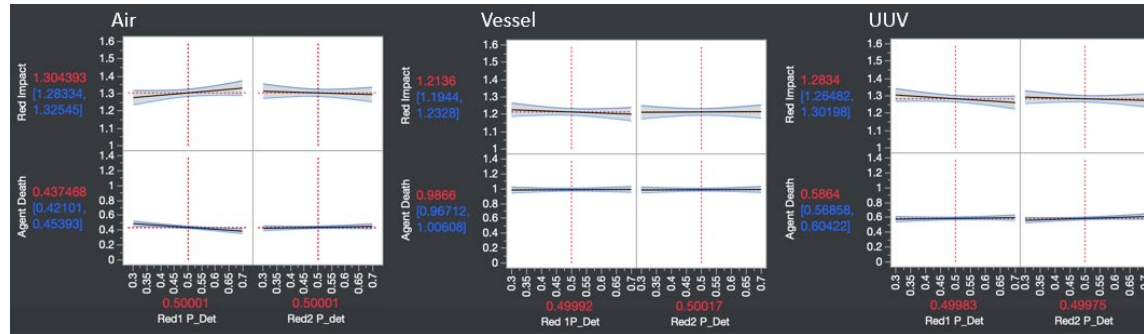


Figure 62. Probability of Detection Prediction Profiles

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APPENDIX C: INPUT VARIABLE CORRELATION

Table 17 and Table 18 correspond to the surface and UUV input variable correlations, also indicating satisfactory independence across all DOE input variables.

Table 17. Surface Vessel Input Variable Correlation

	V_mineDeploy	N_MineDeployed1	Mine1P_Det	Mine1R_ID	Mine1P_hit	N_MineDeployed2	Mine2P_Det	Mine2R_ID	Mine2P_hit	Red1P_tx	Red1V_followWP	Red1P_Death	Red1P_Det	Red1R_mineID	Red1P_cc	Red1P_fix	Red1Angle_cc	Red2P_tx	Red2V_followWP	Red2P_Death	Red2P_Det	Red2R_mineID	Red2P_cc	Red2P_fix	Red2Angle_cc
V_mineDeploy	1.0000	0.0012	0.0001	-0.0003	0.0002	0.0019	-0.0010	-0.0048	-0.0020	-0.0011	0.0008	0.0000	-0.0009	0.0014	0.0004	0.0001	-0.0017	-0.0009	-0.0006	-0.0010	-0.0010	0.0027	0.0003	-0.0016	0.0017
N_MineDeployed1	0.0012	1.0000	0.0095	-0.0030	-0.0026	0.0000	-0.0044	-0.0015	0.0067	-0.0005	-0.0019	-0.0059	-0.0073	-0.0026	0.0003	-0.0018	0.0033	-0.0022	-0.0071	-0.0045	0.0031	0.0085	-0.0027	-0.0086	0.0047
Mine1P_Det	0.0001	0.0095	1.0000	-0.0002	0.0014	0.0010	-0.0001	0.0001	-0.0024	0.0001	0.0000	0.0032	-0.0007	0.0009	0.0026	0.0001	-0.0008	-0.0010	-0.0048	0.0005	-0.0019	0.0025	0.0002	-0.0001	-0.0005
Mine1R_ID	-0.0003	-0.0030	-0.0002	1.0000	-0.0002	0.0020	0.0015	0.0004	0.0013	-0.0002	0.0001	0.0004	-0.0015	0.0029	-0.0004	-0.0041	0.0009	-0.0015	0.0015	-0.0008	-0.0005	-0.0006	-0.0046	0.0009	-0.0018
Mine1P_hit	0.0002	-0.0026	0.0014	-0.0002	1.0000	-0.0097	0.0009	0.0011	0.0006	-0.0024	-0.0004	-0.0005	-0.0011	0.0001	0.0017	-0.0013	-0.0012	-0.0015	-0.0005	-0.0003	0.0033	-0.0032	-0.0024	0.0000	0.0004
N_MineDeployed2	0.0019	0.0000	0.0010	0.0020	-0.0097	1.0000	0.0055	-0.0038	-0.0027	0.0034	-0.0096	-0.0006	0.0001	-0.0011	0.0006	0.0060	-0.0063	0.0049	-0.0020	0.0032	0.0005	-0.0027	0.0012	0.0008	-0.0056
Mine2P_Det	-0.0010	-0.0044	-0.0001	0.0015	0.0009	0.0055	1.0000	0.0047	0.0022	-0.0006	-0.0004	0.0003	-0.0009	0.0009	0.0007	0.0015	-0.0008	-0.0009	0.0012	-0.0024	-0.0003	-0.0026	-0.0010	0.0018	-0.0011
Mine2R_ID	-0.0048	-0.0015	0.0001	0.0004	0.0011	-0.0038	0.0047	1.0000	-0.0004	-0.0002	-0.0022	-0.0017	0.0010	0.0010	0.0016	-0.0014	0.0013	-0.0026	-0.0013	-0.0034	0.0008	0.0001	-0.0014	0.0013	-0.0006
Mine2P_hit	-0.0020	0.0067	-0.0024	0.0013	0.0006	-0.0027	0.0022	-0.0004	1.0000	-0.0043	0.0026	0.0012	-0.0001	0.0012	0.0008	0.0005	0.0025	0.0029	0.0007	0.0033	-0.0005	0.0004	0.0001	0.0034	0.0014
Red1P_tx	-0.0011	-0.0005	0.0001	-0.0002	-0.0024	0.0034	-0.0006	-0.0002	-0.0043	1.0000	-0.0018	-0.0008	-0.0005	-0.0004	-0.0010	-0.0037	0.0015	0.0020	-0.0014	-0.0004	0.0007	-0.0002	-0.0005	0.0018	0.0025
Red1V_followWP	0.0008	-0.0019	0.0000	0.0001	-0.0004	-0.0096	-0.0004	-0.0022	0.0026	-0.0018	1.0000	-0.0023	0.0003	0.0025	0.0026	-0.0007	0.0002	0.0002	-0.0018	0.0000	-0.0003	-0.0009	-0.0013	0.0007	-0.0002
Red1P_Death	0.0000	-0.0059	0.0032	0.0004	-0.0005	-0.0006	0.0003	-0.0017	0.0012	-0.0008	-0.0023	1.0000	0.0019	-0.0012	0.0005	0.0012	-0.0011	-0.0013	-0.0002	0.0006	-0.0009	0.0015	-0.0006	-0.0015	0.0013
Red1P_Det	-0.0009	-0.0073	-0.0007	-0.0015	-0.0011	0.0001	-0.0009	0.0010	-0.0001	-0.0005	0.0003	0.0019	1.0000	0.0054	-0.0017	0.0024	-0.0005	0.0008	0.0022	0.0009	0.0004	0.0011	0.0005	-0.0009	-0.0013
Red1R_mineID	0.0014	-0.0026	0.0009	0.0029	0.0001	-0.0011	0.0009	0.0010	0.0012	-0.0004	0.0025	-0.0012	0.0054	1.0000	-0.0003	-0.0017	-0.0034	-0.0020	-0.0003	0.0025	-0.0003	-0.0008	0.0001	-0.0003	-0.0014
Red1P_cc	0.0004	0.0003	0.0026	-0.0004	0.0017	0.0006	0.0007	0.0016	0.0008	-0.0010	0.0026	0.0005	-0.0017	-0.0003	1.0000	0.0007	-0.0003	-0.0001	0.0017	0.0015	0.0001	0.0017	0.0007	0.0006	-0.0015
Red1P_fix	0.0001	-0.0018	0.0001	-0.0041	-0.0013	0.0060	0.0015	-0.0014	0.0005	-0.0037	-0.0007	0.0012	0.0024	-0.0017	0.0007	1.0000	0.0006	-0.0001	0.0007	0.0004	0.0006	0.0008	-0.0022	-0.0014	0.0007
Red1Angle_cc	-0.0017	0.0033	-0.0008	0.0009	-0.0012	-0.0063	-0.0008	0.0013	0.0025	0.0015	0.0002	-0.0011	-0.0005	-0.0034	-0.0003	0.0006	1.0000	-0.0003	-0.0016	0.0001	0.0009	0.0008	-0.0004	0.0021	0.0014
Red2P_tx	-0.0009	-0.0022	-0.0010	-0.0015	-0.0015	0.0049	-0.0009	-0.0026	0.0029	0.0020	0.0002	-0.0013	0.0008	-0.0020	-0.0001	-0.0001	-0.0003	1.0000	0.0052	-0.0017	0.0020	-0.0002	0.0014	-0.0012	0.0019
Red2V_followWP	-0.0006	-0.0071	-0.0048	0.0015	-0.0005	-0.0020	0.0012	-0.0013	0.0007	-0.0014	-0.0018	-0.0002	0.0022	-0.0003	0.0017	0.0007	-0.0016	0.0052	1.0000	-0.0001	0.0015	-0.0008	0.0018	0.0002	-0.0016
Red2P_Death	-0.0010	-0.0045	0.0005	-0.0008	-0.0003	0.0032	-0.0024	-0.0034	0.0033	-0.0004	0.0000	0.0006	0.0009	0.0025	0.0015	0.0004	0.0001	-0.0017	-0.0001	1.0000	-0.0041	0.0026	0.0037	0.0003	0.0014
Red2P_Det	-0.0010	0.0031	-0.0019	-0.0005	0.0033	0.0005	-0.0003	0.0008	-0.0005	0.0007	-0.0003	-0.0009	0.0004	-0.0003	0.0001	0.0006	0.0009	0.0020	0.0015	-0.0041	1.0000	0.0008	-0.0004	0.0003	-0.0008
Red2R_mineID	0.0027	0.0085	0.0025	-0.0006	-0.0032	-0.0027	-0.0026	0.0001	0.0004	-0.0002	-0.0009	0.0015	0.0011	-0.0008	0.0017	0.0008	0.0008	-0.0002	-0.0008	0.0026	0.0008	1.0000	0.0051	-0.0009	0.0014
Red2P_cc	0.0003	-0.0027	0.0002	-0.0046	-0.0024	0.0012	-0.0010	-0.0014	0.0001	-0.0005	-0.0013	-0.0006	0.0005	0.0001	0.0007	-0.0022	-0.0004	0.0014	0.0018	0.0037	-0.0004	0.0051	1.0000	-0.0011	0.0018
Red2P_fix	-0.0016	-0.0086	-0.0001	0.0009	0.0000	0.0008	0.0018	0.0013	0.0034	0.0018	0.0007	-0.0015	-0.0009	-0.0003	0.0006	-0.0014	0.0021	-0.0012	0.0002	0.0003	0.0003	-0.0009	-0.0011	1.0000	0.0018
Red2Angle_cc	0.0017	0.0047	-0.0005	-0.0018	0.0004	-0.0056	-0.0011	-0.0006	0.0014	0.0025	-0.0002	0.0013	-0.0013	-0.0014	-0.0015	0.0007	0.0014	0.0019	-0.0016	0.0014	-0.0008	0.0014	0.0018	0.0018	1.0000

Table 18. UUV Input Variable Correlation

	V_mineDeploy	N_MinesDeployed1	N_MinesDeployed2	Mine1P_Det	Mine2P_Det	Mine1R_ID	Mine2R_ID	Mine1P_hit	Mine2P_hit	Red1P_tx	Red2P_tx	Red1V_followWP	Red2V_followWP	Red1P_Death	Red2P_Death	Red1P_cc	Red2P_cc	Red1P_fix	Red2P_fix	Red1Angle_cc	Red2Angle_cc	Red1P_Det	Red2P_Det	Red1R_mineID	Red2R_mineID
V_mineDeploy	1.0000	0.0000	0.0001	-0.0002	0.0002	-0.0008	-0.0010	-0.0047	-0.0020	-0.0011	0.0008	0.0000	-0.0009	0.0014	0.0004	0.0001	-0.0017	-0.0009	-0.0006	-0.0010	-0.0010	0.0028	0.0003	-0.0016	0.0017
N_MinesDeployed1	0.0000	1.0000	0.0004	-0.0006	-0.0002	0.0000	0.0001	0.0001	0.0012	0.0012	-0.0008	-0.0025	-0.0016	-0.0062	0.0002	0.0024	0.0003	0.0002	-0.0012	-0.0015	-0.0002	0.0005	-0.0008	0.0002	0.0004
N_MinesDeployed2	0.0001	0.0004	1.0000	-0.0002	0.0014	-0.0005	-0.0001	0.0001	-0.0024	0.0001	-0.0001	0.0032	-0.0007	0.0009	0.0026	0.0001	-0.0008	-0.0010	-0.0047	0.0005	-0.0020	0.0024	0.0002	-0.0001	-0.0005
Mine1 P_Det	-0.0002	-0.0006	-0.0002	1.0000	-0.0002	-0.0012	0.0015	0.0004	0.0013	-0.0001	0.0001	0.0004	-0.0016	0.0029	-0.0004	-0.0041	0.0009	-0.0016	0.0015	-0.0008	-0.0005	-0.0006	-0.0047	0.0009	-0.0018
Mine2 P_Det	0.0002	-0.0002	0.0014	-0.0002	1.0000	-0.0018	0.0008	0.0011	0.0007	-0.0024	-0.0004	-0.0005	-0.0011	0.0001	0.0017	-0.0012	-0.0012	-0.0015	-0.0004	-0.0003	0.0033	-0.0031	-0.0024	0.0000	0.0004
Mine1 R_ID	-0.0008	0.0000	-0.0005	-0.0012	-0.0018	1.0000	0.0040	-0.0009	-0.0037	-0.0017	-0.0002	-0.0008	-0.0022	0.0006	-0.0006	0.0000	-0.0013	0.0004	0.0007	0.0006	-0.0022	0.0017	0.0012	-0.0004	-0.0005
Mine2 R_ID	-0.0010	0.0001	-0.0001	0.0015	0.0008	0.0040	1.0000	0.0047	0.0022	-0.0006	-0.0004	0.0003	-0.0010	0.0009	0.0006	0.0015	-0.0008	-0.0009	0.0012	-0.0024	-0.0002	-0.0026	-0.0010	0.0018	-0.0011
Mine1 P_hit	-0.0047	0.0001	0.0001	0.0004	0.0011	-0.0009	0.0047	1.0000	-0.0004	-0.0002	-0.0022	-0.0017	0.0010	0.0010	0.0016	-0.0014	0.0012	-0.0027	-0.0013	-0.0034	0.0008	0.0001	-0.0014	0.0013	-0.0006
Mine2 P_hit	-0.0020	0.0012	-0.0024	0.0013	0.0007	-0.0037	0.0022	-0.0004	1.0000	-0.0043	0.0026	0.0011	-0.0001	0.0012	0.0008	0.0005	0.0025	0.0029	0.0007	0.0033	-0.0004	0.0004	0.0001	0.0034	0.0014
Red1 P_tx	-0.0011	0.0012	0.0001	-0.0001	-0.0024	-0.0017	-0.0006	-0.0002	-0.0043	1.0000	-0.0017	-0.0008	-0.0005	-0.0004	-0.0010	-0.0037	0.0015	0.0020	-0.0014	-0.0004	0.0006	-0.0002	-0.0005	0.0018	0.0025
Red2 P_tx	0.0008	-0.0008	-0.0001	0.0001	-0.0004	-0.0002	-0.0004	-0.0022	0.0026	-0.0017	1.0000	-0.0023	0.0003	0.0025	0.0026	-0.0007	0.0003	0.0002	-0.0018	0.0000	-0.0002	-0.0009	-0.0013	0.0007	-0.0002
Red1 V_followWP	0.0000	-0.0025	0.0032	0.0004	-0.0005	-0.0008	0.0003	-0.0017	0.0011	-0.0008	-0.0023	1.0000	0.0019	-0.0012	0.0005	0.0012	-0.0011	-0.0013	-0.0002	0.0006	-0.0009	0.0015	-0.0006	-0.0014	0.0014
Red2 V_followWP	-0.0009	-0.0016	-0.0007	-0.0016	-0.0011	-0.0022	-0.0010	0.0010	-0.0001	-0.0005	0.0003	0.0019	1.0000	0.0054	-0.0017	0.0024	-0.0004	0.0008	0.0022	0.0009	0.0004	0.0011	0.0005	-0.0009	-0.0014
Red1 P_Death	0.0014	-0.0062	0.0009	0.0029	0.0001	0.0006	0.0009	0.0010	0.0012	-0.0004	0.0025	-0.0012	0.0054	1.0000	-0.0003	-0.0017	-0.0035	-0.0020	-0.0003	0.0025	-0.0003	0.0001	-0.0002	-0.0014	
Red2 P_Death	0.0004	0.0002	0.0026	-0.0004	0.0017	-0.0006	0.0006	0.0016	0.0008	-0.0010	0.0026	0.0005	-0.0017	-0.0003	1.0000	0.0007	-0.0003	-0.0001	0.0017	0.0014	0.0001	0.0017	0.0007	0.0006	-0.0015
Red1 P_cc	0.0001	0.0024	0.0001	-0.0041	-0.0012	0.0000	0.0015	-0.0014	0.0005	-0.0037	-0.0007	0.0012	0.0024	-0.0017	0.0007	1.0000	0.0006	-0.0001	0.0008	0.0004	0.0006	0.0008	-0.0022	-0.0014	0.0007
Red2 P_cc	-0.0017	0.0003	-0.0008	0.0009	-0.0012	-0.0013	-0.0008	0.0012	0.0025	0.0015	0.0003	-0.0011	-0.0004	-0.0035	-0.0003	0.0006	1.0000	-0.0003	-0.0016	0.0001	0.0010	0.0008	-0.0005	0.0021	0.0014
Red1 P_fix	-0.0009	0.0002	-0.0010	-0.0016	-0.0015	0.0004	-0.0009	-0.0027	0.0029	0.0020	0.0002	-0.0013	0.0008	-0.0020	-0.0001	-0.0001	-0.0003	1.0000	0.0053	-0.0017	0.0020	-0.0002	0.0014	-0.0011	0.0019
Red2 P_fix	-0.0006	-0.0012	-0.0047	0.0015	-0.0004	0.0007	0.0012	-0.0013	0.0007	-0.0014	-0.0018	-0.0002	0.0022	-0.0003	0.0017	0.0008	-0.0016	0.0053	1.0000	-0.0002	0.0015	-0.0008	0.0018	0.0002	-0.0016
Red1 Angle_cc	-0.0010	-0.0015	0.0005	-0.0008	-0.0003	0.0006	-0.0024	-0.0034	0.0033	-0.0004	0.0000	0.0006	0.0009	0.0025	0.0014	0.0004	0.0001	-0.0017	-0.0002	1.0000	-0.0041	0.0027	0.0037	0.0003	0.0014
Red2 Angle_cc	-0.0010	-0.0002	-0.0020	-0.0005	0.0033	-0.0022	-0.0002	0.0008	-0.0004	0.0006	-0.0002	-0.0009	0.0004	-0.0003	0.0001	0.0006	0.0010	0.0020	0.0015	-0.0041	1.0000	0.0008	-0.0004	0.0004	-0.0008
Red1 P_Det	0.0028	0.0005	0.0024	-0.0006	-0.0031	0.0017	-0.0026	0.0001	0.0004	-0.0002	-0.0009	0.0015	0.0011	-0.0008	0.0017	0.0008	0.0008	-0.0002	-0.0008	0.0027	0.0008	1.0000	0.0051	-0.0009	0.0015
Red2 P_Det	0.0003	-0.0008	0.0002	-0.0047	-0.0024	0.0012	-0.0010	-0.0014	0.0001	-0.0005	-0.0013	-0.0006	0.0005	0.0001	0.0007	-0.0022	-0.0005	0.0014	0.0018	0.0037	-0.0004	0.0051	1.0000	-0.0011	0.0018
Red1 R_mineID	-0.0016	0.0002	-0.0001	0.0009	0.0000	-0.0004	0.0018	0.0013	0.0034	0.0018	0.0007	-0.0014	-0.0009	-0.0002	0.0006	-0.0014	0.0021	-0.0011	0.0002	0.0003	0.0004	-0.0009	-0.0011	1.0000	0.0018
Red2 R_mineID	0.0017	0.0004	-0.0005	-0.0018	0.0004	-0.0005	-0.0011	-0.0006	0.0014	0.0025	-0.0002	0.0014	-0.0014	-0.0014	-0.0015	0.0007	0.0014	0.0019	-0.0016	0.0014	-0.0008	0.0015	0.0018	0.0018	1.0000

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