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Considerations for Cross Domain / Mission Resource Allocation and Replanning

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NAVAL POSTGRADUATE SCHOOL

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CONSIDERATIONS FOR CROSS DOMAIN/MISSION RESOURCE ALLOCATION AND REPLANNING

by

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This research project explored emerging innovative data analytic concepts and techniques (including game theory, machine learning, and wargaming) to effectively manage and allocate warfare resources across multiple domains to address multiple missions in dynamic operations. The research team identified and characterized complex tactical situations in which multi-missions need to be prioritized and dynamic replanning is required. The team developed a conceptual approach that leverages advanced data analytics, game theoretics, wargaming, artificial intelligence and machine learning to support and enable decision-making (to best use and allocate warfare resources and forces) during those complex tactical situations. The team developed model-based systems engineering representations of the conceptual design and modeled use case scenarios involving complex tactical, operational, and strategic situations. The team envisioned and modeled an innovative wargaming decision aid to support operational level mission planners that may encounter similar complex situations requiring a dynamic cross-domain multi-mission approach at this higher level.

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ABSTRACT

This research project explored emerging innovative data analytic concepts and techniques (including game theory, machine learning, and wargaming) to effectively manage and allocate warfare resources across multiple domains to address multiple missions in dynamic operations. The research team identified and characterized complex tactical situations in which multi-missions need to be prioritized and dynamic replanning is required. The team developed a conceptual approach that leverages advanced data analytics, game theoretics, wargaming, artificial intelligence and machine learning to support and enable decision-making (to best use and allocate warfare resources and forces) during those complex tactical situations. The team developed model-based systems engineering representations of the conceptual design and modeled use case scenarios involving complex tactical, operational, and strategic situations. The team envisioned and modeled an innovative wargaming decision aid to support operational level mission planners that may encounter similar complex situations requiring a dynamic cross-domain multi-mission approach at this higher level.

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I. INTRODUCTION

A. PROJECT STATEMENT

Complex situations may arise in military operations that require cross-domain and multi-mission operations with limited warfare resources. These situations pose challenges to tactical decision-makers who need to use warfare resources in the moment while they may also be needed for other concurrent mission needs and at later times to accomplish a series of missions. These situations require dynamic replanning during operations to assure that planned missions are achievable and mission modifications support strategic objectives. This project explored artificial intelligence and advanced data analytic methods to develop future automated decision aids for mission planning and tactical decision-making that can support complex cross-domain and multi-mission operations.

B. RESEARCH OBJECTIVES

The primary research objective was to explore emerging innovative data analytic technologies (including game theory, machine learning, and wargaming) to optimize naval resource allocation and replanning across mission domains.

Additional research objectives were to:
- Explore emerging technologies and data analytic tools to address uncertainty and optimize success across mission areas.
- Examine options and capabilities required to balance between domain-specific battle management aids and optimize resource allocation across domains.
- Study how these techniques can be combined to optimize multi-warfare planning, execution support, and replanning across domains.

C. RESEARCH APPROACH

The NPS research team, consisting of NPS researchers and NPS graduate students, applied a systems analysis approach to the project. The team began with a literature review of (1) automated advanced data analytics methods, (2) cross-domain and multi-mission operations, and (3) tactical decision-making and mission planning. The research team identified and characterized complex tactical situations in which multi-missions need to be prioritized and dynamic replanning is required. The team developed a conceptual approach that leverages advanced data analytics, game theoretics, wargaming, artificial intelligence and machine learning to support and enable decision-making (to best use and allocate warfare resources and forces) during those complex tactical situations. The team developed model-based systems engineering representations of the conceptual design and modeled use case scenarios involving complex tactical, operational, and strategic situations. The team envisioned and modeled an innovative wargaming decision aid to support operational level mission planners that may encounter similar complex situations requiring a dynamic cross-domain multi-mission approach at this higher level.

D. REPORT ORGANIZATION

This report is organized into six chapters. Chapter 1 introduces the study. Chapter 2 contains a characterization of the cross domain multi-mission problem domain. Chapter 3 contains a discussion on the use of automated advanced data analytic methods for mission planning. Chapter 4 presents the system analysis of a Multi-Mission Resource Allocation (MMRA) decision aid concept. Chapter 5 contains a use case study of the MMRA capability in three different multi-mission scenarios. Chapter 6 concludes the technical report.

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II. PROBLEM DOMAIN CHALLENGES

A. INTEGRATION ACROSS STRATEGIC, PLANNING, AND TACTICAL DECISION DOMAINS

> "In battles, combatants can win time and space, and they allow one side to take ground, but they do not win wars. The world we operate in today is not defined by battles, but by persistent competition that cycles through varying rates in and out of armed conflict. Winning in competition is not accomplished by winning battles but through executing integrated operations and campaigning. Operations are more encompassing, bringing together varied tactical actions with a common purpose or unifying themes. They are the bridge between the tactical and the strategic." (Townsend 2018)

Cross domain resource allocation for military operations occurs at the strategic level, the planning level and at the tactical level. The strategic level is concerned with higher level decisions—developing large scale strategies for a theater or region; developing fleet-wide objectives. The planning level focuses generally on mission objectives and the planning and allocation of military platforms (ships, aircraft, submarines, etc.). The tactical level focuses on short-term decisions or courses of action to meet the planned mission objectives. In order to support the strategic missions, the planning and tactical levels must be consistent and supportive of the overarching strategies. Figure 1 depicts this cross-domain synergy—illustrating the general complexity of military operations, the heterogeneity of warfare assets, and the multiple mission objectives that are likely to exist in warfare.

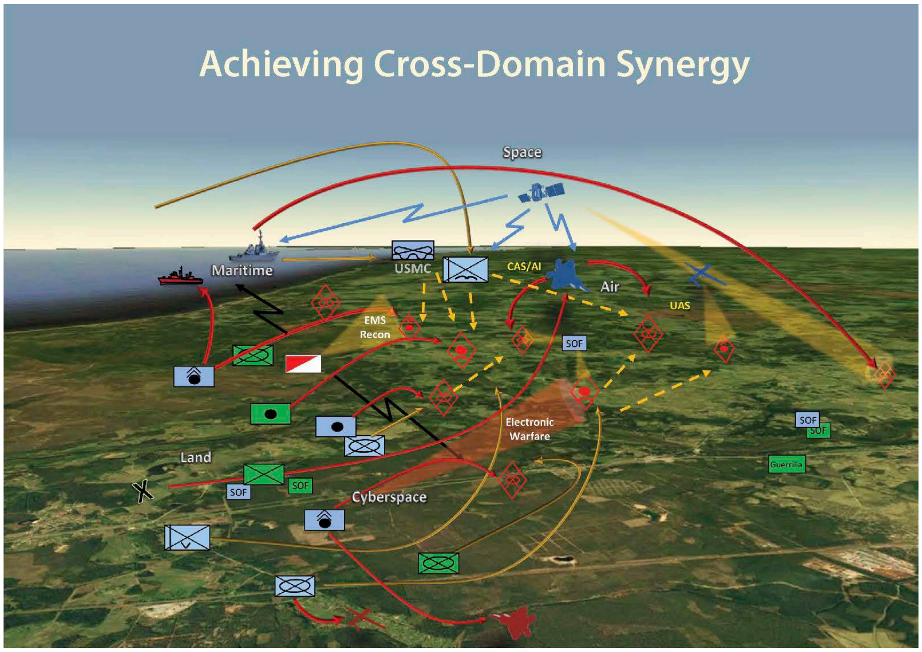


Figure 1. Cross-Domain Concept (Perkins 2017)

B. HIERARCHICAL OPTIMIZATION OF WARFARE RESOURCES ACROSS MULTIPLE MISSION DOMAINS

> “Missions also have dependencies among them. For instance, an Integrated Air and Missile Defense (IAMD) mission may be required in some particular location to cover an antisubmarine warfare (ASW) mission. Combatants are capable of performing more than one mission simultaneously, but with varying degrees of effectiveness depending on the simultaneous mix and the particular combatant’s readiness, training levels, and weapon inventory.” (Brown and Kline 2021)

In the military environment, when the number of resources, or military assets, significantly exceeds the operational needs for their use, the optimization of resource allocation is straightforward and easily accomplished. However, when the number of available resources is not sufficient to support mission objectives, the need arises to optimize the use of the resources. It can become a challenging endeavor to optimize warfare resources, as battlespace environments are dynamic, and threats can arise suddenly and unexpectedly and undergo constant change. This dynamic environment translates into constantly changing threat and mission priorities from the perspective of blue force decision-making. Naval operational environments tend to require multi-mission objectives, as the maritime environment spans underwater, surface, air, space, and cyber domains. Many naval warfare assets, including sensors, weapon systems, processors, communications, platforms, and countermeasures can support multiple missions. This results in the need for cross-domain, hierarchical optimization of naval warfare resources to address multiple mission domains. Figure 2 illustrates linkages between military domains in the land, air, space, and maritime—in an attempt to visualize the overlaps and the connections between events and assets in these geospatial domains.

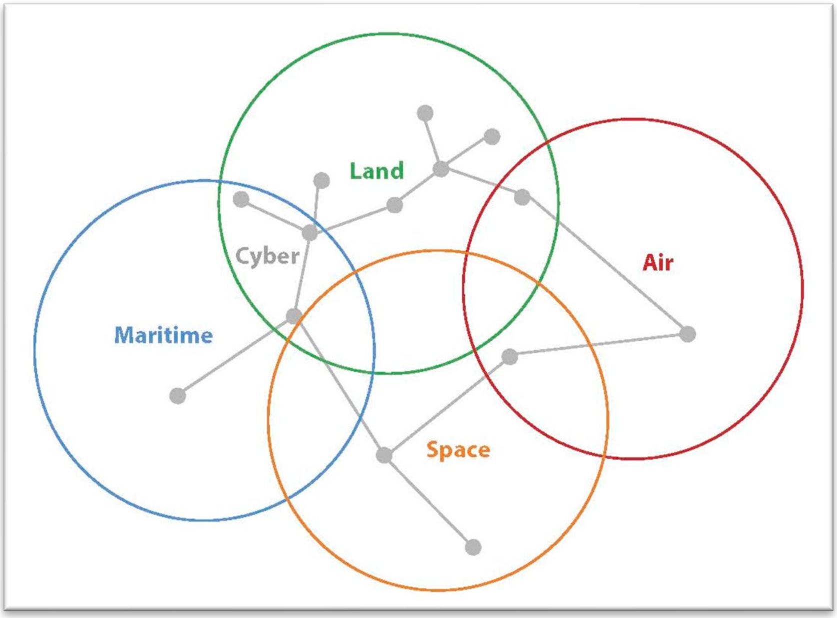


Figure 2. Multidomain Concept (Bartels et al. 2017)

C. DYNAMIC OPTIMIZATION OF WARFARE RESOURCES

> "Problems that are dynamically complex often have long time delays between causes and effects and may have multiple, sometimes conflicting, goals and interests." (Morrison et al. 2008)

Warfare operations exhibit dynamic complexity. Although the engineering of weapon systems is largely focused on individual weapon performance and a weapon's ability to successfully engage a threat, tactical scenarios will generally consist of more than one threat to engage. Warfare operations are likely to be highly dynamic with a continuum of different red force threats, countermeasures, and actions occurring over a period of time. Figure 3 is a system dynamics model showing the blue force (B) elimination of "unfriendlies" (or defense against threats), encircled by a set of dynamic red force (R) considerations, perceptions, and continued actions. A need arises to be able to dynamically "replan" as the operational situation changes. Characterizing the complex dynamics of military conflicts and incorporating this into cross domain allocation solutions enables cross domain dynamic replanning.

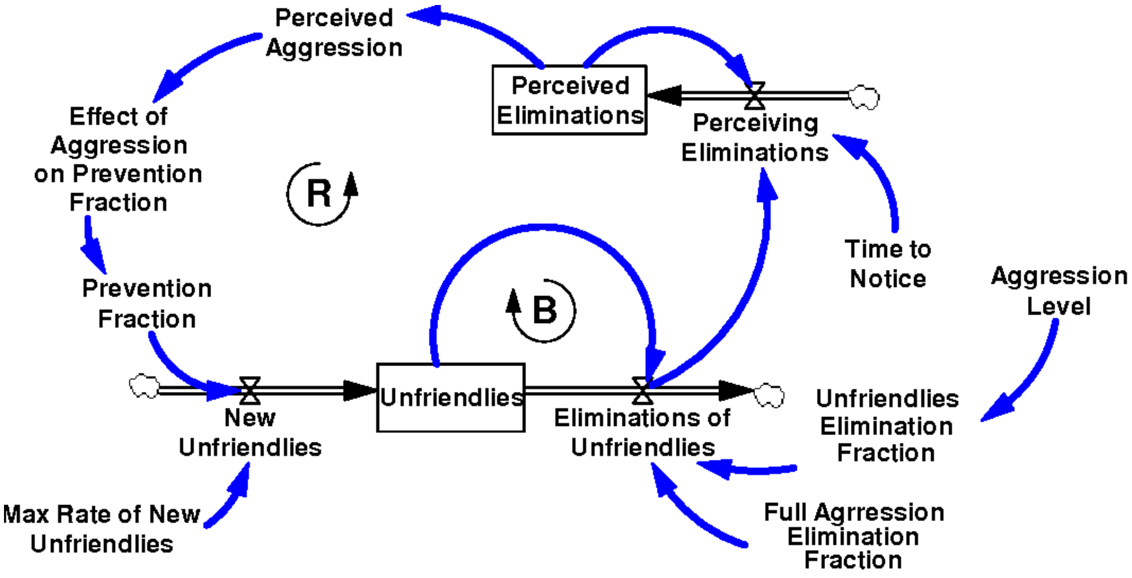


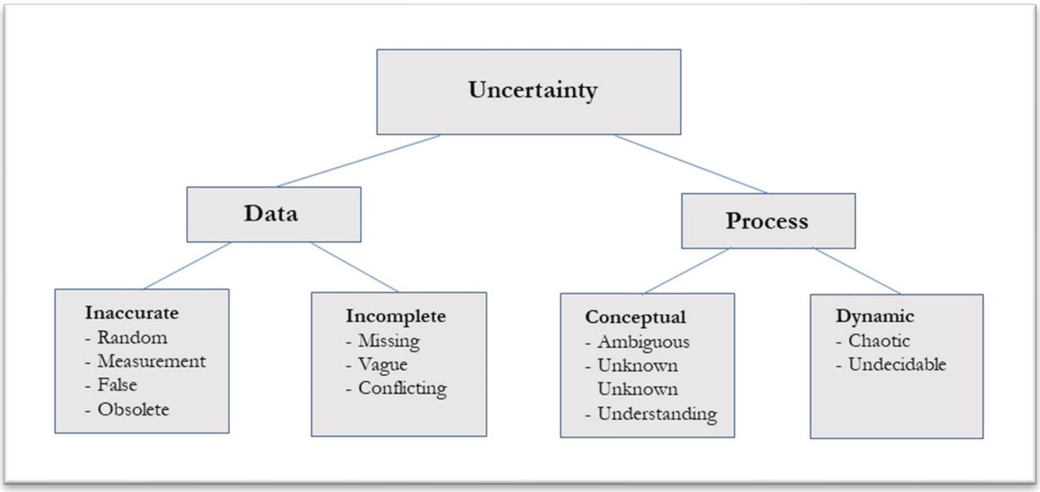
Figure 3. System Dynamics Model for Military Conflict (Morrison et al. 2008)

D. DECISION=MAKING UNDER UNCERTAINTY

> "Uncertainty is a fundamental characteristic of warfare." (Shattuck et al. 2009)

Clausewitz (1984) wrote about four characteristics of warfare: danger, exertion, uncertainty, and chance. He wrote, "….war is the realm of uncertainty; three quarters of the factors on which action in war is based are wrapped in a fog of greater or lesser uncertainty…" Clausewitz 1984). Much research has been conducted (and is ongoing) into military decision making under the conditions of uncertainty. A universal taxonomy of uncertainty groups it according to data and process. Uncertainty emanating from data takes the form of inaccuracy or incompleteness (or both). Uncertainty stemming from process can be conceptual (in the way the information is perceived and understood) or dynamic (arising from the dynamic aspect of the situation). Figure 4 illustrates this taxonomy. Understanding the sources of uncertainty may lead to solution concepts.

Figure 4. Taxonomy of Types of Uncertainty (Bartels et al. 2017)



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III. ADVANCED MISSION PLANNING STRATEGIES[1]

A. INTRODUCTION

Planning has existed as a crucial component of warfare for millennia. Doctrinally, the U.S. suggests two types of planning: deliberate and crisis action or rapid response planning. There is no difference in the planning process for each of these types, the difference lies in the amount of time available. Planning is necessarily a projection of what actions, performed by "entities" (people, forces, platforms, etc.), need to be performed to meet an objective or set of objectives. Therefore, planning is purpose-driven—establishing a set of means to accomplish a desired end state.

Planning faces challenges: how to account for all the entities, especially the opposing forces, since one has incomplete information on them. Second, what are the neutral constraints, such as topography and weather, and how or will they change? Third, the planning process calls for comparing courses of action COAs). The process calls for at least three such executable options. An easy way to satisfy this requirement is divide the planning cell into three equally competent groups, where each produces their own course of action. This is usually not done, because of either time or manpower constraints. The usual practice is to have the intelligence section devise two enemy courses of action, one assumed to be the most likely things the enemy will do, and the second is the most dangerous things the enemy might do. COAs are developed for each of the enemy COAs. A third COA is then just rapidly assembled, then rapidly dismissed in the planning process.

Another planning challenge is planning across multiple missions, especially where entities are designed to be multi-mission platforms, such as DDGs that perform air defense and anti-submarine warfare, or aircraft which can act both in strike missions and in defense missions. Often, planning for each mission is performed separately, then a sort of horse trading amongst mission commanders occurs that sorts out the conflicts inherent in allocating the same resource to dissimilar missions, which often ends up in a demand signal for the entity to be two or more places at once.

Yet another planning issue is the level of fidelity required. Mission planning can be very specific, since it includes specific route, support entities, detailed assumptions about enemy actions, and detailed weaponeering—matching weapons, delivery platforms, and targets. Higher level tactical planning, say at the strike group level, incudes their portion of the Air Tasking Order (ATO) or air plan, various OPTASK messages and their updates, and other update daily intentions messages. Operational planning focuses more on allocating groups of capabilities to act on a set of tasks, which are arranged in order. Strategic planning is even more abstract, depending on the full diplomatic, informational, military, and economic (DIME) considerations.

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[1] This section is adapted from a paper written by Scot Miller (Spring 2022) with help from Arkady Godin, Bruce Nagy, and Bonnie Johnson.

Digitizing the planning entries is also quite a challenge; thousands have tried, no one has ever completely succeeded.

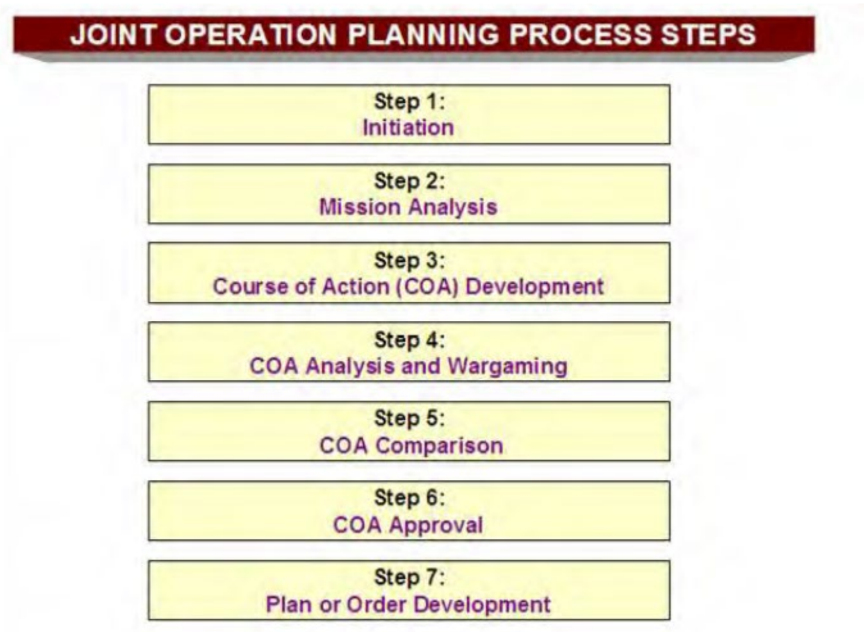
Finally, and the most important fact, is that no plan survives first contact with the enemy, so that a plan can be worthless from the start. This is because the plan is filled with many assumptions, many of which are not true. There are two recourses; first, build a plan that anticipates key assumptions, and designs in branches and sequels, which are really just if-then conditions. Of course, this assumes that one anticipates the key assumption points that must be anticipated. The second approach is to rapidly replan from the now known information. That approach is rarely used, since most planning is by hand, so replanning is not responsive enough compared to the situation.

This research intends to leverage several new planning constructs, combined with existing algorithms used in ingenious ways, to solve many of these issues holistically. We hypothesize that this approach will enable multi-mission planning across tactical and operational levels, enable a more nuanced way to understand uncertainty about the enemy, and enable replanning so quickly as to make it a viable approach. Further, this approach will create numerous courses of action, and highlight the critical junctures in operational execution that might deserve a more detailed look.

This paper is divided into six sections. First, the basics of a planning process. Next, the ingestion of data which supports planning processes. Third, the idea of event verb events (EVE) chains, how they are used in planning, and why they are important. The next section explores how algorithms enable COA development and analysis, and further highlight the role of EVEs. The next section explores why objective functions, carefully chosen, solve the problems of resource allocation across multiple missions. The next section explores anticipated pitfalls of this approach, and why they exist. The final section summarizes the findings and offer areas needing more exploration.

B. BASICS OF THE PLANNING PROCESS

The Joint Operation Planning Process (JOPP), defined in the Joint Targeting School Student Guide (2017), provides the most representative process description of mission planning, shown in 5.


JOINT OPERATION PLANNING PROCESS STEPS

Step 1:
Initiation

Step 2:
Mission Analysis

Step 3:
Course of Action (COA) Development

Step 4:
COA Analysis and Wargaming

Step 5:
COA Comparison

Step 6:
COA Approval

Step 7:
Plan or Order Development

Figure 5. Joint Operation Planning Process (Joint Targeting School, 2017)

While other references generate more definitive definitions of the planning steps, below we’ve captured the highlights of each step.

1. Initiation

Organizations are tasked with planning by higher headquarters, and in turn, these organizations task their subordinates to devise supporting plans. The originating (higher headquarters) group that initiates tasks, defines end state goals. In the military, this is often referred to as the Commander’s intent. This end state aligns with the same precepts that Covey (1990) advised: “begin with the end in mind.” In a perfect world, organizations have time to ask questions of the higher headquarters; to clarify meanings, since much resides on the plan. As we shall see in this advanced planning approach, the desired end state needs as much specificity as possible. Failure to provide detailed specificity creates a more general plan that leaves room for misinterpretation. Plan initiation often includes the number and types of assets, and an estimation of adversary (or Red team) forces and intentions. During the initiation phase, the organizations and higher headquarters should iterate assumptions and end state goals if time permits. Similarly, the organization should iterate with its subordinates to make sure end goals, assumptions, and plan details are fully understood.

2. Mission analysis

During mission analysis, planners assemble information, facts, and assumptions regarding the tasking. Analysts focus on the “when, where, whom, why, how, and what” questions that need to be answered. As one can imagine, this entails the collection of much data. Existing command and control systems help assemble much of it, but some facts, assumptions, and details need to be collected or generated manually through communications and by human analysts. Additionally, the information is not complete—there is uncertainty, and it is never fully comprehensive.

3. COA development

The assemble and sequencing of activities which result in the desired end state, that seem viable and plausible, is called a course of action. Over centuries of wars, Commander's staffs have learned to provide several plans for a commander to consider. The current rule of thumb is to generate three COAs, since that shows some thinking occurred within the staff, but three Is not such a large number that the Commander will have trouble choosing. One can surmise this is a very subjective approach, and not based on any hard research on the process. Still, that is the way. Moreover, most staffs generate three COAs in only one way. As mentioned above, the Intelligence division is asked to consider Red's most likely and most dangerous COAs, and the staff comes up with spare COAs to address each. A third COA is derived from a different planning cell, and I soften just as easily dismissed soon after development. Seems like a waste of time and effort. This COA development practice seems arbitrary, potentially subjective, and generally not inventive. Some staffs have just been told by their Commander not to worry about this step, because the Commander will tell them what the COA will be. There is much room for improvement.

4. COA analysis and wargaming

Once developed, each COA is analyzed for its ability to meet the objectives. Staff will develop various measures of effectiveness and measure of performance to grade the COA. If campaign or mission modeling is available, the COA may be modeled against the Red forces, using Monte Carlo simulation. Additionally, no quantitative factors may also be assumed across diplomatic, information, political, social, cultural, and economic factors. Further, this analysis should include considerations of the risk profile associated with each COA. The staff should be able to explain the various risk factors and recommend mitigations. Also, good staffs realize that a plan never survives contact with Red, so better COAS may include branches and sequels at important decision points.

5. COA comparison

Just the side by side comparison of the COAs across the MOEs, MOPS, and risks. Add consideration of the other qualitative factors, and the Commander's own sense for the quality of each COA, and its plausibility. If there are particular submissions or operations that are key to overall success, the Commander may request a deep dive into the approach that each COA makes.

6. COA approval

At some point, the Commander will decide which COA to proceed with, or may direct the staff to start over. A commander will usually tweak even a well formulated COA, so some changes will be made.

7. Plan or order development

Once the COA is approved, the COA is converted into orders for the various units. In theory, COA development and plan writing ought to be derived from this same system, meaning that order development is merely the push of a button, but that would be an exception today.

Again, time allotted to execute these steps varies from years to hours. Ideally, the staff keeps their higher headquarters informed and engaged while they execute the planning process, and gives their subordinate staff a heads up, or invites them to participate in this planning process. Most Commanders are usually reminded about General Patton's adage: "A good plan executed violently today is worth more than a perfect plan executed next week." That is not always correct, but that is the way most think.

C. INGESTING PLANNING DATA

So, if we are going to "automate" or at least build an agent that can be a planning assistant, it is clear it should do at least two things outlined above. First, from step one, it should somehow characterize the Commander's intent into computationally relevant end states. We will start to address that in the following sections, since it turns out that end state (and initial states), COAs, events, actions, and platforms, are all interrelated.
The second thing is to get a handle on all this data that arrives in the Mission analysis section. If we can't get that data easily, characterize it in a way we can easily use, and know what we might still be missing, then anything we do subsequently is a waste. Acting DOD CIO Lin Wells (2005) outlined the importance of sharing data 15 years ago. Brutzman, et al (2015), have called for the Navy to execute a data strategy since centuries' turn. More recently, Godin (2021) developed a DOD related approach that might actually work. Seltser (2021) applied portions of Godin's approach to an international financial company with success. This firm, while differing in many respects from the DOD, also maintains many data parallels.

Before exploring Godin's ideas, it is worth reviewing what the Navy is doing now in this realm. Garcia (2021) postulated a similar need for advanced mission planning for at least a decade. As the recently retired Technical Director for the Navy's Command and Control Systems Program Office, he directed efforts to better accumulate all the planning data. This effort identified 118 separate key data sources. At last count, they had succeeded in capturing 58 of those sources into a single data store. However, because of the changing data formats and standards, and inadequacies with the storage approach, they already are encountering massive challenges in data integrity, not to mention a configuration management nightmare.

Let's explores Godin's ideas. The problem is complicated, so it stans to reason that an approach which is less complicated would be desired. Perhaps an approach that leverages the human mind but uses automation where practical. We start with the data and signal sources, introduce the idea of ingest and organizing data by ontological types, describe a new approach to data storage, and conclude with approaches to organize the data for use. Suffice to say there are several more steps for the far advanced reader, but completing these first three steps, if the Navy chooses to do them, would consume most of the rest of one's career.

Data arrives from a variety of sources: sensors, reports, internet, information processing facilities, etc. Often it does not arrive at all, and someone must cajole a data "owner" to share the information. Also, we have data from previous operations that we ought to consider as perhaps useful. It may come as a surprise that the Navy does not use most of their historic data, and in many cases (such as air defense) never even kept "old" data, old in this case sometimes measured in seconds. Often the data streaming in needs immediate analysis in real time; there may be data where a few seconds or minutes in a queue makes little difference. Also, some data is just an update of previously received data, such as a ship's position or an aircraft fuel state. Is that new data? Or is that just an update which could be treated as a new temporal event? Handling the onboarding of data is fraught with these and many more complications.

In their step one, Godin and Seltser (2021) imagine a universal data loader to approach this challenge. Besides routine data ingest functions, such as tagging data, noting its source/provenance, or even adding a classification to it, the universal data loader also determines its type (number, integer, text, or one of many other assorted formats, such as a sensor format), and determines where that data would be best stored. For instance, images and weather numbers are stored, correspondingly, in sparse and dense multidimensional data storage arrays, while business systems numbers obtained from Excel spreadsheets, might be better stored in two-dimensional relational tables. In the past, most organizations only maintained one or two different data storage representations, but technology has advanced now so that each data type ought to be stored in its most optimal data storage variation. This has significant ramifications in processing and query speeds. Interestingly enough, with time, it becomes evident that one of several data storage choices is becoming a contender to be considered as a universal data storage choice. Relational tables used to be such a choice, but are no longer due to their brittleness. Considering the breadth of real-world data, including data graphs, support of sparse multi-dimensional arrays becomes a key requirement for a universal data storage.

This is important for the downstream developers. In a perfect world, application developers ought to see the data as one store. This simplifies everything they do. This universal data storage construct is the path to such a vision. Think about current applications. The entire stack, from data sources to data storage to analytical tools and application san displays are all a vertical stovepipe. When one developer sees another source, and says "that data would add value to my process", it is difficult to impossible to add in that source, both technically, but more importantly, organizationally. That is because the "data owner" assumes foul play from the start, and has to be convinced to share. This can take months, as several Capstones have shown.

Step two of the Godin/Seltser process is to organize/categorize the data. Data itself is useless, it is just a signal captured somehow. It may be random noise, or it may be the secret to the universe, but without meaning it is useless. Fortunately, most data are delivered with metadata, that is, a description of the data. For instance, 65 is merely a number, and is useless. But if I tell you that it's from an Excel spreadsheet, and that the row is named Scot Miller, and the column is labeled age, one can surmise that this author is 65 years old. Similarly, -4.6 means nothing. But if that number is from a formatted sensor read out, that format indicates the name and type of platform that reading was recorded, the location and time of the reading, the altitude of the sensor at the time of the reading, the type of emitter, and the orientation of the sensor to the emitter, well, then I know much more.

Organizing data is not a new idea, librarians have been at it for millennia. Moreover, here are plenty of gotchas revealed in organizing data. What system is used to measure distance or time? What are the key values that might tie one observation to another? Many more issues exist. Godin/Seltser suggest that much of this work can be automated, and when the system suspects an issue, it can notify a human to sort out the quandary. If one considers DOD's data, much of it is already organized into various formats. Thus, in theory the DOD has a head start in data organization. Godin imagines a broader data organizing tool, governed by DOD Chief Data Scientists, to adjudicate the data organizing process.

Seltser's work with the financial firm is informative. This firm must stay atop all economic and political trends in the world, which it does by ingesting newspapers, radio broadcast recordings, video, and scraping the internet. One can imagine this is a large amount of data. Further, much of this data has to be processed (natural language processing and translation, etc). One can see that compared to the DOD, they have very little metadata or formatted data. Yet in just three years, Seltser has helped this firm transform their data into well catalogued information collection, and the firm's developers and analysts have been able to produce many new tools to provide faster and more in-depth insights into the world and their financial risks.

As we conclude this section, consider the various DOD customers of planning. We have very tactical level efforts, thousands of them, at any given time. They need very specific information, and timeliness counts. They may have the time to conduct historic analysis on similar situations; they may not. Operational commanders have broader objectives; they are organizing tasks in a sequence, and rationing limited forces to each of these tasks. Their data needs are different, and are also dependent on understanding a Red force that is hard to decipher; for operational planners, the possibilities seem endless. At the strategic level, combatant commanders are much more engrossed in the whole of government approach to world affairs. What are the diplomatic, economic, social, and informational levers they can pull? Their data requirements exist at a different level of reasoning. Still, Godin/Seltser offer an approach that can satisfy all three levels of data needs.

This approach provides a broad array of data, with context, to reason over. To do so, though, requires characterizing our ideas for executing operations. It requires viable courses of action, our next topic.

D. EVENT VERB EVENTS (EVES), EVE CHAINS, VE CHAINS AND OTHER SUPPORTING CONCEPTS

The third step in planning is developing COAs. Given a desired end state, as directed in the Commander's intent and the plan initiation stage, and all the data and information derived in the mission analysis stage, planners are left with two major components; the mission objectives, and the available means at which to conduct that assignment. Again, with many hundreds to thousands of resources, and generalized end state objectives, there might seem an almost unlimited variety of COAs available. Developing three seems both easy, yet impossibly difficult. Generally, the planning process is informed by what is called a Red cell, that generates possible Red COAs, especially the most likely and most dangerous Red COAs. This helps planners identify possibilities for their COAs. Of course, the Red Cell is making educated guesses based on their observational experience, updated intelligence, and even what newspaper and radio reports might say. So it is necessarily subjective.

One cannot be accused of wrongdoing if they believe this entire process is extremely subjective. In many respects, they are quite accurate in this assessment. Of course, the mission analysis provides lots of data that provides constraints to a COA; for instance, one can only do so many things with one aircraft carrier versus two, or one Marine division versus three, etc. There will be plenty of time distance issues. One may be able to plan for the use of a unit, but if that unit is in the wrong place, time and distance have to be considered.

Moreover, as planners generate more detail in their possible COAs, more and more details are required. What are the maneuver speeds of units A and B? How many weapons are available? What is the maintenance readiness of the aircraft squadrons? Are there enough spare parts available?

Planning becomes a subjective and nebulous effort. One might reasonably ask, "what did we do last time?" often the end sate from the Commander's intent is not well phrased. Guesses about Red are often just guesses. Even our own awareness of readiness is hindered by bureaucratic stovepipes and data bases that are neither current or truthful, since many commanders are graded on their readiness figures, those figures are often twisted.

What follows is a proposal for a different approach to creating COAs, an approach based on a more objective process. While this process remains imperfect, at least it attempts to use the best set of known information to crate viable COAs. At the heart of this process is the logical construct of a language which can represent a COA.

From Google:

course of action. 1. ***Any sequence of activities that an individual or unit may follow****. 2. A possible plan open to an individual or commander that would accomplish, or is related to the accomplishment of the mission.* (Military Factory, 2022)

This reference has several more definitions, but these two are sufficient. First, a COA is a sequence of activities. There is a time ordering implied. Second, note the emphasis on the accomplishment of the mission. A COA, successfully executed, accomplishes the mission. As we shall see, we can create many sequences of activities, but not all accomplish the mission. By our definition then, that will not be a COA. Also not the emphasis on the idea that the COA is a possible plan, available to the Commander. So for the following discussion, a COA is a sequence of activities that is possible, that leads to accomplishment of the mission.

So not just any set of activities sequenced together constitute a COA. It has to accomplish the mission and be possible.

For planning purposes, we have already suggested that every military plan has an end state. If we cannot define the end sate in definable terms, then why bother planning? Moreover, we assume that every sequence of activities must have a beginning state, which we can also characterize. Note there will still be some subjective ness here, and planners should take note of that. As one might surmise, how we characterize the beginning state and the end state will likely have a large effect of the COA development process, even if we are using an objective process.

So, the COA will consist of a beginning activity and ending activity, and a set of activities that connect the beginning to the end.

So how should we define an activity. We are fortunate that this has been done already. Nagy (2018) defines an activity as consisting of an event a verb and an event. He calls these EVEs, for event-verb-event. Nagy states that an event has no time, but hat verbs occur over time. Here is an example. The aircraft carrier is in modloc “A”, that is an event. It ***<u>moves</u>*** to modloc “B”. That is a verb. An action occurred here, called ***<u>move</u>***. We can determine how far modloc ”A” and ”B” are apart, assume a transit speed (or assign one), and determine how much time that EVE took.

The first **Event** in the EVE we call the predecessor event. The second **Event** in the EVE we call a successor event. The successor event can now serve as the predecessor event for the next EVE. And further, that we can sequence these EVEs into a much larger sequence, and if we add a starting and ending event, we could produce a COA. Conceptually, this Is not rocket science. However, the astute reader will imagine thousands of such EVEs. And that for each V, we need a time calculation. This seems like a nearly impossible set of tasks to do by hand. And you are correct.
So, the rest of this section attempts to explain how we can characterize all the possible EVEs a priori, and then use computers to do the hard work.

E. FUTURE IDEAS

I'll jump into your write-up and take a look. One thing I'm convinced is good to have is managing all data processing under workflow pipelines managed by the same orchestration engine. One that is popular is called Horovod. It's an open-source Apache invented by Uber.

This orchestration should direct all processing into the appropriate frameworks (i.e. ingest, ML by Spark, storage of features, real-time ingest from ML, DL by different Deep Learning frameworks: TensorFlow, PiTorch, etc.) If it's done this way, we can extend "default", pipeline by tacking on more advanced battle-specific processing based on world situations derived from real-world observations. This way we, seamlessly, bring situations within knowledge representations integrated with ontologies.

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IV. CONCEPT FOR AN AUTOMATED MULTI-MISSION RESOURCE ALLOCATION SYSTEM[2]

A. MMRA STAKEHOLDERS

To begin the process of developing a concept for the AI-enabled MMRA system, the study considered the stakeholders and their key concerns. Stakeholders included Congress, the DOD, the major commands, MMRA system users, and MMRA system developers. Table 1 lists the key concerns for these stakeholders.

Table 1. MMRA Stakeholders

Stakeholder	Key Concerns
Congress	Budgetary impact beyond the system Cost-effectiveness
Department of Defense	Maintaining technological edge over adversaries Interoperability across the services
Major Commands	System reliability Optimized allocation of resources Trust in MMRA AI outputs
MMRA AI Users	Reduce resource allocation decision time Optimized allocation of resources Reliable input data Trust in MMRA AI outputs System reliability Availability of MMRA AI system Ease of use in current mission sets
MMRA System Developers	Low manufacturing costs Achievable technology readiness levels System reliability System capable of processing large amounts of data

B. MMRA INPUTS AND OUTPUTS

Next, the study considered the inputs and outputs for this AI-enabled MMRA system. These were grouped into four groups: controllable inputs (inputs the system users/developers can control), uncontrollable inputs (inputs the system users/developers cannot control), intended outputs (desired end states), and unintended outputs (undesired end states). These inputs and outputs are depicted in an input/output (I/O) model shown in Figure 6.

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[2] This chapter is adapted from an excerpt from the NPS Systems Engineering Capstone team (A.I. Trio) report: “Artificial Intelligence-Enabled Multi-Mission Resource Allocation Tactical Decision Aid” (Ghigliotti et al. 2022)

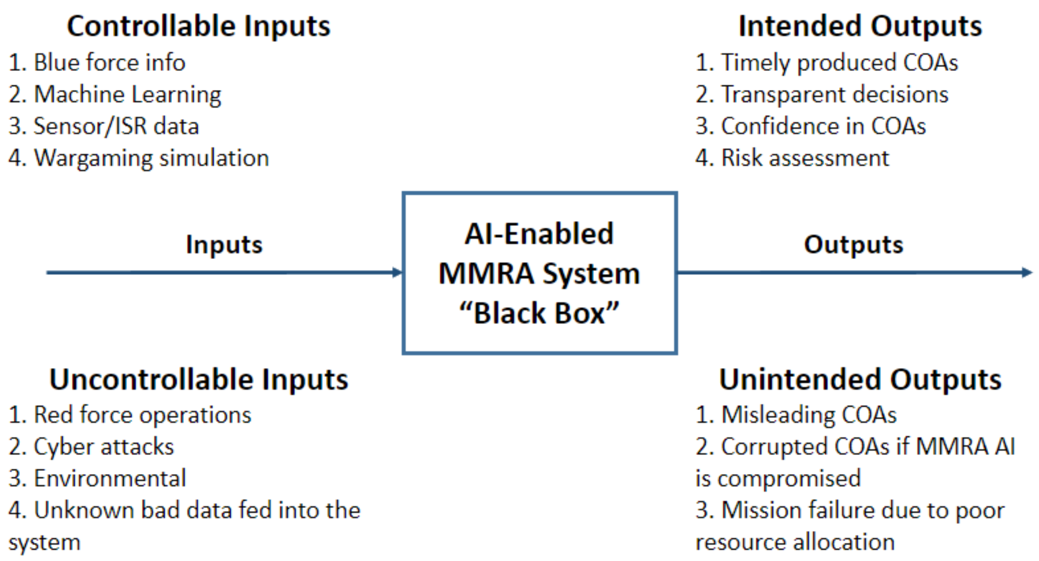

Figure 6. AI-Enabled MMRA System I/O Model

Considering the stakeholders need, a concept for an AI-enabled MMRA system was developed. The MMRA system was envisioned with a human-in-the-loop at discrete decision points. At these decision point events, the MMRA system would be cycled once with the inputs available at that given point in time. These inputs would include the latest information on red and blue forces which are also fed into wargaming simulations such as those performed by the WRAID system. This data would be combined and formatted for processing by the MMRA system. ML utilizing historical data and artificial scenarios would also feed into the MMRA system. The MMRA system then processes the data using algorithms designed to optimize the resource allocation and generates proposed COAs, statistical confidence, and risk assessments. These outputs are displayed to the human-in-the-loop for standard decision-making procedures. These outputs and the results of the chosen COAs would then be fed back into the system for inclusion in the historical data for ML purposes. Figure 7 depicts this process architecture for the MMRA system.

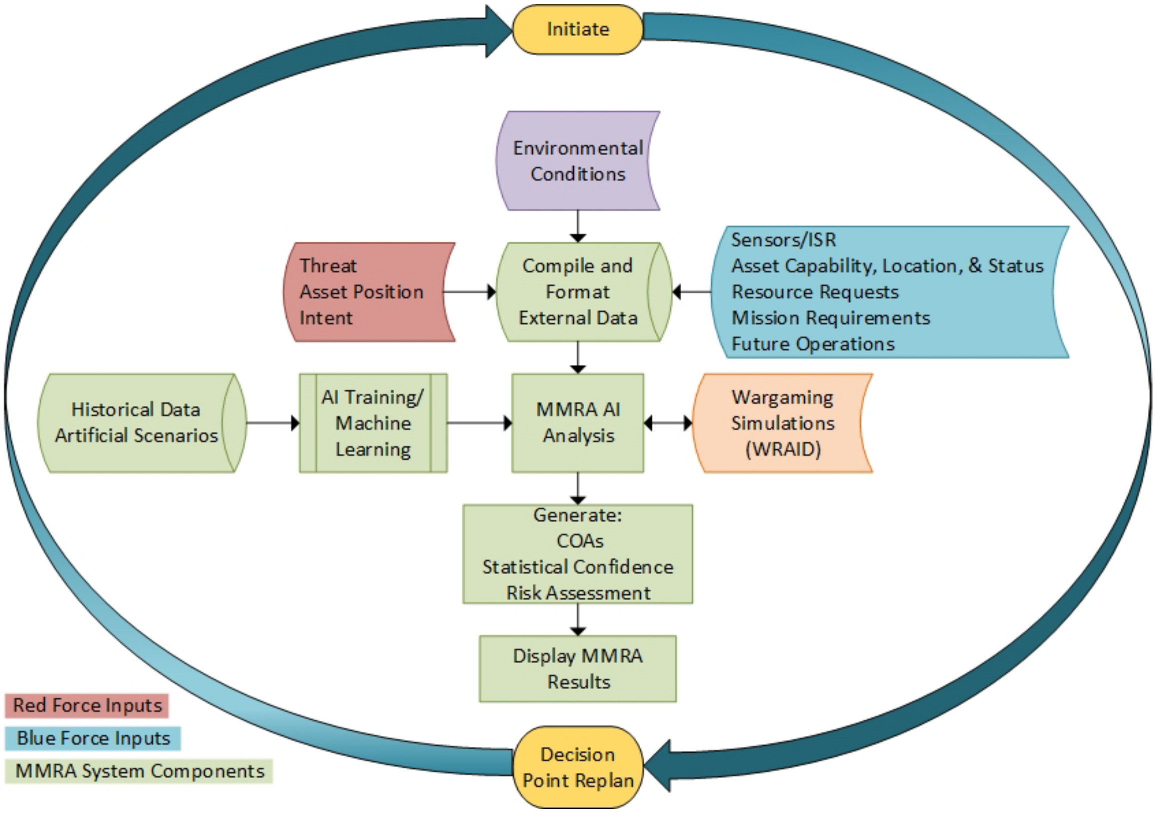

Figure 7. MMRA Process Architecture "Recycle Chart"

The MMRA enhances chain-of-command decisions by providing an objective evaluation in an ever increasingly complex and inter-dependent resource allocation problem. Figure 8 depicts the action diagram for the MMRA system process.

The first action takes all the available data from external data including intelligence on red forces, information on blue forces, commander's intent, and environmental conditions. The system compiles them into a format the MMRA system can use. The MMRA system takes that information and analyzes the various possible resource allocations, considering wargaming simulations based on the input data. The system outputs the resource allocation COAs with supporting statistical results and risk analysis. The goal of the statistical results and risk analysis is to bolster confidence in the AI outputs and aid decision-makers in determining if the COAs will be effective. Lastly, these outputs are displayed to the system user considering human factors engineering. This ensures the information is presented in a way to minimize cognitive fatigue and maximize ease of decision-making. The process is captured in an action diagram shown in Figure 8.

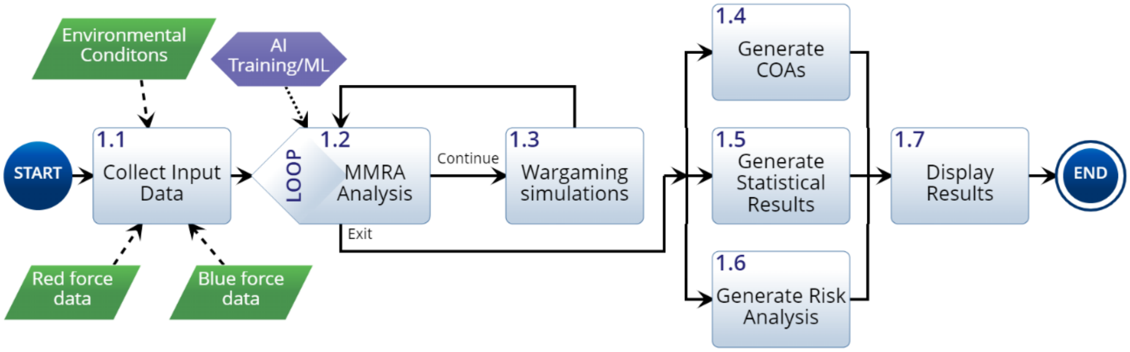

Figure 8. MMRA Process Architecture Action Diagram

MMRA decision making is becoming unreasonably complex even at the tactical level in the soldier's immediate chain-of-command. Contrarily, the operational and strategic perspectives are conducted at the headquarters. An AI-assisted MMRA system could help at all levels of decision-making.

A formal framework of the military guidance hierarchy is provided by the Joint Targeting School and depicted in Figure 9. The DOD-wide doctrine delineates four levels of guidance: national strategic, theater strategic, operational, and tactical. The tactical level is the most rudimentary level that decision-makers provide mission guidance. Decision-makers are trained to assess assigned objectives to measures of effectiveness (MOEs) and tasks to measures of performance (MOPs). Unique to the operational and tactical level decision-makers, a responsibility to provide combat task guidance exists. However, only tactical decision-makers are tasked to re-engage targets and utilize quick decision MMRA replanning.

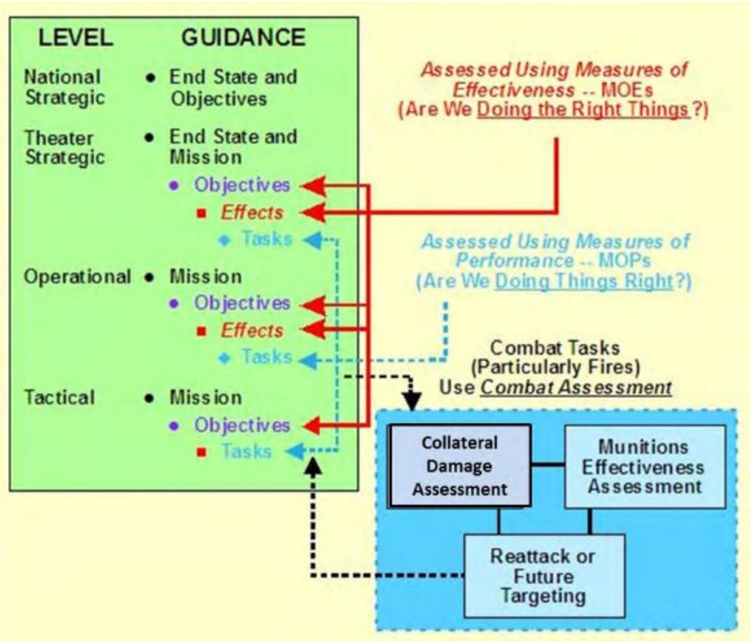

Figure 9. Strategic vs. Operational vs. Tactical (Joint Targeting School 2017, 163)

The graphic in Figure 10, “Tactical Evaluation Process: MMRA Decision Complexity,” depicts how MMRA is conducted over time at decision points in an operational scenario. Initial planning is conducted at t_0 which starts the process depicted in Figure 7 MMRA Process Architecture “Recycle Chart” at the “Initiate” point. The t_1, t_2, t_3, …, t_n decision points correlate to the “Decision Point Replan” yellow activity in Figure 7. Both “Initiate” and “Decision Point Replan” yellow activity blocks initiate a complete MMRA Process Flow, which is all the activities depicted inside the “Initiate” and “Decision Point Replan” continuum.

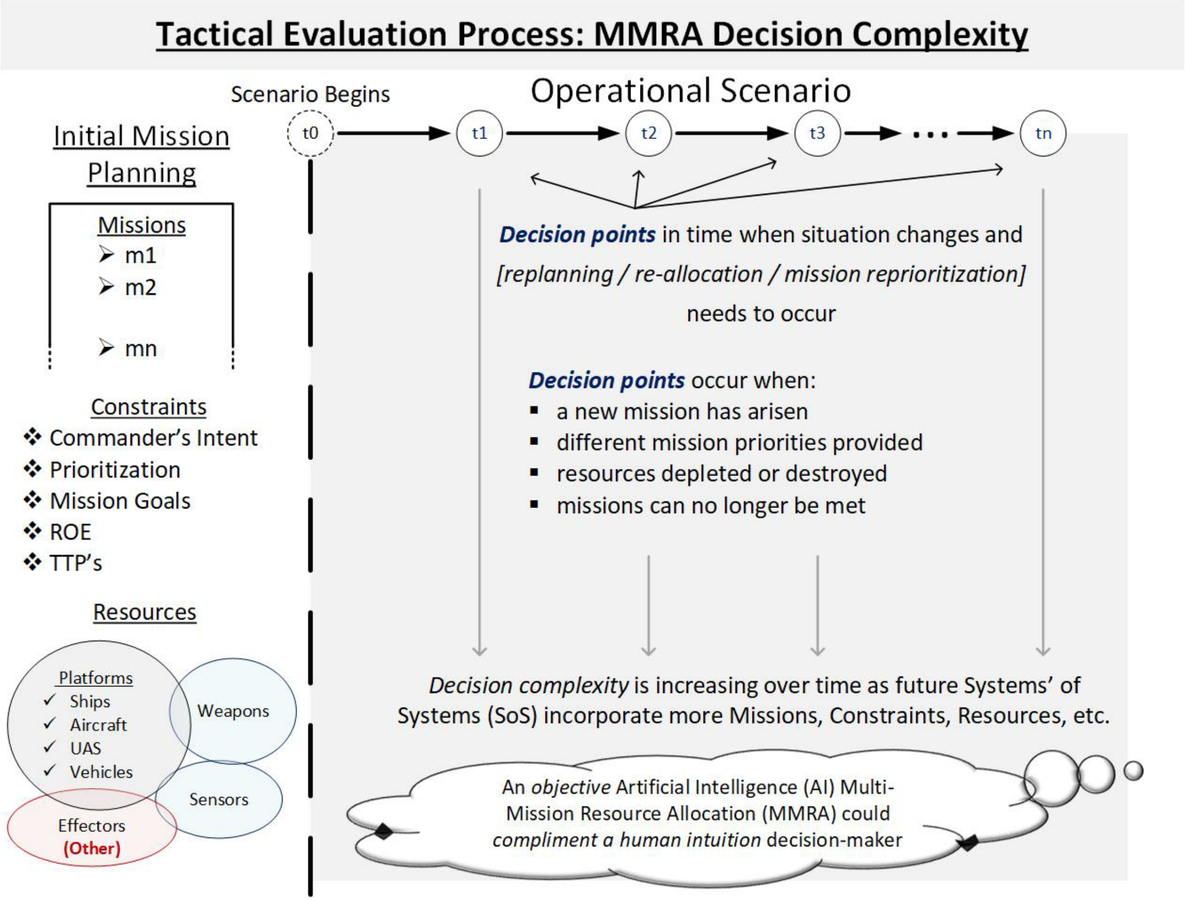

Figure 10. Tactical Evaluation Process – MMRA Decision Complexity (Johnson 2022)

Decision points are commonly defined across the three MMRA use cases. However, unique storylines are applied for context. Commonly, all decision points occur when a new mission has arisen, different mission priorities are provided, resources are depleted, resources are destroyed, or the mission can no longer be met.

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V. MULTI-MISSION RESOURCE ALLOCATION USE CASES STUDY[3]

A. USE CASE ANALYSIS PROCESS

For this capstone, three use cases were explored to determine how AI could aid in multi-mission resource decision-making in those scenarios. The use cases were intentionally selected for the variations in resources and complexity between them. Team AI Trio also sought to highlight the different branches of service and mission areas and explore how an AI-assisted MMRA tool could help across a variety of missions. The background of the team members also drove the choice of each use case. Team AI Trio has experience and expertise in the three specific use cases as highlighted in the team organization section of this Capstone's background. For each scenario, resources were chosen based on research and the author's experiential knowledge for a typical deployment.

The missions for the use cases were selected to represent real-world deployment scenarios. The use cases also highlight the concurrent mission demands placed on the respective commanding officers that create overwhelming resource allocation conflicts. As a scalability analysis, the team explored the evolution of technology over time and the resulting increase of resources available for each example. A complexity analysis was also performed through an imagined realistic sequence of events for each scenario. The focus for each use case was to determine requirements, inputs to initial planning, and re-planning considerations. Chapter **Error! Reference source not found.** then analyzed similarities and difference between the three use cases, and explored the problem set from an SE process perspective.

B. DIRECTED ENERGY CONVOY PROTECTION

DE protection of land convoys was considered in this use case examining the application of the MMRA AI tool. Air defense for convoys is increasing in complexity due to the prevalence of drones and advances in RAM threats. DE is an emerging technology with potential to fill gaps in mobile counter unmanned aerial system (C-UAS) and counter rocket, artillery, and mortar (C-RAM). Many different inputs were identified that the AI-enabled MMRA system would need assist decision makers allocate these DE resources. However, even with the numerous inputs, due to the limited number of system variation and mission sets, the tool is relatively simple in complexity.

For this use case, the initial situation was multiple convoys in a region that requested C-RAM and/or C-UAS protection due to red force activity and intent based on ISR data collected through various sensors and resources. The convoys consisted of various vehicles including tanks, troop transports, and supply transports along with one or more mobile DE air defense systems. An operational viewpoint one (OV-1) is depicted in Figure 11.

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[3] This chapter is adapted from an excerpt from the NPS Systems Engineering Capstone team (A.I. Trio) report: "Artificial Intelligence-Enabled Multi-Mission Resource Allocation Tactical Decision Aid" (Ghigliotti et al. 2022)

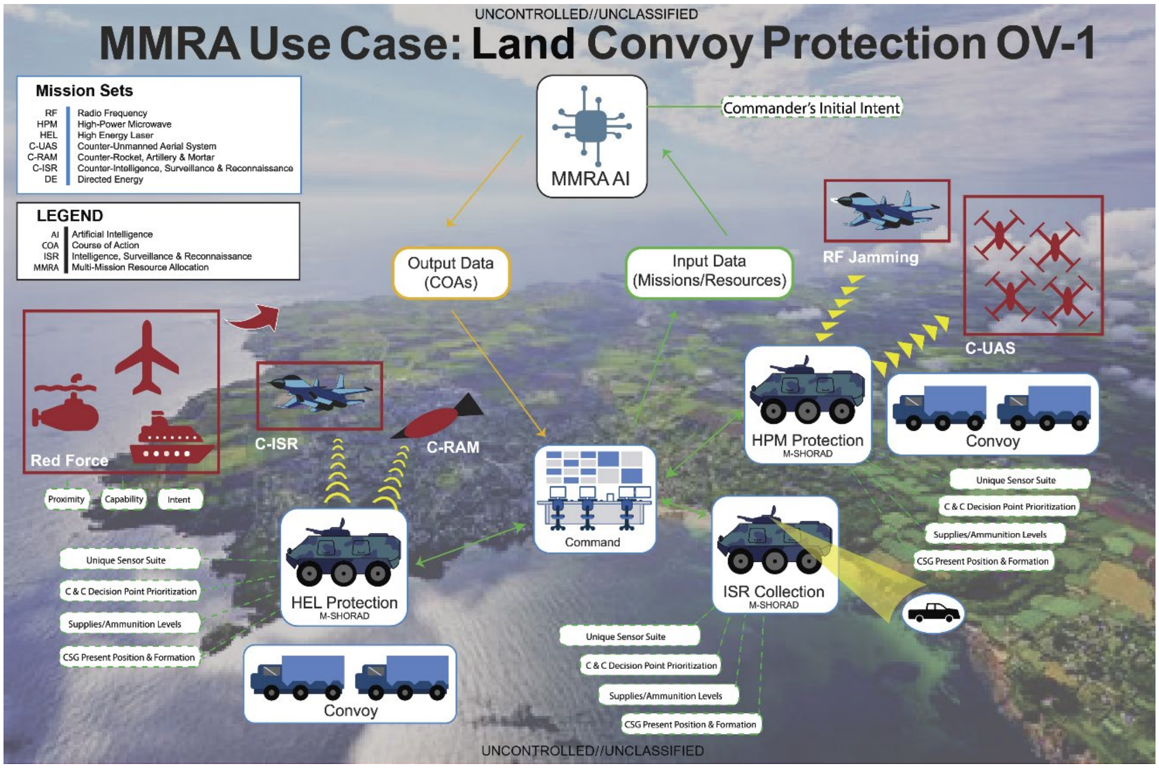


Figure 11. DE Convoy Protection OV-1

1. Convoy Operations

Military convoys have been in use for many years to move supplies over land. "A tactical convoy is a military operation used to securely move personnel and cargo by ground transportation" (Beckman n.d.). Most convoy missions are "friendly-oriented (deliver what, to who, where, when, and why)" (United States Marine Corps n.d.). In addition to moving troops and equipment, intelligence collection and route clearing are implied tasks of the convoy (United States Marine Corps n.d.). The vehicles in the convoy can range "from tracked and wheeled tactical vehicles to civilian tractor-trailers" (United States Marine Corps n.d.). Table 2 shows examples of tactical vehicles and their purpose in the convoy.

Table 2. Example Convoy Vehicles (USMC n.d., Leonardo DRS n.d.)

Vehicle	**Purpose**
Medium Tactical Vehicle-Replacement (MTVR)	Troop/cargo carrier
Up-Armored HMMWV (UAH)	Security element, C2, mounted patrols
Mine-Resistant Ambush Protected (MRAP)	Lead vehicle, C2, security element
Maneuver Short-Range Air Defense (M-SHORAD)	Destroys or defeats ground and air threats using multiple kinetic effectors (direct fire and missiles)
Civilian tractor-trailers	Cargo carrier

For convoy operations to be successful, they require deliberate and careful planning (United States Marine Corps n.d.). In addition to the vehicles, there are many considerations when planning convoy operations. Considerations for route options include battlespace, organic fire support, air support, quick reaction forces, explosive ordnance disposal, casualty evacuation capabilities, and recovery assets (United States Marine Corps n.d.). The Commander's intent, which should be formed around the idea to "keep the convoy moving", must also be considered (United States Marine Corps n.d.). Another important consideration is the scheme of maneuver (SOM). Convoy operations have a combination of six elements that form the SOM: task organization, distribution of forces, route (primary & alternate), movement formations, tactical control measures, and actions on the objective (United States Marine Corps n.d.). Of these, two are particularly important for this case study:

a. Task organization

"Convoys are task organized into a Lead Security Unit, Main Body, and Rear Security Unit. The Lead Sec Unit provides security to the front and flanks of roughly the first half of the convoy and is usually tasked to "screen to the front." Similarly, the Rear Sec Unit provides security to the rear and flanks of roughly the second half of the convoy and is, therefore, tasked to "screen to the rear." The Main Body consists of the vehicles that are transporting the personnel/cargo that make up the mission and is most often tasked to "protect" that cargo. The Main Body vehicles should be located within the middle of the convoy and will supplement flank security if they are also equipped with CSWs" (United States Marine Corps n.d.).

b. Movement formations

Open Column: "Distance between vehicles is approximately 100m-200m. This formation works best in open terrain and on roads that allow for travel at higher rates of speed" (United States Marine Corps n.d.).

Closed Column: "Distance between vehicles is anything less than 100m. This formation works best at night, in urban areas, or in high-traffic areas" (USMC n.d.).

As can be seen, convoy mission planning can be very complex. Different vehicles with different purposes and capabilities, resources both internal and external to the convoy, organization, and formation all increase the available options. This is assuming the convoy operations run smoothly. There are a variety of events that can add to the complexity of convoy operations. Examples of these events are shown in Table 3.

Table 3. Convoy Events

Event	**Description**
Short halt	Convoy is estimated to be stopped for 10 minutes or less
Long halt	Convoy is estimated to be stopped for more than 10 minutes
Danger area crossing	Any specific area that poses an added threat
Deliberate Recovery	Vehicle is disabled and there is no enemy contact
Hasty Recovery	Vehicle is disabled in an enemy kill zone
Unblocked Ambush	In an enemy kill zone or taking fire with no roadblock
Blocked Ambush	In a kill zone or taking fire and the road is blocked

Event	Description
IED Spotted	IED is identified prior to detonation
IED Detonates	IED detonates, possible casualties

2. Mobile C-RAM and C-UAS Defense Missions

For convoy defense, there exists a gap for C-RAM. For land-based C-RAM there is the Land-based Phalanx Weapon System (LPWS) depicted in Figure 12. However, this is meant to be stationary and could not provide C-RAM defense for a convoy that was underway. The M-SHORAD depicted in Figure 13 is capable of engaging UASs, however, would not be able to handle a UAS swarm type attack (Leonardo DRS n.d.). As can be seen in the conflict between Russia and Ukraine, weapons such as explosive-laden UASs and laser-guided artillery have proven to be highly effective against convoys on the front lines. In addition to the casualties on the front lines, Operation Enduring Freedom and Iraqi Freedom showed that convoys in areas that were considered secure because they were rear of the front line could still sustain heavy casualties (Thompson 2012). This leaves a need for mobile C-RAM and C-UAS defense, something DE promises to fulfill.

Figure 12. Land-based Phalanx Weapon System (U.S. Army n.d.)

Figure 13. Maneuver Short-Range Air Defense (Leonardo DRS n.d.)

3. Legacy Directed Energy Weapon Systems

DE systems have been in development for several decades. However, thus far these DE systems have only existed as prototypes, there have been no programs of record. Two of the first DOD DE programs were the Army's Tactical High Energy Laser and the Air Force's Airborne Laser (ABL) which were both megawatt class chemical lasers (Shwartz 2003); (Airborne Laser System (ABL) YAL 1A 2000). Both programs started in 1996 and proved that high energy laser (HEL) systems had the ability to provide C-RAM along with cruise missile defense (Shwartz 2003); (Airborne Laser System (ABL) YAL 1A 2000). However, safety risks with the large amount of chemicals needed and the logistics associated with moving the chemicals ultimately led to the cancellation of these programs (Shwartz 2003); (Airborne Laser System (ABL) YAL 1A 2000).

4. Mobile Directed Energy Weapon System Mission Sets

The Army's DE M-SHORAD shown in Figure 14 will be equipped with a 50kW class laser capable of C-RAM. Due to the scalable power of the HEL, the system will also be capable of operating in the grey zone and provide counterintelligence, surveillance, and reconnaissance without destroying the target (Jones-Bonbrest 2020). The powerful optics on the DE M-SHORAD will allow the collection of intelligence, surveillance, and reconnaissance (ISR) data by observing red force activity. The Army is also developing a high-power microwave (HPM) version of the M-SHORAD platform (Eversden 2021). Figure 15 shows a concept drawing of the HPM M-SHORAD. The HPM M-SHORAD will provide C-UAS capability, particularly against swarms of unmanned aerial systems (UASs) and would also be capable of counter electronics such as signal jamming (Eversden 2021). Both DE systems provide unique capabilities with the HEL systems focused on C-RAM and HPM systems focused on defeating swarms of UASs.

Figure 14. DE M-SHORAD (Jones-Bonbrest 2020)

Figure 15. HPM M-SHORAD (Eversden 2021)

5. Directed Energy Convoy MMRA Analysis

a. MMRA from a DE Perspective

While this use case was lower in complexity with respect to the other two use cases presented in this report, there were quite a few inputs identified that should be considered when determining the best allocation of resources. Table 4 lists these inputs.

Table 4. DE Resource Allocation Considerations

Inputs	**Area of Interest**	**Considerations**
Red force	Proximity to convoy route	Are they within striking range?
		Can they maneuver within striking range?
	Capability	Rocket, artillery, mortar (RAM), UAS?

Inputs	Area of Interest	Considerations
	Capability	Can they disrupt the mission?
		Can they cause casualties?
	Intent	Cause casualties?
		Collect ISR?
Blue force	Convoy	Mission requirements based on expected red force capability (HEL verses HPM, number requested)?
		Asset value?
		Ability to evade red forces (speed, maneuverability, etc.)?
		Timing (can the convoy be moved up or delayed to a time when a DE system is available?)
	DE System	Can it defeat the expected threat?
		Is it available (down for maintenance, near the convoy, will it return in time for a future mission of higher importance)?
		Projected to have enough "ammo" for the mission?
WRAID	Engagement simulations	Best possible mission outcome among convoy missions based on current available DE resources and red force data?
AI Training (machine learning)	Theoretical simulations	Various possible engagements
	Historical data	Past attacks on convoys and exercise data
Environment	Weather	Performance impact due to weather conditions?
	Ground clutter	Limited field of view (buildings in urban areas, vegetation in a jungle, etc.)
Collateral/friendly damage	Personnel	Injury or death of non-combatants or friendly forces
	Buildings and equipment	Sustain laser/HPM damage
	Aircraft/Satellites	Sustain laser/HPM damage

This table shows there are numerous variables and a tremendous amount of information needed to determine the best allocation of these DE resources.

b. Decision Points

Ideally, the MMRA AI tool would constantly reassess the allocation of DE resources, however this has the potential to consume large amounts of computer processing power. This large amount of processing power may be too resource heavy and require reassessing only at major decision points. These major decision points that may call for rerunning the MMRA AI tool are:

- Changes to DE system availability
- Changes to convoy timetable
- Significant changes to intelligence on red forces
- Changes to convoy assets
- Convoy(s) under attack

6. Analysis

a. Scalability Analysis

RAM munitions have been around for centuries. Early versions were "dumb" and were fired in numbers in hopes that some would inflict damage on the enemy. From those humble beginnings, these weapons have advanced to become more accurate and effective. This can be seen in the conflict between Russia and Ukraine where laser guided artillery is being used (Axe 2022). This improvement to accuracy leads to an increased chance of a convoy sustaining casualties if attacked. The proliferation of cheap UASs makes it even easier to locate targets and deploy laser designators.

In addition to small-scale UASs providing a means to find and target convoys, these relatively cheap UASs can be used to carry explosives. These explosive laden UASs can be used against personnel and soft targets. To attack armored vehicles within the convoy, UASs such as the Switchblade 600 can be used (Capaccio 2022). These technological advancements increase the threat to assets within a convoy and increase the complexity of defending convoys.

b. Complexity Analysis

Time adds to the complexity of the elements already discussed, especially at the tactical level where the time epoch is in minutes, hours, and days. The initial scenario is run through the AI-enabled MMRA tool at t_0 which proposed the DE resource allocation for convoys A, B, and C based on the missions, constraints, resources, and available data. Convoy A is a low priority material transport convoy which will be traveling through mostly an urban environment that is known to have red forces that use UASs. It is allocated two HPM systems. Convoy B is a high priority troop and equipment convoy that will be traveling through a mix of urban and mountainous environments with a high amount of red force artillery activity. This convoy is allocated one HPM system and three HEL systems. Convoy C is a medium priority material convoy traveling mostly open terrain. It is allocated two HEL systems. Two HPM and two HEL systems remain behind as base defense and serve as emergency reserves.

At some point in the future after the convoys have set out, it was discovered that the red force mortar activity in the vicinity of convoy A was heavier than expected. Convoy A requested HEL systems to assist with protecting the convoy. This is considered decision point t_1 which called for the MMRA AI tool to be run to check if changes in the resource allocation should be made. In this case the MMRA tool quickly calculated COAs based on all factors available (especially resource time to location) and suggests reallocation of one HEL system from the base reserve.

At decision point t_2, convoy B is reporting less than expected red force activity while convoy C is experiencing higher red force activity and lost one of its HEL systems due to red force fire. Considering the priority of the missions and probability of mission success, the MMRA tool suggests reallocating one HEL system from convoy B to convoy C. The MMRA tool also took into consideration the time for the DE system to reach the convoy. The amount of time required to adjust to this new allocation is a key factor. If resources can be reallocated in minutes, that might be feasible, given the tactical situation. Without this consideration, the MMRA tool may recommend a set of allocations that would take too much time to implement.

After the convoys had completed their missions, three new convoy missions were planned. Information on an additional two HPM and two HEL systems scheduled to be deployed to the base in the coming days marks decision point t_3. With this new information, the MMRA tool recommended a shift in the execution timing of the future COAs due to significant increase in mission success probabilities from simulations from the wargaming tool. However, in this case the commander's intent for one of the future convoys required the COA for that convoy to be executed at the planned time. Table 5 shows the scenario events at the decision points.

Table 5. DE Convoy Protection Complexity Analysis Decision Points

Decision Point	DE Convoy Protection Scenario Event Resource Allocation
t_0	In reserve: HPM: 2, HEL: 2 Convoy A: HPM: 2, HEL: 0 Convoy B: HPM: 1, HEL: 3 Convoy C: HPM: 0, HEL: 2
t_1	In reserve: HPM: 2, HEL: 1 Convoy A: HPM: 2, HEL: 1 Convoy B: HPM: 1, HEL: 3 Convoy C: HPM: 0, HEL: 2
t_2	In reserve: HPM: 2, HEL: 1 Convoy A: HPM: 2, HEL: 1 Convoy B: HPM: 1, HEL: 2 Convoy C: HPM: 0, HEL: 1 (along with two damaged)
t_3	In reserve: HPM: 4, HEL: 3 Convoy A: HPM: 2, HEL: 1 Convoy B: HPM: 1, HEL: 2 Convoy C: HPM: 0, HEL: 1

C. ROTARY WING AVIATION MISSIONS

The aviation support use case explores one of the US Army's many aviation platforms in legacy and future systems, the UH-60 Blackhawk and FLRAA, respectively. Both systems fulfill the US Armed Forces utility-class helicopter capability set, as defined in US Army Field Manual (FM) 1-113. Further, both systems provided a suitable system to decompose the MMRA problem set. It was verified through DOD architecture framework (DODAF) perspectives and systems decomposition that the resource allocation needs of a legacy UH-60 aircraft are complex and require skilled human decision-making. Further, it was validated through a scalability analysis and complexity analysis that the initial and replanning demands are increasing over time. The near-term US Armed Forces needs for an AI-assisted MMRA tool may have a trade space with a relatively small increase of 15% from legacy to future resource allocation complexity. However, the overall SoS complexity is considerably more interconnected and only shows trends of increasing demands. Future research is strongly encouraged to future decompose the AI-assisted

MMRA aviation use case, such as Human Systems Integration (HSI), cyber security and computer hardware specifications for aircraft weight savings.

The need for a FLRAA intends to fill the FVL utility-class helicopter mission sets. A helicopter is considered utility class if it can transport a small team of fully equipped personnel to support a range of roles, such as internal/external lift, combat assault, MEDEVAC, C&C, disaster relief, aerial firefighting, search and rescue, special operations, and very important person transport. Utility class helicopters are generally deployed in multiples with various aerial and ground supports. The collective team that supports these utility class missions sets can be considered the aerial formation and require a system of systems resource allocation network.

Figure 16 illustrates a high-level operational view of this use case.

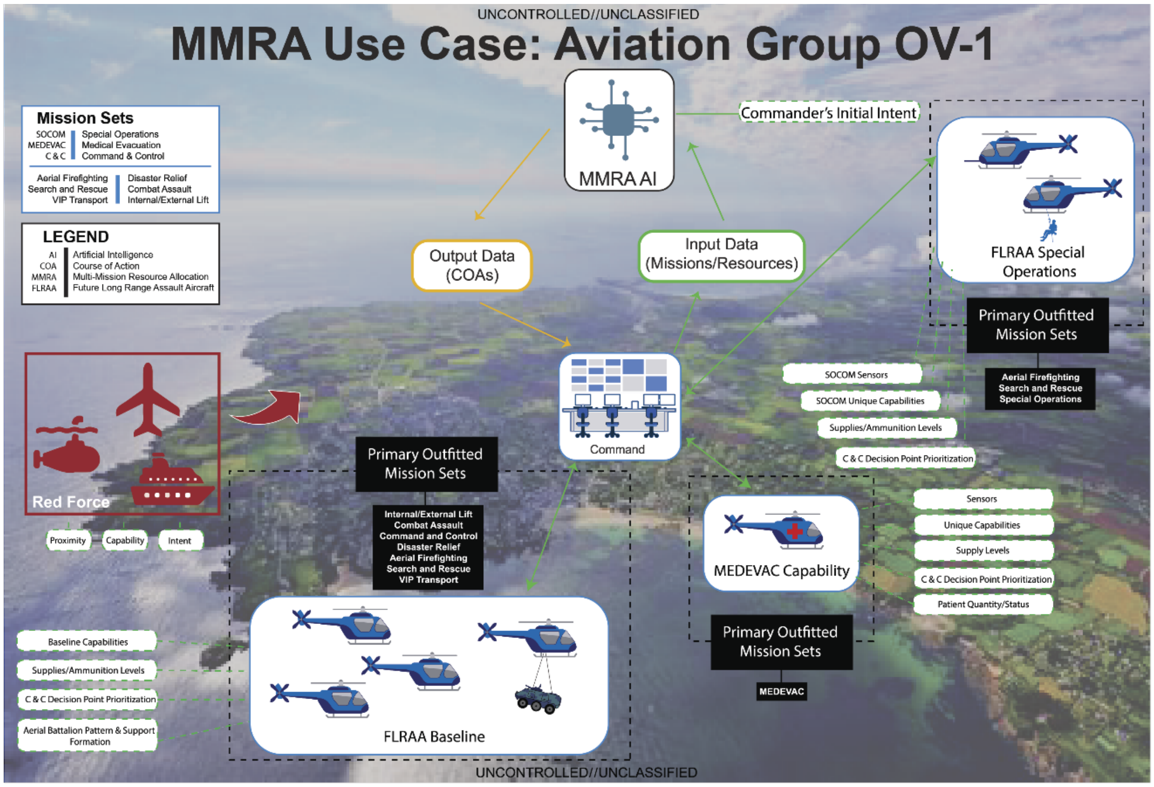


Figure 16. MMRA Use Case: Aviation OV-1

1. Legacy Utility-Class Helicopters

The UH-60 Blackhawk family of helicopters as depicted in Figure 17 has been a beloved aircraft of the US Military and US foreign military partners for many decades. Since its induction into the US Army in 1979, the UH-60 has served a broad range of missions sets in the utility class helicopter capability set.

Figure 17. UH-60 Blackhawk (PEO Aviation 2020)

As depicted, the Blackhawk has multiple resource needs to meet the utility class mission sets. Considerations that formulate mission inputs across all aviation mission sets include supply levels, baseline capabilities, command and control decision prioritization, aerial battalion pattern, and enemy (red) force intelligence, as depicted in Figure 16. Although red force intelligence is fluid, the red force inputs for an AI MMRA have been restricted to proximity/asset positions, capability/threat, and intent. Less fluid and ambiguous is the USG and allied (blue) force conditions for this study. **Error! Reference source not found.** organizes the legacy UH-60 utility class helicopter MMRA inputs into these generic categories, red force, blue force, WRAID, and AI Training.

Table 6. Legacy Aviation Resource Allocation Considerations

Inputs	Area of Interest	Considerations
Red force	Proximity	Are they within striking range?
		For what duration are they within range?
		Are red forces mobile/stationary? Ground/air?
		Red force targets for blue force in range?
	Capability	Weapons, Strategic Assets to target?
		Can they disrupt the mission?
		For how long/supplies can they disrupt?
		Can they cause casualties?
	Intent	Cause casualties?
		Stall/distract? Active denial?
		Collect ISR?
Blue force	Aerial formation	Overall Mission Requirements (which aircraft support which functions)
		Strategic Positioning & Flight pattern
		Ability to defend against red forces (unit positioning, maneuverability, Aircraft Survivability Equipment (ASE))?
		Timing considerations (how long to move the formation into position? Pre-flight spin-up?)

Inputs	Area of Interest	Considerations
		Can it out run, camouflage from, or defeat the expected threat?
	Outfitted Variants	Availability (range with current supplies, operational status, proximity to command and control (C&C)/target, maintenance downtime considerations)?
		Medical evacuation (MEDEVAC) / special operations command (SOCOM) capability mission requirements?
		Outfitted weapons capabilities
		Does the theater/mission permit reliable communications and assured positioning?
		Intended overall mission outcome among unit missions based on current available resources and red force data?
WRAID	Engagement simulations	Various possible engagements
AI Training (machine learning)	Theoretical simulations	live virtual constructive (LVC) data inputs
		Aviation SoS weapons capabilities data
	Historical data	Specific topological/area considerations
		Past attacks on aerial formations

The UH-60 Blackhawk has served as the US Military's premier utility-class helicopter for decades through diligent lifecycle engineering effort. Since entering the US Army aviation fleet in 1979, the UH-60 family has undergone half a dozen variants, a dozen special purpose spin-offs, and nearly three dozen foreign military sale models (PEO Aviation 2020). Across so many variations, maintaining a modular platform that is free of obsolescence and equipped for a growing set of technology insertions has been increasingly difficult.

However, it has become increasingly necessary to rebaseline the platform utility-class helicopter for the near-future technology insertions. The Army's Program Executive Office Aviation seeks to enable future Joint US Military operations through their FVL programs (Geerges, Rugen and Barrie 2021). The FLRAA program is the Army's future utility-class helicopter, which will enable cheaper sustainment, farther reach, faster airspeeds, and increased personnel seating.

a. US Army FVL FLRAA Down-select Alternatives

The FVL FLRAA down-select alternatives to represent the Army's future medium lift, utility helicopter are alluring. Many factors are considered when two comparable technology alternatives are in competition. However, the Army has identified its top three objective capability needs to be increased speed, range and personnel transport payload. Figure 18 shows a picture of the Sikorsky Boeing SB-1 Defiant X. Figure 19 shows a picture of the Bell V-280 Valor aircraft.

Figure 18. Sikorsky Boeing SB-1 Defiant X (Lockheed Martin 2022)

Figure 19. Bell V-280 Valor (Bell 2022)

Both of these aircraft alternatives are currently flight worthy with varying levels of technology maturation in subsystems. Overall, the Bell V-280 Valor has demonstrated far greater capability as shown in Table 7. Unfortunately, Sikorsky Boeing experienced severe setbacks in initial testing prior to 2019 and has not yet demonstrated threshold capability levels (Gill 2021). However, Sikorsky Boeing has projected technology maturation goals. Table 7 serves as a visual for comparable tilt-rotor aircraft technology such as the CV-22 Osprey, a legacy aircraft similar to the V-280, shown in Figure 19. Whereas **Error! Reference source not found.** serves as a visual for comparable compound and rigid dual-coaxial aircraft technology such as the AH-56 Cheyenne and Russian Kamov KA-52 Alligator. The vertical flight capabilities of the first practical helicopter, Sikorsky's VS-300A, are included as an anchoring reference for rotorcraft technological evolution.

Table 7. Comparable Tilt-Rotor Aircraft Technology (Bell 2022, AFSOC 2020)

Aircraft	True Airspeed	Range	Payload
V-280 Valor	322.2 mph (280 kn)	575-920 mi (500-800 nm)	14 (seated personnel); 4 crew
CV-22 Osprey	333.2 mph (280 kn)	575.4 mi (500 nm)	24 (seated personnel)

A comparative analysis of the V-280 Valor is best made with its parent company legacy, the Bell Boeing V-22 Osprey. The V-22 is a 21st century aircraft with multiple proven capability sets. Due to its engineering and tilt-rotor design, the V-22 touts an impressive speed, range and payload which has successfully been emulated in Bell's V-280 smaller profile. Unfortunately, these advanced capabilities set the US Air Force back approximately $90 million per unit (AFSOC Public Affairs 2020). Further, the V-22 is infamous for high maintenance cost, particularly due to the novel rotorcraft technology and numerous moving parts. The parent company Bell has long understood this perception, sensitivity to cost and has reiterated across multiple platforms that the V-280 Valor has taken the lessons learned from the V-22. To reaffirm this, Bell has conducted flight test operations well in excess of the US Army's requirements and their competitor Sikorsky Boeing.

Table 8. Aircraft Comparison (Lockheed Martin 2020, Pfau 2018, Sof 2017)

Aircraft	True Airspeed	Range	Payload
SB-1 Defiant	242~[287] mph (211~[250] kn)	~[526] mi ([848] km)	12 (seated personnel); 4 crew
AH-59 Cheyenne	243.9 mph (212 kn)		0 (Attack/Recon a/c); 2 pilots
Ka-52 Alligator	186.4 mph (300 km/hr)	285.8 mi (460 km)	0 (Attack/Recon a/c); 2 pilots

A comparative analysis of the SB-1 Defiant X is difficult to be made due to limited proven flight data, the novel combination of multiple rotorcraft technologies, and differences in aircraft mission sets. Two similar aircraft to the SB-1 Defiant are the AH-59 compound helicopter utilizing a rear push propeller and the KA-52 rigid dual-coaxial helicopter. Contrary, the AH-59 and KA-52 are classified as Attack and Reconnaissance aircraft, per US Army Regulation (AR) FM 1-112 l: Attack Helicopter Operations. Albeit the SB-1 Defiant is designed to meet the capability sets defined by medium lift Utility aircraft, per AR FM 1-113 Army FM: Utility and Cargo Helicopter Operations. Regardless of the contractual down-selectee, both materiel solutions provide an exceptional cutting-edge FVL aircraft to the US Armed Forces and allies. Both down-select alternatives provide similar future capability sets and have been generalized for the purpose of this capstone report.

2. Rotary Wing Aviation MMRA Use Case Analysis

The aviation use case has a robust historical context. However, future resource allocations can be categorically compared to better understand future solution sets. In the context of tactical decision making, a need exists to understand changes from legacy MMRA to modern. Understanding these aviation inputs for classical human-centered decision making will guide future AI-complimented MMRA solution sets. There were several inputs to consider when determining the best allocation of resources. Table 9 lists these inputs that must be considered. As shown, many categories under consideration for MMRA inputs are expanding over time.

Table 9. FLRAA Aviation Resource Allocation Considerations

Input		Legacy Utility-class Helicopter	Future-specific Resources
Red force	Proximity	Are they within striking range?	Future, near peers have over-the-horizon striking
		For what duration are they within range?	Speed is increasing, thus allowable response time is decreasing
		Are red forces mobile/stationary? Ground/air?	Future peers include cyber attacks
		Red force targets for blue force in range?	Unknown future condition
	Capability	Weapons, Strategic Assets to target?	Modern society has a robust commercial base which doubles as militia assets
		Can they disrupt the mission?	Survivability equipment trending percentile effectiveness
		For how long/supplies can they disrupt?	Potentially no change over time, mass-manufacturing is an industrial era capability
		Can they cause casualties?	Unknown future condition
	Intent	Cause casualties?	Unknown future condition
		Stall/distract? Active denial?	Potentially increase over time as attack domains expand to Cyber
		Collect ISR?	Unknown future condition
Blue force	Aerial formation	Overall Mission Requirements (which aircraft support which functions)	Potentially no change or decrease, FLRAA also to support variants with emphasis on modularity
		Strategic Positioning & Flight pattern	Potentially more MMRA alternatives with UAS teaming
		Ability to defend against red forces (unit positioning, maneuverability, ASE)?	An increase of ASE systems is needed over time to meet new threats.
		Timing considerations (how long to move the formation into position? Pre-flight spin-up?)	Potentially no change. However, FLRAA will have twice the range and speed as legacy
		Can it out run, camouflage from, or defeat the expected threat?	Unknow future condition
	Outfitted Variants	Availability (range with current supplies, operational status, proximity to C&C/target, maintenance downtime considerations)?	Mission sets such as MEDEVAC can participate in more trade-off with extended range, faster speeds at higher altitudes

Input		Legacy Utility-class Helicopter	Future-specific Resources
		MEDEVAC / SOCOM capability mission requirements?	Expanded alternatives with enhances and improved comms
		Outfitted weapons capabilities	Potentially decreasing on aircraft as technology in missiles and space expand, and speed/range are prioritized
		Does the theater/mission permit reliable communications and assured positioning?	Likely increasing MMRA consideration in near-peer engagements
		Intended overall mission outcome among unit missions based on current available resources and red force data?	Unknown future condition
WRAID	Engagement simulations	Various possible engagements	Future scenario is considerably more complex, permutations are exponential
AI Training (machine learning)	Theoretical simulations	LVC data inputs	Unknown future condition. Will include empirical analysis.
		Aviation SoS weapons capabilities data	Unknown future condition
	Historical data	Specific topological/area considerations	Unknown future condition, potentially more diverse than previous decades wars in arid, dessert scape
		Past attacks on aerial formations	Unknown future condition
Environment		Weather	Performance impact due to weather conditions?
		Ground topology	Limited field of view (buildings in urban areas, vegetation in a jungle, etc.)
Collateral/friendly damage		Personnel	Injury or death of non-combatants or friendly forces
		Buildings and equipment	Sustain damage
		Aircraft/Satellites	Sustain damage

3. Decision Points

The decision points across all use cases, aviation, DE convoy, and CSG follow the same generic decision point criteria. As a simplifying assumption, the MMRA AI replanning cycles were assessed at storyline points instead of incremental temporal sampling points. This assumption was made as a derivation of the AI black box study simplification. By

focusing on storyline decision points, our study was better able to conduct the intended SE input and output systems analysis required to decompose the MMRA problem set.
A unique subset of the aviation storyline points resides within the generic decision point criteria. If any of the below storyline points occurred throughout an aviation mission, then the resulting MMRA decision would be classified as mission critical. These major decision points that by criteria would call for rerunning the MMRA AI tool are:

- Loss of comms.
- Loss of fuel efficiency / management
- Unexpected / inaccurate red force intelligence on proximity, capability, or intent
- Commander's initial intent changes

4. Analysis

a. Scalability Analysis

The below scalability analysis sought to display the aviation problem set from a static t_0, initial planning perspective. Effort was applied to quantitatively assess the percentile increase of the resources requiring allocation between the legacy UH-60 Blackhawk and future FLRAA aviation platforms. Table 10 follows the afore mentioned resource allocation table formats to consolidate enabling capability trends. It was proposed, that if the scaled trend is increasing then the future resources allocation needs are becoming more objectively complex. As decision makers are pressed to the human limit, an opportunity to augment with machine learning AI exists.

Table 10. FLRAA Aviation Resource Allocation Considerations

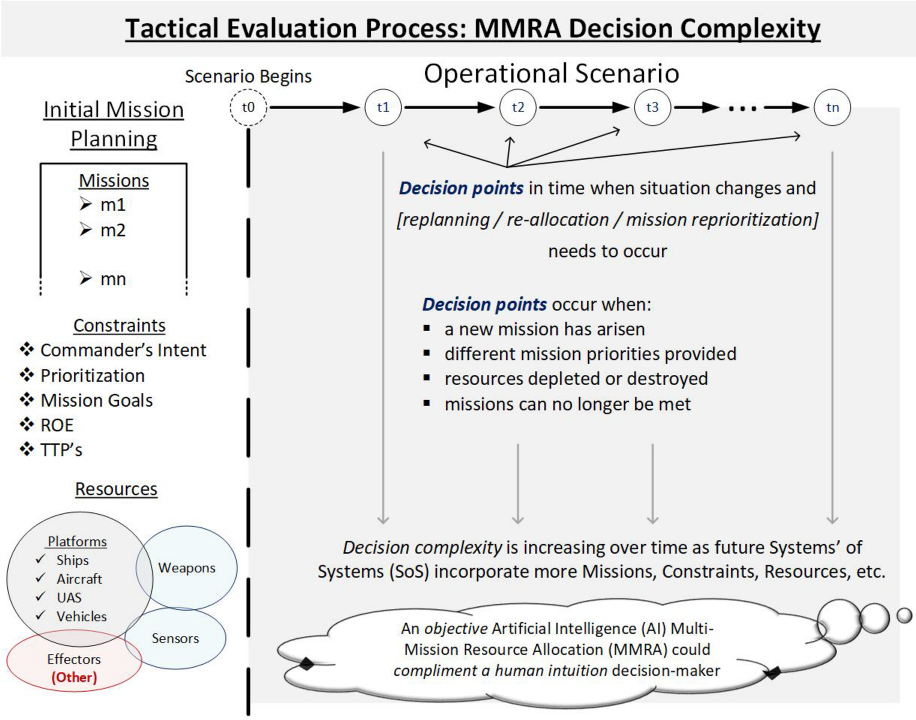
		Legacy Scale	**Future Scale**	**Future Trend**
Red force	Proximity	5	7	Increasing
		5	7	Increasing
		5	7	Increasing
		5	5	Unknown
	Capability	5	7	Increasing
		5	3	Decreasing
		5	5	No change
		5	5	Unknown
	Intent	5	5	Unknown
		5	7	Increasing
		5	5	Unknown
Blue force	Aerial formation	5	3	Decreasing
		5	7	Increasing
		5	7	Increasing
		5	5	No change
		5	5	Unknown
	Outfitted Variants	5	7	Increasing
		5	7	Increasing
		5	7	Increasing
		5	7	Increasing
		5	5	Unknown

		Legacy Scale	Future Scale	Future Trend
WRAID	Engagement simulations	5	7	Increasing
AI Training (ML)	Theoretical simulations	5	5	Unknown
		5	5	Unknown
	Historical data	5	5	Unknown
		5	5	Unknown
Scalability Instantiations		130	150	

Based on the aviation scalability analysis, a recognizable increase in static state MMRA may exist between the legacy and future system. Comparing legacy and future, a scaled trend is a 115% increase over time. A consideration for future MMRA study may include a HSI analysis to deep-dive the aviation decision-makers demands. Potentially, the resource allocations decision process may be manageable for some near future with effective HSI management. Alternatively, if a MMRA AI was developed an HSI analysis may greatly compliment the integration of machine and human teaming.

b. Complexity Analysis

Complimentary to the scalability analysis, the complexity analysis was a dynamic study of the MMRA replanning cycle. This analysis sought to study the story points over a temporal epic as part of the tactical decision replanning. Time was observed at decision points t_1, t_2, t_n. Though previously discussed, the Tactical Evaluation Process: MMRA Decision Complexity graphic is displayed in Figure 20 for reference.



Decision points in time when situation changes and *[replanning / re-allocation / mission reprioritization]* needs to occur

Decision points occur when:
- a new mission has arisen
- different mission priorities provided
- resources depleted or destroyed
- missions can no longer be met

Decision complexity is increasing over time as future Systems' of Systems (SoS) incorporate more Missions, Constraints, Resources, etc.

An *objective* Artificial Intelligence (AI) Multi-Mission Resource Allocation (MMRA) could *compliment a human intuition* decision-maker

Figure 20. Tactical Evaluation Process – MMRA Decision Complexity

The aviation complexity analysis was conducted as a thought experiment placed in a fictional storyline. The below storyline decision points were envisioned in a dynamic simulation.

- t_0: Start mission
- t_1: The FLRAA pilot sees a flare in the distance [Potentially, a new mission has arisen]
- t_2: Error displays on the pilot's dashboard [Potentially, the mission can no longer be met]

At the beginning of the mission, t_0, the MMRA AI was initially ran via the MMRA process architecture. At this time, the aviation command was provided an objective COA to best suit the present scenario. It was at this time that the human decision-maker in the loop made the final decision to execute an individual MEDEVAC FLRAA for a medium range, uncontested mission.

During early flight, the FLRAA aircraft pilot relays to command that they have seen a rescue flare in the distance. At this time, the aviation command distinguishes this relay as a MMRA decision point: a new mission has arisen. The command rerun the MMRA AI, which follows the MMRA process architecture "Recycle Chart" and outputs a best scenario COA. Since the MMRA AI is centrally positioned, it is aware of the second MEDEVAC FLRAA scheduled to perform a non-critical patient transport later in the day. Considering all inputs, the MMRA AI outputs a COA to maintain initial mission and reallocate other resources for the potential new mission ISR. The human in the loop receives this COA and decides to proceed.

Later during the return flight, the FLRAA aircraft pilot relays to command that they are experiencing a fault code and may have a non-critical issue. At this time, the aviation command again distinguishes this relay as a MMRA decision point: potentially the mission can no longer be met. The command representative thus reruns the MMRA. Due to the MMRA AI's input of historical data to include maintenance work logs, the objective COA is determined to maintain flight back to command and reallocate to unscheduled maintenance immediately following. The human in the loop receives this COA and has a general uneasiness as they are unfamiliar with the criticality of the error code. Currently, the human in the loop rereviews the MMRA AI's associated COA statistical confidence risk assessment. They still have uneasiness and call a trusted contact in the maintenance shop for validation before deciding to proceed to successfully conclude the mission. Table 11 lists the decision points for the aviation scenario.

Table 11. Aviation Support Complexity Analysis Decision Points

Decision Point	**Aviation Support Scenario Event Resource Allocation**
t_0	Start mission. MEDEVAC variant aircraft, full fuel levels.
t_1	The FLRAA pilot sees a flare in the distance [Potentially, a new mission has arisen]. MEDEVAC variant aircraft, depleting fuel stores, non-critical patient on-board.

Decision Point	Aviation Support Scenario Event Resource Allocation
t_2	Error displays on the pilot's dashboard [Potentially, the mission can no longer be met]. MEDEVAC variant aircraft, heavily depleting fuel stores, non-critical patient on-board, potential aircraft failure.

The above fictional aviation storyline is an oversimplification of the real-world scenarios that MMRA decision makers face every day. As the operational scenarios become more difficult and complex, the military historically relies on trust overcome. An area of future research may bundle HSI analysis with building trust with AI and computer aided partners. Though potentially not needed soon, the aviation space is becoming increasingly complex especially with UASs and modern engagement policies.

D. CARRIER STRIKE GROUP OPERATIONS

The CSG is another use case that the team studied for the application of AI-enabled MMRA tool. A CSG is comprised of ships, a submarine or two, and aircraft working toward a common main goal. Most platforms are capable of supporting several missions, creating conflict when the same resources are allocated to competing missions. The varied capabilities also lead to different resource allocations for each ship, submarine, and aircraft. On any given day, the individual units of the CSG will have a particular mission set and unique resource contributions. The following sections explore the CSG composition, individual unit requirements, how AI-assisted MMRA might assist in the resource planning for a CSG, and decision points for re-planning specific to the CSG scenario.

1. Background

The first carrier was commissioned on March 20, 1922, as an experiment (United States Navy 2019). The strategic advantage of the aircraft carrier was quickly identified, and the CSG was born. Since that time, the CSG has been the cornerstone of the United States Navy (USN) mission. Rear Admiral James P. Downey remarked when he assumed command of the program executive office of aircraft carriers on June 21, 2019, that "The aircraft carrier is our [US] Navy's centerpiece, our flagship, and a constant reminder to the rest of the world of our enduring maritime presence and influence. These ships touch every part of our Navy's mission to project power, ensure sea control, and deter our adversaries" (United States Navy 2019).

As the name implies, the CSG centers on the aircraft carrier and air dominance in a given mission location. The USN website on the aircraft carrier states that "aircraft carriers support and operate aircraft that engage in attacks on airborne, afloat and ashore targets that threaten free use of the sea and engage in sustained power projection operations in support of [US] and coalition forces" (United States Navy 2021). The CSG is comprised of many units that not only support the air power of the carrier, but also specialize in other missions to support the interests of the United States. Each ship in the CSG has a range of specialized missions it can execute. The cruisers and destroyers perform anti-air warfare (AAW), anti-submarine warfare (ASW), anti-surface warfare (ASUW), strike (STK), and ballistic missile defense (BMD). The submarine mission includes ASW, ASUW, STK, plus the added mission sets of intelligence (INTL) gathering, reconnaissance (RCN), and surveillance (SV). The supply ship (T-AO) serves the CSG with a primary mission set of emergency response (ER) and resupply (RESUP). Together, the ships that make up a CSG and the ten basic mission sets they execute bring the full power of the USN all around the globe. Table 12 lists the specific resources and mission sets for each unit, and Table 13 lists example mission sets of the CSG SoS.

Table 12. CSG Resources Mapped to Missions

Resource	**Missions**
Aircraft Carrier (CVN)	AAW, aircraft support (ACS), ER, ASUW
Cruiser (CG)	AAW, ASW, ASUW, STK, BMD
Destroyer (DDG)	AAW, ASW, ASUW, STK, BMD
Submarine (SSN)	AAW, ASUW, STK, INTL, RCN, SV
Fleet Replenishment Oiler (T-AO)	ER, RESUP

Table 13. Example CSG Mission Sets

CSG	**Mission**
CSG-1	"To conduct carrier air warfare operations and assist in the planning, control, coordination and integration of air wing squadrons in support of carrier air warfare." (United States Navy UD)
US Second Fleet (CSG-2, CSG-8, CSG-10, CSG-12)	"Command and control mission-ready forces to deter and defeat potential adversaries. Defend maritime avenues of approach between North America and Europe. Strengthen our ability to operate with allies and partners in competition and conflict." (United States Navy UD)
CSG-4	"trains and delivers combat-ready naval forces to U.S. Fleet Forces Command and U.S. 2nd Fleet, which are capable of conducting full-spectrum integrated maritime, joint and combined operations in support of U.S. national interests." (United States Navy UD)

2. Theater Use Case

For this use case, a forward deployed CSG with the following ship make up was considered: an aircraft carrier (CVN), three guided missile destroyers (DDG), two cruisers (CG), one Virginia-class submarine (SSN), and a fleet replenishment oiler (T-AO). The scenario also included all the resources associated with each vessel. Examples of those resources are personnel, sensors, armament, aircraft, and specific capabilities for the given mission of each vessel and resource therein. Figure 21 depicts the complexity of the CSG scenario.

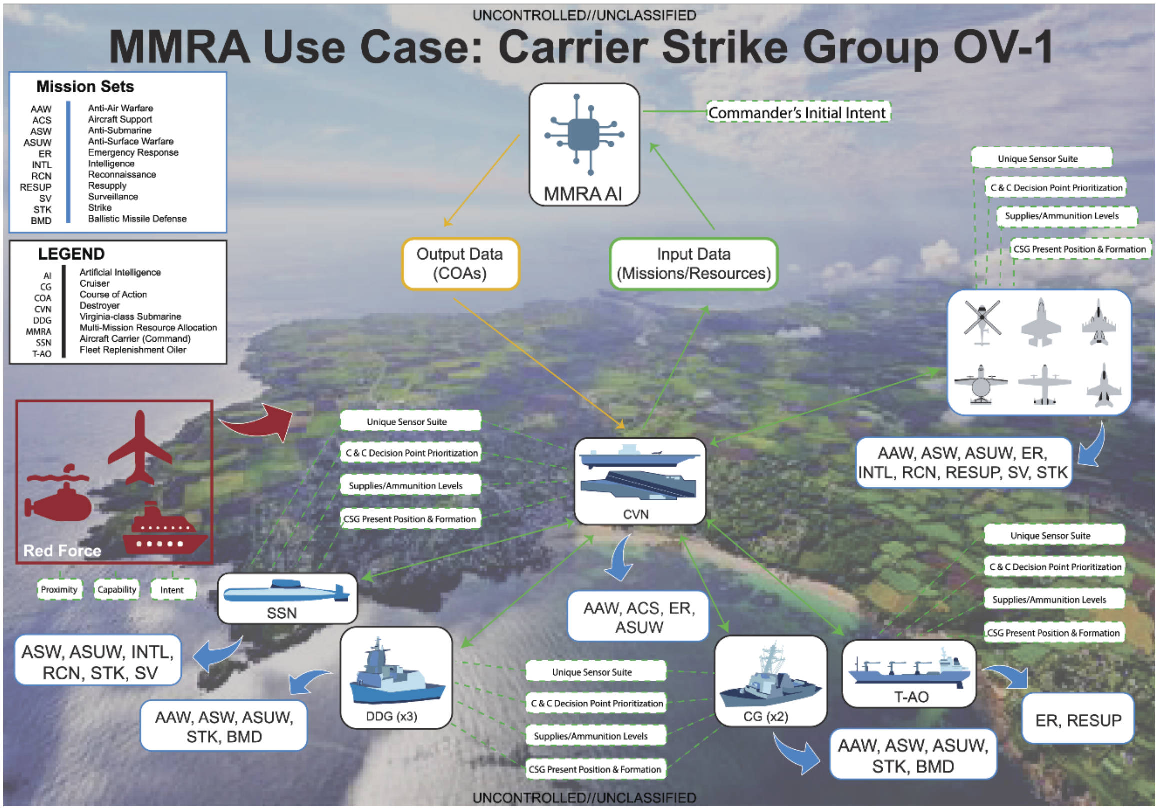


Figure 21. CSG Scenario OV-1 Diagram

The resources of the CSG must be allocated to ensure the mission are prioritized and fulfilled. With the duplication of certain mission sets, unit assignments can be flexible if a given ship is unavailable due to RESUP needs. However, both the SSN and the T-AO perform unique functions that must take priority if required. In contrast to the first two use cases examined, the CSG mission sets are scoped over days, weeks, and months. MMRA must consider the geographical disbursement of resources and minimum time limits to reposition assets.

3. Tactical Decision Making

a. MMRA from a CSG Perspective

The CSG use case was the most complex that Team AI Trio explored for this capstone. Within a CSG, there are thousands of resources which are required to perform the multiple mission sets of the group. Table 14 lists the resource allocation considerations and depicts the complexity of the MMRA problem set for a CSG.

Table 14. CSG Resource Allocation Considerations

Inputs	**Area of Interest**	**Considerations**
Red force	Proximity to CSG	Are they within striking range?
		Can they maneuver within striking range?
		Red force targets for blue force in range?
	Capability	Weapons, Strategic Assets to target?

Inputs	Area of Interest	Considerations
		Can they disrupt the mission?
		Can they cause casualties?
	Intent	Cause casualties?
		Collect ISR?
Blue force	CSG	Overall Mission Requirements (commander's intent)
		Strategic Positioning
		Ability to defend against red forces (unit positioning, maneuverability, CSG defense)?
		Timing considerations (how long to move the CSG into position?)
		Can it defeat the expected threat?
	Individual Units	Availability (RESUP needs, operational status, proximity to CVN, will it return in time for a future mission of higher importance)?
		Unit Special Mission Requirements?
		Weapons capabilities? Weapons RESUP.
		Best possible overall mission outcome among unit missions based on current available resources and red force data?
		Sensor outputs
WRAID	Engagement simulations	Various possible engagements
AI Training (ML)	Theoretical simulations	LVC data inputs
		CSG SoS weapons capabilities data
	Historical data	Past attacks on CSG
Environment	Weather	Performance impact due to weather conditions?
	Ocean effects	Limited detection range of sensors (ducting effects)
Collateral/friendly damage	Personnel	Injury or death of non-combatants or friendly forces
	Other units	Sustain accidental friendly fire
	Aircraft	Sustain accidental friendly fire

Within the table above, each consideration in the third column encompasses many data points that go into the MMRA AI system. As an example, a single CG within the group could have two helicopters, multiple radars providing inputs on enemy forces, 122 missile cells capable of a mix of missiles, 8 Harpoon missiles, 2 torpedo tubes, Phalanx

Close-In Weapons System (CIWS), multiple gun systems, and electronic warfare (EW) capability. At a given time, the inputs to the MMRA AI could easily number in the thousands.

b. Decision Points

Initially, the CSG commander would employ the MMRA AI tool when high level mission requirements are set. With the complexity of resources involved in the CSG use case, replanning with the MMRA AI tool would be required when changes to resource availability reach a threshold that impacts commander's intent. Additionally, a significant change in red force inputs would also necessitate replanning of CSG resources. These decisions points are:

- Changes to individual unit availability (becomes available/unavailable)
- Significant changes to intelligence on red forces (change in proximity, capability, or intent)
- Red forces attack and deplete resources
- Emergency operations (within the CSG, external to the CSG, natural disaster aid response)

With individual unit RESUP requirements, regular MMRA AI replanning would likely occur every 5-7 days. The other decision points would occur on an ad hoc basis.

4. Analysis

a. Scalability Analysis

Over time, the mission set of each unit in a CSG has increased. Consider the destroyer's role in the CSG. The replacement of the Charles F. Adams class (DDG-2) with the Arleigh-Burke (DDG-51) class destroyer program brought new resources and capabilities to the CSG. In addition, the Arleigh-Burke class has been significantly upgraded three times in the lifetime of the program. Each new variant added resources and capabilities to the platforms (SEA 00D 2021). The original mission set of the Flight I/II was expanded in fiscal year (FY)1994 with the Flight IIA design. The Flight IIA design increased capability in multiple areas; most notably to incorporate helicopters (Congressional Research Service 2011). An overview of the resources allocated to the various ship classes from the Charles F. Adams class to the Arleigh-Burke Class Flight III are listed below in Table 15.

Table 15. Destroyer Resources by Surface Combatant

Category	**Charles F. Adams Class (Susalla 1984)**	**Arleigh-Burke Class (SEA 00D 2021)**		
		Flight I	**Flight IIA**	**Flight III**
Complement Total (officer/enlisted)	354 (24 / 330)	329 (59 / 270)		

Category	**Charles F. Adams Class (Susalla 1984)**	**Arleigh-Burke Class (SEA 00D 2021)**		
		Flight I	**Flight IIA**	**Flight III**
Missiles	Harpoon, Tarter, ASROC. (40-missile magazine)	Harpoon, Standard Missile, Vertical Launch anti-submarine rocket (ASROC), Tomahawk (96-cell magazine)	Harpoon, Standard Missile, Vertical Launch ASROC, Tomahawk, Evolved SeaSparrow Missile (ESSM), BMD, (96-cell magazine)	
Guns	2 five-inch 54 caliber	CIWS, 5-in. MK 45 Gun		
Anti-Submarine	2 triple torpedo tubes	2 triple torpedo tubes		
Radar	3D search, 2D air search, surface search, fire control	Integrated Aegis Weapons System with AN/SPY-1D		Integrated Aegis Weapons System with AN/SPY-6(V)1 Air and Missile Defense Radar
Countermeasures	Mk 36 super Rapid Bloom Offboard Countermeasures	MK 36 MOD 12 Decoy Launching System, MK 53 Nulka Decoy Launching System, AN/SLQ-39 chaff buoys		
Sonar	SQS23 or SQQ23	SQQ89		
Aircraft	NA	NA	Two LAMPS MK III MH-60 B/R helicopters with Penguin/Hellfire missiles and MK 46/MK 50 torpedoes	

It is clear from Table 15 that over time the capability of each subsequent ship class has increased. The available missile types doubled between the Adams class and the Flight III ships, and the number of cells onboard more than doubled from 40 cells to 96 cells capable of supporting any mix of loadout. The countermeasure capability tripled between the Adams and Arleigh-Burke class. The Flight IIA and Flight III ships add two helicopters as resources aboard, further scaling up the resource allocation challenge.

As demonstrated with the destroyer, the resources allocated to a CSG have likely more than doubled in the past 50 years. In addition, the mission set has also increased for each unit of the CSG. The Flight III Arleigh-Burke class destroyer, for example, has an expanded mission set to now include aviation missions, BMD, and area defense for the other ships in the group. A decision-aid using AI for MMRA could undoubtedly assist the mission planners for both each individual unit as well as the overall CSG mission planner.

b. Complexity Analysis

The resource allocation challenge mission planners face also incorporates a time component that must be considered. For the ships in the group, and especially the aircraft carrier itself, turning or stopping takes considerable time and distance. The initial mission planning for the CSG would include the overall CSG mission as well as each unit's individual missions and resources.

For this capstone, the overarching CSG mission set of the US Second Fleet was selected: to "command and control mission-ready forces to deter and defeat potential adversaries. Defend maritime avenues of approach between North America and Europe. Strengthen our ability to operate with allies and partners in competition and conflict." (United States Navy UD) This mission, the mission sets of each unit in Table 12, and all inputs discussed in Table 14 (CSG Resource allocation) would be passed to the MMRA AI. With this information, the MMRA AI would be exercised, and the initial resource allocation based on priority would be passed back to each unit.

The ships move out on their individual missions, and the MMRA AI CSG scenario begins at t_0. An example decision point: if a previously unknown red force unit (red force 1) attacked the CSG with several anti-ship cruise missile (ASCM). CG1 could expend two STANDARD missiles, three ESSMs, and several hundred rounds of CIWS before she suffers a casualty and must reprioritize her individual mission to ER damage control. By this time the CG2, SSN, DDG1, and DDG2 are each geographically dispersed. DDG1 is closer to the CG1, but one of her helicopters is undergoing maintenance and out of operation. CG2 can return from her individual mission but will take several hours to reposition. DDG2 has both helicopters operational, but the fuel she has onboard would require the T-AO to provide a RESUP mission to DDG2. The SSN is executing a SV mission, but based off the location of the ASCM could be in the general area of the adversary force who launched the ASCM. The commanding officer also has limited intelligence on if there are any additional red forces in the area. This one event leads to many different available COAs for the CSG commanding officer to deal with. Clearly, the CG1 needs help. Which resources to reallocate, and how to factor in new information such as the presence of previously undetected enemy forces can clearly overwhelm a decision-maker. This incident would trigger decision point t_1 where the MMRA AI would need to be engaged to recalculate COAs for the mission commander. In this instance, the available resources and overall mission priority would have both likely changed.

With the AI-assisted MMRA tool, the CSG commander can quickly decide to reallocate resources. Some of the CVN resources and the T-AO are immediately reallocated to ER.

Despite only having one helicopter, the DDG1 is ordered to also return for ER since the AI determined some of the CVN air assets can return quickly and assist with ER. The CG2 is ordered to strategically locate to defend the units attending to the CG1. The DDG2 and SSN are reprioritized to establish where red force 1 is located and determine if any additional threats exist.

As the CG1 struggles to contain the casualty, the DDG2, SSN, and deployed aircraft from the CVN report additional contacts that potentially could be red forces. This information triggers decision point t_2. The data from all available sensors are passed back to the AI-assisted MMRA tool. With the help of the tool, COAs and the associated statistics are again presented to the decision-maker for resource allocation. The CSG commander can determine to strategically maneuver the DDG1 to an optimal location to help CG2 provide area defense for the wounded CG1, CVN, and T-AO. Additionally, the AI MMRA tool indicated that the available weapons on the DDG2 and SSN are more than sufficient to neutralize the threat. Armed with the output from the tool, the CSG commander can efficiently assign resources.

Sometime later, CG1 could overcome the ER damage control scenario and be available to again support the greater CSG mission. This would trigger time t_3 when the mission planners would engage the MMRA AI to get the set of COAs based on new available resources. With CG1 damaged, weapons and sensors may need to be supplemented by aircraft from the CVN where possible. The MMRA tool could help mission planners determine which resources to allocate for this purpose. Table 16 lists the decision points for the CSG scenario.

Table 16. CSG Complexity Analysis Decision Points

Decision Point	**CSG Scenario Event Resource Allocation**
t_0	Initial missions established and executed. CVN (ACS), CG1 (AAW, ASW, ASUW, BMD), CG2 (AAW, ASW, ASUW), DDG1 (AAW, ASW, ASUW), DDG2 (AAW, ASW, ASUW), SSN (SV), T-AO (RESUP)
t_1	CG suffers casualty and must abandon her mission for ER. CVN (ACS, ER, INTL, RCN, SV), CG1 (ER), CG2 (AAW, ASW, ASUW), DDG1 (ER), DDG2 (AAW, ASW, ASUW, STK), SSN (INTL, RCN), T-AO (ER)
t_2	CVN aircraft, DDG2, and SSN report contacts that could be additional enemy forces. CVN (ACS, AAW, ASW, ASUW, ER), CG1 (ER), CG2 (AAW, ASW, ASUW), DDG1 (AAW, ASW, ASUW, ER), DDG2 (AAW, ASW, ASUW, STK), SSN (INTL, RCN, STK), T-AO (ER)
t_3	CG1 overcomes ER and can return to the overall CSG mission in a diminished capacity. CVN (ACS, AAW, ASW, ASUW), CG1 (AAW, ASW, ASUW), CG2 (AAW, ASW, ASUW), DDG1 (AAW, ASW, ASUW), DDG2 (AAW, ASW, ASUW, STK), SSN (INTL, RCN, STK), T-AO (RESUP)

Mission planners could engage the MMRA AI at any time to determine if reallocation of resources is warranted. However, caution is warranted to ensure missions are executed prior to reallocation unless superseding external factors warrant abandonment of a particular mission. An enemy attack during RESUP could be one scenario in which the RESUP mission must be terminated before completion. Similarly, ER is an emergent requirement that most often pulls resources from other mission allocations.

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VI. CONCLUSIONS

A. SUMMARY

This study produced findings in three general areas: (1) the characterization of complex tactical situations where cross-domain multi-mission operations are required, (2) the need for mission planning, dynamic replanning, and tactical decision-making that can address these complex situations, and (3) concepts for leveraging advanced data analytics to provide automated planning and decision aids for these applications. The study addressed the research objectives by first conducting a literature review of mission planning, tactical decision-aids, advanced analytics, game theory, and artificial intelligence. The research team, consisting of NPS research faculty and systems engineering students applied a systems analysis to characterize cross-domain multi-mission situations and develop system concepts for AI-enabled mission planning and tactical decision-aids for multi-mission resource allocation and dynamic replanning. The team conducted a needs analysis, requirements analysis, and conceptual design using model-based systems engineering tools to capture system and architectural design artifacts. The students developed names for the automated systems: the Strategic Operational Decision Aid for the automated system that could support future mission planning (Lee, 2022), and the Multi-Mission Resource Allocation system for future tactical-level automated decision support (Ghigliotti et al., 2022).

The NPS research team studied the operational need for automated planning and decision aids for cross-domain multi-mission situations that arise during military operations. The team drew upon former research that the P.I. performed that characterized instances of complexity in military operations that result in situations that require automated decision support systems. Highly complex tactical military decision spaces can be characterized as having extremely short reaction or decision timelines, significant levels of uncertainty in situation awareness knowledge, extreme dynamics in the threat tempo in terms of heterogeneity, number, and kinematics, and information confusion with too little or too much information. These complex situations can cross military domains and involve operations in space, air, land, sea, undersea, and cyber. These complex situations can also involve concurrent multiple missions, such as anti-surface warfare, air and missile defense, undersea warfare, mine warfare, strike operations, cyber operations, operations in communication denied environments, expeditionary missions, etc. When warfare resources are needed for concurrent multiple missions, the decision space for resource allocation becomes complex. This complexity increases in cross-domain situations. Automated decision aids leveraging AI and advanced analytics is a candidate for improving (and even enabling) effective mission planning and tactical decision-making in these situations.

The study topic sponsor can use the findings of this research project as a basis for funding the research and development of advanced analytics capabilities for multi-mission cross-domain mission planning and tactical decision aids. One step is to continue studying AI and advanced data analytic methods as a means of automating mission planning and tactical decision-making. Another step is to continue studying operational scenarios that involve concurrent multi-mission cross domain operations. The topic sponsor can use the foundational knowledge from this study to continue to pursue these critical capabilities for the Navy.

B. RECOMMENDATIONS AND FUTURE WORK

The NPS study team recommends that automated methods including advanced data analytics and AI be pursued for mission planning and tactical decision aids that can improve cross-domain multi-mission resource allocation and dynamic replanning. The team recommends further study into (1) the characterization of complex tactical situations where cross-domain multi-mission operations are required, (2) the need for mission planning, dynamic replanning, and tactical decision-making that can address these complex situations, and (3) concepts for leveraging advanced data analytics to provide automated planning and decision aids for these applications. The team recommends the following specific research initiatives as future work:

- Operational concept studies – to understand how/when complex military operational situations arise that involve cross-domain and concurrent multi-mission solutions.
- Development of modeling and simulation capabilities to support more detailed study into these complex operational situations and potential solutions.
- Continued research into advanced AI and data analytic methods
- Study into system architectures that can enable dynamic replanning to occur during tactical operations

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