NPS-IS-20-005

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

COMPUTATIONAL MODELING AND SIMULATION OF DISTRIBUTED MARITIME OPERATIONS

by

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December 2020

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Prepared for: Chief of Naval Operations, N9

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE ***(DD-MM-YYYY)*** December 2020	**2. REPORT TYPE** Technical Report	**3. DATES COVERED** ***(From-To)*** 01/01/2020 – 12/31/2020

4. TITLE AND SUBTITLE Computational Modeling and Simulation of Distributed Maritime Operations	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Dr. Mark E. Nissen and Dr. Shelley P. Gallup	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES) Naval Postgraduate School 1 University Circle Monterey, CA 93943	**8. PERFORMING ORGANIZATION REPORT NUMBER** **NPS-IS-20-005**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Chief of Naval Operations, N9 Pentagon, Washington, DC	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release. Distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

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15. SUBJECT TERMS
Autonomous systems; combatant-sensor integration; distributed maritime operations; simulation.

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	None	69	
					19b. TELEPHONE NUMBER *(include area code)*

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

NAVAL POSTGRADUATE SCHOOL
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The report entitled “Computational Modeling and Simulation of Distributed Maritime Operations” was prepared for and funded by Chief of Naval Operations, N9.

Further distribution of all or part of this report is authorized.

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ABSTRACT

The technologic capabilities of autonomous systems continue to accelerate, and teams of autonomous systems and people (TASP) are becoming increasingly important, particularly where distributed maritime operations (DMO) are concerned. Computational experimentation offers unmatched yet largely unexplored potential to address DMO research questions, and we employ the POWer computational environment to model and simulate DMO organizations and phenomena. We begin by building upon prior research to establish a baseline model for comparison. Then we adapt such model to represent DMO, and we compare key results to elucidate important insights into both the potential and difficulty associated with DMO.

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I. INTRODUCTION

A. AUTONOMOUS SYSTEMS

The US Department of Defense (DoD), along with the militaries of NATO members and other allied nations, has discovered and begun to capitalize upon the value of robots, unmanned vehicles and other autonomous systems (AS) for a variety of different missions, ranging from search and rescue, through aerial bombing, to Cyberspace surveillance. To a large extent, people in such military organizations operate and control the AS, much the same way that people in many factories operate and control machines for production, assembly and packaging. The AS are basically slaves to their human operators.

The technologic capabilities of AS continue to accelerate, however, and systems in some domains have reached the technical point of total autonomy: they can perform entire missions without human intervention or control. For instance, in 2001 a Global Hawk flew autonomously on a non-stop mission from California to Australia, making history by being the first pilotless aircraft to cross the Pacific Ocean (AMoD, 2001). As another instance, in 2013 a Northrop Grumman X-47B unmanned combat air vehicle successfully took off from and landed on an aircraft carrier underway at sea (BBC, 2013).

Further, as technologic sophistication continues to advance rapidly (e.g., in computational processing, collective sense making, intelligent decision making), a wide array of diverse robots (e.g., in hospitals; see Feil-Seifer & Mataric, 2005), unmanned vehicles (e.g., for highway driving; see Muller, 2012) and other intelligent systems (e.g., for industrial control; see McFarlane et al., 2003) continue to demonstrate unprecedented capabilities for extended, independent and even collective decision making and action (e.g., offensive and defensive swarming; see Bamberger et al., 2006). Indeed, the technologic maturity of many AS available today (e.g., UCLASS – Unmanned Carrier-Launched Airborne Surveillance and Strike; see Dolgin et al., 1999) exceed the authority delegated to them by organizations and leaders; that is, their performance is limited more by policy than technology (e.g., see DoDD 3000.09, 2012).

In many skilled mission domains and under demanding environmental conditions (e.g., tactical surveillance; see Joyce, 2013), AS are replacing people at an increasing rate (e.g., unmanned vs. manned aircraft sorties; see Couts, 2012). These machines can outperform their human counterparts along many dimensions (e.g., consistency, memory, processing power, endurance; see Condon et al., 2013), yet they fall short in other ways (e.g., adaptability, innovation, judgment, ethics; see HRW, 2012). Task performance by AS is optimal in some situations, and performance by people is best in others, but in either case, the respective capabilities of autonomous machines and people remain complementary. As such, *integrated* performance, by complementary autonomous systems and people *working together*, can be superior in an increasing number of circumstances, including those requiring skillful collective action (Nissen & Place, 2013).

Hence there is more to this trend than simple technologic automation of skilled work by machines (e.g., numeric control machining) or employment of computer tools by skilled people (e.g., computer aided drafting). Where autonomous systems and people collaborate together in coherent teams and organizations, we refer to this increasingly important phenomenon as Teams of Autonomous Systems and People (TASP).

Such collaboration between autonomous systems and people represents an important element of Distributed Maritime Operations (DMO). Available manned and unmanned, surface and air, combatants and sensors require integration to serve as a cohesive, networked force despite their distribution through physical space-time. DMO represents a considerable technical challenge, but this kind of cohesive combatant-sensor integration is distributed organizationally as well. Hence DMO represents a considerable command and control (C2) challenge also, as a variety of different platforms (e.g., CVNs, DDGs, CGs), services (e.g., Navy, Marines, Air Force) and even nations (e.g., coalition operations) are likely to assert simultaneous control over the diverse combatants and sensors.

B. OPEN DMO QUESTIONS

In 2017, the Navy Warfare Development Command created the term *Distributed Maritime Operations*, which looks at distributed forces in a broad, Fleet-centric manner. The key goal is to allow commanders a greater diversity of options or combinations of sensors, platforms and weapons, along with both decision and execution speed, to outpace and defeat adversaries. DMO considers the merging of resources, information and technologies with key decision makers at all levels of an organization. Indeed, DMO views warfare via a distributed network that has the integration capability of all available platforms across all operational domains (Winstead et al., 2018).

DMO raises a plethora of open, research, policy and decision making questions. For one, under what circumstances should people work subordinate to AS (e.g., robot supervisor) versus controlling them (e.g., robot subordinate)? Few researchers, policy makers or organization leaders are even asking this question today, much less trying to answer it, as the conventional, conservative and often naïve bias is overwhelmingly toward people controlling machines.

Nonetheless, empiric evidence shows that AS can produce superior results—in some circumstances—when people are subordinate (e.g., see Bourne, 2013). This represents revolutionary change, and our millennia of accumulated knowledge in terms of C2, organization, management, leadership, information science, computer science, human-systems integration and like domains leaves us largely unprepared to seize upon such situated performance superiority.

For another, under what circumstances should units comprised of people be organized, led and managed separately from counterparts comprised of AS (e.g., separate aircraft squadrons), and what circumstances favor instead organization integration[1] of people and AS into combined units (e.g., integrated or composite squadrons; see CFFC, 2014)? Because every mission-environment context manifests some uniqueness, the answer may vary across diverse missions, environments, times and organizations; even individual personnel skills, team trust levels, leadership characteristics, political risk aversion, and like factors may affect the approach leading to greatest mission efficacy. Indeed, a central aspect of mission planning and execution may require explicit consideration of how people and AS should be organized, how cohesive combatant-sensor integration can be achieved, and how such DMO organization may even require dynamic replanning and change mid-mission.

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[1] For instance, HSM-35, located at NAS North Island, has been organized and configured to manage and support both the Fire Scout UAS and the MH-60 aircraft (e.g., integrated technicians and operators have been trained to maintain and operate both systems). Additional information and guidance is available in the USFF/CNAF UAS Concept of Operations. Nonetheless, several questions remain: Is such integration a good idea? On what science is it based? What are the comparative advantages and disadvantages? How could it become even more effective?

For a third, how can researchers, policy makers and leaders develop confidence that their chosen DMO organization approach (e.g., to subordinating or superordinating robots to people, to separating or integrating AS and personnel units, to selecting missions involving collaboration between people and AS, to cohesive combatant-sensor integration) will be superior? These technology-induced research questions are so new and foreign that negligible theory is available for guidance, and it is prohibitively time-consuming, expensive and error-prone to systematically test the myriad different approaches via operational organizations. This is the case in particular where loss of life, limb or liberty may be at stake.

This research project seeks to understand how to enable cohesive combatant-sensor integration for DMO and to model and outline the kinds of system capabilities and behaviors necessary for their integrated implementation. The project builds upon our prior work on manned and unmanned systems and sensors (e.g., Nissen & Place, 2014; Place & Nissen, 2015; Nissen & Place, 2016; Nissen, 2017; Nissen & Gallup, 2019; UAS, ACTUV, MDUSV, TASP) and focuses directly on the DMO challenges noted above

This leads to three primary research questions:

RQ1: What technologic trajectories of manned and unmanned systems are most relevant to DMO over the coming decade?

RQ2: What kinds of DMO approaches, organizations and technologies are most appropriate to leverage such technologic trajectories?

RQ3: What kinds of decisions, specifications and training modifications are needed to guide DMO over the next ten years?

C. COMPUTATIONAL EXPERIMENTATION

Computational experimentation offers an unmatched yet largely unexplored potential to address DMO questions along these lines. If computational models can be developed to represent the most important aspects of organizations with existing, planned or possible DMO benefits, then researchers could employ such models to address the kinds of open questions posed above. Moreover, organization leaders, managers and policy makers could develop confidence in their situated decisions and actions involving the organization, integration and leadership of AS and people.

Further, once such computational models have been developed and validated, they can become virtual prototype DMO organizations to be examined empirically and under controlled conditions through efficient computational experiments (e.g., see Oh et al., 2009). Indeed, tens, hundreds, even thousands of diverse approaches to DMO can be examined very quickly, with their relative behavior and performance characteristics compared to match the best DMO approach with a variety of different missions, environmental conditions, technologic capabilities, autonomy policies, personnel characteristics, skill levels and job types. Moreover, such computational experimentation and comparison can be accomplished very quickly and at extremely low cost relative to that required to experiment with teams or organizations in the laboratory—or especially in the field—with no risk of losing life, equipment or territory in the process (e.g., see Nissen & Buettner, 2004).

The central problem is, this kind of DMO organization experimentation capability has yet to be developed and demonstrated. Notwithstanding current, lower level work addressing fatigue and like issues affecting individual unmanned system operators (e.g., see Yang et al., 2012), the higher level DMO experimentation capability envisioned here remains absent.

D. RESEARCH OVERVIEW

This is where our research project seeks to make an important contribution. Building upon a half century of research and practice in modeling and simulation in general (e.g., see Forrester, 1961; Law & Kelton, 1991), and a quarter century of *organization* modeling and simulation work in particular (e.g., see Carley & Prietula, 1994), we have access to computational modeling and simulation technology representing the current state of the art (i.e., VDT [Virtual Design Team]; see Levitt et al., 1999). Such technology leverages well-understood organization micro theories and behaviors that emerge through agent-based interaction (e.g., see Jin & Levitt, 1996).

Agent-based organization models developed through this technology have also been validated dozens of times, over a period of roughly three decades, to represent faithfully the structure, behavior and performance of counterpart real-world organizations (e.g., see Levitt, 2004). Plus, we have adapted the same computational modeling and simulation technology over several years to the military domain (e.g., see Nissen, 2007) to examine joint task forces, distributed operations, computer network operations, and other missions that reflect increasingly common joint and coalition endeavors.

The research project described in this report seeks to leverage computational modeling to understand how to enable cohesive combatant-sensor integration for DMO and to model and outline the kinds of system capabilities and behaviors necessary for their integrated implementation. Planned as a multiyear project, the first effort described in our prior report (Nissen & Gallup, 2019) focuses on establishing a computational environment suitable for DMO modeling, simulation and analysis. In this first effort, we model, simulate and analyze maritime operations as they are conducted today, with a particular focus on both manned and unmanned aircraft intelligence, surveillance and reconnaissance (ISR) missions. This establishes a baseline for comparison with one or more DMO organizations conducting ISR missions. It also establishes a baseline for comparison with other missions (e.g., strike, air defense, surface warfare). The second stage then proceeds to model, simulate and analyze one or more, alternate DMO organizations.

Now in this follow on effort, we adapt the baseline model from above to characterize DMO in the same ISR mission context. In the balance of this technical report, we first provide an overview of the POWer computational experimentation environment along with an example to help delineate computational modeling of DMO organizations and phenomena. We summarize in turn the research method. Key results follow, and we conclude then by summarizing our agenda for continued research along these lines. The results should increase greatly our understanding and ability to enable cohesive combatant-sensor integration for DMO and to model and outline the kinds of system capabilities and behaviors necessary for their integrated implementation.

II. BACKGROUND

A. POWER COMPUTATIONAL ENVIRONMENT

This section draws heavily from Gateau and colleagues (2007) to provide an overview of the POWer computational environment. POWer builds upon the planned accumulation of collaborative research over roughly three decades to develop rich, theory-based models of organization processes (Levitt, 2004). Using an agent-based representation (Cohen, 1992; Kunz et al., 1999), micro-level organization behaviors have been researched and formalized to reflect well-accepted organization theory (Levitt et al., 1999). Extensive empiric validation projects (e.g., Christiansen, 1993; Thomsen, 1998) have demonstrated the representational fidelity and shown how the qualitative and quantitative behaviors of our computational models correspond closely with a diversity of enterprise processes in practice.

This research stream continues today with the goal of developing new micro-organization theory and embedding it in software tools that can be used to design organizations in the same way that engineers design bridges, semiconductors or airplanes—through computational modeling, analysis and evaluation of multiple virtual prototypes. Such virtual prototypes also enable us to take great strides beyond relying upon the kinds of informal and ambiguous, natural-language descriptions that comprise the bulk of organization theory and Navy doctrine today.

For instance, in addition to providing textual description, organization theory is imbued with a rich, time-tested collection of micro-theories that lend themselves to computational representation and analysis. Examples include Galbraith's (1977) information processing abstraction, March and Simon’s (1958) bounded rationality assumption, and Thompson’s (1967) task interdependence contingencies. Drawing upon such micro-theory, we employ symbolic (i.e., non-numeric) representation and reasoning techniques from established research on artificial intelligence to develop computational models of theoretical phenomena. Once formalized through a computational model, the symbolic representation is “executable,” meaning it can be used to emulate organization dynamics.

Even though the representation has qualitative elements (e.g., lacking the precision offered by numeric models), through commitment to computational modeling, it becomes semi-formal (e.g., most people viewing the model can agree on what it describes), reliable (e.g., the same sets of organization conditions and environmental factors generate the same sets of behaviors) and explicit (e.g., much ambiguity inherent in natural language is obviated). This, particularly when used *in conjunction with* the descriptive natural language theory of our extant literature, represents a substantial advance in the field of organization analysis and design, and it offers direct application to research and practice associated with DMO.

Additionally, when modeling aggregations of people—such as work groups, departments or whole organizations—one can augment the kind of symbolic model from above with certain aspects of numeric representation. For instance, the distribution of skill levels in an organization can be approximated—in aggregate—by a Bell Curve; the probability of a given task incurring exceptions and requiring rework can be specified—organization wide—by a distribution; and the irregular attention of a worker to any particular activity or event (e.g., new work task or communication) can be modeled—stochastically—to approximate collective behavior. As another instance, specific organization behaviors can be simulated hundreds of times—such as through Monte Carlo techniques—to gain insight into which results are common and expected versus rare and exceptional.

Of course, applying numeric simulation techniques to organizations is hardly new (Law and Kelton, 1991), but this approach enables us to *integrate* the kinds of dynamic, qualitative behaviors emulated by symbolic models with quantitative metrics generated through discrete-event simulation. It is through such integration of qualitative and quantitative models—bolstered by reliance upon sound theory and empiric validation—that our approach diverges most from extant research methods and offers new insight into organization and DMO dynamics.

We summarize the key POWer elements via Table 1 for reference. Most of these elements are discussed below, but this table provides a concise summary. The interested reader can refer to the work by Gateau and colleagues (2007) for details.

Table 1 POWer Elements and Descriptions

Model Element	Element Description
Tasks	Abstract representations of any work that consumes time, is required for project completion and can generate exceptions.
Actors	A person or a group of persons who perform work and process information.
Exceptions	Simulated situations where an actor needs additional information, requires a decision from a supervisor, or discovers an error that needs correcting.
Milestones	Points in a project where major business objectives are accomplished, but such markers neither represent tasks nor entail effort.
Successor links	Define an order in which tasks and milestones occur in a model, but they do not constrain these events to occur in a strict sequence. Tasks can also occur in parallel. POWer offers three types of successor links: finish-start, start-start and finish-finish.
Rework links	Similar to successor links because they connect one task (called the *driver* task) with another (called the *dependent* task). However, rework links also indicate that the dependent task depends on the success of the driver task, and that the project's success is also in some way dependent on this. If the driver fails, some rework time is added to all dependent tasks linked to the driver task by rework links. The volume of rework is then associated with the project error probability settings.
Task assignments	Show which actors are responsible for completing direct and indirect work resulting from a task.
Supervision links	Show which actors supervise which subordinates. In POWer, the supervision structure (also called the exception-handling hierarchy) represents a hierarchy of positions, defining who a subordinate would go to for information or to report an exception.

B. POWER IMPLICATIONS

POWer has been developed directly from Galbraith’s information processing view of organizations. This view of organizations, described in detail by Jin and Levitt (1996), has three key implications.

The first is ontological: we model knowledge work through interactions of *tasks* to be performed, *actors* communicating with one another and performing tasks, and an *organization structure* that defines actors’ roles and constrains their behaviors. Figure 1 illustrates this view of tasks, actors and organization structure. As suggested by the figure, the organization structure ontology is a network of reporting relations, which can capture micro-behaviors such as managerial attention, span of control and empowerment. The task structure ontology is a network of activities, which can capture organization attributes such as expected duration, complexity and required skills. Within the organization structure, we further model various *roles* (e.g., marketing analyst, design engineer, manager), which can capture organization attributes such as skills possessed, levels of experience and task familiarity. Within the task structure, we further model various sequencing constraints, interdependencies and quality/rework loops, which can capture considerable variety in terms of how knowledge work is organized and performed.

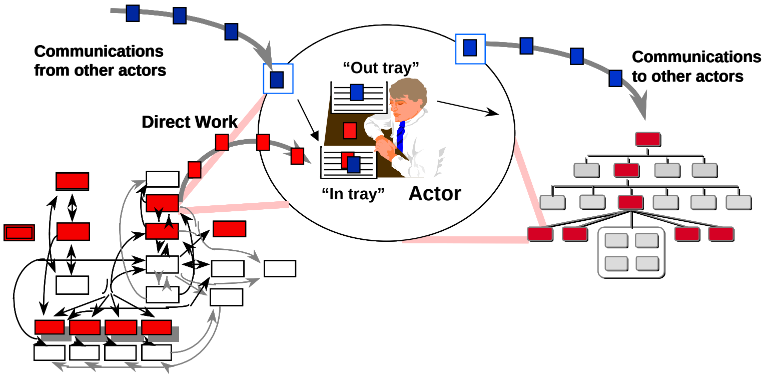

Figure 1 Information Processing View of Knowledge Work

As suggested by the figure also, each actor within the intertwined organization and task structures has a queue of information tasks to be performed (e.g., assigned work activities, messages from other actors, meetings to attend) and a queue of information outputs (e.g., completed work products, communications to other actors, requests for assistance). Each actor processes such tasks according to how well the actor's skill set matches those required for a given activity, the relative priority of the task, the actor's work backlog (i.e., queue length), and how many interruptions divert the actor's attention from the task at hand.

The second implication is computational: *work volume* is modeled in terms of both *direct work* (e.g., planning, design, manufacturing) and *indirect work* (e.g., decision wait time, rework, coordination work). Measuring both direct and indirect work enables the quantitative assessment of (virtual) process performance (e.g., through schedule growth, cost growth, quality degradation).

The third implication is validational: the computational modeling environment has been validated extensively, over a period spanning roughly three decades, by a team of over 30 researchers (Levitt, 2004). This validation process has involved three primary streams of effort: 1) internal validation against micro-social science research findings and against observed micro-behaviors in real-world organizations, 2) external validation against the predictions of macro-theory and against the observed macro-experience of real-world organizations, and 3) model cross-docking experiments against the predictions of other computational models with the same input data sets (Levitt et al., 2005). As such, ours is one of the few, implemented, computational organization modeling environments that has been subjected to such a thorough, multi-method trajectory of validation.

Further, in addition to the broad and general validation noted here, as noted above, POWer has been adapted specifically to the military domain (Looney & Nissen, 2006) and employed effectively on many occasions (e.g., see Nissen, 2007; Gateau et al., 2007; Koons et al., 2008; Oros & Nissen, 2010). This provides a powerful capability to model and analyze military organizations, environments and contexts such as DMO.

C. POWER MODEL EXAMPLE

As an example, Figure 2 depicts a screenshot of the POWer computational environment that was used to model a US Military joint task force (JTF) at a relatively high level (e.g., see Gateau et al., 2007). The organization structure is represented by the light (green) person icons at the top of the figure. These correspond to the top three hierarchical levels of the JTF. There are clearly many levels below these that remain obscured in this abstracted model. The task structure is represented by light (yellow) rectangle icons, which are interconnected by dark (black) precedence, medium (red) feedback and other (colored) links. The dark (blue) links interconnect organization actors with their tasks (i.e., depicting job assignments), and the medium (purple) trapezoid box at the top represents the set of standing meetings (e.g., Commander’s Brief) that occur routinely. Similarly colored (purple) links indicate which actors are required to participate in such meetings.

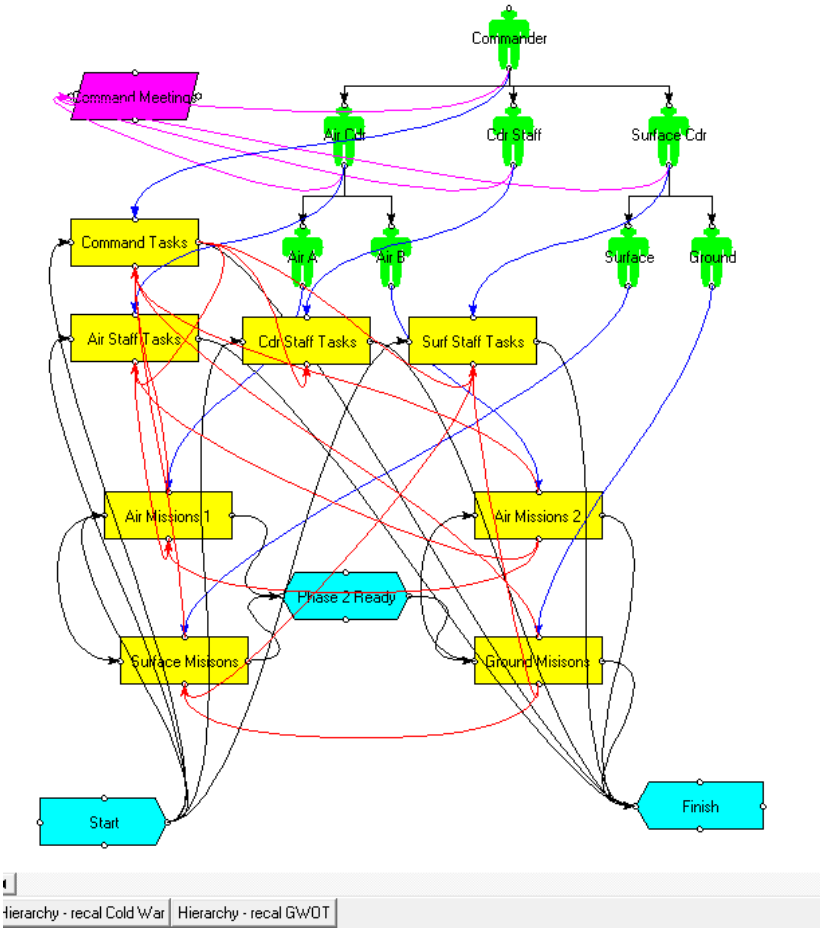

Figure 2 POWer Model Screenshot

Behind this graphic interface lies the sophisticated modeling and simulation facility of POWer, complete with many dozens of model parameters that can be set to specify a diversity of different organizations and environments. Clearly our DMO models may look somewhat different than the JTF representation depicted in the screenshot, but a major aspect of our modeling approach entails specifying such models in terms of the organization and task structures; their associated links; precedence, feedback, job-assignment and meeting links; and the many model parameters required to represent faithfully the structure and behavior of DMO organizations and environments in the field.

III. RESEARCH METHOD

A. METHOD SUMMARY

We employ the method of computational experimentation to conduct this research project, and we use the POWer modeling and simulation environment described above for such purpose. Like laboratory or field experimentation, computational experiments are designed in advance and conducted with precise controls and theoretically driven manipulations. The key difference is that computational experiments enable *complete control* over variables and constants—hence incredible internal validity—and they permit *unlimited and exact replication*. This supplies experimentation power unavailable through other methods.

Alternatively, computational experimentation does not provide the same level of external validity available through laboratory and especially field experiments. Thus, computational experimentation can be viewed best as a complement to its laboratory and field counterparts. Indeed, viewing research as a *trajectory* of experimentation, one can begin prudently with computational experiments—through which hundreds or even thousands of experiments can be conducted—and then select a relatively small number of highly promising conditions and results to take into the physical laboratory—which is costlier and more time-consuming but offers greater external validity. From there, in turn, one or two exceptionally promising experiments can be taken into the field—which is still more costly and time-consuming but offers even greater external validity. With a skillful experimentation trajectory such as this, the best results can be integrated in turn into the organization.

In short, we employ POWer to develop a computational model that represents our DMO organization, technology and environment, and we analyze maritime operations at sea to specify such model. This is accomplished deliberately in two stages, with the corresponding research planned as a multiyear project.

1. First Stage

The first stage described in our previous report (Nissen & Gallup, 2019) focuses on establishing a computational environment suitable for DMO modeling, simulation and analysis. In this first effort, we model, simulate and analyze maritime operations as they are conducted today, with a particular focus on both manned and unmanned aircraft intelligence, surveillance and reconnaissance (ISR) missions. This establishes a baseline for comparison with one or more, alternate DMO organizations conducting ISR missions. It also establishes a baseline for comparison with other missions (e.g., strike, air defense, surface warfare). The second stage then proceeds to model, simulate and analyze one or more, alternate DMO organizations.

2. Second Stage

The second stage builds upon its baseline predecessor to specify and analyze ISR in a DMO environment. The corresponding research method is comprised of four tasks:

1. Research the academic, doctrinal and professional literatures to understand the current state of the art and future trajectories in terms of unmanned systems and DMO.
2. Adapt the computational model POWer to characterize the DMO structure, behavior and performance of as they operate, in limited form, today.
3. Simulate the comparative structure, behavior and performance of alternate approaches to C2, UxS technology and DMO.
4. Work with project sponsors to draft an outline for the kinds of decisions, specifications and training modifications that will be needed to guide DMO over the next ten years.

Recapitulating the work accomplished previously (Nissen & Gallup, 2019), in the balance of this section we first summarize our computational experiment, then we outline the specification and tailoring of the POWer computational environment, followed by a summary of independent and dependent variables. We proceed in turn to specify the computational models used for comparison with DMO.

B. COMPUTATIONAL EXPERIMENT DESIGN

Our focal AS domain in this study centers on the use of multiple, manned and unmanned aerial vehicles (UAVs) in an operational military context; that is, different aircraft are employed in a potentially hostile environment. More specifically, we focus on aircraft employed onboard one or more ships underway at sea. Both manned and unmanned aircraft are capable of conducting missions at sea, and manned-unmanned aircraft interactions appear to be particularly interesting, problematic and challenging in terms of DMO, both as combatants and sensors.

In this particular study, we concentrate on manned and unmanned aircraft that conduct ISR missions, which require searching for, identifying, tracking and relaying real-time information regarding vessels and like items of interest in the open ocean. Future studies can address the combatant role more specifically, and they can work to integrate combatant-sensor roles more closely.

Aircraft under investigation in this study must take off from ships underway at sea, navigate to their operating areas, conduct ISR operations, and then return to ship without exhausting their fuel. Weather and other conditions permitting, the aircraft operate 24 x 7 x 365, and we set the nominal duration of an ISR mission at approximately 24 hours in this research scenario. Where a particular aircraft type is unable to stay aloft for a whole day's mission, the organization must plan and operate a succession of aircraft sorties to replace one another on station until the mission is complete. We discuss these and like details in greater depth below.

The focal organization in this study is a representative but generic Task Force, to which we refer as "CTF" (Task Force). Within the CTF organization we have multiple representative but generic Task Groups, to which we refer as "CTG" (Task Group; e.g., CTG-1, CTG-2, CTG-n). Within the particular CTG organization of focus in this study (i.e., CTG-1), we have multiple representative but generic platform organizations, including "CVW-1" (Air Wing), "DDG-1" (Destroyer 1) and "DDG-2" (Destroyer 2). It important to note that these refer to (in some cases large) organizations of people, not the commanders alone[2].

Additionally, within each of these platform organizations, we have representative but generic operators. Specifically, within CVW-1, we include two F-18 jets ("F18-1" and "F18-2") and two MH-60 helicopters ("H60-1c" and "H60-2c"; the "c" refers to carrier based helos), along with four UAVs ("L4-1," "L4-2," "L5-1" and "L5-2") all based on the carrier. Within DDG-1, we include two MH-60 helicopters ("H60-1d" and

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[2] We are familiar with the various warfare commanders (e.g., Air Warfare Commander [AW]) with prominent roles in task force organizations today. However, we wish to focus on the platforms (esp. ships and aircraft) and the corresponding organizations and people who operate them.

"H60-2d"; the "d" refers to DDG-1 based helos) and two ScanEagles ("SE-1" and "SE-2"). Within DDG-2, we include two MH-60 helicopters ("H60-1l" and "H60-2l"; the "l" refers to DDG-2 based helos) and two FireScouts ("FS-1" and "FS-2"). Beyond the CTG organization, we also include two Tritons among assets controlled at the CTF level ("TR-1" and "TR-2"). We diagram and discuss this organization structure in greater detail below, but this provides the high level perspective reflected in Figure 3.

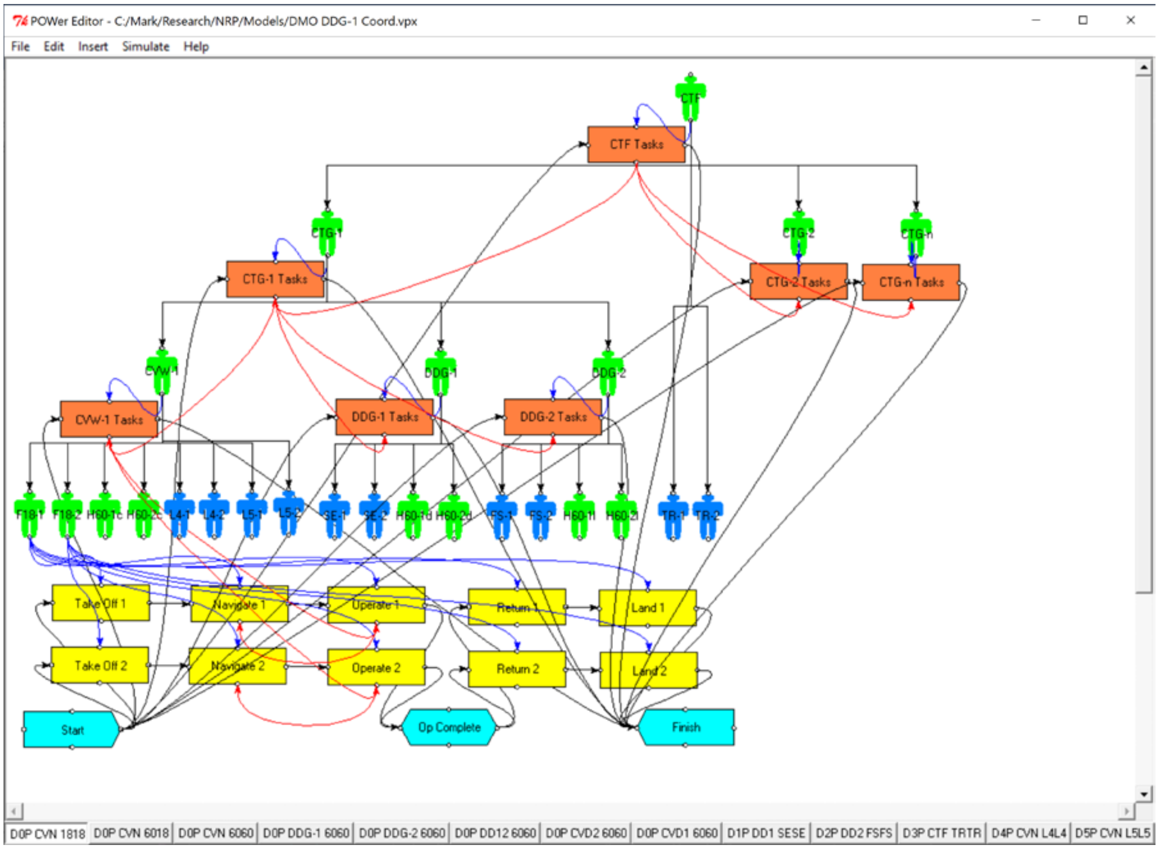

Figure 3 Representative and Generic Organization

Further, we utilize a two dimensional framework to examine a range of increasingly complex employment characteristics. These two dimensions include *autonomy* and *interdependence*. On the autonomy dimension we account for the technologic sophistication of the UAVs (Degree 0 – 5); on the interdependence dimension we account for the interdependence between multiple aircraft in concurrent operation (pooled, sequential, reciprocal, integrated), including both manned-only, unmanned-only and integrated manned-unmanned missions. We discuss each in turn.

1. Autonomy

Numerous frameworks have been developed to address and create taxonomies for autonomy (Martin et al., 2019). For several instances, the autonomy scale created for the Uninhabited Combat Air Vehicle program consisted of four levels, and that created for the Army's now-defunct Future Combat Systems program consisted of ten levels (Committee on Autonomous Vehicles in Support of Naval Operations, 2005). A 2013 RAND study for the Navy employed a scale with seven levels (Savitz et al., 2013). Prior to this work, Thomas Sheridan advocated an autonomy scale consisting of ten levels along with proposing four dimensions (i.e., information acquisition, information analysis, decision selection, action implementation) for evaluation (Sheridan, 2002). The Committee on Autonomous Vehicles in Support of Naval Operations proposed looking at levels of mission autonomy, incorporating two degrees of freedom (i.e., mission complexity, degree of automation; Committee on Autonomous Vehicles in Support of Naval Operations, 2005). The National Institute of Standards and Technology developed its generic Autonomy Levels for Unmanned Systems framework encompassing three degrees of freedom (i.e., human independence, mission complexity, environmental difficulty; Huang, 2008).

Informed by but dissatisfied with the plethora of complicated, incomplete and incompatible frameworks outlined above, which do not support the TASP context well, the six autonomy degrees employed in this study derive from the domain of autonomous automobiles and are discussed in part by the National Highway Traffic Safety Administration (Fisher, 2013). This autonomy framework is relatively straightforward yet covers a substantial range of autonomy, and it accounts for tasks accomplished by both humans and machines, which aligns very well with our focus. Here we outline first the five degrees for autonomous automobiles, then we map such degrees to the UAV domain.

Briefly, in the autonomous automobile domain, Degree 0 corresponds to no autonomy; the car must be controlled continuously by a person in the driver's seat. Degree 1 corresponds to incorporation of standard safety features (e.g., antilock brake system [ABS], electronic stability system [ESS], adaptive cruise control [ACC]) that assist the driver with one specific aspect of controlling a vehicle. Degree 2 corresponds to two or more Degree 1 capabilities (e.g., automatic lane centering and adaptive cruise control) that integrate to enable a car to drive itself to a limited extent (e.g., within one particular lane of a specific road; person in driver's seat ready to take control at any time). Degree 3 corresponds to incorporation of an autopilot, which enables the car to change lanes and roads to reach a predetermined destination, but the driver must stay engaged and ready to resume control if the car gets confused or into a situation beyond its capability. Degree 4 corresponds to a car that can start and complete an entire trip without human engagement (e.g., no driver or passengers; no one in driver's seat). We also include Degree 5, which is not part of the NHTSA scheme but is useful to differentiate between two progressive degrees of AS capability as summarized below.

Mapping this loosely to the UAV domain, an important difference centers on the plural nature of autonomy. With autonomous cars, on the one side, the driving itself represents the key autonomous activity. With UAVs, alternatively, autonomous flying is clearly an important activity, but many of the aerial vehicles in our context are employed for ISR, and they carry a diversity of "payload" sensors (e.g., electro-optical, infrared, radar), which must be directed and controlled. Indeed, in several respects autonomous flight represents the simpler activity, with autonomous payload control constituting the more difficult undertaking, particularly in a tactical setting. We integrate these two activities for UAVs in Table 2.

Degree 0 describes a (manned) aircraft that must be controlled continuously and locally by a person in the cockpit; this represents a relatively direct mapping from the automobile domain to its UAV counterpart. Additionally, one or more people in the cockpit must control the ISR sensors manually. An example could include missions flown in F/A-18 jets or MH-60 helicopters. Degree 1 describes an aircraft (e.g., UAV) that can be controlled continuously by a remote person (no one in the cockpit). This manual control applies to both flight and sensor operation. An example could include missions flown with ScanEagle[3] UAVs.

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[3] Remote manual control is an option, but not required.

Table 2 Cross-Domain Autonomy Degree Mapping

Degree	Automobile	UAV
0	No autonomy; continuous human control	Manned aircraft; continuous local control of flight and sensor operation (F/A-18, MH-60)
1	Safety features (ABS, ESS, ACC)	Remote manual control of flight and sensor operation (ScanEagle)
2	Limited autonomous driving (lane control)	Preprogrammed flight; remote manual control of sensor operation (FireScout)
3	Autopilot (lane & road changes)	Preprogrammed flight and sensor operation based on senior level tasking (Triton or Global Hawk)
4	Full autonomy; human driver not required	Autonomous decisions and flight and sensor operation (Future capability) fall short of manned system capability & performance
5	n/a	Autonomous systems match or outperform manned system capability & performance (Future capability)

Degree 2 represents a departure from those above and describes a UAV that can fly without continuous human control (e.g., via preprogrammed navigation), albeit with a human ready to take (remote) control when deemed necessary. Alternatively, the sensor payload must be controlled manually by remote. An example could include missions flown with FireScout UAVs. Degree 3 describes in turn a UAV that can both fly and operate sensors without continuous human control (e.g., via preprogrammed navigation and payload tasking). An example could include missions flown with the Triton or Global Hawk. As suggested via the examples, each of these degrees is represented by aircraft and technologies in use today.

In contrast, Degree 4 describes a UAV that can both fly and operate sensors without continuous human control, but in addition to capabilities included in Degree 3, such aircraft do not require preprogramming (with the exception of initial mission tasking); they can determine their own flight paths, identify their own sensor targets, and operate their own payloads on the fly (esp. with artificial intelligence). At the time of this writing, such UAVs represent future capabilities. For experimentation purposes, we define Degree 4 systems as falling short of manned system capability and performance, however.

Alternatively, Degree 5 extends to match or exceed the capability and performance achievable through manned aircraft systems. In other words, both Degree 4 and 5 systems represent future capabilities that enable autonomous flight and sensor operation; the former are unable to match the capability and performance of manned systems, whereas the latter are able to meet or surpass manned aircraft capability and performance.

For each manned and unmanned aircraft identified to correspond with the six autonomy degrees summarized above, we conduct both archival and field research to specify computational models in a manner that mirrors physical aircraft behavior and performance through the corresponding models. For reference, Appendix A – Section A summarizes performance characteristics (e.g., *endurance, crew, cost per flight hour, required sorties, cost per head*) for each of the seven types of aircraft examined in this study (i.e., F/A-18, MH-60, ScanEagle, FireScout, Triton, Level 4 & Level 5 UAVs).

2. Interdependence

The interdependence dimension derives from Organization Theory (Thompson, 1967). It characterizes the intensity of interactions and behaviors within an organization. At its most basic, pooled interdependence describes how different units of an organization (e.g., different departments, groups, functions) can each contribute to the overall operation and success of the organization but without direct interaction with one another. An organization’s legal department and its building maintenance unit, for instance, reflect pooled interdependence as such: they both contribute to the same organization’s overall operation and success, but the legal and maintenance units do not interact with one another commonly. Coordination between units characterized by pooled interdependence is minimal and accomplished through rules and standards generally, for each unit operates independently.

Sequential interdependence subsumes its pooled counterpart but incorporates the additional interactions associated with one unit in the organization producing outputs necessary for subsequent performance by another unit. An organization’s engineering and manufacturing units, for instance, reflect sequential interdependence as such: the designs developed within the engineering unit are used as inputs to the products built within the manufacturing unit. Coordination between units characterized by sequential interdependence is more intensive and accomplished via plans and schedules generally.

Reciprocal interdependence subsumes its pooled and sequential counterparts but incorporates the additional interactions associated with two units working simultaneously on a common task. A surgeon and nurse operating on a patient, for instance, reflect reciprocal interdependence as such: the surgeon and nurse must perform certain tasks simultaneously, even switching some common tasks over time, and neither surgeon nor nurse can anticipate all possible outcomes or issues that might emerge through surgery (e.g., they must observe and communicate together, and they must react and adjust jointly as the surgery progresses). Coordination between units characterized by reciprocal interdependence is highly intensive and accomplished via recurring feedback and mutual adjustment generally.

We include the integrated interdependence type also—although it extends the organization theory summarized above—to characterize two different *organizations* that work together in manners reflecting reciprocal interdependence. Hence, beyond having two different units *within* the same organization performing reciprocally (e.g., as described above), such units must do so *across* different organizations, for example in a joint project where neither organization is solely "in charge" of the whole effort; many strategic partnerships, joint spinoffs and complex endeavors, for several instances, reflect this property (e.g., see Alberts & Hayes, 2003).

In the UAV domain, pooled interdependence refers to two or more, different aircraft—manned *or* unmanned—that contribute to the overall operation and success of the organization but without direct interaction with one another. Say that two different aircraft perform surveillance missions in separate geographical areas. The surveillance from both aircraft is useful to the organization, but neither aircraft interacts with the other. Coordination can be via specific deconfliction rules, for instance, that prohibit two aircraft from flying in the same airspace at the same time.

Sequential interdependence refers to two or more, different aircraft that share pooled interdependence but also depend upon one another over time. Say that one aircraft performs a surveillance mission and provides targeting information for a different aircraft. Coordination can be via air plans, for instance, that schedule the second aircraft to fly after receiving useful targeting information from the first one.

Reciprocal interdependence refers to two or more, different aircraft that share pooled and sequential interdependence but must also work simultaneously on a common task. Say that two—manned *or* unmanned—aircraft are required to defend one another if either is attacked, or consider two different aircraft conducting surveillance, together, in common airspace. Coordination requires frequent communication between the aircraft, for instance, and both must adjust their actions depending upon circumstances.

Integrated interdependence refers to reciprocally interdependent missions with both manned and unmanned aircraft "organizations" flying and working together toward a common objective. Say that two—manned *and* unmanned—aircraft from different squadrons are required to defend one another if either is attacked, or consider such different aircraft conducting surveillance, together, in common airspace. Coordination entails all of the aspects associated with reciprocal interdependence, but they must take place across both manned and unmanned aircraft (e.g., squadrons). Table 3 summarizes this interdependence scheme for the UAV domain.

Table 3 Interdependence Level Summary

Interdependence Level	Mission Characteristics
Pooled	Aircraft performing surveillance missions in different geographic areas
Sequential	Surveillance from one aircraft provides surveillance or targeting information for another
Reciprocal	Manned OR unmanned aircraft work together in common airspace
Integrated	Manned AND unmanned aircraft work together in common airspace

3. Experiment Conditions

With these two dimensions, we can consider—in a systematic and orderly manner—a 6x4 matrix of increasingly complex DMO baseline contexts, which comprise collectively our set of experiment conditions. We summarize this context matrix in Table 4. At the one extreme, we consider two manned aircraft that are deployed in separate geographical regions of controlled airspace (e.g., within the vicinity of its host ship) or in the same geographical region but at different times. This corresponds to Degree 0 autonomy with pooled interdependence (i.e., labeled "D0P" in the table).

Table 4 Computational Experiment Design Summary

Degree\Interdependence	Pooled	Sequential	Reciprocal	Integrated
Degree 0	D0P	D0S	D0R	D0I
Degree 1	D1P	D1S	D1R	D1I
Degree 2	D2P	D2S	D2R	D2I
Degree 3	D3P	D3S	D3R	D3I
Degree 4	D4P	D4S	D4R	D4I
Degree 5	D5P	D5S	D5R	D5I

At the other extreme, we consider a squadron of completely autonomous, Level 5 UAVs and a squadron of manned aircraft flying integrated missions in uncontrolled airspace. This corresponds to a group of Degree 5 UAVs reflecting both reciprocal interdependence among themselves and integrated interdependence with their manned aircraft counterparts (i.e., labeled "D5I" in the table). Each of the key intermediate conditions (i.e., Degree 0 to Degree 5 autonomy, across all four interdependence conditions) is examined systematically also for completeness. This matrix summarizes our computational experiment design.

As described in greater detail below, each of these 24 experiment design cells is represented by a separate computational model, which is simulated 50 times, across eight performance dimensions, to create a substantial performance space for analysis. In our previous study (Nissen & Gallup, 2019), we examined each of these 24 test cases in terms of *extant* maritime aircraft ISR missions. This established a rich baseline for comparison. Alternatively, in the present study, we examine only a subset of the experiment design cells: those involving Degree 0 autonomy (i.e., manned missions) and pooled interdependence (i.e., separate airspace-time). This represents the most critical subset in terms of understanding DMO implications, and the results are highly illuminating. Future studies can push to examine higher autonomy degrees and interdependence levels.

C. POWER SPECIFICATION AND TAILORING

As noted above, POWer is designed and validated to represent and simulate the structures and behaviors of organizations in a manner that supports computational experiments. Such design and validation focus on *people* in the organization that use many different kinds of tools, machines and other technologies to perform work. To the extent that our maritime ISR context centers on people using aircraft, communication and other technologies to accomplish work, the POWer computational environment serves us very well, for as noted in the introduction, we have adapted it for and validated it in the military domain previously (e.g., see Looney & Nissen, 2006; Nissen, 2007; Gateau et al., 2007; Koons et al., 2008; Oros & Nissen, 2010).

For instance, all of the conditions reflecting Degree 0 and 1 sophistication (i.e., across all interdependence cases) appear to be well within extant POWer capability, and one can argue that those reflecting Degree 2 and 3 sophistication are within such capability too, for humans remain in charge of machines and are ready to retake control at any time. This is not much different than a human operating a machine that is capable of performing a limited set of actions on its own but that requires human input and attention to perform the complete set.

Air traffic controllers (ATCs), as one example, use sophisticated radar, computer and communication technologies to keep track of and manage myriad aircraft flying through their assigned regions of airspace. Although many such technologies can operate independently (e.g., automatic radar position tracking)—and the aircraft themselves are capable of flying without ATC or pilot input—the ATC remains in charge of the airspace and is ready to control the aircraft’s position at any time (esp. in case of potential collision or emergency).

Another example, albeit somewhat trivial, pertains to the exceedingly common case of a person using a washing machine to clean laundry. Once loaded with laundry and detergent, and set for the desired water level and temperature, the washing machine can complete the cleaning cycle without human intervention. Nonetheless, few washing machines can load or unload themselves, and the human must at least monitor the machine in case it gets off balance or manifests some other issue. POWer can model these and like cases well in its present condition.

Further, we consider Degree 4 and 5 UAVs and other AS to behave in manners that are consistent with the behaviors of *people* (esp. their human counterparts) in our maritime ISR context. Degree 4 UAVs behave consistently with, and their Degree 5 counterparts further match (or exceed) the capability and performance of, comparable manned systems. Indeed, most extant AS are designed to emulate human behaviors, and the more sophisticated the AS, the more closely its behavior mirrors that of human counterparts. However, people and machines possess different characteristics and capabilities (e.g., machines excel at consistency, memory, processing power, endurance; people excel at judgment, innovation, adaptation and working with uncertainty), and understanding their relative behaviors in the maritime ISR context demonstrates both the novelty and potential of our present line of research.

D. SUMMARY OF CONTROLS, MANIPULATIONS AND MEASURES

Here we summarize the controls, manipulations and measures used in our computational experiments. The POWer computational environment has roughly 100 model variables and parameters that can be set and manipulated across different values and levels. Also, the models themselves can be set up in many different ways—as delineated via the model screenshots in the sections below—but the set of key variables and parameters associated with maritime ISR models along the lines of those developed and analyzed in this investigation numbers roughly 30.

1. Controls

Appendix A – Section B summarizes the model task specifications, which refer to POWer model parameter settings related to the tasks that actors perform within the organization. Such tasks include those required for operational leadership, decision making and staff work at various levels of the organization (i.e., CTF, CTG, CVW, DDG-1 and DDG-2 organizations), along with those performed by aircrews themselves (e.g., Take Off, Navigate, Operate). Principal task parameters include *type, effort, skill, requirements complexity, solution complexity, uncertainty* and *rework*. The set of tasks examined through this study is held constant throughout all experiment conditions; that is, the exact same set of ISR mission tasks is conducted by every aircraft type, at every autonomy degree and across every interdependence level. Hence model tasks—and their corresponding parameter settings—serve as one set of *controls* in our computational experiment. For instance, the simulated ISR mission has a *planned* duration[4] set at 24 hours, and this planned duration is constant across all experiment cells.

Appendix A – Section C summarizes the model staffing specifications, which refer to POWer model parameter settings related to the organization actors that perform tasks. The model includes 12 actor positions, five at the command/staff level (i.e., CTF, CTG, CVW, DDG-1, DDG-2) and one for each aircrew corresponding to our seven aircraft types (i.e., F/A-18, MH-60, ScanEagle, FireScout, Triton, Level 4 & Level 5 UAVs). Principal organization staffing parameters include *position, level, role, application experience, culture experience, full time equivalent, salary* and *skill*. The set of staffing positions examined through this study is held largely constant throughout all experiment conditions; that is—with two exceptions (i.e., *role, application experience*)—the exact same organization and staff conduct missions across every aircraft type, autonomy degree and interdependence level. Hence model staffing—and the corresponding parameter settings—serve as another set of *controls* in our computational experiment. For instance, the simulated ISR mission is conducted by exactly two aircraft, and this number of aircraft is constant across all experiment cells.

Appendix A – Section D summarizes baseline model parameters, which serve to further specify the DMO model. Most of these parameters are subject to manipulation across experiment conditions, and hence are summarized below, but *functional exception probability, mission exception probability, mission priority, work day* and *work week* are all held constant across conditions and serve therefore as additional controls; that is, the level for each of these parameters is constant across all experiment cells.

2. Manipulations

Alternatively, Appendix A – Section E summarizes the model parameters subject to manipulation: *team experience, centralization, formalization, matrix strength, communication probability, noise probability, role* and *application experience*. These are

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[4] Planned mission duration does not necessarily correspond to the amount of time actually required for successful mission performance, however. Missions that progress relatively smoothly (e.g., with few interruptions or mistakes) may be completed within the planned duration, whereas those that encounter problems may require (much) longer to complete successfully, and *actual mission duration* represents an important performance measure, which we examine expressly through the computational experiments discussed below.

all manipulated expressly to specify each POWer model across our set of 24 experiment conditions.

3. Measures

Finally, Appendix A – Section F summarizes the eight model measures: *duration, rework, coordination, wait, work cost, functional risk, mission risk* and *maximum backlog*. These measures enable us to gauge maritime ISR performance robustly through multiple dimensions.

E. DMO BASELINE MODEL

We begin by specifying the DMO baseline (i.e., DM0P) model. This represents an extension of the baseline D0P model developed previously to depict ISR as it is conducted today. Drawing from our previous work (Nissen & Gallup, 2019), we first summarize the current baseline. Then we discuss how to adapt it to represent the DMO environment.

1. Baseline Current Model (D0P)

Regarding how ISR missions are organized and conducted currently, Figure 4 delineates a screenshot of our baseline CTG organization and platform set. This is the same organization outlined above and delineated via Figure 3. The light (green) person icons represent organizations at four levels (i.e., CTF, CTG, Platform [e.g., DDG-1, DDG-2], Aircraft Operators [e.g., F/A-18, MH-60]). The dark (brown) rectangle icons represent operational leadership, decision making and staff work in addition to common tasks (e.g., planning, maintenance, air traffic control), whereas the light (yellow) rectangle icons represent the aircraft ISR mission tasks; each aircraft must take off, navigate to its area of interest, operate in ISR mode, and then return to the ship for landing or recovery. Organizations and tasks are represented at appropriate levels: sufficiently low to capture the important structural and behavioral dynamics, but sufficiently high to abstract away details that do not impact the results in terms of maritime ISR.

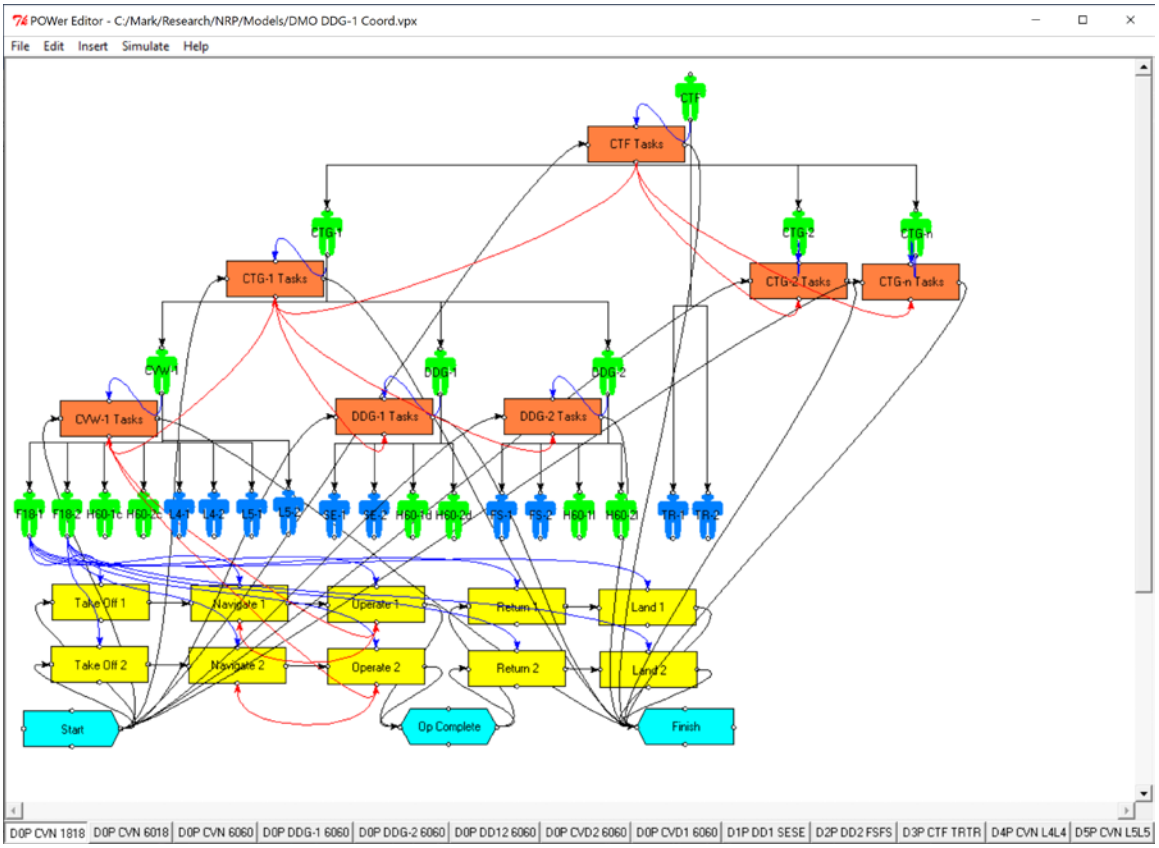

Figure 4 Baseline Model (D0P) – CVN F/A-18s

At the lowest level in the organization lies an array of diverse manned (light/green) and unmanned (dark/blue) aircraft. F/A-18s (Degree 0) are assigned to the CVN. MH-60s (Degree 0) are assigned to the DDGs as well as the CVN. ScanEagles (Degree 1) are assigned to DDG-1, and FireScouts (Degree 2) are assigned to DDG-2. Tritons (Degree 3) are examined as an asset from beyond the CTG itself (e.g., controlled by the CTF), and we examine two future AS (Degree 4 & 5 UAVs) principally in terms of CVN assignment here[5].

The many lines linking various icons in the figure are used to symbolize organization hierarchy, job assignment, task precedence, communication and other important model relations. For instance, the (dark/red) links connecting the Operate and Navigate tasks denote *rework*; if the Operate task fails to produce satisfactory ISR results

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[5] Understanding that the corresponding Degree 4 and 5 technology has yet to be fielded and developed, respectively, these UAVs could be either fixed or rotary wing (or both), and hence could potentially operate effectively from the CVN and other ship platforms (esp. DDGs).

(e.g., a promising contact is not located, insufficient intelligence is gathered, sensor data cannot be relayed), then the aircraft may have to Navigate to some other region and Operate there. The interested reader can refer to Gateau and colleagues (2007) for detailed explanations for all key model links and parameters.

In the baseline screenshot above, two (manned) F/A-18s are assigned to fly ISR missions in separate airspaces (i.e., D0P: Degree 0 autonomy, pooled interdependence). This task assignment is evident from the five (dark/blue) links between each F/A-18 actor and the aircraft ISR mission tasks (e.g., Take Off, Navigate, Operate); the first actor (labeled “F18-1” in the figure) is assigned to the upper sequence of tasks (e.g., labeled “Take Off 1,” “Navigate 1,” “Operate 1”), and the second actor (labeled “F18-2” in the figure) is assigned to the lower sequence of tasks (e.g., labeled “Take Off 2,” “Navigate 2,” “Operate 2”). Here both (manned) aircraft are assigned to the same (CVN) platform and (CVW) organization, and each flies in a different region of airspace (pooled interdependence). This represents a very common and relatively straightforward maritime ISR context.

As noted above, the simulated ISR mission has a *planned* duration[6] set at 24 hours. For aircraft such as the F/A-18s depicted in this model, such nominal 24 hour duration exceeds the endurance of a single aircraft sortie, so a sequence of sorties must be planned to span the whole 24 hour period, and sorties may have to continue beyond 24 hours in order to accomplish all mission objectives. We consider each aircraft’s performance characteristics (esp. endurance) when specifying the computational model, and we record each aircraft’s simulated performance level (e.g., actual mission duration) in the computational experiment. Refer to Appendix A for model specification details.

The MH-60 represents another Degree 0 (manned) aircraft, so we also model and examine the baseline (D0P) case with missions conducted by two helicopters for comparison. This is depicted in the screenshot of Figure 5. As above, this task assignment is evident from the five (dark/blue) links between each MH-60 actor and the aircraft ISR mission tasks (e.g., Take Off, Navigate, Operate). Here both (manned) aircraft are assigned to the same (CVN) platform and (CVW) organization, and each flies in a

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[6] Not all missions are equally effective, however, so some may take less than 24 hours to accomplish all ISR objectives successfully, whereas other may require (much) more time to complete.

different region of airspace. This represents another very common and relatively straightforward maritime ISR context.

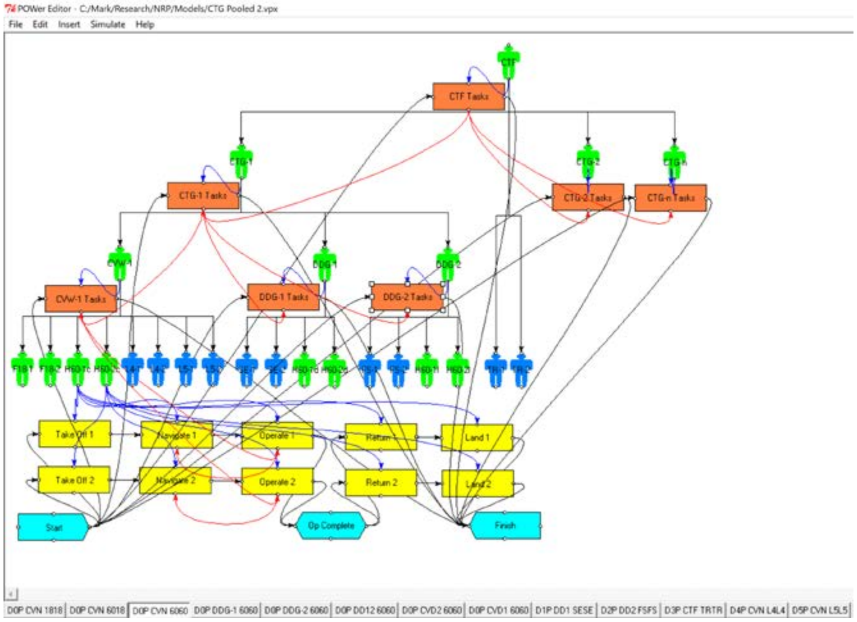

Figure 5 Baseline Model (D0P) – CVN MH-60s

As one would expect, two different kinds of aircraft can fly ISR missions in separate regions of airspace as well. For instance, we further model and examine the baseline (D0P) case with missions conducted by two, different, manned aircraft (i.e., one F/A-18 and one MH-60). This is depicted in the screenshot of Figure 6. As above, this task assignment is evident from the five (dark/blue) links between each actor (i.e., F/A-18 & MH-60) and the aircraft ISR mission tasks (e.g., Take Off-1, Navigate-1, Operate-1, Take Off-2, Navigate-2, Operate-2). Here both (manned) aircraft are assigned to the same (CVN) platform and (CVW) organization (albeit different squadrons), and each flies in a different region of airspace. This represents another relatively straightforward maritime ISR context, but it draws in actors from different squadrons, and it requires coordinating and controlling two different types of aircraft (e.g., fixed wing jet and rotary wing helo).

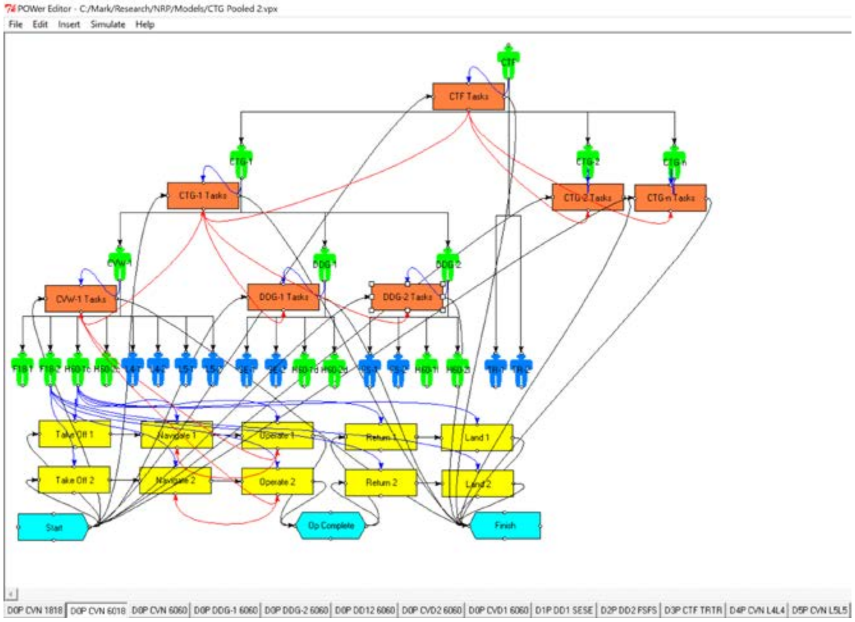

Figure 6 Baseline Model (D0P) – CVN F/A-18 & MH-60

Further, suitably capable aircraft can conduct these same missions from other ships as well. MH-60s, for instance, can operate from the DDGs. The screenshot in Figure 7 delineates two helos operating from DDG-1.

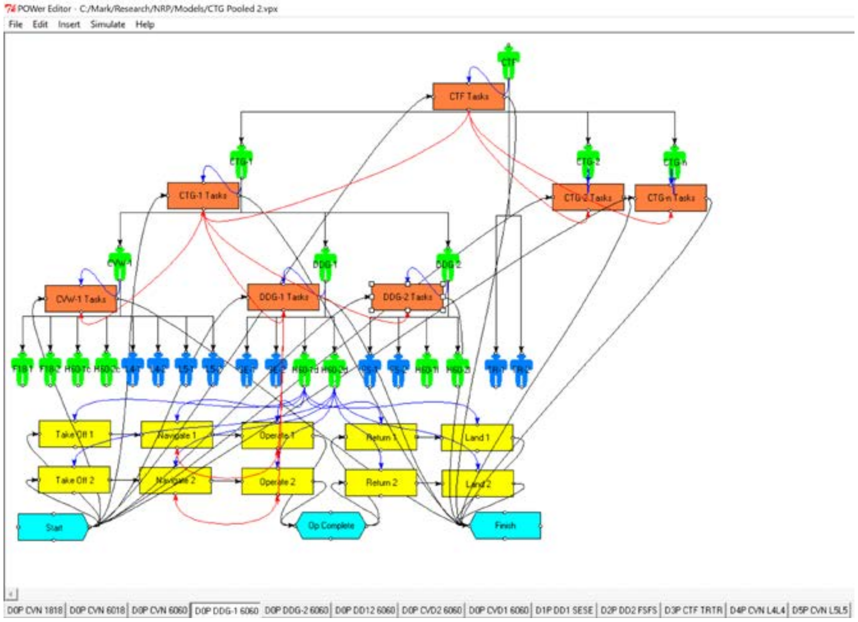

Figure 7 Baseline Model (D0P) – DDG-1 MH-60s

Still further, suitably capable aircraft can operate simultaneously from different ships. For instance, Figure 8 reflects a screenshot of the model representing one MH-60 helicopter conducting its ISR mission from DDG-1 and another conducting its mission (in separate airspace) from DDG-2. In some contrast to the previous models—where aircraft were from the same ship—here we have aircraft performing the ISR missions from two different DDGs. Despite the pooled interdependence (esp. flying in different airspace-times), some additional coordination between ships is implied (e.g., which ship's aircraft will fly in which airspace-time). Such additional coordination is represented in the model via green communication links between the two destroyers, which impose some extra coordination load on the organizations. Other combinations (e.g., CVN-DDG-1, CVN-DDG-2; not shown) are modeled and simulated too for completeness.

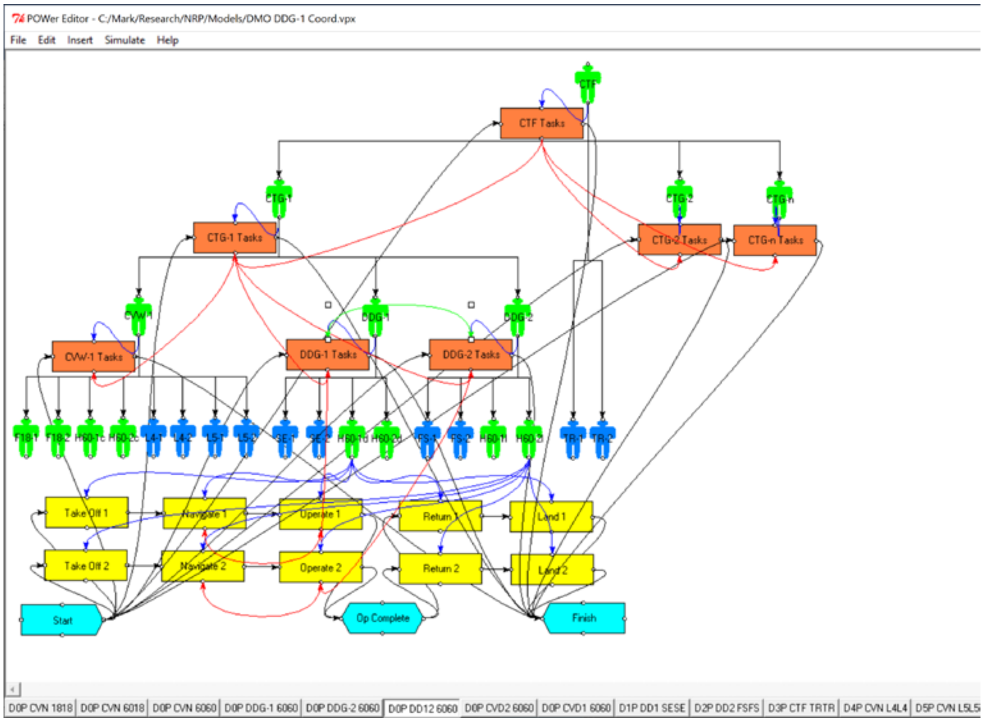

Figure 8 Baseline Model (D0P) – DDG-1 MH-60 & DDG-2 MH-60

Hence our D0P experiment condition includes eight[7] different models. Each such model depicts Degree 0 autonomy (i.e., manned aircraft) and pooled interdependence

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[7] Technically additional models can be envisioned also. For instance, an F/A-18 can operate from the carrier, and a MH-60 can operate from either or both of the DDGs. As another instance, multiple (manned) aircraft types can operate from multiple ship platforms. Our eight models provide adequate coverage of organization and platform variations, so we do not endeavor to model exhaustively here.

(i.e., separate airspace), but the eight models vary as the ISR mission is conducted by different types of aircraft (i.e., F/A-18, MH-60) from various platforms (i.e., CVN, DDG-1, DDG-2). To limit confusion, each of these “D0P” models includes additional information to identify the specific ships and aircraft involved. For several instances, “D0P CVN 1818” refers to the (pooled interdependence) ISR mission being conducted by two (Degree 0) F/A-18 aircraft from the CVN; “D0P CVN 6018” refers to the ISR mission being conducted by one MH-60 and one F/A-18 aircraft from the CVN; “D0P CVN 6060” refers to the ISR mission being conducted by two MH-60 aircraft from the CVN; and so forth; We summarize these eight models in Table 5.

Table 5 D0P Model Summary

Label	Ships	Aircraft
D0P CVN 1818	CVN	F/A-18, F/A-18
D0P CVN 6018	CVN	MH-60, F/A-18
D0P CVN 6060	CVN	MH-60, MH-60
D0P DDG-1 6060	DDG-1	MH-60, MH-60
D0P DDG-2 6060	DDG-2	MH-60, MH-60
D0P DD12 6060	DDG-1, DDG-2	MH-60, MH-60
D0P CVD2 6060	CVN, DDG-2	MH-60, MH-60
D0P CVD1 6060	CVN, DDG-1	MH-60, MH-60

2. DM0P Adaptation

Here we discuss how to adapt the contemporary baseline model above to reflect the DMO environment. Drawing heavily from *A Design for Maintaining Maritime Superiority 2.0* (Richardson, 2018) and *Surface Force Strategy* (Rowden, 2016), we note several important aspects of DMO. From the former, four lines of effort (LOEs) are important to consider: 1) strengthen naval power at and from the sea; 2) achieve high velocity outcomes, 3) strengthen our Navy team for the future; and 4) expand and strengthen our network of partners.

The first and second LOEs are most relevant to this project. LOE 1 includes a direct call for DMO and for realistic testing through Large Scale Exercise (LSE) 2020. This call informs and motivates directly, but LSE 2020 has been postponed due to the

COVID pandemic. LOE 2 includes a call to design and implement a comprehensive operational architecture to support DMO. Such architecture includes a tactical grid to connect distributed nodes; data storage, processing power, and technology stacks at the nodes; an overarching data strategy; and analytic tools such as artificial intelligence/machine learning (AI/ML), and services that support fast, sound decisions.

From the latter, the concept *distributed lethality* helps to flesh out DMO with some important detail. It is achieved by increasing the offensive and defensive capability of individual warships, employing them in dispersed formations across a wide expanse of geography, and generating distributed fires with resources for persistence. Several aspects of such detail are important for our DMO modeling effort. First, by increasing the offensive and defensive capability of individual warships, ships should improve their ability to break off from the relatively current large formations that comprise the carrier centric strike group (CSG) and task group (CTG).

Indeed, this represents the central thrust behind employing ships in dispersed formations across a wide expanse of geography: the *distributed* aspect of DMO. Turning to other DMO documents that we do not cite or reference here (esp. due to classification), the strategy envisions, for instance, how one or more destroyers (DDGs), cruisers (CGs) or submarines (SSNs) may break away from the larger formation (e.g., CTG) for auxiliary, subordinate or other missions, perhaps in geographically distant regions. This would clearly distribute lethality, but it would also leave the CTG more vulnerable. It imposes a command and control (C2) burden too, as the breakaway ships may be beyond range of communications employed routinely for CTG C2. This C2 burden provides a predominate focus of the current research project.

Further, generating distributed fires with resources for persistence represent important aspects of DMO as well. By distributing fires, many different targets can be engaged across a geographically dispersed region that is potentially one or more orders of magnitude broader than possible with the centralized CTG formation, even with the carrier air wing. This expands greatly the metaphoric footprint of the CTG. Moreover, providing resources for persistence implies that ships are able to fight through battle damage and sustain operations in a degraded C2 environment. This degraded C2 environment provides a second predominate focus of the current research project.

Additionally, although not necessarily a centerpiece of the DMO strategy and guidance noted above, human-unmanned teaming is clearly very important, and as such represents the central focus of this current research project. For instance, one novel and emerging approach involves the lightly manned autonomous combat capability (LMACC). Referred to also as the next generation Corvette, LMACC represents a comparatively small, inexpensive, lightly manned, highly autonomous, missile carrier class of ship designed for offensive strike missions far from centralized CTGs, CSGs and like ship formations. Together with a small group of autonomous surface and subsurface vessels under its control, the LMACC could span considerable geographic area—well beyond the safe distance that carriers and like high value ships must maintain from certain land and sea based missiles and like threats—and employ myriad diverse sensing, deception and offensive capabilities in support of the Corvette mission. This represents an exciting, novel, surface and subsurface warfare capability, one to be studied in depth on the next phase of this research project stream.

Alternatively, here we continue with our prior focus on human-machine *aircraft* teaming, including our prior emphasis on the ISR mission, for which the baseline POWer models have been developed and employed. In order to address DMO, we consider that one or more ships in a CTG formation are assigned geographically remote missions, bringing their unmanned aircraft systems (UAS) with them. Many different configurations can be envisioned and modeled, but we describe one for illustration. A follow on study can examine all possible configurations.

Specifically, here we characterize a DMO instance by designating one of the destroyers to break off from the CTG and conduct a different, geographically separate mission. The two destroyers are modeled as identical in capability, except for the UAVs aboard: in addition to MH-60s, DDG-1 carries two ScanEagles, and DDG-2 carries two FireScouts. Since the ScanEagle represents a Degree 1 system, we model DDG-1 as the breakaway ship here. As above, a subsequent study can examine all combinations.

Figure 9 reflects a screenshot of this model. Notice how the DDG-1 platform is shown as detached from CTG-1. For illustration, we position the destroyer far away from the CTG in the diagram, as we wish to emphasize its geographic separation. Notice also how this destroyer is linked directly to the CTF here (i.e., via black supervision link) instead of CTG-1. This represents a situation in which the CTG gives up control over the asset during the period that the breakaway DDG remains apart from the group. Further, we delineate (i.e., via red rework link) how DDG-1 is influenced directly by the CTF instead of indirectly via CTG-1, and we include a new (green) communication link directly between DDG-1 and the CTF to reflect an increase in coordination between them. Likewise, with DDG-1 breaking away from the CTG, we also include new communication links directly between the remaining CTG organizations (i.e., CTG-1, CVW-1, DDG-2), as additional coordination will be required for DDG-2 to pick up the extra work left behind by DDG-1. All other links and interrelationships remain unchanged.

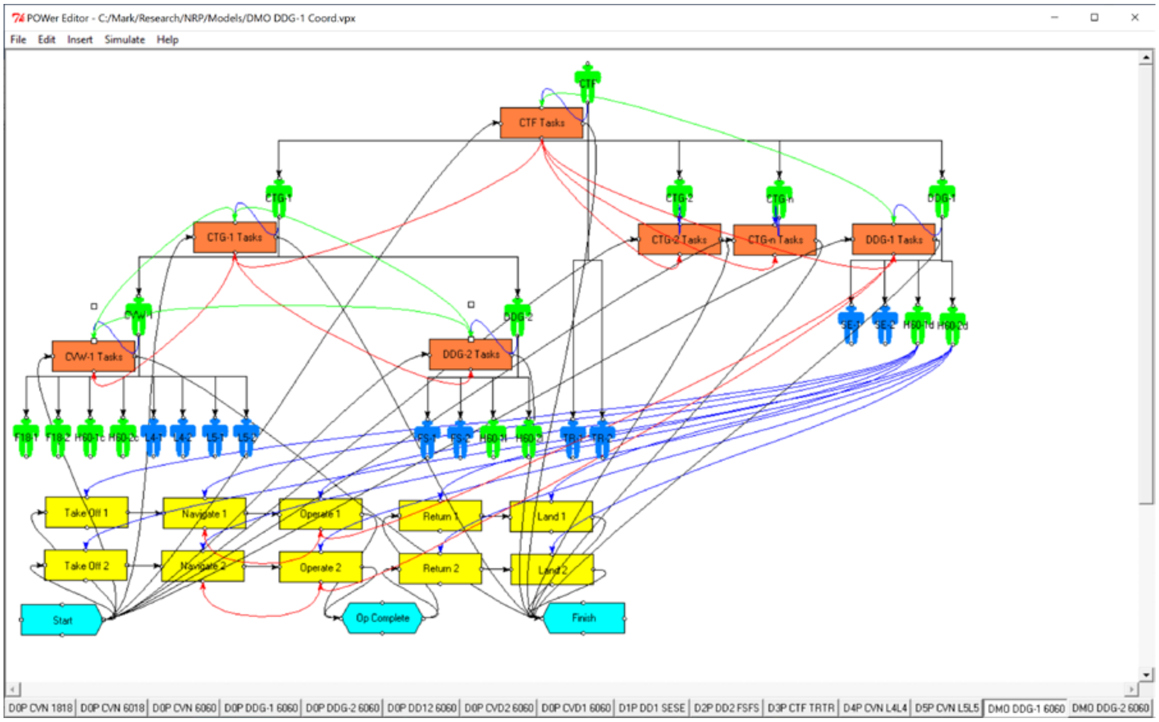

Figure 9 DMO DDG-1

Within the model, however, a number of parameters change with this DMO scenario, for at present this configuration diverges from the routine in multiple ways: CTG-1 is required to accomplish its same mission without support from DDG-1. This adds particular complexity and stress to DDG-2, but the group as a whole faces greater complexity and becomes more stressed[8]. Also, CTF gains direct responsibility for DDG-1, which adds some complexity and coordination cost at the JTF level[9]. Finally, DDG-1 is required to operate under different conditions than those customary in its usual CTG role, which adds complexity and novelty to the destroyer[10]. All other model parameters remain unchanged, and we examine the same nominal ISR mission for DDG-2[11] across these different contexts[12] (i.e., first with DDG-1 as a part of CTG-1, then with DDG-1 broken away under CTF control).

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[8] We represent this by increasing values of four model parameters associated with DDG-2 Tasks: Priority, Requirement Complexity, Solution Complexity and Uncertainty all increment from the level Medium to High. The same applies to the CTG. We also reduce Application Experience for DDG-2 and the CTG from the level Medium to Low. This reflects the nonroutine nature of the DDG-1 breakaway mission and the additional burden on DDG-2 and the CTG.

[9] We represent this by incrementing CTF Uncertainty from the level Medium to High.

[10] We represent this by increasing values of four model parameters associated with DDG-1 Tasks: Priority, Requirement Complexity, Solution Complexity and Uncertainty all increment from the level Medium to High. The same applies to the CTG. We also reduce Application Experience for DDG-1 from the level Medium to Low. This reflects the nonroutine nature of the DDG-1 breakaway mission and the additional burden on DDG-2 and the CTG.

[11] The focus here is on the impact to the JTF of DDG-1 breaking away for some other mission via DMO configuration. We examine such impact with DDG-2 performing its ISR mission while DDG-1 performs its missions, first as part of the CTG, then as a breakaway asset under DMO.

[12] As a very minor point, to help reduce clutter in the diagram, we do not show the (blue) task assignment links from DDG-2 to its helos, yet we include all DDG-2 efforts in the simulation runs.

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IV. RESULTS

For each simulation, the model is run 50 times to examine varying conditions via Monte Carlo techniques. Table 6 summarizes the simulation results. The first column lists seven key performance measures: *duration, rework, coordination, wait, functional risk, mission risk* and *maximum backlog* (see Appendix A – Section F for details). The second column lists JTF performance results in the baseline scenario of both destroyers participating in CTG-1. The third column lists such results for the DMO configuration.

Table 6 Simulation Results

Result	**CTG** (D0P DDG-2 6060)	**DMO** (DMO DDG-2 6060)
Duration (hours)	30.4	38.6
Rework (P-hours)	64.3	66.0
Coordination (P-hours)	14.4	15.8
Wait (P-hours)	12.4	12.2
Functional Risk (%)	39	40
Mission Risk (%)	37	37
Max Backlog (hours)	1.7	8.4

To summarize briefly, duration (measured in hours[13]) represents the total clock or calendar time required to complete a mission. In the CTG configuration, 30.4 hours are required to complete the ISR mission. Duration increases to 38.6 hours in the DMO configuration. We attribute the increase to the additional tasks that DDG-2 is required to take on while DDG-1 breaks away from the CTG. Such attribution is common across all performance measures, and the simulation is capturing effectively the increased stress, complexity and effort of the DMO configuration.

Rework (measured in person-hours or P-hours) represents the amount of effort expended on correcting mistakes for the CTG (64.3) and DMO (66.0) configurations. Coordination (measured in P-hours) represents the amount of effort expended on coordinating mission activities for the CTG (14.4) and DMO (15.8) configurations. In this model, rework and coordination pertain to leadership and staff work (e.g., at the

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[13] To accommodate the POWer model calibration, these simulations calculate all measurements as factors of 10. For instance, the 30.4 CTG duration value shown in Table 6 is calculated as 304 in the model. This technical detail does not impact our results, as we use this same calculation across all models and simulation runs, and only the *comparative* results are important to the study.

CTF, CTG and ship levels). Given the challenges of DMO, one would expect to see this additional rework and coordination.

Wait (measured in P-hours) represents the amount of effort expended while awaiting information or direction. Wait time stems from the operational work required to complete the ISR missions from DDG-2. Wait time is nearly the same in the CTG (12.4) and DMO (12.2) configurations. Performing the familiar ISR mission is not impacted appreciably by DMO.

Functional risk (measured as a percentage) represents the fraction of effort required to address residual functional (esp. skill based) mistakes that are left unattended. The CTG value (39%) indicates that an additional 39% of total mission effort would be required to address all mistakes that have been left unattended. Clearly a higher number of unattended mistakes increases the risk of a serious issue arising. The DMO value (40%) in nearly the same, suggesting that DMO does not pose a serious risk increase to the familiar ISR functional performance. Likewise, mission risk (measured as a percentage) represents the fraction of effort required to address residual mission (esp. coordination) mistakes that are left unattended. The CTG and DMO values (37%) are identical, suggesting the same interpretation: DMO does not pose a serious risk increase to the familiar ISR mission performance.

Finally, maximum backlog (measured in hours) represents the amount of effort required to address tasks ready for accomplishment. Think of this as the backlog of tasks that need to be accomplished in terms of an eight hour day. The CTG value (1.7) suggests that everyone is busy but not overwhelmed, as the maximum backlog can be addressed in less than two hours. Every organization in the CTF has its backlog measured throughout the simulation, and we report here only the maximum backlog for the organization that experiences the highest level. In this case, the DDG-2 organization got furthest behind in terms of workload. In contrast, the DMO value (8.4) reveals that the CTG-1 organization got over a whole day (8 hours) behind at one point (i.e., about two thirds of the way through the mission).

Although not shown in the table, the DDG-1 (6 hours) and DDG-2 (7 hours) organizations experience substantial backlogs also, albeit a bit earlier (i.e., about half way through the mission). Higher backlogs can lead to increased rework, coordination and wait time, as important information is not disseminated and key decisions are not made in time. Such backlogs can also increase both functional and mission risk, as well as duration. These results suggest that mission duration, rework and coordination are impacted the most, but overall, the DMO mission does not present serious issues *for the familiar ISR mission assigned to DDG-2*.

Alternatively, these results do not address the breakaway DMO mission performed under CTF control of DDG-1. We also model and simulate a comparable and familiar ISR mission assigned to DDG-1, but the results do not differ appreciably from those reported and discussed above. The key reason is that the ISR mission—especially conducted entirely from a single ship platform (i.e., DDG-1 *or* DDG-2)—is highly familiar and routine. This is the case in particular with the Degree 0 air vehicles (i.e., MH-60s) conducting missions under conditions of pooled interdependence (i.e., separate airspace-times).

Simulations of the ISR mission conducted with higher degrees of autonomy (e.g., Degree 1-5) and levels of interdependence (e.g., Reciprocal or Integrated) would largely follow the results of our previous study (Nissen & Gallup, 2019), with one major exception: with DDG-1 detached from the CTG and conducting its missions from far away geographically, the JTF is limited in its ability to integrate such detached destroyer into CTG missions and operations.

For instance, consider one MH-60 from DDG-1 attempting to conduct an ISR or other mission with an MH-60 from DDG-2 or another ship: the large geographical separation could make operations in common airspace-time infeasible. Alternatively, the CTG has other air assets onboard the carrier, so this problem does not appear to impact the JTF severely. As noted above, the most challenging aspects of DMO appear to pertain to DDG-2 picking up the extra effort left behind by DDG-1 as it breaks away from the CTG and the additional coordination required within the CTG and the JTF.

One interesting idea for a future study would be to model and simulate one or more alternate missions beyond the ISR examined through the present project. Any number of such alternate missions (e.g., air defense, surface defense, submarine defense, ballistic missile defense, strike) could potentially be modeled and simulated, and the results would likely both complement and reinforce the impacts of DMO on JTF operations presented here. We leave this interesting idea for future work and discuss it further at the end of our conclusion section.

V. CONCLUSION

The technologic capabilities of autonomous systems (AS) continue to accelerate, and teams of autonomous systems and people (TASP) are becoming increasingly important, particularly where distributed maritime operations (DMO) are concerned. Computational experimentation offers unmatched yet largely unexplored potential to address DMO research questions, and we employ the POWer computational environment to model and simulate DMO organizations and phenomena.

This POWer environment represents the state of the art in terms of organization modeling and simulation. Extensive empiric validation projects have demonstrated the representational fidelity and shown how the qualitative and quantitative behaviors of our computational models correspond closely with a diversity of enterprise processes in practice. Further, POWer has been adapted specifically to the military domain and employed effectively on many occasions. This provides a powerful capability to model and analyze military organizations, environments and contexts such as DMO.

After reviewing background information regarding computational modeling via POWer, we outline the research method centered on computational experimentation, which supports incredible internal validity and supplies experimentation power unavailable through other methods. The first stage described in our previous report focuses on establishing a computational environment suitable for DMO modeling, simulation and analysis. In this first effort, we model, simulate and analyze maritime operations as they are conducted today, with a particular focus on both manned and unmanned aircraft intelligence, surveillance and reconnaissance (ISR) missions. This establishes a baseline for comparison with one or more, alternate DMO organizations conducting ISR missions. It also establishes a baseline for comparison with other missions (e.g., strike, air defense, surface warfare).

The second stage builds upon its predecessor baseline to specify and analyze ISR in a DMO environment. Essentially we adapt the contemporary baseline model above to reflect the DMO environment. Such adaptation considers lines of effort (LOEs) from *A Design for Maintaining Maritime Superiority 2.0* and the concept *distributed lethality* from *Surface Force Strategy* to flesh out DMO with some important detail. We diverge briefly from our aircraft ISR mission focus to discuss the lightly manned autonomous combat capability (LMACC), which offers considerable potential as a comparatively small, inexpensive, lightly manned, highly autonomous, missile carrier class of ship designed for offensive strike missions far from centralized CTGs, CSGs and like ship formations.

However, the center thrust of our model adaptation for DMO vectors to human-machine *aircraft* ISR teaming, for which the baseline POWer models noted above have been developed and employed. In order to address DMO, we consider that one or more ships in a CTG formation are assigned geographically remote missions, bringing their unmanned aircraft systems (UAS) with them. Specifically, we characterize a DMO instance by designating one of the destroyers to break off from the CTG and conduct a different, geographically separate mission.

This represents a situation in which the CTG gives up control over the asset during the period that the breakaway DDG remains apart from the group. This involves some novel coordination, in addition to considerable complexity and stress for the CTG that is required to accomplish its same mission without support from the breakaway destroyer. After detailing the POWer model changes employed to represent this DMO configuration, we examine comparative CTG performance through simulation of the same ISR mission via current and DMO configurations.

For each simulation, the model is run 50 times to examine varying conditions via Monte Carlo techniques, and comparative performance is gauged via seven key performance measures: *duration, rework, coordination, wait, functional risk, mission risk* and *maximum backlog*. Succinctly, the DMO configuration increases ISR mission duration by nearly 25%, and it adds to both the rework of mistakes and coordination load within the CTG. Alternatively, shifting to DMO has negligible effect on wait time, functional or mission risk.

Maximum backlog, however, increases roughly fourfold, as requirements aboard the carrier and both destroyers pile up. Higher backlogs can lead to increased rework, coordination and wait time, as important information is not disseminated and key decisions are not made in time. Such backlogs can also increase both functional and mission risk, as well as duration. These results suggest that mission duration, rework and coordination are impacted the most, but overall, the DMO mission does not present serious issues *for the familiar ISR mission assigned to DDG-2*.

Thus, we provide some novel insight and unique quantification of DMO impacts to the CTG stemming from a breakaway destroyer in the context of a manned ISR mission. Through examination of the areas of increased complexity and stress—in addition to the most affected mission performance measures (esp. duration, rework, coordination and backlog)—experienced people can begin to assess the root causes and start outlining approaches to obviate or at least mitigate performance degradation.

Toward this end, we offer three suggestions. First, complexity and uncertainty are higher in a DMO configuration than the CTG baseline, and organization experience is necessarily considerably less as well. These combine to complicate and stress the mission. One key approach to obviation or at least mitigation is practice: realistic testing through Large Scale Exercise (LSE) should be made a priority.

Second, the increased complexity and stress faced by a CTG in DMO configuration may be eased somewhat through anticipation and augmented staffing. Several additional people may be added across the key CTG ships (esp. the carrier and destroyers) to step in and assist in DMO specific ways whenever one or more ships break away for geographically and organizationally separate missions.

Third, technology can play a key role also. The more that ships, commands and crews can understand their situations; receive and utilize timely, actionable knowledge and information; and coordination their activities across ships, times and locations; the better their individual and collective performance will become. This requires a robust, reliable and extensible network that can perform well under conditions of degraded communication (e.g., sans satellites) as well as ideal conditions. We have the basics of such network today, along with plans for enhancement over time, but more is needed, and we need to practice under degraded as well as ideal conditions.

As with every study, this one involves several limitations and offers suggestions for productive future research along these lines. In terms of limitations, clearly we are examining DMO via modeling and simulation. Despite the extensive internal and external validation—and Navy tailoring—associated with POWer, simulations are not the same as manned (and unmanned) ships and aircraft at sea, so we must accept some inherent bias and inaccuracy in the results. Nonetheless, simulation provides us with the ability to examine myriad different configurations, very quickly, without the time and expense required to tax busy people onboard ships at sea. Particularly as a campaign of research, we can identify the most promising configurations that emerge through simulation—thus mitigating the need to expensive and time consuming trial and error at sea—and then examine *only the most promising* via ships at sea. This represents a very exciting proposition.

Additional limitations pertain to the focus of this study on the familiar, manned, ISR mission under conditions of pooled interdependence. This present study does not examine the use of unmanned vehicles or interdependence conditions beyond pooled (esp. reciprocal or integrated), nor does it consider missions beyond ISR. Every investigation must begin somewhere, and no study can take on too many different variables, factors, conditions and considerations, lest it become unwieldy. Rather, the nature of science is incremental: each successive study builds upon the ones before and adds some unique knowledge and insight. Here we illustrate an accepted DMO configuration—where one destroyer breaks away from the CTG to perform a geographically distributed mission under CTF control—and we both quantify and discuss the key implications. This represents a substantial step forward.

Moreover, the additional “limitations” from above highlight opportunities for productive future research along these lines. One or more follow on studies, for several instances, can examine this same DMO configuration but with a mix of manned and unmanned vehicles (e.g., Degree 0 through 5 autonomy), under conditions of reciprocal and integrated interdependence, to delve into the details of manned-unmanned teaming for DMO. Incorporating manned and unmanned surface and subservice vehicles (e.g., LMACC) into the configuration offers potential to expand the analysis considerably, as does the adaptation to consider strike and other missions beyond ISR. These represent exciting future research studies, ones that offer great potential to inform our DMO thinking. All we need is time, talent and funding to complete them.

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VII. APPENDIX A

In this appendix we include detailed model specifications for reference from our previous study (Nissen & Gallup. 2019). Details pertain in sequence to A) aircraft performance characteristics, B) model task specifications, C) model staffing specifications, D) baseline model parameters, E) model manipulations, and F) performance measures. These model specifications serve as something of a Rosetta Stone: they translate the physical and operational aspects of ISR aircraft missions conducted by military organizations into parameters and values needed to drive POWer computational modeling and experimentation.

In many cases, physical and operational variables and values can be input directly into POWer (e.g., aircraft cost per flight hour), but in other cases, characteristics that are observable in the physical world (e.g., relative skill of unmanned aircraft controllers with respect to manned aircraft pilots) must be matched with one or more corresponding POWer parameters (e.g., Aviation Skill) and set at appropriate levels (e.g., Medium for manned missions, Low for unmanned missions).

Where POWer parameter levels have been established generally across many models, we stay with such levels unless driven in a compelling way otherwise; most POWer parameter settings at Medium, for instance, reflect this approach. This enables us to benefit from the many empirical validation projects that POWer and its predecessors have undergone, and it gives us considerable confidence that the organization structures and behaviors modeled here represent faithfully those of their corresponding real-world organizations operating in the field.

There is ample room for discussion and argument regarding the precise values used for modeling. Nonetheless, where the same values are held constant across computational models and corresponding simulation runs, the exact *level* specified for each parameter becomes somewhat irrelevant: the *relative* performance across experiment conditions is of greatest interest in this study. We welcome other researchers to specify and run the models using alternate parameter settings, as sensitivity analysis along such lines will help to build confidence in the models.

A. AIRCRAFT PERFORMANCE CHARACTERISTICS

Performance characteristics of the seven aircraft types are summarized in Table 7. Briefly, *endurance* represents the flight time (in hours) expected for each aircraft type. For instance, we list the F/A-18 at 1.5 hours; this value is not exact but should be about the right level in comparison with the other aircraft types. *Crew* represents the number of flight personnel onboard (manned) or involved with operating (unmanned) aircraft. For instance, we show the Navy F/A-18 with its single pilot; this value should be appropriate for most ISR missions. *CFH* represents the rough cost per flight hour ($k) associated with each aircraft. For instance, the F/A-18 CFH is listed at $10k; this value is approximate. *Sorties* represents the number of sorties required for each aircraft type to perform a nominal 24 hour ISR mission. For instance, we list the F/A-18 at 16 sorties; this value is simply the number of nominal mission hours (24 hours) divided by aircraft endurance (1.5 hours). Finally, *CPH* represents cost per head ($k) and reflects a value input into the computational model for each flight crew member; it is subject to the same limitations as noted for *CFH* above, considering, for instance, several of the other performance characteristics listed here.

Table 7 Aircraft Performance Characteristics

Type	Endurance	Crew	CFH ($k)	Sorties	CPH ($k)
F/A-18	1.5 hrs	1	10.0	16	15.0
MH-60	4.0 hrs	3	4.0	6	5.3
FireScout	4.0 hrs	3	3.0	6	4.0
ScanEagle	24.0 hrs	1	0.5	1	12.0
Triton	24.0 hrs	3	1.5	1	12.0
L4	24.0 hrs	1	0.5	1	12.0
L5	24.0 hrs	1	0.5	1	12.0

Values for the F/A-18 and MH-60 reflect relatively well-known performance data. We have less confidence in values for the FireScout, which has not been in service for very long. The same applies to the Triton, the values for which come principally from limited Global Hawk experience. ScanEagle estimates are our own and intended only to reflect the right order of magnitude. The L4 and L5 (i.e., Degree 4 and 5) UAV values simply mirror those estimated for the ScanEagle. **Cost values are included only for very rough comparison *across experiment conditions,* and absolute values should not be considered official or used for decision making**.

B. MODEL TASK SPECIFICATIONS

Task specifications refer to POWer model parameter settings related to the tasks that actors perform within the organization. The parameter names and settings are technical, specific to the POWer computational environment, and probably not interesting to non-modelers. We include them here nonetheless for completeness and for reference. These parameter settings pertain to the baseline (pooled) level of interdependence and remain constant across all experiment manipulations. We list them in Table 8.

Table 8 Baseline Model Task Specifications

Task	**Type**	**Effort**	**Skill**	**Rcmplx**	**Scmplx**	**Uncert**	**Rework**
CTFs	Duration	150d	Generic	Medium	Medium	Medium	0.30
CTGs	Duration	150d	Generic	Medium	Medium	Medium	0.30
CVWs	Duration	120d	Air	Medium	Medium	Medium	0.10
DDG-1s	Duration	120d	Air	Medium	Medium	Medium	0.10
DDG-2s	Duration	120d	Air	Medium	Medium	Medium	0.10
TO	Duration	10d	Air	Low	Low	Low	0.10
Nav	Duration	30d	Air	Low	Low	Low	0.10
Op	Duration	120d	Air	Medium	Medium	Medium	0.10
RTB	Duration	30d	Air	Low	Low	Low	0.10
Land	Duration	10d	Air	Low	Low	Low	0.10

The first five tasks represent operational leadership, decision making and staff work in addition to common tasks (e.g., planning, maintenance, air traffic control) at various levels of the organization. The first two rows reflect such tasks at the CTF and CTG levels, respectively, with the next three reflecting like tasks for the carrier air wing (CVW), destroyer (DDG-1) and littoral combat ship (DDG-2) organizations. These include the kinds of planning, organizing, decision making, commanding, controlling, maintenance and like tasks conducted onboard various ships underway at sea.

Type represents a POWer parameter for the kind of work involved; here we specify *Duration* (in model days[14]), with *Effort* reflecting the model parameter level input for each task. All actors have Generic skill, which corresponds to *Skill* required for the first two tasks. Most other tasks in this table require Air skill (e.g., aviation knowledge) also. *Rcmplx* and *Scmplx* represent requirements complexity and solution complexity, respectively, of the tasks; parameter values range from Low to High, with settings at Medium[15] unless compelling reasons suggest otherwise. *Uncert* represents the uncertainty level; the same comment applies pertaining to settings at Medium. Finally, *Rework* reflects the strength of rework links emanating from the tasks; this represents roughly the amount (expressed as a fraction of the original work affected) of effort required to handle exceptions and correct mistakes.

The remaining tasks represent operations flight work performed by aircrew members, and they follow the natural sortie process: take off or launch (TO), navigate to the operating area (Nav), conduct ISR on site (Op), return to the ship (RTB), and land or recover (Land). Their durations are set nominally to represent approximately 20 hours. All of these aircrew tasks require Air skill, reflect High priority, and are set with 0.10 rework strength. With the exception of Operate, they all reflect Low complexity and uncertainty; the Medium levels set for Operate adjust for the relative difficulties associated with finding, following, sensing and analyzing ISR targets once on station.

C. MODEL STAFFING SPECIFICATIONS

Staffing specifications refer to POWer model parameter settings related to the organization actors that perform tasks. The parameter names and settings are technical, specific to the POWer computational environment, and probably not interesting to non-modelers. We include them here nonetheless for completeness and for reference. These

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[14] POWer is designed to represent organization behavior and performance over relatively long periods of time. Because our simulated ISR mission is specified at a nominal 24 hours, we manipulate the POWer model to preserve its fidelity on such relatively short duration. To translate the model's pure output values into mission performance levels, one can simply divide mission time by 10. Thus, an input duration of 150 days would represent approximately 15 hours' mission time, during which the corresponding actors would be engaged actively. Hence these values include time for rest, meals, shift and watch changes, equipment maintenance and downtime, and like factors associated with everyday work.

[15] Most ordinal parameters are set nominally at Medium throughout POWer. This establishes and maintains a stable baseline for comparison across various models and runs.

parameter settings pertain to the baseline (pooled) level of interdependence. Some of them vary across experiment conditions as summarized in Table 9.

Table 9 Baseline Model Staff Specifications

Position	**Level**	**Role**	**AXp**	**CXp**	**FTE**	**Sal**	**Skill**
CTF	4	PM	Medium	Medium	1	0	G(M)
CTG	3	PM	Medium	Medium	1	0	G(M)
CVW	2	PM	Medium	Medium	1	0	A(M)
DDG-1	2	PM	Medium	Medium	1	0	A(M)
DDG-2	2	PM	Medium	Medium	1	0	A(M)
F/A-18	1	SL	High	High	16	15.0	A(M)
MH-60	1	SL	High	High	18	5.3	A(M)
ScanEagle	1	SL	High	Medium	1	12.0	A(L)
FireScout	1	SL	High	Medium	18	4.0	A(L)
Triton	1	SL	High	Medium	3	12.0	A(L)
L4	1	SL	High	High	1	12.0	A(M)
L5	1	SL	High	High	1	12.0	A(H)

The first five positions represent leadership roles, associated command staffs and common tasks performed at various levels of the organization. The first two rows pertain to the CTF and CTG organizations, respectively, with the next three pertaining to the carrier air wing (CVW), destroyer (DDG-1) and littoral combat ship (DDG-2) organizations. These include tasks like planning, organizing, decision making, commanding, controlling, maintenance and like tasks conducted onboard various ships underway at sea.

Level refers to the organization level represented in our model; because we focus on DMO in this model, we include the three highest operational levels[16] of command and staff work (i.e., CTF at Level 4; CTG at Level 3; and CVW, DDG-1 and DDG-2 at Level 2) along with a single level of operations work (i.e., pertaining to each of the various manned and unmanned aircraft flown: F/A-18, MH-60, ScanEagle, FireScout, Triton, and L4 & L5 advanced UAVs). These positions correspond to the command/staff and

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[16] Clearly there are very many rank levels spanning the range from lowest level Seaman (e.g., E3) to JTF Commander (e.g., O9). Abstracting away details that are unnecessary for our examination of TASP C2, however, we find that three levels of command and staff (i.e., Levels 2 – 4) and a single level of operations (i.e., Level 1) roles are sufficient.

operations tasks summarized above; that is, the CTF position (e.g., commander and staff) performs the CTF tasks, the CTG[17] position (e.g., commander and staff) performs the CTG tasks, and so forth.

Role refers to a POWer parameter that characterizes the kind of organization work performed generally (i.e., PM = Project Manager; SL = Subteam Leader; ST = Subteam); this parameter impacts model behaviors such as attention to handling exceptions, correcting mistakes and attending to communications. *AXp* refers to the parameter *application experience*, which reflects how much experience with this or similar kinds of work (e.g., joint task force missions) actors within each role possess. Most roles are specified at Medium unless there is a compelling reason to adjust the parameter setting upward (i.e., High) or downward (i.e., Low). In the case of these command and staff positions, many commanders and staffs rotate between various jobs frequently (e.g., every two to three years), whereas most aircraft operators (esp. manned aircraft pilots) fly the same planes throughout their aviation careers; we apply the same reasoning to unmanned aircraft operators.

The parameter *CXp* refers to culture experience and is specified similarly (e.g., Low/Medium/High, baseline at Medium). We specify this parameter at High for the manned aircraft positions, because they tend to work within a relatively homogeneous organization culture throughout most of their careers. Alternatively, because UAVs remain a comparatively nascent and still emerging organization phenomenon, we do not give the corresponding positions the same credit in terms of culture experience.

FTE refers to full time equivalent, which does not equate to headcount within the command/staff organization but does capture aircrew size. It is a POWer parameter that we combine with *sorties, CFH* and other variables to compare ISR operations costs. *Sal*, for instance, refers to the cost per FTE and incorporates the number of sorties required for a nominal 24 hour ISR mission as discussed above.

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[17] The designator *CTG* obscures the likelihood that a CTF has more than a single CTG in the organization. We label and specify them numerically (i.e., "CTG-1," "CTG-2," "CTG-3," … "CTG-n") in the model, but we show only the generic "CTG" in this table. The same applies to carrier air wings (e.g., CVW-1 – n), destroyers (e.g., DDG-1-1 – n), littoral combat ships (e.g., LCS-1 – n) and other command/staff organizations, as well as operators of the various manned and unmanned aircraft (e.g., F/A-18-1 – n, MH-60-1 – n, ScanEagle-1 – n).

Finally, *Skill* represents the kind and level of skill possessed by actors in each position, with Generic (G) and Air (A) matching the skills required by various tasks as noted above. For instance, the CVW position *possesses* the Air skill (A), and the CVW task *requires* that same Air skill (A), thereby representing a good role-task match and generating competent job performance through the model. All of the command/staff and manned aircraft operator roles are specified with skill levels at Medium, reflecting demonstrably competent performance capabilities, whereas *current* unmanned aircraft operators (i.e., ScanEagle, FireScout, Triton) are specified with Low skill levels, reflecting continued development required to match the proficiency of manned aircraft operators. Alternatively, the *future capability* unmanned aircraft operators are specified at Medium (i.e., L4) and High (i.e., L5) skill, parameterizing our model assumption that future UAVs may be able to match (L4) and even exceed (L5) the capability and performance of their manned aircraft counterparts. This assumption is clearly subject to disagreement, and other modelers are encouraged to substitute alternate assumptions to conduct sensitivity analysis through the model.

D. BASELINE MODEL PARAMETERS

POWer model parameters serve to further specify the DMO model. The parameter names and settings are technical, specific to the POWer computational environment, and probably not interesting to non-modelers. We include them here nonetheless for completeness and for reference. These parameter settings pertain to the baseline (pooled) level of interdependence. Some of them vary across experiment conditions as summarized in Table 10.

Team Experience refers to the amount of time members of work teams have spent performing as a team together; frequent personnel rotation suggests that Medium is appropriate for this parameter setting. *Centralization* refers to the degree to which information flows to and decisions are made by senior leaders; although the Military is highly centralized generally in this regard, particularly in terms of C2, the nature of manned and unmanned ISR missions suggests alternately that much information and many decisions remain with aircraft operators. The same logic applies for *Formalization*, which refers to the formality of work, jobs and communications: highly formal for command/staff organizations but comparatively less formal among aircraft operators while on ISR missions. *Matrix Strength* refers to the degree to which people communicate with peers (High) or attend formal meetings (Low) as a principal source of situational knowledge; as with centralization and formalization, the Medium setting strikes a balance within this DMO organization model[18]. Each of these model parameters ranges from Low to High.

Table 10 Baseline Model Parameters

Parameter	**BL Setting**
Team Experience (Low – High)	Medium
Centralization (Low – High)	Medium
Formalization (Low – High)	Medium
Matrix Strength (Low – High)	Medium
Communication Prob (0.20 – 0.90)	0.20
Noise Prob (0.01 – 0.20)	0.05
Functional Exception Prob (0.05 – 0.10)	0.08
Mission Exception Prob (0.05 – 0.20)	0.10
Mission Priority (Low – High)	Medium
Work Day (s)	480
Work Week (s)	2400

Communication Prob refers to the likelihood that any particular task in the model will require communication with another one; this parameter centers on (green) communication links that appear only with reciprocal and integrated levels of interdependence, with probabilities in the range listed. *Noise Prob* refers to the likelihood that an actor performing a model task will encounter some kind of distraction; interruptions from telephones, radios, unexpected visitors, unplanned task assignments and like distractions are all modeled through this parameter, with probabilities in the range listed.

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[18] As a note, we could build one model for the command/staff part of the organization and another for the operator part, and we would likely specify each such model differently along the lines of these parameters (e.g., *centralization*, *formalization*, *matrix strength*), but it would become more difficult to model the interactions between them, which is central to our interest in understanding TASP C2 better.

Functional Exception Prob refers to the likelihood that a model task will incur an exception or experience an error or mistake of some kind; relatively routine and well-practiced tasks have lower likelihood than their comparatively novel and less-performed counterparts, with probabilities in the range listed. *Mission Exception Prob* is similar but applies at the mission or project as opposed to the task level; the ISR mission is the project in our model, with probabilities in the range listed. *Mission Priority* refers to the relative importance of the mission or project when compared to the range experienced by the modeled organization; conducting or defending against an attack, for instance, would generate High priority very clearly, whereas getting food on the table would generate Low priority. Finally, the parameters *Work Day* and *Work Week* define the length of a typical "day" and "week" within the model, with each measured in seconds (s). The model settings listed in the table reflect ample time for breaks, watch changes, maintenance, repairs, meals and other downtime. They also conform to our comment above regarding how "days" within the POWer model correspond to the nominal 24 hour project length specified for our ISR mission.

E. MODEL MANIPULATIONS

Model manipulations refer to POWer model parameter settings that serve as experiment manipulations, and hence are varied deliberately and systematically across the diverse computational models and simulation runs. The parameter names and settings are technical, specific to the POWer computational environment, and probably not interesting to non-modelers. We include them here nonetheless for completeness and for reference. They are summarized in Table 11. Parameter settings under the "Pooled" column correspond with those listed above and elsewhere as "baseline" values in the model.

Team Experience is discussed above and set at Medium for the baseline (pooled) POWer model. This Medium setting applies to the reciprocal level of interdependence also, but it becomes Low at the integrated level; this reflects the lack of experience that human and machine aircrews have in terms of flying together. *Centralization, Formalization* and *Matrix Strength* are discussed similarly above and set likewise at Medium for the baseline (pooled) POWer model. Each of these parameter settings changes (i.e., to Low, Low, High) for both the reciprocal and integrated models, however, as many more decisions and communications are made locally (esp. between aircraft flying together).

Table 11 Model Manipulations

Parameter	**Pooled**	**Reciprocal**	**Integrated**
Team Experience	Medium	Medium	**Low**
Centralization	Medium	**Low**	**Low**
Formalization	Medium	**Low**	**Low**
Matrix Strength	Medium	**High**	**High**
Comm Prob	0.20	**0.50**	**0.90**
Noise Prob	0.05	0.05	**0.20**
Operator Role	SL	SL	**ST**
Operator AXp	High	**Medium**	**Low**

Communication Prob changes substantially across interdependence levels, ranging from 0.20 in the pooled condition, through 0.50 in reciprocal, to 0.90 in integrated. For reciprocal interdependence, this represents the considerable increase in communication between aircrews flying missions together in common airspace. Additionally for integrated interdependence, manned and unmanned aircrews are flying missions together in common airspace, and considerably more communication is required (esp. between manned and unmanned aircrews). *Noise Prob* is the same across pooled and reciprocal levels of interdependence, for manned aircraft fly only with their manned counterparts, and unmanned fly likewise only with unmanned. The additional distractions and interruptions stemming from integrated manned-unmanned missions account for the increased Noise.

Finally, two parameters associated with (both command/staff and) aircrew staff specifications are manipulated across interdependence levels also. The first pertains to the role. As noted in the baseline staff specifications above, the command/staff roles (e.g., CTF, CTG, CVW) are all set at PM, and the aircraft operator roles (e.g., F/A-18, FireScout, L5) are all set at SL. These same settings apply to reciprocal interdependence as well. In the integrated case, however, the roles change to SL for command/staff and ST for aircrew; this represents the very different organization environment exhibiting integrated manned-unmanned aircraft missions. Likewise with *AXp*, there is likely to be some additional application experience required for ISR missions involving reciprocal interdependence, even more so with the integrated interdependence corresponding to manned-unmanned missions.

F. MODEL MEASURES

Model measures refer to POWer dependent variables employed to gauge, assess and compare DMO behavior and performance across experiment conditions. Among many POWer parameters that can be used as dependent variables, we focus in particular on eight model measures appropriate for our context. These measures are summarized in Table 12.

Table 12 Performance Measures

Measure	**Description**
Duration (hours)	Total clock or calendar time required to complete a mission
Rework (person-hours)	Amount of effort expended on correcting mistakes
Coordination (person-hours)	Amount of effort expended on coordinating mission activities
Wait (person-hours)	Amount of effort expended while awaiting information or direction
Work Cost ($k)	Direct cost of effort expended on mission tasks
Functional Risk (%)	Fraction of effort required to address residual functional mistakes
Mission Risk (%)	Fraction of effort required to address residual mission mistakes
Maximum Backlog (hours)	Amount of effort required to address tasks ready for accomplishment

Briefly, *duration* represents the total clock or calendar time required to complete a mission successfully. It is measured from the time that a mission begins until it is completed successfully. In the case of the nominal 24 hour ISR mission specified for this study, one would anticipate most missions to require approximately 24 hours to complete, hence most missions would be expected to have duration of roughly 24 hours. Not all missions go exactly as planned, however, and myriad different impacts—from random variation and events, through unplanned mistakes and delays, to inefficient organization, command and control—can either accelerate or decelerate mission performance. Faster mission performance is preferred generally to slower. Duration is measured in hours of elapsed time.

Rework represents the amount of effort expended to correct mistakes that are committed during mission performance. Such mistakes can be made *functionally* (i.e., within one or more functional departments or like organizations participating in mission performance) or *integrationally* (i.e., across multiple functional departments or like organizations participating in mission performance). Lesser rework is preferred often to greater, but if mistakes are not corrected by reworking errant mission tasks, then the risk of both functional and mission failure rises. Rework is measured in person-hours; that is, the number of people involved with rework activities multiplied by the number of hours each expends on such activities. For instance, 1 person working for 100 hours would represent 100 person-hours, as would 100 people working for 1 hour, 10 people working for 10 hours, and so forth.

Coordination represents the amount of effort expended to coordinate mission activities. Meetings, memos, conversations, radio interactions and like communication modes all contribute to the coordination load of a C2 organization, as do planning and control activities. Lesser coordination is preferred often to greater, but if people do not know what to do or how, when, where and with whom to do it, then mission performance may accumulate a greater number of mistakes, take longer to complete, and be less effective generally. Coordination is measured in person-hours.

Wait represents the amount of effort expended while awaiting information or direction. It reflects time that people are "working on the clock" but not performing productively or contributing positively toward mission accomplishment. *Idle time* is a term that captures the essence of wait: some people in the organization are unproductive for periods of time while waiting for others to provide important information or to make important decisions that are necessary for them to proceed with their assigned work tasks. Lesser wait time is preferred almost always to greater. Wait is measured in person-hours.

Work Cost represents the direct cost of effort expended on mission tasks. It is calculated roughly as the number of hours worked directly on a mission (e.g., excluding rework, coordination and wait effort) times the hourly cost of each actor in the organization. It is important to note that this represents a POWer model measure that is *understood best in terms of comparison across experiment conditions, not as absolute values*. For instance, work cost excludes cost for rework, coordination and wait efforts, the latter of which are certainly included in the costs of operating organizations in the field, and relative costs across different aircraft types are more informative than absolute costs. Work cost is measured in thousands of (US) dollars ($k).

Functional Risk represents the fraction of effort that would be required to address residual functional mistakes. The more functional mistakes (i.e., within one or more functional departments or like organizations participating in mission performance) that are made—and not reworked satisfactorily—during mission performance, the higher the risk of mission failure becomes. Lesser functional risk is preferred generally to greater, but many organizations are required to trade off some performance measures versus others. For instance, performance measured in terms of duration may require a tradeoff against functional risk, hence a decision maker may elect to accept greater risk to achieve faster mission performance. Functional risk is measured as a percentage of total work cost.

Mission Risk represents the fraction of effort that would be required to address residual mission mistakes. The more integrational mistakes (i.e., across multiple functional departments or like organizations participating in mission performance) that are made—and not reworked satisfactorily—during mission performance, the higher the risk of mission failure becomes. Lesser mission risk is preferred generally to greater, but many organizations are required to trade off some performance measures versus others. For instance, performance measured in terms of duration may require a tradeoff against mission risk, hence a decision maker may elect to accept greater risk to achieve faster mission performance. Mission risk is measured as a percentage of total work cost.

Maximum Backlog represents the amount of effort required to address tasks that are ready for accomplishment but have not yet been accomplished. The best metaphor for backlog is the in-basket on an actor's desk. Such an in-basket holds the work that has arrived for that actor to complete but that has not yet been accomplished by the actor. Another way to think about backlog is via scheduled work: backlog is the amount of work that is scheduled for accomplishment but that has not yet been completed. Backlog varies—for every actor in an organization—throughout mission performance. Some actors accumulate backlogs early during mission performance, whereas others accumulate them in the latter parts, and still others maintain steady backlogs. Maximum backlog is a measure of any individual actor's backlog at its highest level during mission performance. Lesser backlog is preferred generally to greater, but an actor with nothing in its in-basket has nothing productive to do, so some backlog is desirable. Maximum backlog is measured in hours.

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