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THESIS

NAVY OPERATIONAL PLANNER

by

Jason F. Deleon

March 2015

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NAVY OPERATIONAL PLANNER

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Submitted in partial fulfillment of the
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ABSTRACT

This thesis presents Navy Operational Planner (NOP), a decision support aid for mission-based maritime operational planning. Operational plans consist of individual missions grouped into phases—we must accomplish a given fraction of each mission in a phase to declare completion and move to the next phase. Rather than trying to achieve as many missions as possible in a fixed time horizon, NOP advises how to allocate multiple ships to multiple missions in order to accomplish those missions to a prescribed level of completion as quickly as possible; this allows a transition to the next phase of a larger mission, such as a war, or a large-scale humanitarian aid and disaster relief operation. Knowing how long it could take to complete a mission phase is more useful in determining feasibility in the planning process and can help in assessing risks associated with employing a limited number of ships. Criteria for mission phase transitions are derived from assumptions surrounding mission-based accomplishment thresholds. The carrying out of a mission or level of effort applied contributes toward cumulative accomplishment. In addition, when mission efforts are interrupted for some period of time, the mission may require additional later effort to resume and complete.

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LIST OF ACRONYMS AND ABBREVIATIONS

AD	air defense
AO	area of operations
ASW	anti-submarine warfare
CAPT	captain
CLF	combat logistics force
COA	course of action
EOD	explosive ordinance disposal
GAMS	general algebraic modeling system
INTEL	intelligence
JFMCC	Joint Force Maritime Component Commander
JP	joint publication
KTS	knots
LOE	level of effort
MCM	mine countermeasures
MIO	maritime interdiction operation
MNV	mine neutralization vehicle
MOC	maritime operations center
MSC	Military Sealift Command
MW	wine warfare
NCC	naval component commander
NFC	numbered fleet commander
NM	nautical mile
NMP	Navy mission planner
NOP	Navy operational planner
NPP	naval planning process
NSFS	naval surface fire support
NWP	naval warfare publication
OPNAV N42	Chief of Naval Operations Strategic Mobility and Combat Logistics Division
PACOM	United States Pacific Command

RASP	replenishment at sea planner
STRIKE	strike warfare
SUW	surface warfare
TBMD	theater ballistic missile defense
USN	United States Navy

EXECUTIVE SUMMARY

Navy operational planning staffs are responsible for assigning missions to naval assets in theater to support maritime operations. This task can be daunting because of the Navy's ability to carry out multiple mission requirements with some ships capable of carrying out multiple missions simultaneously. Operational plans traditionally consist of a sequence of phases, and each phase is characterized by a set of missions. Proceeding from one phase to the next requires that some given fraction of current-phase missions be completed. Planners must also consider mission dependencies (or concurrencies) where some missions must be completed before others can begin (or simultaneously begin). Over the course of a campaign, ships will eventually have applied enough effort to complete missions in a mission phase to enable transition to a subsequent phase. Traditional planning efforts have been accomplished primarily without the assistance of automated planning tools. Using only manual planning methods can be cumbersome, time consuming and prone to error.

This thesis develops the Navy Operational Planner (NOP) mission accomplishment model. The goal of this model is to advise how to allocate limited resources to accomplish missions as quickly as possible to transition from one mission phase to the next. Criteria for mission phase transitions are derived from assumptions surrounding mission-based accomplishment thresholds. The carrying out of a mission or level of effort applied contributes toward cumulative accomplishment. In addition, when mission efforts are interrupted for some period of time, the mission may degrade (i.e., reconstitute) and require additional later effort to resume and complete.

From a set of maritime mission types considered in this thesis, the analyzed scenario incorporates only mine warfare, specifically mine hunting mine countermeasures (MCM). In a more complex model, multiple mission types can be incorporated to account for a more complex scenario. Input factors specific to mine hunting MCM missions include: sensor search speed, sensor search width, probability of detection, and area of the minefield. Other varying factors specific to the model include: the number of missions, degradation rate, cooldown duration (i.e., the rate at which achieved mission

completion is lost if the mission is interrupted), the number of ships available in each time period, and accomplishment threshold.

Given several scenarios with varying parameters, each analysis provides a minimum amount of time to complete a mission phase. This is particularly useful in assessing risk induced by limited assets. An additional asset reassigned to a mission phase may result in a quicker phase transition. Additionally, NOP provides the progress of each mission throughout the time horizon, giving insight into the behavior of how the naval assets cooperatively apply effort and where mission interruption occurs to cause mission degradation.

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To Professor Matt Carlyle, for your patience and guidance in directing this thesis. Know that your commitment to students and passion for making a difference by applying your expertise to Department of Defense related problems is the reason why Operations Research at Naval Postgraduate School is a world-renowned program led by world-class faculty. You have an exceptionally positive attitude and your constant encouragement kept me motivated. I am truly grateful for the experience of working with you. Without your support, this thesis would not have come to fruition.

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I. INTRODUCTION

Military commanders can be presented with a large amount of information in decision-making. The critical element to effective military planning is the ability to present the right amount of detail in order to provide a commander and staff a clear path to a desirable end state. The dynamic interaction and balance between operational factors of space, time and force require effective planning.

Joint Publication (JP) 5–0 outlines operational design methods for planning activities associated with military operations in a joint organization (Joint Chiefs of Staff, 2011b). The U.S. Navy incorporates and refines similar techniques in its own Navy Planning Process (NPP), which is found in U.S. Navy Warfare Publication (NWP) 5–01 (Department of the Navy, 2013a). NWP 5–01 details the Navy planning principles for naval component commanders (NCCs), numbered fleet commanders (NFCs) or joint force maritime component commanders (JFMCCs) and their respective staffs within service, joint or multinational operations (Department of the Navy, 2013a).

A. NAVY OPERATIONAL PLANNING

The U.S. Navy must be able to address a full spectrum of potential scenarios because of the uncertainty in enemy capability and threat. The scope of naval operations spans from vast open oceans to the littorals, "and often places the lowest tactical commander in critical strategic roles, necessitating that a thorough planning process be used" (Department of the Navy, 2013a, pp. 1–2). Naval planning in contested environments has shifted from threat-based planning to mission-based planning, but still relies mostly on the fundamental requirement to establish and maintain some degree of maritime superiority (Department of the Navy, 2013a).

1. Maritime Operations Center

Maritime operations centers (MOCs) plan, command, and employ naval assets in support of joint forces at the operational level of war. Commanders rely on their staffs' expertise and proficiency to provide a standardized level of planning and execution across the full range of military operations. The design and tactical employment of U.S. naval forces has evolved with multi-mission platforms providing a wide range of capabilities for countering threats and projecting power in the maritime domain (Department of the Navy, 2013b). Maritime planners are constantly challenged to maintain visibility and situational awareness as conventional and unconventional threats continue to emerge.

2. Maritime Planning

Maritime operational planning in joint warfare addresses the daunting task of assigning multiple maritime forces to complete multiple maritime missions across multiple areas of operation. A limited number of ships, combined with mission requirements that can change over the course of days or hours, compounds this task's difficulty. Further complexity is added when integrating logistics support with planning, for example, the proper employment of logistics ships in support of combatants in the area of operations. Given a set of mission completion objectives for a theater of operations, ship assignments to these missions must consider the characteristics and priorities of each mission, ship capabilities, ship availability, and the time and distance between each mission.

Mission interdependencies also add to the overall complexity and can require some prerequisite mission to be completed before subsequent ones can begin. For example, in order to have a ship begin an amphibious assault mission, that ship might require an air defense (AD) and/or anti-submarine warfare (ASW) mission to be completed. Developing effective assignments for large sets of ships can be daunting if the operation lasts longer than a few days. It is especially cumbersome if it is accomplished solely through manual planning efforts.

3. Navy Planning Process

The NPP is conducted continuously and is divided into six steps (summarized in Figure 1). As defined in NWP 5–01 (Department of the Navy, 2013a):

> The NPP is the process that assists commanders and their staffs in analyzing the operational environment and distilling a multitude of planning information in order to provide the commander with a coherent framework for determining the what and why (ends) as well as developing the method for execution (ways), given the forces and resources available (means) and the level of risk to the mission and forces.

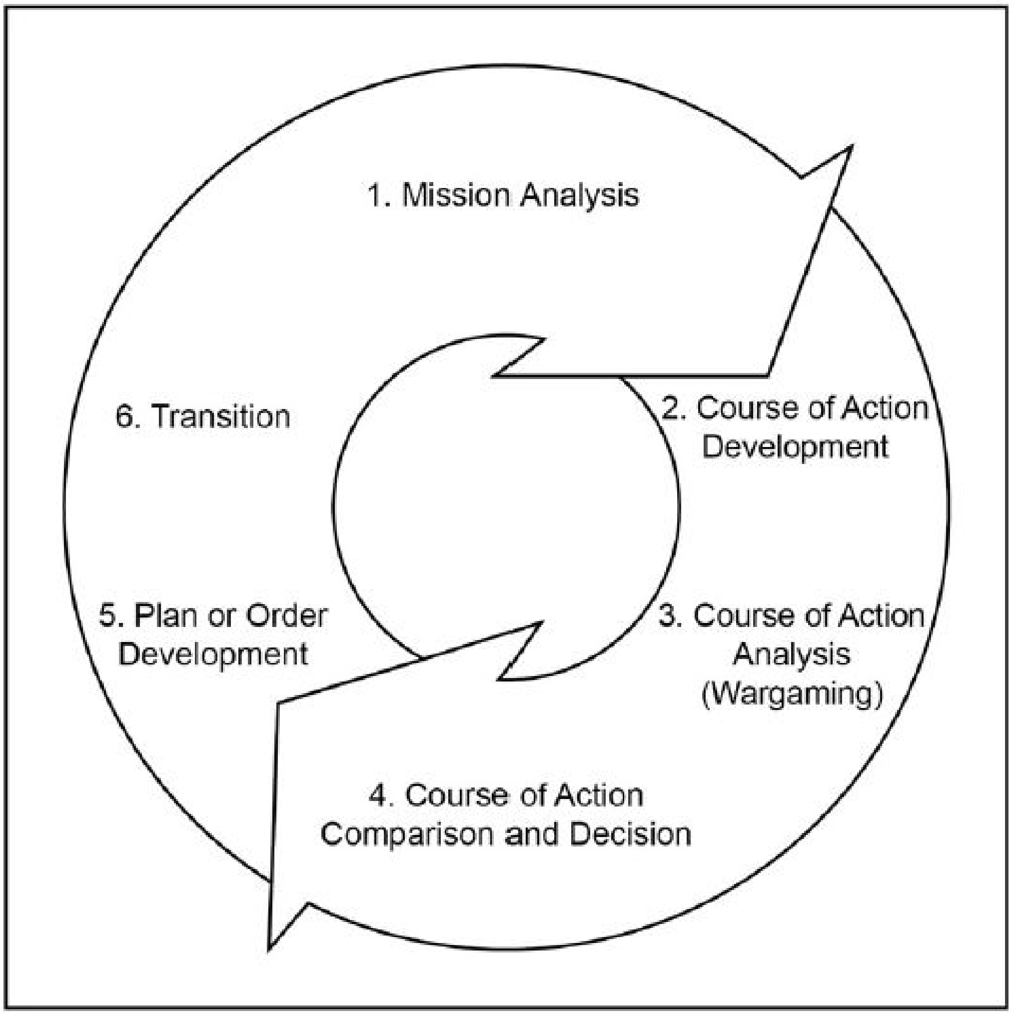

Figure 1. The Navy planning process (from Department of the Navy, 2013a).

Some planning efforts are largely accomplished by using dry-erase markers and whiteboards, simple spreadsheets, or even butcher-block paper. For example, in step two of the NPP—Course of Action (COA) development—planning cells frequently utilize spreadsheets to outline a list of mission requirements and available assets. This allows the planning cells to roughly associate assets and their capabilities with specific mission requirements to help frame COA development, identify shortfalls, and critique space, time and force-planning factors. A sample spreadsheet is shown in Figure 2.

Tangible Factors	Adversary Quantity	Friendly Quantity	Show of force	Maritime superiority	Amphibious Operations	Maritime Interdiction	Stability Operations		Planning Considerations
Aircraft carriers	0	1	X	X		X			- CVOA location relative to majority of fixed and likely dynamic targets; requirement to maintain air superiority at sea; op protection issues - Adds increased capacity, capability, and mobility to Pinkland based Blueland air; greater flexibility WRT op protection and fires
Cruisers	0	2	X	X		X			- Where locate to provide optimal op protection vs. Redland land based air? - Only Shiloh (SHI) BMD capable - Aegis to provide air picture ICW AEW-required for op protection
Destroyers		5	X	X		X			- How/when employ TLAMs; TLAM baskets; location use of DDG prior to strike; BMD responsibilities; All 5 TLAM capable - Additional strike capability; Aegis can assist with op protection
Frigates	3	5 LCS, 3 coalition FF	X	X		X			- Optimal configuration for LCS; coalition ROE WRT self- defense/mission accomplishment - LCS versatility; coalition aspect increases regional legitimacy; LCS enhances tactical C2
Patrol craft	11								- Maintaining locating data; possibility of swarm and suicide tactics - Allows red to maintain presence and increases op intel
Corvettes	5	3 coalition	X	X		X			
Small craft	8 fast attack craft w/SSM								- Requirement to maintain locating data given SSM capability; possible early dynamic target priority if required to seize the initiative - PCs, corvettes, small craft, and civ craft that can sow mines are numerous, maneuverable, and excel in the littorals
Mine layers	All ships and subs mine capable	P-3, subs		X					- Maintain ISR on storage facilities, rapid reaction fires presence as required; ROE and authorities to take out mine storage facilities and VSLs loaded with mines left of splash; limited MCM capability - Red can sortie several vessels with mines; increases ISR problem and makes it more difficult to eliminate all left of splash
MCM Platforms		1		X					- Focus on decisive points to include choke point, Blueland SLOCs, and possible amphib landing area. - **Possible RFF for MCM capability**. Only one-may need more MCM assets. Good chance Red could get some mines in the water.

Figure 2. Example COA development spreadsheet table (from Department of the Navy, 2013a).

Given a list of required missions and available assets, this form of COA development is insufficient if the analysis involves a large number of mission requirements and several types of multi-mission capable ships. Manual planning can be time consuming, prone to error, and may not be compatible with quick sensitivity and tradeoff analysis. Planning may end up simply as a reactionary exercise where long-range plans become low priority because it is too difficult to manage multiple ships and multiple missions (Dugan, 2007). Commanders need the flexibility to make more efficient decisions in planning and executing maritime force employment in a timely manner.

B. LITERATURE REVIEW OF PRIOR WORK

In addressing potential limitations of paper planning, the Navy has continued research in the application of scientific and mathematical approaches to develop automated decision aids to complement and assist manual planning efforts. Recent research from the Operations Research Department at the Naval Postgraduate School has combined the effort of faculty and a multi-service military student body (with a wide range of first-hand operational experience) to develop optimization- and simulation-based decision support tools (Stewart, 2013). The continuous refinement, improvement and evolution of these tools show a relevant need for robust approaches to maritime operational planning.

1. Navy Logistics

The Combat Logistics Force (CLF) Planner (Brown & Carlyle, 2008) has been a source for many theses and follow-on research. It is a logistics operational planning aide that uses a fixed set of operational missions to optimize employment schedules for CLF ships replenishing battle groups involved in various worldwide operational conflicts. An integer linear program is used to evaluate whether or not anticipated missions are supportable by CLF ships and if so, it prescribes where and how to operate those available assets to efficiently fulfill the battle group’s logistics requirements.

Replenishment at Sea Planner (RASP) is another example of an operational planning tool. RASP focuses on fuel conservation as it optimizes schedules for CLF ships. Brown, Carlyle and Burson (2010) revamped CLF Planner to account for greater fidelity of operational planning factors in order to meet customer requirements. Customers who have a deep interest in and have provided support for RASP include various maritime operational organizations such as the Chief of Naval Operations Strategic Mobility and Combat Logistics Division (OPNAV N42), Military Sealift Command (MSC), and United States Pacific Command (PACOM).

2. Navy Mission Planner

Dugan's (2007) Navy Mission Planner (NMP) is a multi-ship, multi-mission planning aid operating in a fixed time horizon in which the goal is to accomplish as many missions as possible. Dugan explains that NMP generates near-optimal employment schedules for surface combatant ships from a pre-defined set of mission requirements and a finite time horizon in a specific area of operations. NMP provides an optimal selection of employment schedules from a subset of the potentially enormous pool of feasible schedules.

Silva (2009) extends Dugan's NMP model by constraining the total number of possible schedules, reducing the overall computational burden at the cost of a suboptimal solution. He then tests it on a realistic, large-scale theater scenario involving many ships over a planning horizon of several weeks with daily fidelity.

Further research by Hallman (2009) adds logistic planning capabilities to NMP in order not only to evaluate when and where combatant ships should be located to perform their missions, but also how to employ CLF supply ships providing logistics support for these warships. He describes the general considerations for modeling logistics. Input factors include: time, geographic regions, commodities (type of fuel, stores, and ordinance), units, consumption factors and inventory thresholds. He also introduces additional mission types not only for the CLF ships, but for the surface combatants that could provide protection to CLF ships as escorts. The results of his work verify the applicability of a practical decision aid to theater commanders as it was used in the planning efforts during Trident Warrior 2009, a Navy's Fleet Forces Command exercise.

Pearlswig (2012) continues to improve the base NMP model by improving runtimes and adding a heuristic algorithm to generate more high-quality routes not realized through the limited enumeration routines in previous versions.

C. A DECISION AID FOR OPERATIONAL PLANNING

Wars are not necessarily fought with the constraint of a fixed time horizon to complete a mission phase where the goal is to complete as many missions as possible. Given a limited number of assets, it would be more realistic to complete each individual mission in a mission phase as fast as possible in order to swiftly transition to the next phase of the war. Knowing how long it could take to complete a mission phase is more useful in determining feasibility in planning and can help in assessing risks associated with employing a limited number of combatant ships. Additionally, with a limited availability of surface combatant and CLF ships, and having a fixed set of mission requirements as input in a fixed time horizon, end results can lead to infeasible solutions in some planning scenarios, which is a limitation of previous models.

This research primarily focuses on the development of the Navy Operational Planner (NOP), an optimization-based decision aid to support maritime operational planning. Rather than trying to achieve as many missions as possible in a fixed time horizon, NOP advises how to allocate multiple ships to multiple missions in order accomplish those missions to a prescribed level of completion as quickly as possible, to allow a transition to the next phase of a larger operation such as a war, or a large-scale humanitarian aid and disaster relief operation.

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II. NAVY OPERATIONAL PLANNER

Navy Operational Planner (NOP) uses an integer linear program to accomplish missions as quickly as possible to transition from one mission phase to the next. The criteria for transitioning between mission phases, level of effort, and mission degradation have been developed and reinforced through discussions with an experienced Surface Warfare Officer and operational planner (J. Kline, personal communication, August 27, 2014).

A. DESCRIPTION

Navy Operational Planner (NOP) considers 10 standard warfare *mission types*, defined by Joint Publication 1–02 (Joint Chiefs of Staff, 2010), as representative of the potential requirements in maritime military operations. Refer to Appendix A for the definition of each of these mission types. A *mission* is defined as a combination of mission type with a location and specific data for that particular instance of that mission type. A *mission phase* is defined as a set of required missions, some fraction of which must be accomplished prior to transitioning to the next phase. NOP advises how to allocate limited resources (in our case, surface combatant ships) to accomplish missions as quickly as possible to transition from one mission phase to the next. A *transition* between mission phases represents the accomplishment of one or more strategic goals that allow commanders to start focusing on a new set of objectives, and depends on completing, to some acceptable level, the missions in the current phase. This "acceptable" level can account for different definitions of success for the strategic goals, but at the very least needs to account for the level of effort applied toward each mission, and for mission degradation in some cases where missions must be suspended temporarily and other events (such as enemy activity) can undo some or all of the effort towards completion in the meantime.

1. Mission Phase Transitions

A mission phase transition is dependent upon completion of some fraction of all individual maritime missions defined for that particular phase. Defining what level of completed maritime missions meets the criteria to allow us to transition to the next phase is a key assumption in our model. The line that separates the end of the previous phase and the start of the next phase is not necessarily clear and can be scenario dependent. For example, the requirements for transitioning from a set of missions in one phase to those in the next phase could be described quantitatively by any of the following alternatives:

- Every mission must be completed to 100 percent;
- A percentage, say 80 percent, of all missions are 100 percent completed;
- Every mission must be completed up to a certain accomplishment threshold, say 0.85; or
- 100 percent of some missions are complete, while the remaining missions are completed up to a defined accomplishment threshold, say 0.85.

The requirements for phase transition can easily be adjusted to account for each alternative. For NOP, we establish the transition requirement to be that every mission must be completed up to a mission-specific accomplishment threshold.

2. Level-of-Effort Curves

The application of effort of a ship on a mission contributes to mission completion. When a mission is completed to an acceptable threshold, it will have had enough time and effort spent to allow the ship(s) assigned to that mission to work on other missions or transition to the next phase. A commander's experience can also influence mission completion thresholds. The variability in a commander's definition of completion of these missions can allow for some trade-off analysis and risk assessment.

A *level-of-effort* (LOE) curve provides a mapping between ship-days of effort and the corresponding fraction of mission accomplishment. Each mission's LOE curve will depend on the particulars of the mission area being modeled. Figure 3 shows a specific example of an LOE curve of a single ship conducting a mine countermeasures (MCM) mission where ship-days of effort are applied towards mission accomplishment. A horizontal line indicates a 0.85 threshold for mission accomplishment, meaning that 85 percent of the mines in that minefield have been cleared. The derivation of this LOE curve is discussed in detail in Chapter III.

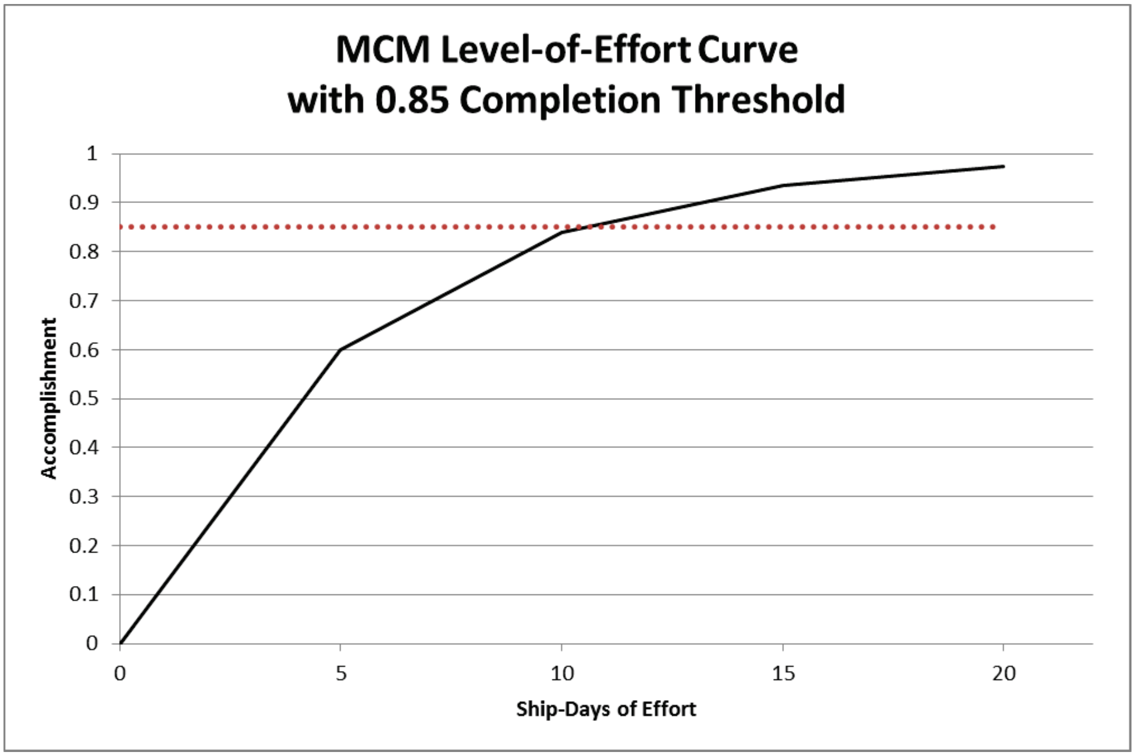

Figure 3. Chart showing LOE curve for a single ship conducting an MCM mission. The (red) horizontal dotted-line indicates the 0.85 threshold for mission accomplishment, meaning 85 percent of mines in that minefield have been cleared. After five ship-days of effort, the LOE curve indicates that 0.60 of the mission will be achieved. After 10 ship-days of effort, the LOE curve indicates we will have reached the completion threshold of 85 accomplishment.

If enough effort has been applied to a specified mission completion threshold, then that individual mission is considered complete. With a 0.85 completion threshold, after 10 ship-days of effort the mission can be considered complete. A single ship can complete the mission to the desired threshold in 10 days, and adding additional ships will increase the rate of progress on the LOE curve.

3. Mission Degradation

We account for the possibility of mission *degradation* over time, when a particular mission has been inactive for a certain number of consecutive periods, (possibly zero), called the *cooldown* for that mission; for every period after the cooldown in which there is no effort put towards the mission, it is considered to be *idle*, and the total cumulative effort applied to the mission is reduced by a fixed number of ship-days per idle period, called the *erosion* rate for that mission.

Each warfare mission can be defined as durable or non-durable. *Durable missions* are missions that do not degrade after a reasonable period of inactivity within the scope of a mission phase. The erosion rate for a durable mission is therefore zero. Once a durable mission is completed, no further effort is required to be accomplished given a period of inactivity. For example, a strike mission can be considered durable. Once a target or capability is damaged or destroyed as a result of a strike mission, it remains damaged or destroyed. *Non-durable missions* are missions that, if deemed complete after reaching an LOE threshold, the cumulative effort applied previously would degrade over time if the mission is in cooldown and continues to remain idle. If the degradation of cumulative effort falls below the completion threshold, then that mission is no longer considered complete and would require a ship to re-visit that mission and apply enough effort to reach mission accomplishment again. An example of a non-durable mission is a surface ship assigned to search for submarines to ensure a clear path and safe passage for an aircraft carrier. Once the surface ship has completed the mission and leaves the search area, the confidence that no submarine is in that area degrades with time.

Figure 4 illustrates cumulative accomplishment for a notional non-durable mission with a cooldown of three time periods. As continuous effort is applied in each time period, cumulative accomplishment increases with a goal of completing the mission when that cumulative accomplishment has met or exceed a given threshold. If the mission is in cooldown, then the LOE towards cumulative accomplishment of that mission would degrade each day it remains idle, which would require that mission to be re-visited and ships be reallocated to work on it.

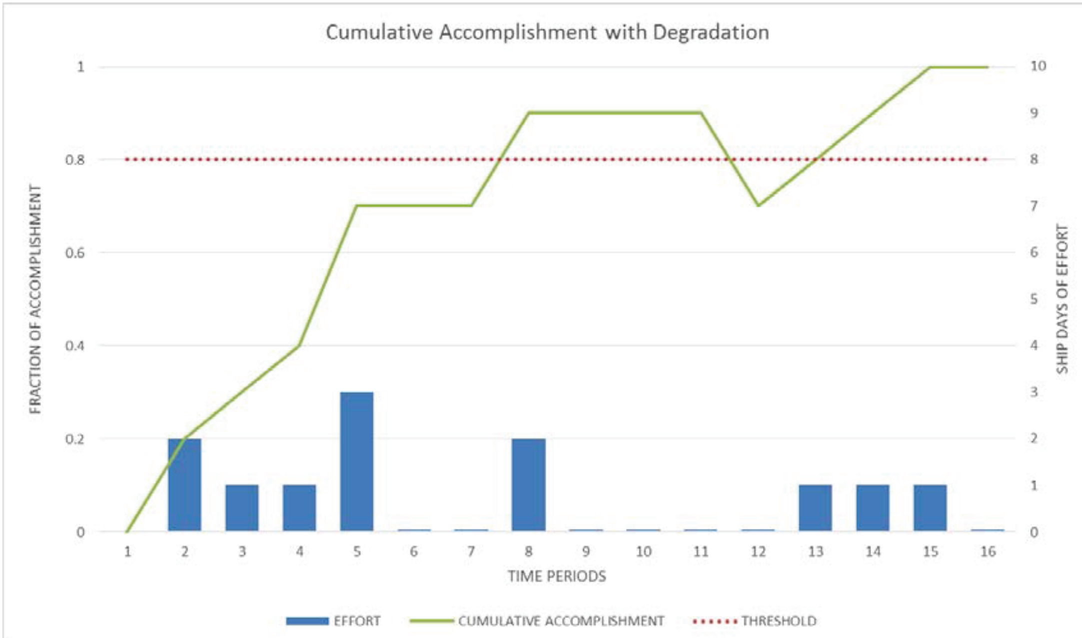

Figure 4. Chart showing accomplishment of a single mission associated with effort applied throughout the time horizon of the model. Continuous effort is applied in periods t2 – t5 resulting in a total cumulative effort of 2+1+1+3=7 ship-days, which yields a fractional mission accomplishment of 0.7. No effort occurs in periods t6 and t7, but because the cooldown is three days, no effort (and therefore no accomplishment) is lost. The mission accomplishment threshold of 0.8 is met in period t8. Cooldown occurs over periods t9 – t11. The mission is therefore considered idle in period t12, and degradation occurs at t12 at an erosion rate of two ship-days per idle period. After period t12, enough accomplishment is lost to fall below the completion threshold, resulting in an allocation of ships in periods t13-t15 to re-accomplish the mission.

In anticipation of an unavoidable cooldown period, we may advise to complete more than the required fraction of accomplishment for mission completion to mitigate the effects of cooldown. In a multiple mission scenario, mission accomplishment and possible degradation will occur for each mission with a limited number of available ships. The optimal application of effort of a limited number of ships to a set of mission requirements is the core of this model.

B. MISSION ACCOMPLISHMENT MODEL

The following solves an operational planning problem to suggest how to accomplish enough missions to advance to the next phase of the operation as quickly as possible. Ships will take on missions based on their capabilities. We assume that all ships are capable of accomplishing each mission. The accomplishment of each mission can be approximated by a level-of-effort (LOE) curve using a piecewise linear concave function that maps ship-days of effort to a fractional mission accomplishment value. Figure 5 captures this approximation. In more involved models, a particular mission could also include additional specific data: start times, location and precedence relationships between missions. Here, for illustration, we simply provide the threshold, erosion rate, cooldown time and LOE curve data for each mission.

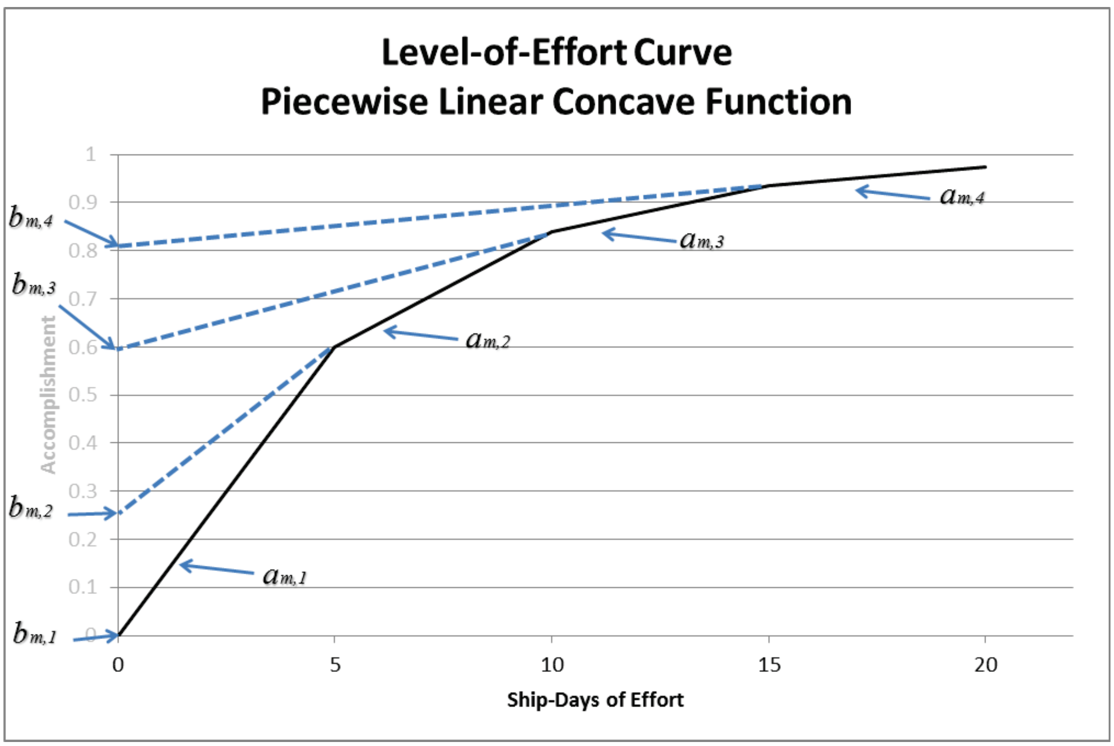

Figure 5. Chart capturing LOE curve data for a mission m. Note that $b_{m,1} = 0$. Each segment k of the LOE curve is defined by the slope ($a_{m,k}$) and y-intercept ($b_{m,k}$) and as $b_{m,k}$ increases, $a_{m,k}$ decreases. The slope and y-intercept are derived from the base-rate and work-size of a mission.

1. Sets and Indices [Cardinality]

$m \in M$	Missions [~10]
$k \in K$	Segments of the level-of-effort curve [~4]
$t \in T$	Time periods (alias t') [~30]

2. Data [Units]

$thresh_m$	Threshold fraction required for accomplishing mission *m* [0.0-1.0]
$baserate_m$	Base clearing rate for mission *m* [0.0-1.0]
$work\_size_m$	Ship days required for a complete pass on mission *m* [ship-days]
$a_{m,k}$	Slope of level-of-effort curve on segment *k* of mission *m* [0.0-1.0/ship-period]
$b_{m,k}$	y-intercept of level-of-effort curve on segment *k* of mission *m* [0.0-1.0]
$erosion_m$	Rate of loss of accomplishment per idle day for mission *m* [ship-day/day]
$cooldown_m$	Consecutive days idle before any erosion occurs for mission *m* [days]
max_effort_m	Maximum ship days of effort that can be put into mission *m* [days]
$ships_t$	Number of ships available in period *t* [ships]

3. Decision Variables [Units]

$ACCOMP_{m,t}$	Fraction of accomplishment of mission *m* in period *t* [0.0-1.0]
$CUM\_EFFORT_{m,t}$	Cumulative net effort (effort – erosion) expended on mission *m* in period *t* [ship-days]
$EFFORT_{m,t}$	Ship days of effort expended on mission *m* in period *t* [ship-days]
$DONE_{m,t}$	Mission *m* completed by period *t* [binary]
$WORKING_{t}$	Still working on at least one mission by period *t* [binary]
$ACTIVE_{m,t}$	Mission *m* had ships assigned in period *t* [binary]
$IDLE_{m,t}$	Mission *m* had no ships assigned in period *t* [binary]
$IDLE\_RESET_{m,t}$	Mission *m* has eroded below single period erosion amount in period *t* [binary]

4. Formulation

$$\min \quad \sum_t WORKING_t - \sum_{m,t} (0.001) ACCOMP_{m,t} \qquad (\text{P0})$$

$$\text{s.t.} \quad ACCOMP_{m,t} \le a_{m,k} CUM\_EFFORT_{m,t} + b_{m,k} \qquad \forall m,t,k \quad (\text{P1})$$

$$thresh_m DONE_{m,t} \le ACCOMP_{m,t} + thresh_m (1 - WORKING_{t-1})\big|_{t>1} \qquad \forall m,t \quad (\text{P2})$$

$$WORKING_t + DONE_{m,t} \ge 1 \qquad \forall m,t \quad (\text{P3})$$

$$\sum_m EFFORT_{m,t} \le ships_t \qquad \forall t \quad (\text{P4})$$

$$ACTIVE_{m,t} \le EFFORT_{m,t} \qquad \forall m,t \quad (\text{P5})$$

$$IDLE_{m,t} \ge 1 - \sum_{t':t\text{-}cooldown_m < t' \le t} ACTIVE_{m,t} - IDLE\_RESET_{m,t} \qquad \forall m,t \quad (\text{P6})$$

$$CUM\_EFFORT_{m,t} \le max\_effort_m (1 - IDLE\_RESET_{m,t}) + erosion_m \qquad \forall m,t \quad (\text{P7})$$

$$CUM\_EFFORT_{m,t} = CUM\_EFFORT_{m,t-1} + EFFORT_{m,t} - erosion_m IDLE_{m,t} \qquad \forall m,t \quad (\text{P8})$$

$$0 \le ACCOMP_{m,t} \le 1 \qquad \forall m,t$$

$$EFFORT_{m,t} \ge 0 \qquad \forall m,t$$

$$CUM\_EFFORT_{m,t} \ge 0 \qquad \forall m,t$$

$$DONE_{m,t} \in \{0,1\} \qquad \forall m,t$$

$$WORKING_t \in \{0,1\} \qquad \forall t$$

$$ACTIVE_{m,t} \in \{0,1\} \qquad \forall m,t$$

$$IDLE_{m,t} \in \{0,1\} \qquad \forall m,t$$

$$IDLE\_RESET_{m,t} \in \{0,1\} \qquad \forall m,t$$

5. Discussion

Our objective (P0) calculates the number of periods required to achieve phase completion, minus a small reward for accomplishing missions. The fraction of accomplishment achieved for each mission in each time period is bounded (P1) by a piecewise linear function of the cumulative ship-days of effort applied (Figure 5). Each mission is considered complete (P2) only if enough accomplishment has been achieved to meet the threshold. We continue to work on missions in each time period (P3) if any mission is not yet complete. The total effort across all missions in each period cannot exceed (P4) the number of ships available that period. Each mission can only be considered being actively worked on (P5) when some effort has been expended on that mission in each period. Each mission is considered idle (P6) unless there is at least one ship expending effort in that time period or when the mission has eroded beyond a single period erosion amount. When a mission has eroded beyond a single period erosion amount (P7), cumulative effort cannot erode below zero. Cumulative effort in each period is defined (P8) as the cumulative effort expended up to and including the previous period, plus any effort expended in current period, minus any eroded effort as a result of being idle.

III. MINE WARFARE AND SCENARIO

The Navy Mission Planner (NMP) (Dugan, 2007), presents 10 mission types listed in Appendix A. In a more complex model, multiple mission types can be incorporated to account for a more complex scenario. We have thought through the implications of each of these mission types, and ensured that our modeling example could be extended to each of these. For the purposes of this thesis, we provide further detail using only the mine countermeasures (MCM) mission type.

A. MINE WARFARE

Maritime mine warfare (MW) involves the strategic, operational and tactical employment of sea mines and mine countermeasures (MCM) (Joint Chiefs of Staff, 2011a). It consists of mining, the physical placement of mines that will weaken the capabilities of the enemy to conduct operations in all domains; and the countering of enemy mining capability or the actual emplaced mines. Figure 6 summarizes the division of MW and its various sub elements.

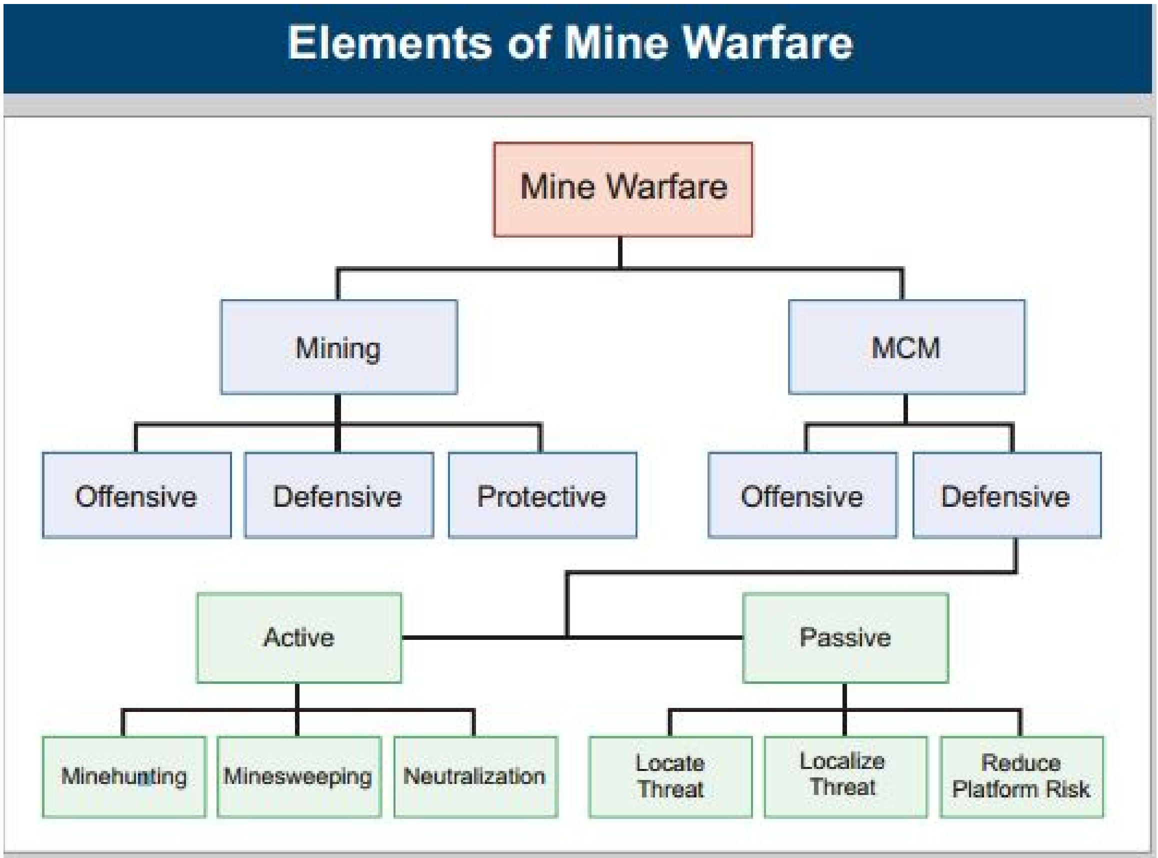

Figure 6. Elements of mine warfare (from Joint Chiefs of Staff, 2011a).

Without physically targeting the mines, a ship can counter mines that have already been emplaced by reducing its electronic signature and susceptibility to actuating the mine. In addition to this risk reduction, localization of safe transit routes or *q-routes*, and the detection and avoidance of minefields are techniques known as passive MCM (Joint Chiefs of Staff, 2011a).

Active MCM may also be employed if passive efforts are not enough. Active MCM involves the actual targeting of emplaced mines, either by destroying them or by triggering them to explode (Joint Chiefs of Staff, 2011a). Two primary methods of active MCM are minesweeping and mine hunting.

Mine hunting involves the use of air, surface, or subsurface sensors and neutralization systems to detect and clear individual mines. It is used to confirm the presence or absence of mines in a given area or when it is not feasible or desirable to conduct minesweeping (Joint Chiefs of Staff, 2011a). Once a mine has been detected, the mine can be neutralized by several methods: a remote mine neutralization vehicle (MNV), an explosive ordinance disposal (EOD) diver or marine mammal system. Mine hunting is considered to pose less risk to MCM forces, offers more thorough coverage of minefields and provides a higher probability of detection than minesweeping.

Minesweeping involves the use of a towed mechanical or influence sweep system by a surface vessel or aircraft (Joint Chiefs of Staff, 2011a). A mechanical sweep system uses special cables to cut moored mines so they would float to the surface for EOD divers to neutralize. Influence sweep systems tow specialized devices that emulate a ship's acoustic and magnetic signature to actuate influence mines.

B. MCM ANALYSIS

For modeling maritime mission accomplishment, we derive our analysis using the MW mission type, specifically mine hunting MCM. An LOE curve would be built for each other mission type in a similar fashion. Similar decisions about mission durability and the effects of mission degradation on non-durable missions would also have to be made for each maritime mission.

1. LOE Curve Derivation

For the mine hunting MCM mission, we assume a uniform distribution of mines and the detection and neutralization of individual mines are included in the search times. Given a probability of detection, say 0.6, we assume a deterministic search pattern, so when an MCM-capable ship has made its first pass through a minefield, it will have detected and neutralized 60 percent of the mines. The minefield's area and an MCM ship's search speed and width is used to calculate how long it may take to achieve a certain *level of clearance*, defined as the fraction of mines in the minefield that have been cleared. The combined effort of multiple minesweepers would reduce the overall time proportional to the number of ships conducting the mission.

As previously shown, Figure 3 presents a specific example of an LOE curve derived for a single ship conducting an MCM mission. This MCM mission assumes ship parameters and a minefield area summarized in Table 1. A single MCM ship is tasked to conduct a deterministic exhaustive search over a minefield of area A (18.6 square nautical miles). Using an exhaustive search equation for a uniformly distributed target, $T = A / VW$ (Washburn, 2002), it takes five days for a single complete pass through the minefield. The probability of detection in a deterministic search will be the rate at which mines are being cleared in a single pass; we refer to this as the *base-rate.* Given a base-rate of 0.6, the search results in detection and clearance of 60 percent of potential mines in the field after a single pass. After a second pass, it takes an additional five days to neutralize 60 percent of the remaining 40 percent of the mines, and so forth. If the level of clearance reaches the threshold for completing an MCM mission, then the mission is considered complete and the minesweeper can work on another mission, if any remain that have not been accomplished to their required threshold.

Table 1. MCM ship's search parameters and minefield area. An MCM ship has a search speed V in nautical miles per hour (kts), search width W in nautical miles (NM) and base-rate. The area A of the minefield is in square NMs.

Search Speed (kts) = V	5
Search Width (NM) = W	0.028
Area (sq. NM) = A	18.6
Base-rate	0.6

Information from the LOE curve provides parameter inputs for the model to accomplish an MCM mission. The time it takes for a single complete pass, or *work-size,* is calculated from the minefield's area. If the minefield's work-size is five, it takes five ship-days for one pass, the base-rate parameter specifies the clearance proportion for each pass. Consequently, a base-rate of 0.6 means that 60 percent of the mines are detected and cleared on each full 5-day pass.

2. Mine Countermeasures Mission Durability

MCM missions are non-durable. If ships with mine detecting and/or clearing capability have completed their MCM mission, those ships can potentially be reassigned to start working on other missions in another location. If no additional ships arrive in the location where mines have been cleared to conduct any follow-on missions and a period of inactivity past the cooldown period has elapsed, we assume that the mines can be reconstituted by the enemy. If ships with a mission requiring operations in that mine-cleared location do not resume their work in that location before the end of the cooldown, the MCM mission would eventually degrade below the completion threshold and must be re-visited, because it is no longer a completed mission.

C. SCENARIO RESULTS

The model was implemented using GAMS (GAMS Development Corporation, 2014) and solved using IBM's CPLEX solver (IBM, 2014). All model runs were conducted using a 2.16Ghz Intel Celeron Asus notebook with 4.0 GB of RAM, running the Windows 8 operating system. Our main scenario model has 3001 equations and 2131 variables, 1530 of which are binary. The model formulation for our main scenario solves within 0.062 seconds.

An unclassified scenario involving a notional series of operational events surrounding the Korean Peninsula area of operations (AO) is used as a test demonstration for the model. The Korean Peninsula scenario has been adopted and refined through several legacy theses previously mentioned (Silva, 2009). Figure 7 shows the AO focused on the Korean Peninsula.

Figure 7. Map of the Korean Peninsula area of operations (after Google Maps, 2015).

Each model assessment represents a mission phase where there are more missions (minefields) than ships available. For each assessment, we assume the same search speed, search width and base-rate previously summarized in Table 1, for each MCM ship. We also assume several variables for each mission to be constant: threshold of completion at 0.85, cooldown of three periods and a base-rate of 0.60.

The output of each assessment reveals the minimum amount of time it would take to complete all missions in that phase and transition to the next phase. The output also provides the status of each mission as it progresses through each time period. The parameters we vary include the number of minefields, the number of ships available in each time period, the erosion rate, and the minefield's size (work-size), or the time it takes to make a single complete pass. As previously shown in Figure 3, the minefield's size and an MCM ship's search profile can be used to determine the minefield's work-size.

The number of time periods is also varied, but only to allow for feasibility. Adding additional time periods will not change the solution, but will allow a solution to be found. This is an important consideration, because we cannot reckon a priori how long a complex war plan will take to prosecute, if it can be prosecuted at all. Thus, we are not constrained to a fixed time horizon.

1. Initial Assessment

In the initial assessment, we test a simple case where there are seven ships available in each time period tasked to 10 MCM missions. Half of the minefields have a work-size of one and the other half have a work-size of two. The erosion rate is set to 0.05 and a summary of all parameters are provided in Table 2

Table 2. Initial assessment parameters. We have seven ships available in each time period to work on 10 missions in a 20 period time horizon. The mission work-sizes are split where half have a work-size of one and the other half have a work-size of two. The erosion rate is 0.05.

Time periods	20
Ships	7 in all periods
Erosion	0.05
Minefields	**work_size**
m1	1
m2	1
m3	1
m4	1
m5	1
m6	2
m7	2
m8	2
m9	2
m10	2

The initial assessment obtains a solution that achieves phase transition by the end of period t6. The output in Table 3 is organized by time periods and summarizes each mission's status at the end of the period t6.

Table 3. Initial assessment output for period t6. The EFFORT column shows how many ship-days of effort is applied to each mission at period t6. The ACCOMP column shows the cumulative accomplishment based on the effort applied by those ships up to the end of period t6. Each mission has reached the completion threshold of 0.85 by the end of period t6. They are all flagged completed as indicated in the DONE column and phase transition can now occur.

PERIOD	MISSION	EFFORT	CUM_EFFORT	ACCOMP	DONE
t6	m1	0.0	3.0	0.94	1.0
t6	m2	0.0	3.0	0.94	1.0
t6	m3	0.0	3.0	0.94	1.0
t6	m4	1.0	4.0	0.97	1.0
t6	m5	1.0	4.0	0.97	1.0
t6	m6	1.0	5.0	0.89	1.0
t6	m7	1.0	5.0	0.89	1.0
t6	m8	1.0	5.0	0.89	1.0
t6	m9	1.0	5.0	0.89	1.0
t6	m10	1.0	5.0	0.89	1.0

Table 4 presents a different organization of the output. It provides the status of a single mission (m10) as it progresses through each time period.

Table 4. Initial assessment output for mission m10. As effort is applied in each time period, the ACCOMP column shows the cumulative accomplishment achieved. Completion is accomplished in period t6 when the mission reaches 0.85 accomplishment. There is no ship effort applied periods t2 and t3, but the mission does not go idle because no cooldown occurs has activity resumes in period t4.

MISSION	PERIOD	EFFORT	CUM_EFFORT	ACCOMP	DONE	IDLE
m10	t1	2.0	2.0	0.60	0.0	0.0
m10	t2	0.0	2.0	0.60	0.0	0.0
m10	t3	0.0	2.0	0.60	0.0	0.0
m10	t4	2.0	4.0	0.84	0.0	0.0
m10	t5	0.0	4.0	0.84	0.0	0.0
m10	t6	1.0	5.0	0.89	1.0	0.0

Because the work-sizes of each mission are relatively small in this phase, the amount of time it takes to complete all missions is relatively short, finishing by period t6. We do not observe any ships going idle, however, if there was no activity in period t4, then we would have been in cooldown where we may observe mission degradation.

2. Second Assessment

In the second assessment, we vary the number of available ships in each time period and each mission's work-size to provide more insightful results. We decrease the total number of ships in each time period and define a mix of mission work-sizes as summarized in Table 5.

Table 5. Second assessment parameters. We increase some of the minefield work-sizes and reduce the number of ships available in each time period. The number of time periods is also increased to have a fewer number of ships accomplish missions where work-sizes are larger.

Time periods	30
Ships	4 in all periods
Erosion	0.05
Minefields	**work_size**
m1	5
m2	5
m3	5
m4	5
m5	5
m6	5
m7	4
m8	3
m9	2
m10	1

For this scenario we have fewer ships, and larger work-sizes for some of the minefields. It is not surprising that completion of all missions and the resulting phase transition takes longer, occurring at the end of period t24. Table 6 shows the status of mission m10 in each period. In this case, there are several instances where cooldown occurs, causing the mission to be flagged as idle and degradation in cumulative accomplishment.

Table 6. Second assessment output for mission m10. In periods t5 and t15, we observe the first and second instances where the mission is idle, as indicated in the IDLE column. As a result, we observe degradation of cumulative effort in the CUM_EFFORT column and subsequent decrease in accomplishment as shown in the ACCOMP column each period the mission is in an idle state.

MISSION	PERIOD	EFFORT	CUM_EFFORT	ACCOMP	DONE	IDLE
m10	t1	1	1	0.6	0	0
m10	t2	1	2	0.84	0	0
m10	t3	0	2	0.84	0	0
m10	t4	0	2	0.84	0	0
m10	t5	0	1.95	0.828	0	1
m10	t6	0	1.9	0.816	0	1
m10	t7	0	1.85	0.804	0	1
m10	t8	0	1.8	0.792	0	1
m10	t9	0	1.75	0.78	0	1
m10	t10	0	1.7	0.768	0	1
m10	t11	0	1.65	0.756	0	1
m10	t12	1	2.65	0.9024	0	0
m10	t13	0	2.65	0.9024	0	0
m10	t14	0	2.65	0.9024	0	0
m10	t15	0	2.6	0.8976	0	1
m10	t16	0	2.55	0.8928	0	1
m10	t17	0	2.5	0.888	0	1
m10	t18	1	3.5	0.9552	0	0
m10	t19	0	3.5	0.9552	0	0
m10	t20	0	3.5	0.9552	0	0
m10	t21	1	4.5	0.9936	0	0
m10	t22	0	4.5	0.9936	0	0
m10	t23	0	4.5	0.9936	0	0
m10	t24	0	4.45	0.99168	1	1

When comparing the notional mission's cumulative accomplishment with degradation, presented earlier in Figure 4, Figure 8 illustrates similar behavior using the output of our second assessment. In periods t1 and t2, one ship-day of effort is applied and cumulative accomplishment reaches 0.84. Accomplishment remains the same for the next two periods of inactivity. From period t5 - t11, the number of contiguous periods of mission inactivity has exceeded the cooldown period and now the mission is in an idle state. We observe the declining slope of accomplishment up until ship effort resumes in period t12. The accomplishment threshold is now reached and continues to stay above that threshold throughout the phase.

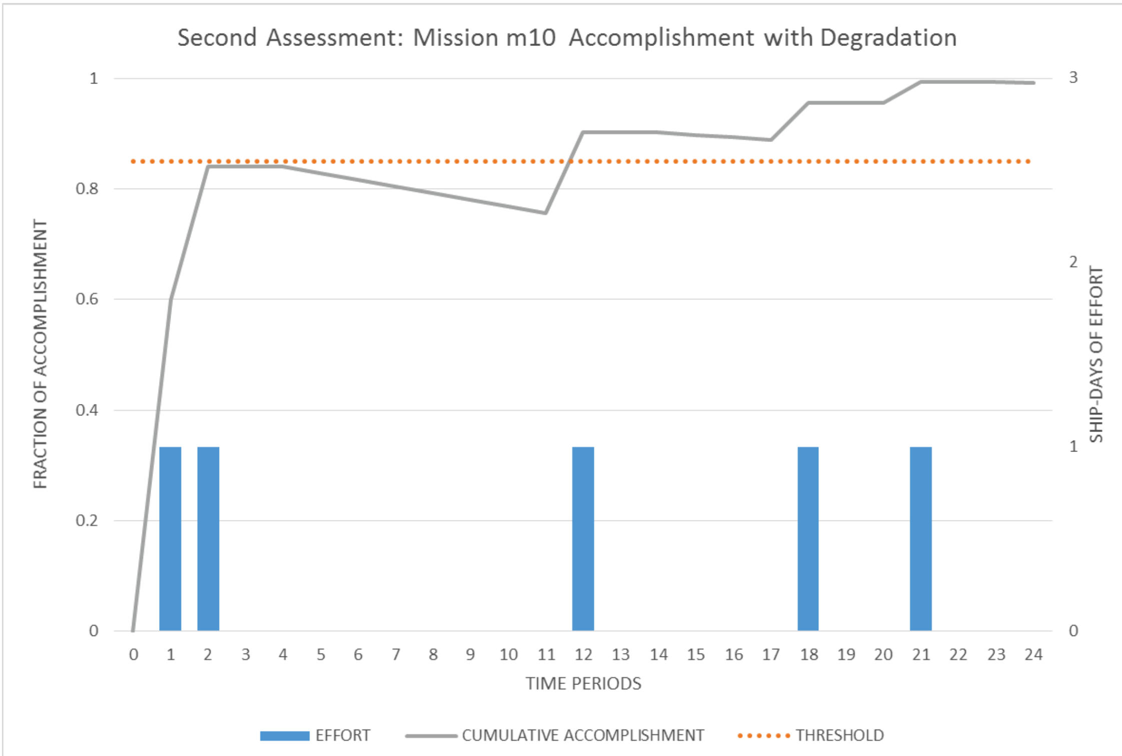

Figure 8. Chart showing accomplishment of mission m10 of second assessment output. Continuous effort is applied in periods t1 and t2 and cumulative accomplishment reaches 0.84. Cooldown occurs over periods t3-t5. The mission is now in an idle state and degradation occurs at the start of period t6. Activity resumes in period t12 and cumulative accomplishment has reached the completion threshold.

In this assessment, mission m10 has a work-size of one. The solution allows mission m10 to go idle in this scenario because less effort is required to reach the accomplishment threshold in a smaller minefield. The ability to recover from a declining slope of accomplishment to reach the accomplishment threshold is faster for a small minefield. From this solution, we may recommend missions on which to focus our effort based on the work-size of the minefields.

3. Third Assessment

In the third assessment, we increase the mission accomplishment erosion rate, and change the number of ships available in each time period so that the number of ships is no longer constant. The breakdown of ships available in each period is shown in Table 7.

Table 7. Third assessment parameters. We increase the mission accomplishment erosion rate, and change the number of ships available in each time period so that the number of ships is no longer constant. There are four ships available in periods t1 – t15 and three ships in periods t16 – t30.

Time periods	30
Ships	4 in periods 1-15,
	3 in period 16-30
Erosion	0.1
Minefields	**work_size**
m1	3
m2	3
m3	3
m4	5
m5	7
m6	7
m7	6
m8	4
m9	3
m10	3

Having a different number of ships available from one time period to the next may represent an operational scenario where a ship is reallocated to work on a more emergent mission or an anticipation of future phase duties calls for an early departure from the current phase. The completion of all missions in this assessment allows for a phase transition to occur at the end of period t26. There are similar results to the prior, second assessment, where we observe instances where idle states occur in only the relatively smaller minefields, namely minefields m1 – m3, and m8 – m10, where their work-sizes are three or four.

Figure 9 captures how ship activity is spread throughout the entire phase for each mission. Multiple ships may be assigned to a single minefield in any given period. As previously observed, idling occurs where the mission work-sizes are relatively smaller.

Figure 9. Chart showing ship activity throughout the phase. The solid (green) bars represent how effort is applied by the ships in each mission. In periods t1 – t5, at most seven ships can be active. In periods t16 – t20, when there are only two ships available, there are at most two ships working. The cross-hashed (red) bars indicate when each mission has gone idle and LOE towards mission accomplishment is degrading.

IV. CONCLUSIONS AND FUTURE RESEARCH

A. SUMMARY

We present NOP as a decision support aid to complement manual operational planning efforts. NOP suggests the minimum amount of time for a phase transition by accomplishing missions as quickly as possible. Knowing how long it takes for a mission phase transition is more useful in determining feasible courses of action in planning and can help in assessing risks associated with depending on too few combatant ships.

We define and establish proof of concept for the use of mission level-of-effort (LOE) curves, assumptions of mission degradation parameters and accomplishment thresholds to determine how long it takes complete a mission. We then use that information as input to NOP in order to determine the amount of time required to transition to the next mission phase.

B. FUTURE DEVELOPMENT

1. In-Depth Analysis in Other Mission Warfare Areas

Analysis of only the MW mission type, specifically, mine-hunting MCM missions, limits the potential mix of warfare missions in a mission phase to realize the complexity of maritime operational planning. Establishing similar LOE curves, mission degradation parameters and assumptions of accomplishment thresholds through the use if tactical analysis for each maritime mission is the next logical step in improving the model and adding fidelity to this decision aid.

2. Scenario Integration with NMP

NMP divides the area of operations (AO) into regions. The integration between NMP and NOP considers distances between missions and mission phases. It should include multi-mission-capable ships and multi-mission requirements with their inherent interdependencies. It should also incorporate concurrent mission capable sets or sets of maritime missions that a ship can execute simultaneously (Dugan, 2007). Incorporating the embellishments of NOP into the generality of NMP would contribute greatly to the evolution of Navy mission planning.

3. Adding a Logistics Component

Just as NMP was enhanced to take into account the logistics requirements from CLF ships, including similar logistics planning capability for NOP would be a major enhancement to the model. Deriving LOE curves for missions associated with logistics replenishments would add depth to the inherent characteristics of maritime operations.

APPENDIX

A. USE OF MISSION DEFINITIONS

The following is the definition of mission types as published by Silva, minus the Submarine Intelligence Collection mission (Silva, 2009, Chapter IV, Section A, Part 1). It is used as a reference for the mission types we have considered in this research, but not explicitly included here. (i.e., we have thought through the implications of each of these mission types, and ensured that our modeling example could be extended to each of these).

B. MISSION TYPES

Acronyms or abbreviations in parenthesis denote NMP notation. Joint Publication 1–02 (Joints Chiefs of Staff, 2010) defines the following mission, except as otherwise noted:

1. Air Defense (AD)

Air defense measures are designed to destroy attacking enemy aircraft or missiles in the atmosphere, or to nullify or reduce the effectiveness of such attack. We consider air defense separately from missile defense.

2. Theater Ballistic Missile Defense (TBMD)

A ballistic missile is any missile which does not rely upon aerodynamic surfaces to produce lift and consequently follows a ballistic trajectory when thrust is terminated.

Missile defense is defensive measures designed to destroy attacking enemy missiles, or to nullify or reduce the effectiveness of such attack.

We use the term TBMD to describe the naval mission of providing ballistic missile defense to a theater of operations.

3. Antisubmarine Warfare (ASW)

Antisubmarine warfare operations are operations conducted with the intention of denying the enemy the effective use of submarines.

4. Surface Warfare (SUW)

Surface warfare is the portion of maritime warfare in which operations are conducted to destroy or neutralize enemy naval surface forces and merchant vessels.

5. Strike

A Strike mission involves an attack to damage or destroy an objective or a capability. Naval fire resources are sea based or sea supported, and include Navy and Marine Corps lethal and nonlethal air-delivered weapons, maritime-based gunfire and land-attack missiles, and maritime-based naval special warfare units. (NWP 3–09, 2011)

6. Naval Surface Fire Support (NSFS)

Naval surface fire support is fire provided by Navy surface gun and missile systems in support of a unit or units.

7. Maritime Interception Operations (MIO)

Maritime interception operations involve efforts to monitor, query, and board merchant vessels in international waters to enforce sanctions against other nations such as those in support of United Nations Security Council Resolutions and/or prevent the transport of restricted goods.

8. Mine Countermeasures (MCM)

Mine countermeasures are all methods for preventing or reducing damage or danger from mines.

9. Mine Warfare (MW)

Mine warfare is the strategic, operational, and tactical use of mines and mine countermeasures. Mine warfare is divided into two basic subdivisions: the laying of mines to degrade the enemy's capabilities to wage land, air, and maritime warfare; and the countering of enemy-laid mines to permit friendly maneuver or use of selected land or sea areas.

10. Intelligence Collection (INTEL)

Intelligence missions involve the collection of available information concerning foreign nations, hostile or potentially hostile forces or elements, or areas of actual or potential operations.

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