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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

COMPUTATIONAL EXPERIMENTATION TO UNDERSTAND C2

FOR TEAMS OF AUTONOMOUS SYSTEMS AND PEOPLE

by

Dr. Mark E. Nissen & W. David Place

December 2014

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ABSTRACT

The technological capabilities of autonomous systems (AS) continue to accelerate. Although AS are *replacing* people in many skilled mission domains and demanding environmental circumstances, people and machines have complementary capabilities, and *integrated* performance by AS and people *working together* can be superior to that of either AS or people working alone. We refer to this increasingly important phenomenon as Teams of Autonomous Systems and People (TASP), and we identify a plethora of open, command and control (C2) research, policy and decision making questions. Computational experimentation offers unmatched yet largely unexplored potential to address C2 questions along these lines. The central problem is, this kind of C2 organization experimentation capability has yet to be developed and demonstrated in the TASP domain. This is where our ongoing research project begins to make an important contribution. In this technical report, we motivate and introduce such TASP research, and we provide an overview of the computational environment used to experiment on TASP C2 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.

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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 technological 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).

This elucidates many emerging issues in terms of command and control (C2). Who, for instance, commands and controls unmanned aircraft when they fly autonomously? Clearly there are operators who monitor such vehicles, and there are commanders who authorize their missions, but the mission itself is conducted autonomously, and it remains somewhat unclear whom to hold accountable (e.g., the commander, the operator, the engineer, the manufacturer) if something goes wrong or whom to credit if all goes well.

Further, as technological 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 technological 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 in 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 under uncertainty; 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 technological automation of skilled work by machines (e.g., numerical 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).

B. OPEN C2 QUESTIONS

TASP raises a plethora of open, C2 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, empirical 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, and such TASP organization may even require dynamic replanning and change mid-mission.

For a third, how can researchers, policy makers and leaders develop confidence that their chosen C2 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) 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.

C. COMPUTATIONAL EXPERIMENTATION

Computational experimentation offers an unmatched yet largely unexplored potential to address C2 questions along these lines. If computational models can be

[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 H-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?

developed to represent the most important aspects of organizations with existing, planned or possible TASP 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 C2 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 TASP C2 can be examined very quickly, with their relative behavior and performance characteristics compared to match the best C2 approach with a variety of different missions, environmental conditions, technological 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 C2 organization experimentation capability has yet to be developed and demonstrated in the TASP domain. 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 C2 experimentation capability envisioned here remains absent.

D. RESEARCH OVERVIEW

This is where our ongoing research project begins 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 two decades 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 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 (i.e., POWer [Project, Organization and Work for edge research]; see Nissen, 2007) to examine joint task forces (e.g., see Looney & Nissen, 2006), distributed operations (e.g., see Oros & Nissen, 2010), computer network operations (e.g., see Koons et al., 2008), and other missions that reflect increasingly common joint and coalition endeavors (e.g., see Gateau et al., 2007).

In the balance of this technical report, we first provide an overview of the computational environment used to experiment on TASP C2 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.

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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 two 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 empirical 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 C2 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 on 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 numerical 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 C2.

Additionally, when modeling aggregations of people—such as work groups, departments or firms—one can augment the kind of symbolic model from above with certain aspects of numerical 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 numerical 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 empirical validation—that our approach diverges most from extant research methods and offers new insight into organization and C2 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, we model the organization structure as a network of reporting relations, which can capture micro-behaviors such as managerial attention, span of control and empowerment. We represent the task structure as a separate 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.

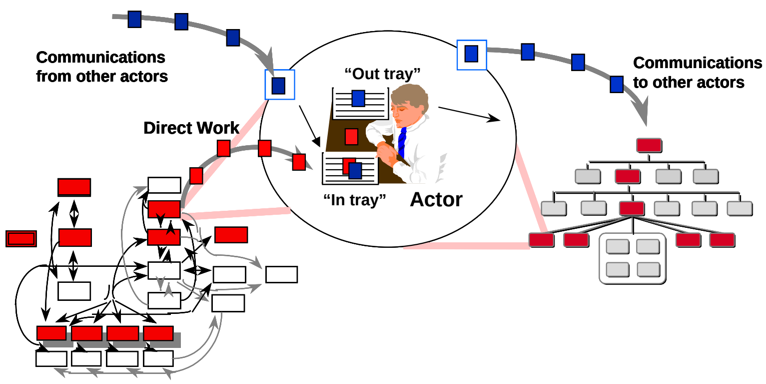

Figure 1. Information Processing View of Knowledge Work

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 indirect work enables the quantitative assessment of (virtual) process performance (e.g., through schedule growth, cost growth, quality).

The third implication is validational: the computational modeling environment has been validated extensively, over a period spanning more than two 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.

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 unshown 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. The interested reader can peruse several articles for details (e.g., see Looney & Nissen, 2006; Nissen, 2007; Gateau et al., 2007; Koons et al., 2008; Oros & Nissen, 2010).

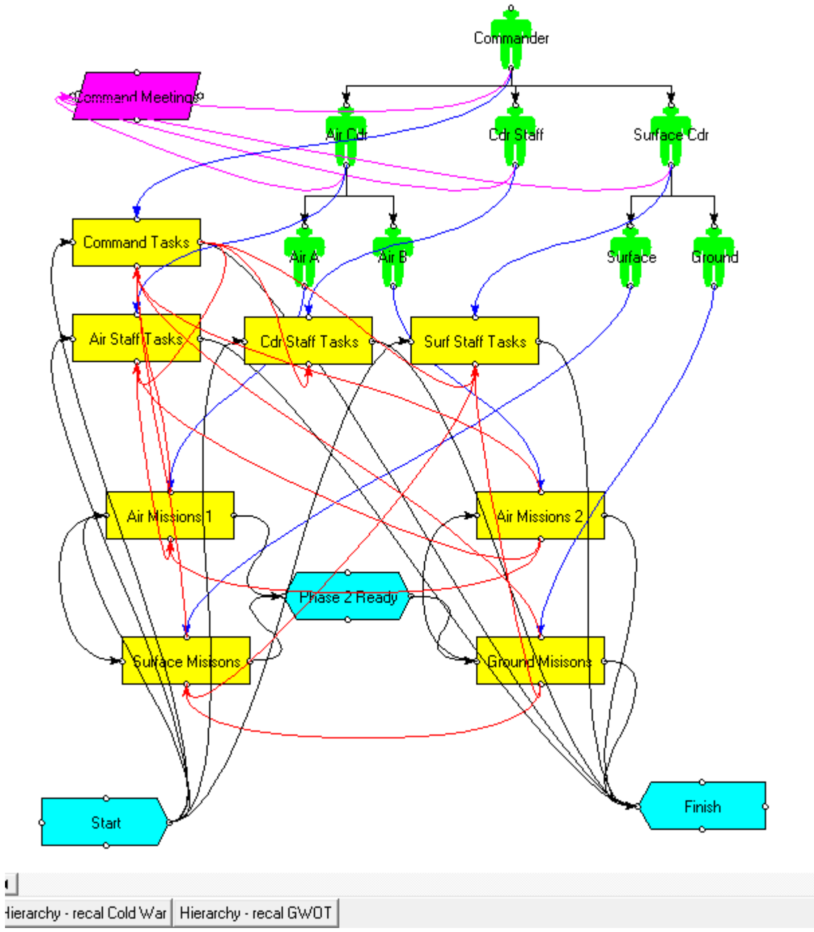

Figure 2. POWer Model Screenshot

Behind this graphical 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 C2 organizations and environments. Clearly our TASP C2 model will look different than the JTF representation depicted in the screenshot, and a major aspect of our modeling approach will entail determining how to specify such model 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 TASP C2 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 more costly and 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 TASP C2 organization, technology and environment, and we analyze AS operations at sea to specify such model. We then identify a set of manipulations to represent different autonomy degrees and interdependence levels, and we specify a robust battery of dependent measures to gauge comparative performance across manipulations. This defines a set of computational experiments, which produce empirical results for analysis.

In the balance of this section we first summarize our computational experiment, then we outline the specification and tailoring of our POWer computational environment, followed by a summary of independent and dependent variables. We proceed in turn to specify the baseline and alternate computational models representing 24 experiment conditions, organizing the discussion by interdependence level: pooled, sequential, reciprocal and integrated.

B. COMPUTATIONAL EXPERIMENT DESIGN

Our focal AS domain in this study centers on the use of multiple unmanned aerial vehicles (UAVs) in an operational military context; that is, a group of UAVs is employed in a potentially hostile environment. More specifically, we focus on UAVs employed onboard one or more ships underway at sea. Both manned and unmanned aircraft are capable of conducting missions at sea, and although our focus is on unmanned aircraft, we examine their manned counterparts also, for as explained below, manned-unmanned aircraft interactions appear to be particularly interesting, problematic and challenging in terms of C2.

These manned and unmanned aircraft conduct intelligence, surveillance and reconnaissance (ISR) missions, which require searching for, identifying, tracking and relaying real-time information regarding vessels and like items of interest in the open ocean. Aircraft 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.

Further, we utilize a two dimensional framework to examine a range of increasingly complex employment characteristics in terms of C2. These two dimensions include *autonomy* and *interdependence*. On the autonomy dimension we account for the technological 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

The six autonomy degrees derive from the domain of autonomous automobiles and are discussed in part by the National Highway Traffic Safety Administration (Fisher, 2013). 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 intelligence, surveillance and reconnaissance (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.

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 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[2] UAVs.

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 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

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

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 (e.g., 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.

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 our computational models in a manner that mirrors physical aircraft behavior and performance through the corresponding models. For reference, Appendix A – Section A (see Table 7) 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 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 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 reflect reciprocal interdependence as such; the surgeon and nurse must perform certain tasks simultaneously, switching 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 reflect this property (e.g., see Alberts & Hayes, 2006).

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 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. 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 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 TASP C2 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). At the other extreme, we consider a squadron of completely autonomous 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.

Table 4. TASP C2 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

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 this present study, we examine each of these 24 test cases in terms of *extant* C2 organizations and approaches. In follow-on work, we can examine each of these cases in terms of the *best* C2 organizations and approaches.

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 TASP C2 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 C2 organization context. Degree 4 UAVs behave consistently, 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 C2 organization 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 at 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 C2 models along the lines of those developed and analyzed in this investigation numbers roughly 30 (Looney & Nissen, 2006; Nissen, 2007; Gateau et al., 2007; Koons et al., 2008; Oros & Nissen, 2010).

1. Controls

Appendix A – Section B (see Table 8) 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 and LCS 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[3] set at 24 hours, and this planned duration is constant across all experiment cells.

Appendix A – Section C (see Table 9) 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, LCS) 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 (see Table 10) summarizes baseline model parameters, which serve to further specify the TASP C2 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.

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[3] 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.

2. Manipulations

Alternatively, Appendix A – Section E (see Table 11) summarizes the model parameters subject to manipulation: *team experience, centralization, formalization, matrix strength, communication probability, noise probability, role* and *application experience*. These are all manipulated expressly to specify each POWer model across our set of 24 experiment conditions.

3. Measures

Finally, Appendix A – Section F (see Table 12) summarizes the eight model measures: *duration, rework, coordination, wait, work cost, functional risk, mission risk* and *maximum backlog*. These measures enable us to gauge TASP C2 performance robustly through multiple dimensions.

E. POOLED INTERDEPENDENCE COMPUTATIONAL MODELS

We begin by specifying the baseline (i.e., D0P) model and then characterize variations across the matrix of experiment conditions pertaining to pooled interdependence. This takes us from Degree 0 through Degree 5 autonomy. Here in the main body of the report we keep our discussion at a relatively high level. Detailed model specifications are included for reference in Appendix A.

1. Baseline Model (D0P)

Figure 3 delineates a screenshot of our baseline CTG organization and platform set. The light (green) person icons represent organizations at four levels (i.e., CTF, CTG, Platform [e.g., DDG, LCS], 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 TASP C2.

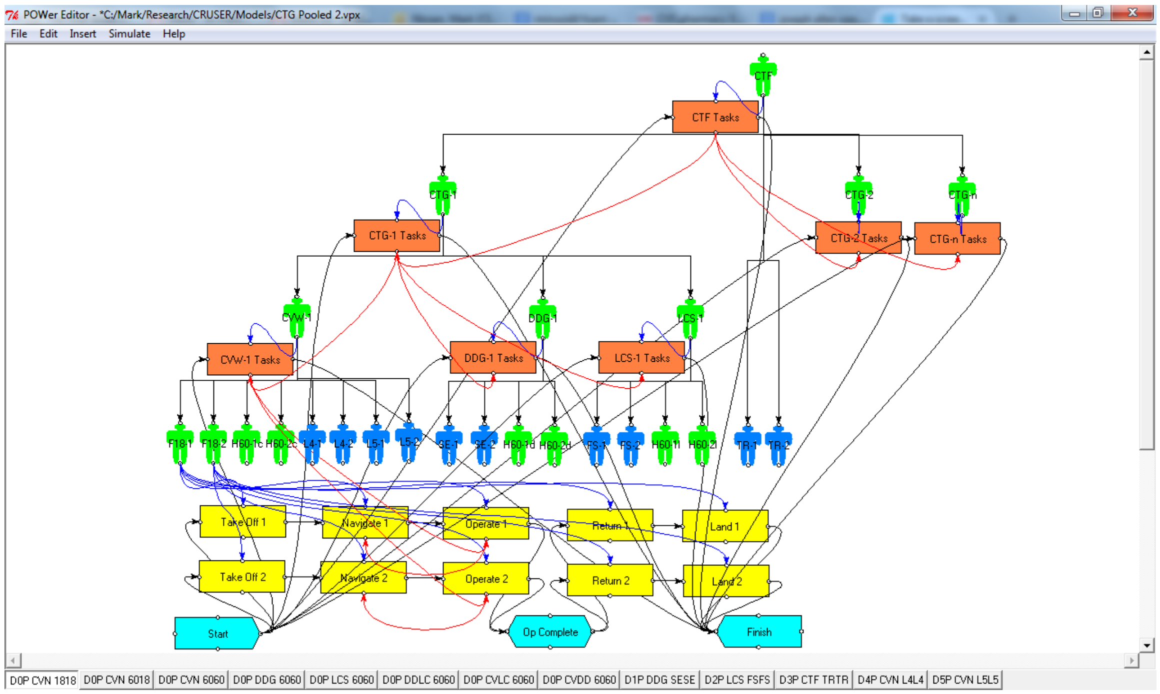

Figure 3. Baseline Model (D0P) – CVN F/A-18s

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 one or more DDGs and LCSs as well as the CVN. ScanEagles (Degree 1) are assigned to the DDGs, and FireScouts (Degree 2) are assigned to the LCSs. 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[4]. 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 (e.g., a promising contact is not located, insufficient intelligence is gathered, sensor data cannot be relayed), then the aircraft may have to

[4] 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. DDG, LCS).

Navigate to some other region and Operate there. The interested reader can refer to Gateau et al. (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 C2 context.

As noted above, the simulated ISR mission has a *planned* duration[5] 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 take into account 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 4. 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 different region of airspace. This represents another very common and relatively straightforward C2 context.

[5] 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.

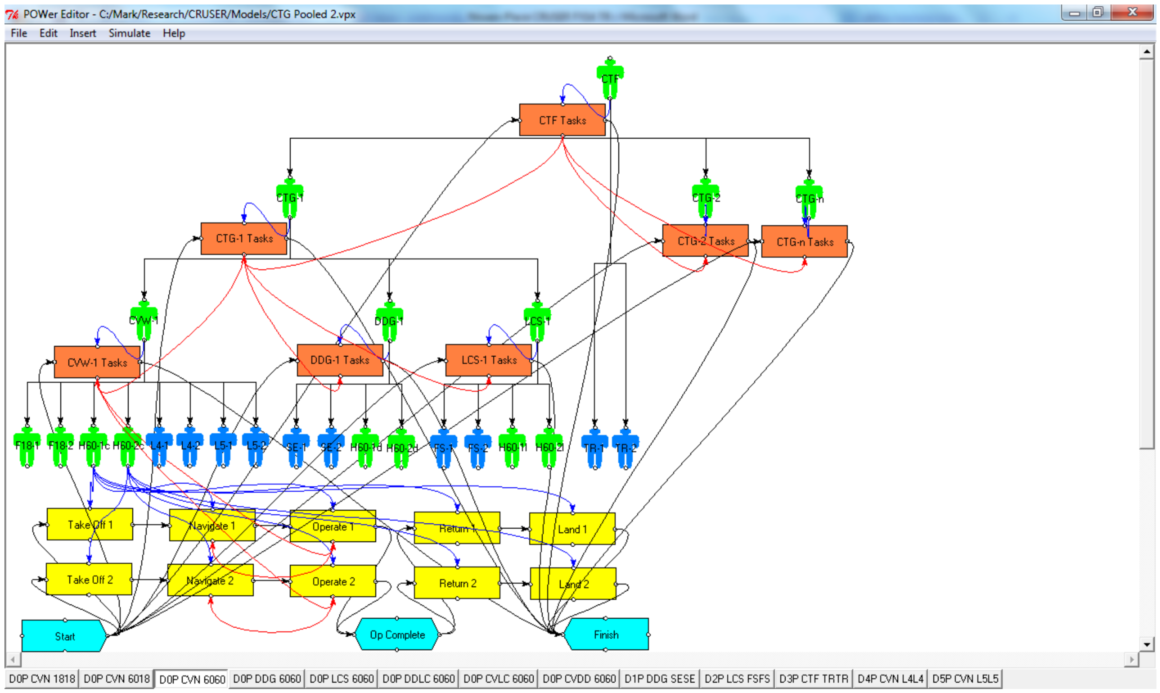

Figure 4. Baseline Model (D0P) – CVN MH-60s

As one would expect, two different kinds of aircraft can fly ISR missions in separate regions of airspace. 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 5. 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 C2 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).

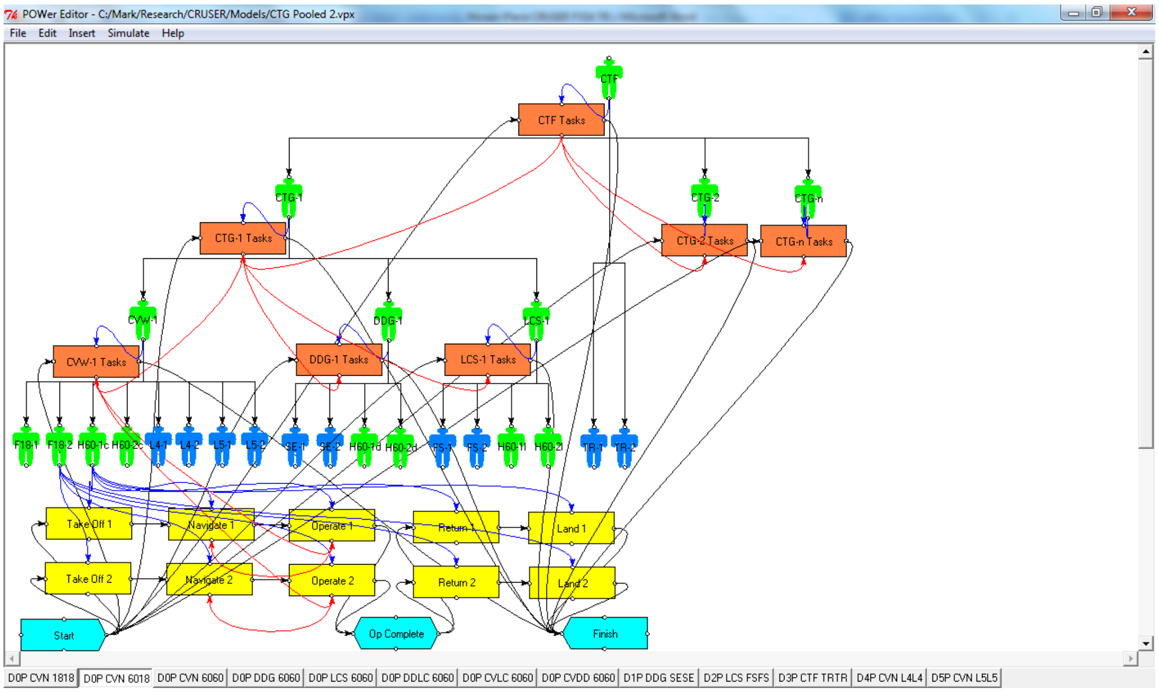

Figure 5. Baseline Model (D0P) – CVN F/A-18 & MH-60

Further, suitably capable aircraft can conduct these same missions from other ships as well. MH-60s, for instance, can operate from the DDG and LCS. The screenshot in Figure 6 delineates two helos operating from one or more DDG platforms[6].

[6] Another model (not shown) represents two MH-60s operating from one or more LCS ship platforms. C2 demands and implications are highly similar.

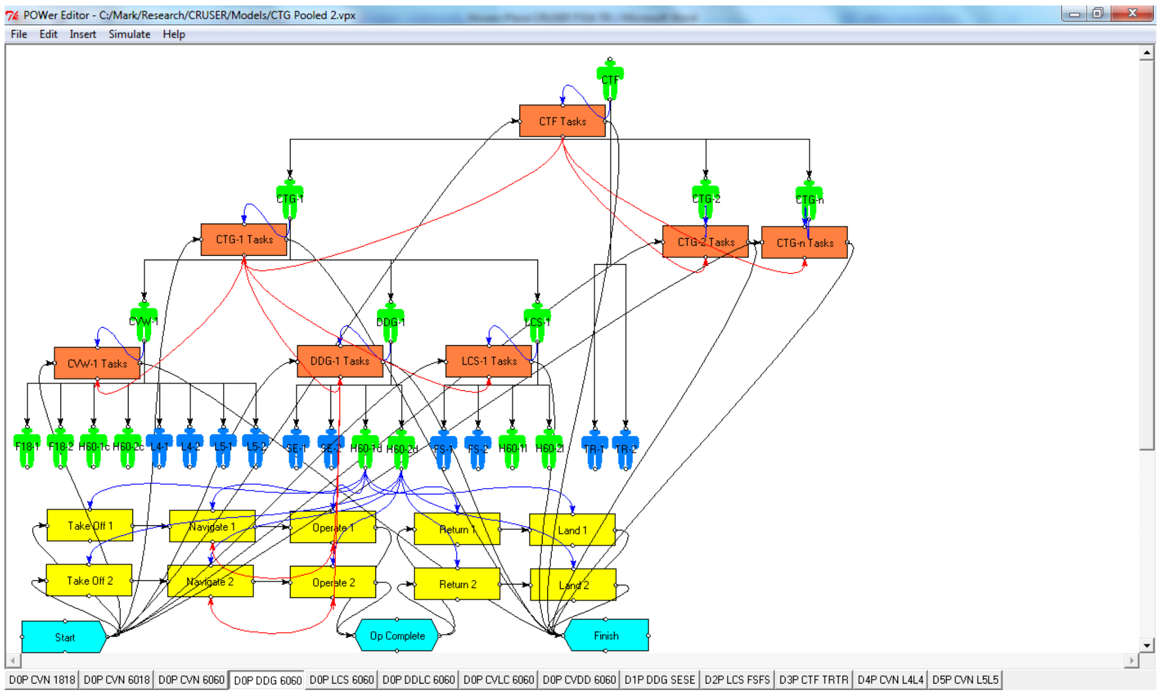

Figure 6. Baseline Model (D0P) – DDG MH-60s

Still further, suitably capable aircraft can operate simultaneously from different ships. For instance, Figure 7 reflects a screenshot of the model representing one MH-60 helicopter conducting its ISR mission from a DDG and another conducting its mission (in separate airspace) from an LCS. Other combinations (e.g., CVN-DDG, CVN-LCS; not shown) are modeled and simulated too for completeness.

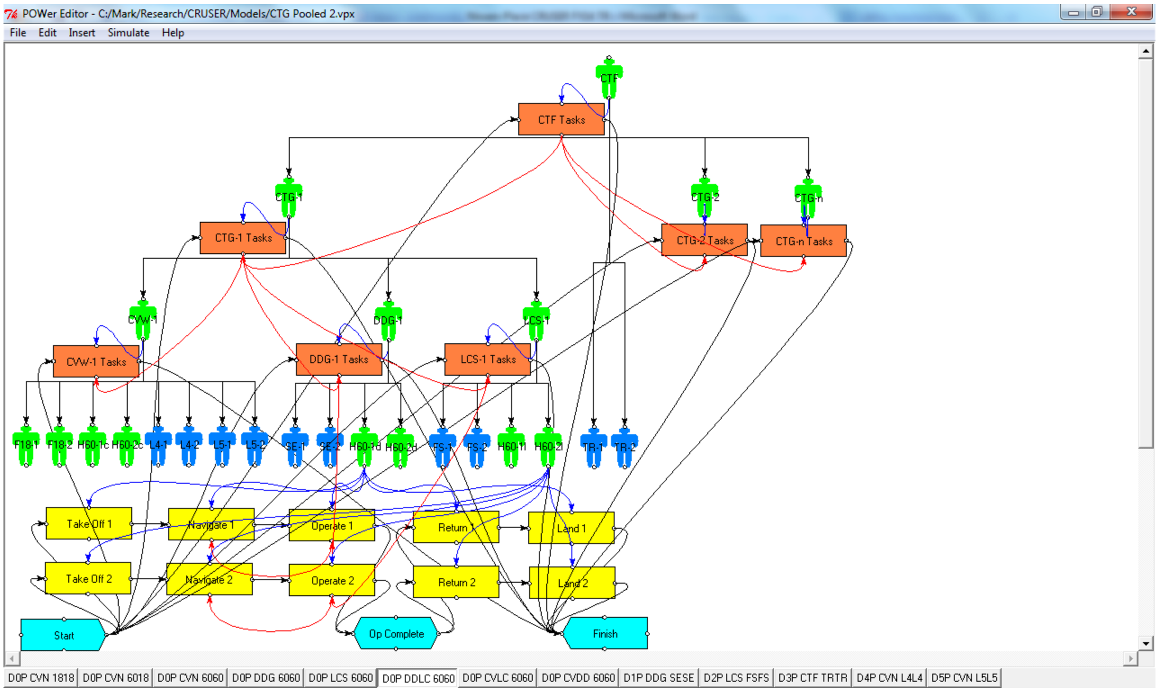

Figure 7. Baseline Model (D0P) – DDG MH-60 & LCS MH-60

Hence our D0P experiment condition includes eight[7] different models. Each such model depicts Degree 0 autonomy (i.e., manned aircraft) and pooled interdependence (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, LCS). To limit confusion, each of these "D0P" models includes additional information to identify the specific ships and aircraft involved. For instance, "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.

[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 the LCS. As another instance, multiple (manned) aircraft types can operate from multiple ship platforms. Our eight models provide adequate coverage of TASP C2 variations, so we do not endeavor to model exhaustively here.

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 6060	DDG	MH-60, MH-60
D0P LCS 6060	LCS	MH-60, MH-60
D0P DDLC 6060	DDG, LCS	MH-60, MH-60
D0P CVLC 6060	CVN, LCS	MH-60, MH-60
D0P CVDD 6060	CVN, DDG	MH-60, MH-60

2. D1P Model

Following the format used to describe the baseline D0P model above, here we characterize Degree 1 autonomy models with pooled interdependence (D1P). Unlike with the eight baseline D0P models discussed above, we have only one model to represent D1P: two ScanEagles operate from one or more DDG platforms ("D1P DDG SESE"). Because the (unmanned) ScanEagle aircraft operate in separate airspaces, one each can be controlled from a separate DDG ship. One can consider further the mission conducted with two ScanEagles controlled from a single, suitably configured ship—operating in separate airspaces—without undue complication in terms of C2, although shipboard launch and recovery must be coordinated more closely, and additional technical details require attention[8]. We include a screenshot for this model in Figure 8.

[8] This also creates some technical issues in terms of locating and operating multiple control stations, placing multiple antennae, selecting compatible frequencies, and like considerations that we abstract away in this study.

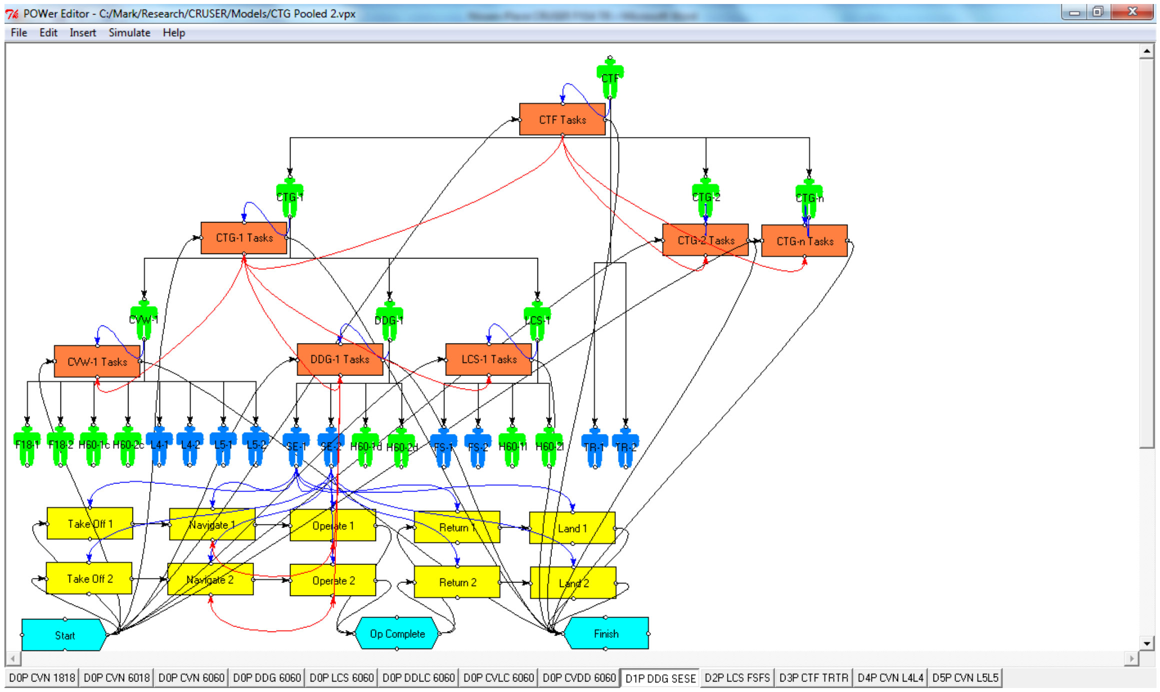

Figure 8. Model D1P – DDG ScanEagles

3. D2P Model

Continuing with this same format, here we characterize Degree 2 autonomy models with pooled interdependence (D2P). As with the D1P case discussed above, we have only one model to represent D2P: two FireScouts operate from one or more LCS platforms ("D2P LCS FSFS"). Because the (unmanned) FireScout aircraft operate in separate airspaces, one each can be controlled from a separate LCS ship. One can consider further the mission conducted with two FireScouts controlled from a single, suitably configured ship—operating in separate airspaces—without undue complication in terms of C2, although shipboard launch and recovery must be coordinated more closely, and additional technical details require attention. We include a screenshot for this model in Figure 9.

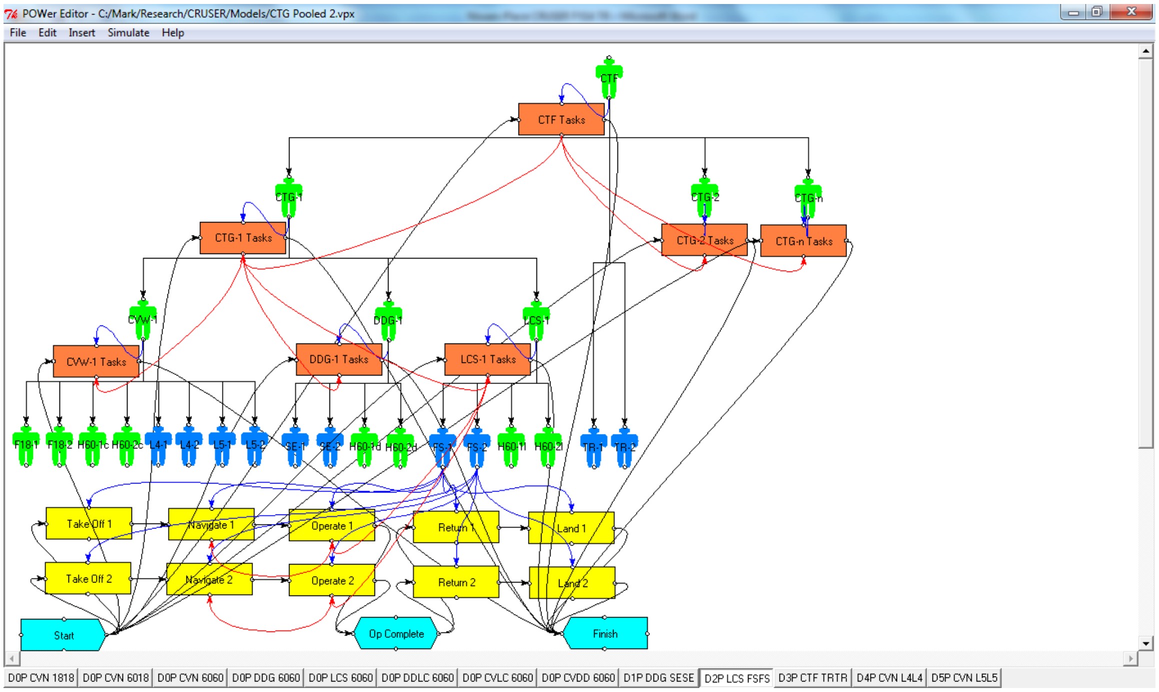

Figure 9. Model D2P – LCS FireScouts

4. D3P Model

Continuing with this same format, here we characterize Degree 3 autonomy models with pooled interdependence (D3P). As above, we have only one model to represent D3P: two Tritons operate from land ("D3P CTF TRTR"). Here we presume that the CTF asserts authority over the Tritons and that they operate in separate airspaces. We include a screenshot for this model in Figure 10.

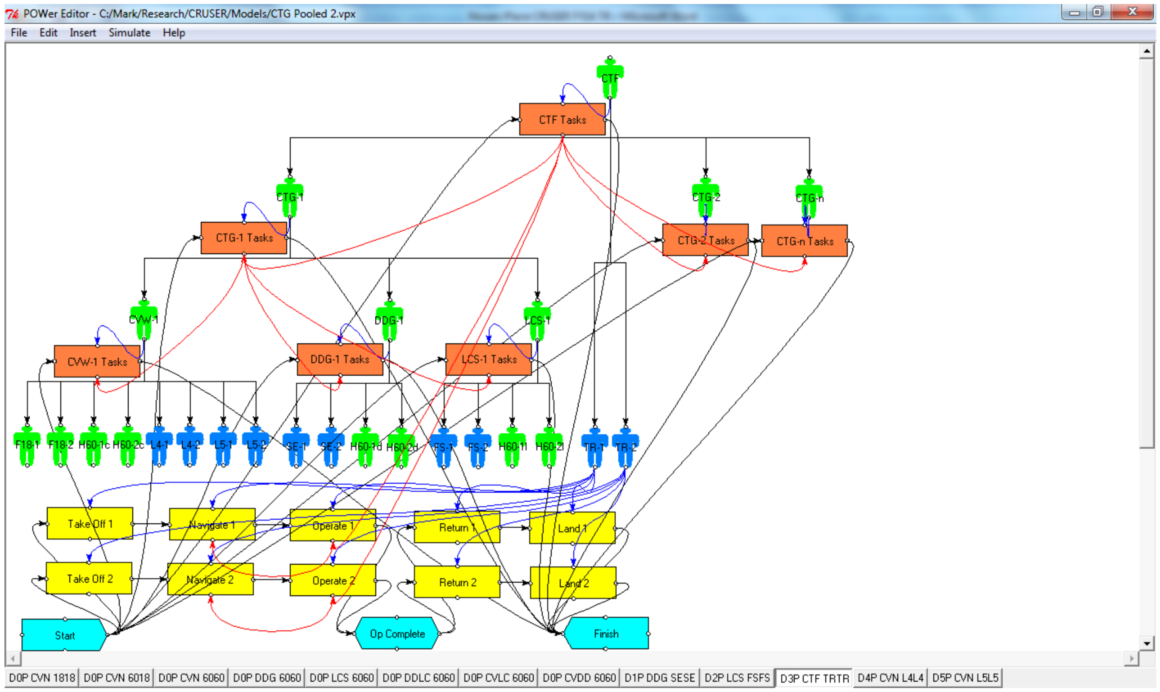

Figure 10. Model D3P – Tritons

5. D4P Model

Continuing with this same format, here we characterize Degree 4 autonomy models with pooled interdependence (D4P). We present one of several models to represent D4P: two "Level 4" UAVs operate from the CVN ("D4P CVN L4L4"). As noted above—depending upon the technology and capability that end up being developed and fielded (e.g., fixed wing, rotary wing)—such Level 4 UAVs could potentially be based on other ship platforms (e.g., DDG, LCS), but we associate them solely with the CVN here in this model[9]. We include a screenshot for this model in Figure 11.

[9] Some model iterations representing integrated interdependence include L4 and L5 UAVs operating from other ship platforms. We describe these in their corresponding sections below.

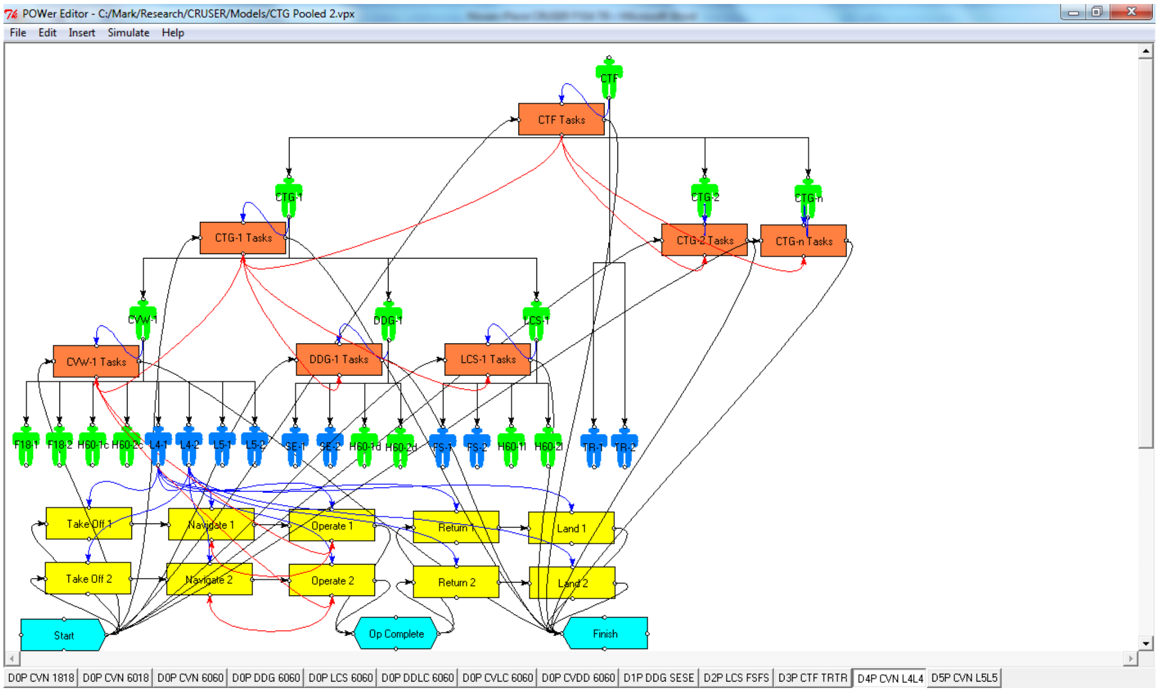

Figure 11. Model D4P – L4 UAVs

6. D5P Model

Completing this format for the pooled interdependence models, here we characterize Degree 5 autonomy models (D5P). As above, we present one of several models to represent D5P: two "Level 5" UAVs operate from the CVN ("D5P CVN L5L5"). As above—depending upon the technology and capability that end up being developed and fielded (e.g., fixed wing, rotary wing)—such Level 5 UAVs could potentially be based on other ship platforms (e.g., DDG, LCS), but we associate them solely with the CVN here in this model. We include a screenshot for this model in Figure 12.

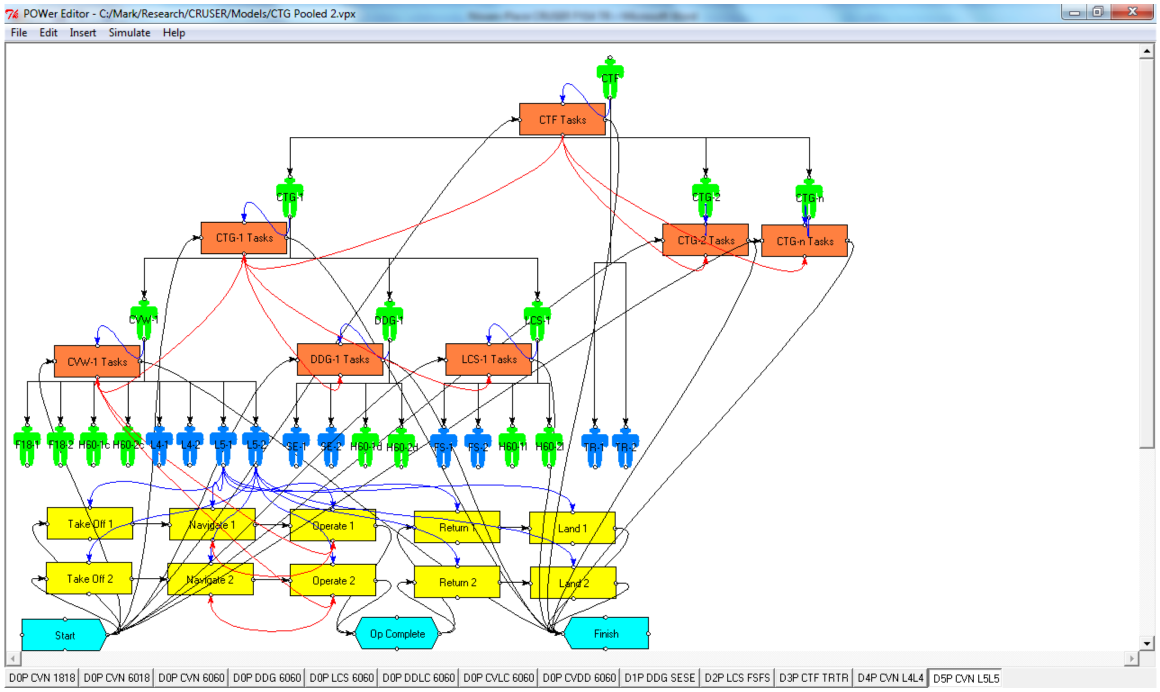

Figure 12. Model D5P – L5 UAVs

F. SEQUENTIAL INTERDEPENDENCE COMPUTATIONAL MODELS

Sequential interdependence computational models are specified next. In our TASP C2 domain, particularly with respect to the nominal 24 hour ISR mission specified in these models, pooled and sequential interdependence do not differ appreciably. Consider, for instance, the case of two aircraft sorties that must be conducted, in succession (e.g., due to endurance limitations), in a common area of airspace. Under sequential interdependence, information gleaned by the first aircraft (e.g., noteworthy intelligence) would be used as a basis for the second aircraft's mission. This is practically identical to tasking a second aircraft to conduct ISR operations in the same region of airspace in which the first aircraft is operating. For example, a second aircraft could be assigned to continue surveilling a vessel of interest located and identified by a first aircraft that runs low on fuel.

In some contexts and missions, sequential interdependence will likely have important modeling and analytical implications. In our current TASP C2 context and nominal 24 hour ISR mission, alternatively, this sequential interdependence experiment condition reveals little above what we discover through the pooled interdependence models and simulations, so we do not discuss it further in this technical report.

G. RECIPROCAL INTERDEPENDENCE COMPUTATIONAL MODELS

In great contrast to sequential interdependence, our examination of reciprocal interdependence reveals much. We continue by characterizing variations across the matrix of experiment conditions pertaining to reciprocal interdependence. As above, this takes us from Degree 0 through Degree 5 autonomy. Also as above, here in the main body of the report we keep our discussion at a relatively high level. Detailed model specifications are included for reference in Appendix A.

1. D0R Model

Continuing with the format used to describe the pooled interdependence models above, here we characterize Degree 0 autonomy models with reciprocal interdependence (D0R). As with the eight baseline D0P models discussed above, we have all of the same (manned and unmanned) aircraft and ship platform combinations to model. However, for space considerations, we present only one D0R model here: two F/A-18s operate from the CVN ("D0R CVN 1818").

The key difference between this model and its pooled interdependence counterpart discussed above is that the two aircraft (F/A-18s in this case) fly and conduct the ISR mission *together, in common airspace*. Consider, for instance, one aircraft operating as Wingman for the other operating as Leader. Operating as such in common airspace exerts additional C2 demands.

It also requires additional, ongoing communication, which is represented in the model via (light/green) communication links between key tasks (esp. Navigate 1 and Navigate 2; Operate 1 and Operate 2). Notice, for instance, how such links interconnect two tasks performed by each of the aircraft (i.e., the task Navigate-1, which is assigned to the actor F/A-18-1 [Leader], is linked to the task Navigate-2, which is assigned to the actor F/A-18-2 [Wingman]; the task Operate-1, which is assigned to the actor F/A-18-1 [Leader], is linked to the task Operate-2, which is assigned to the actor F/A-18-2 [Wingman]). This reflects the need for the two aircraft to communicate frequently throughout the mission, but in particular as they navigate to and operate on station for the ISR mission. We include a screenshot for this model in Figure 13.

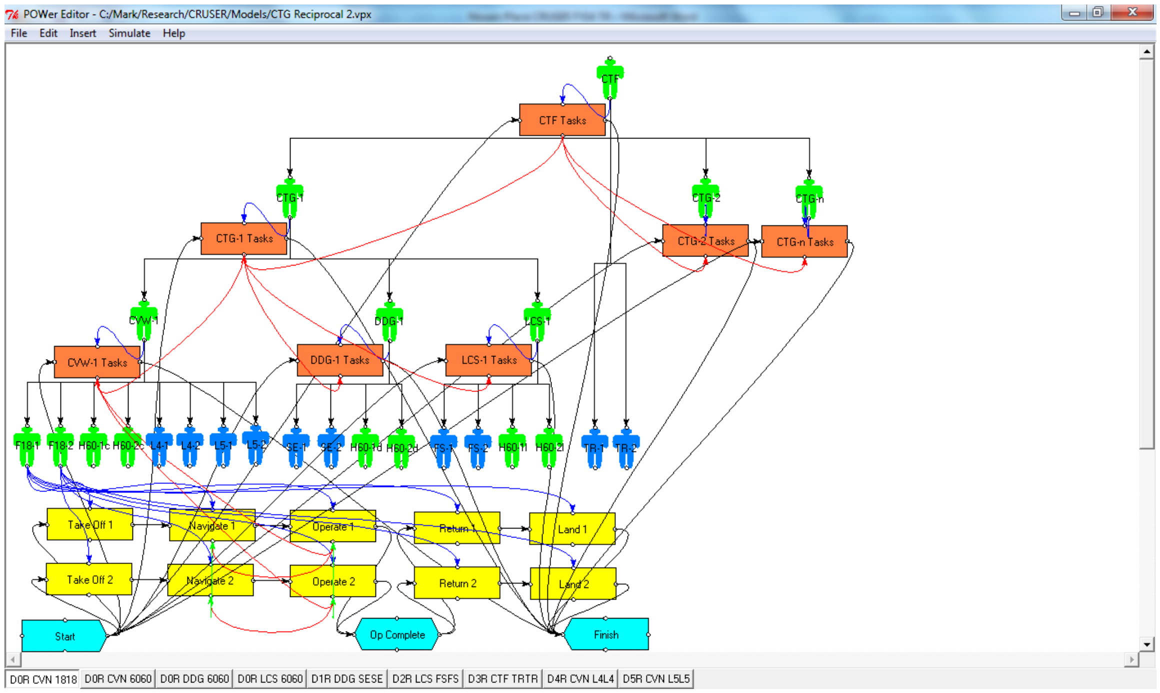

Figure 13. Model D0R – CVN F/A-18s

2. D1R Model

Following the format used to describe the baseline D0R model above, here we characterize Degree 1 autonomy models with reciprocal interdependence (D1R). As above, we have only one model to represent D1R: two ScanEagles operate in common airspace from one or more DDG platforms ("D1R DDG SESE"). Also as above, operating as such in common airspace exerts additional C2 demands, and it requires additional, ongoing communication, even between such unmanned aircraft. In particular, because these Degree 1 autonomy aircraft are operated remotely, most such communication is conducted between remote aircrews[10] (onboard ship). We include a screenshot for this model in Figure 14.

[10] An additional consideration of interest pertains to the ScanEagle's inability to sense other aircraft in flight. Such sensing must be accomplished by the remote aircrews.

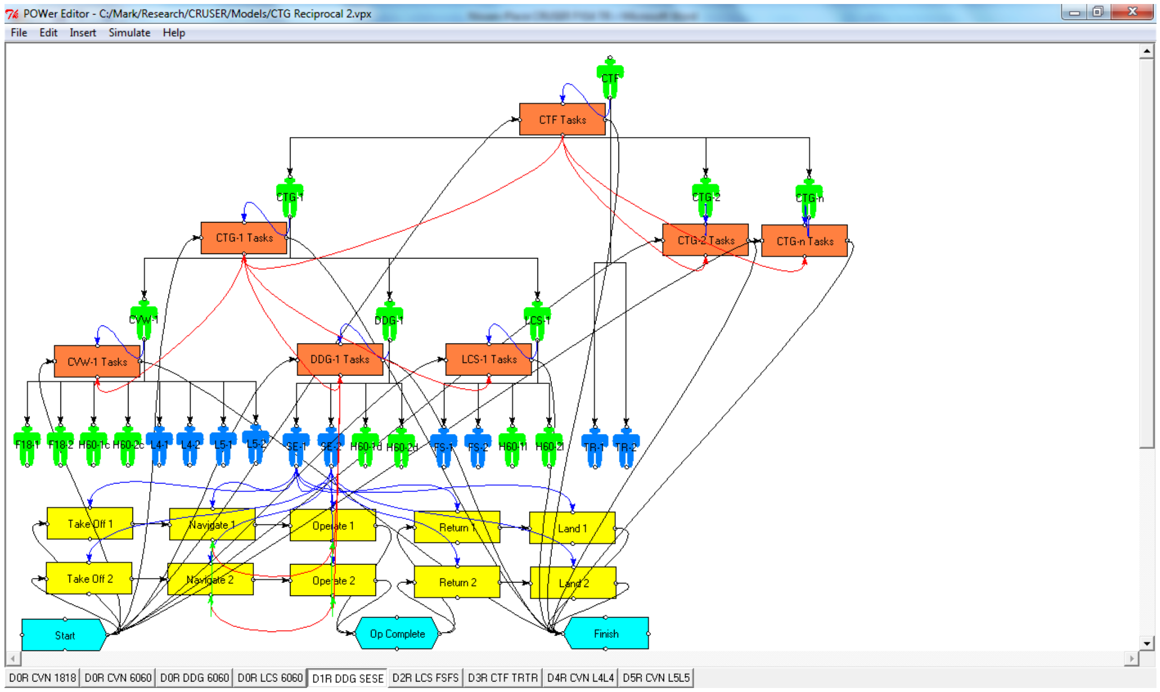

Figure 14. Model D1R – DDG ScanEagles

3. D2R Model

Continuing with this same format, here we characterize Degree 2 autonomy models with reciprocal interdependence (D2R). As above, we have only one model to represent D2R: two FireScouts operate in common airspace from one or more LCS platforms ("D2R LCS FSFS"). Also as above, operating as such in common airspace exerts additional C2 demands, and it requires additional, ongoing communication, even between such unmanned aircraft. In particular, because these Degree 2 autonomy aircraft are operated remotely, most such communication is conducted between remote aircrews[11] (onboard ship). We include a screenshot for this model in Figure 15.

[11] An additional consideration of interest pertains to the FireScout's inability to sense other aircraft in flight. Such sensing must be accomplished by the remote aircrews.

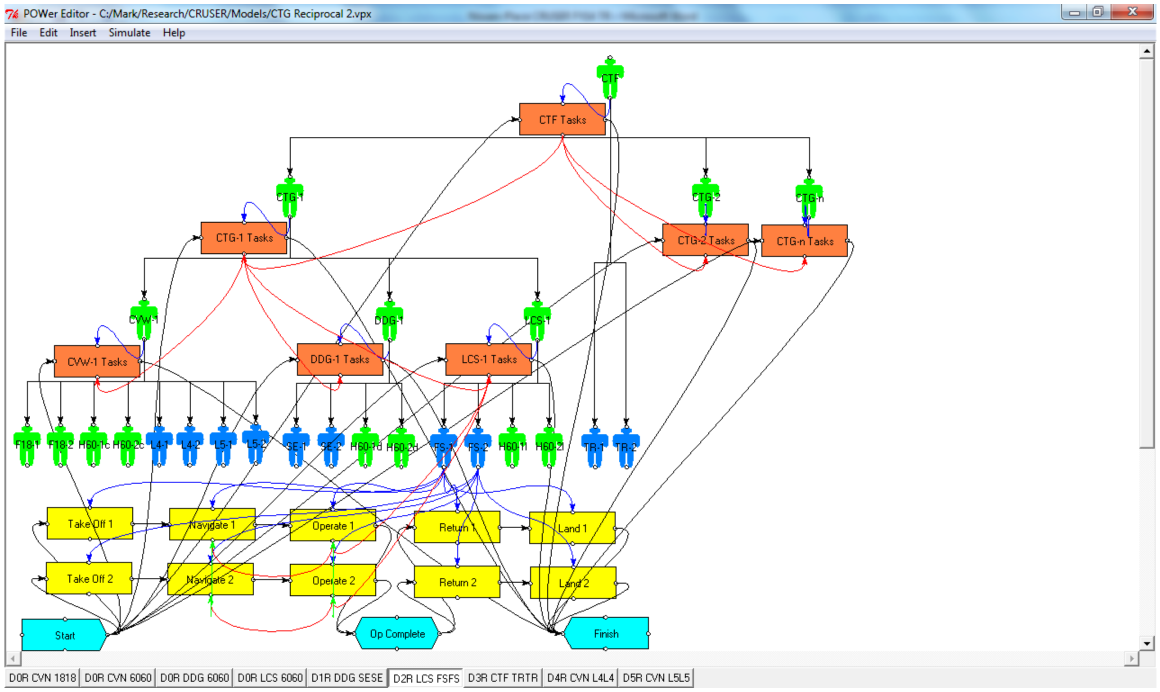

Figure 15. Model D2R – LCS FireScouts

4. D3R Model

Continuing with this same format, here we characterize Degree 3 autonomy models with reciprocal interdependence (D3R). As above, we have only one model to represent D3R: two Tritons operate from land in common airspace ("D3R CTF TRTR"). Here we presume that the CTF asserts authority over the Tritons and that they operate in common airspace. Also as above, operating as such in common airspace exerts additional C2 demands, and it requires additional, ongoing communication, even between such unmanned aircraft. However, because these Degree 3 autonomy aircraft are operated somewhat autonomously (e.g., preprogrammed flight), most such communication is conducted between remote aircrews[12] (on land). We include a screenshot for this model in Figure 16.

[12] An additional consideration of interest pertains to the Triton's inability to sense other aircraft in flight. Such sensing must be accomplished by the remote aircrews.

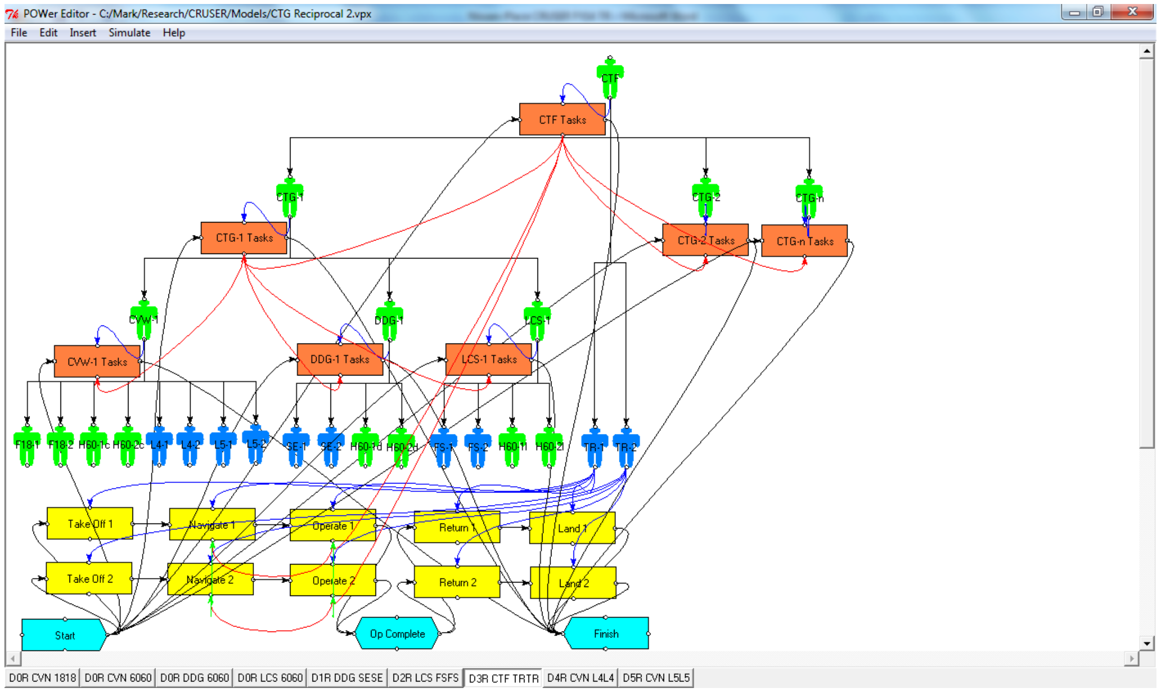

Figure 16. Model D3R – Tritons

5. D4R Model

Continuing with this same format, here we characterize Degree 4 autonomy models with reciprocal interdependence (D4R). As above, we have only one model to represent D4R: two “Level 4” UAVs operate in common airspace from the CVN (“D4R CVN L4L4”). Also as above, operating as such in common airspace exerts additional C2 demands, and it requires additional, ongoing communication, even between such unmanned aircraft. However, because these Degree 4 autonomy aircraft operate autonomously, *most such communication is conducted between the UAVs themselves*. This represents a notable advance over the current state of the practice[13]. We include a screenshot for this model in Figure 17.

[13] We presume this UAV’s ability to sense other aircraft in flight. Remote aircrews are not required to accomplish such sensing.

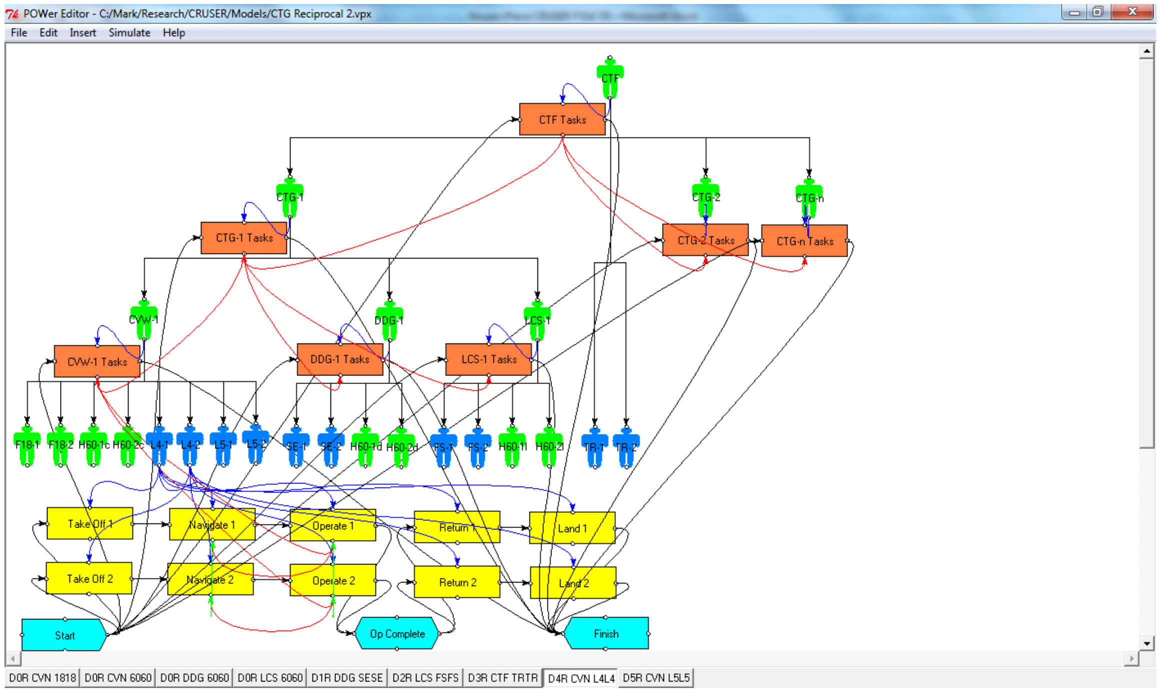

Figure 17. Model D4R – L4 UAVs

6. D5R Model

Completing this format for the reciprocal interdependence models, here we characterize Degree 5 autonomy models (D5R). As above, we have only one model to represent D5R: two "Level 5" UAVs operate in common airspace from the CVN ("D5R CVN L5L5"). Also as above, operating as such in common airspace exerts additional C2 demands, and it requires additional, ongoing communication, even between such unmanned aircraft. However, as with Degree 4 counterparts, because these Degree 5 autonomy aircraft operate autonomously, *most such communication is conducted between the UAVs themselves*. This represents a notable advance over the current state of the practice[14]. We include a screenshot for this model in Figure 18.

[14] We presume this UAV's ability to sense other aircraft in flight. Remote aircrews are not required to accomplish such sensing.

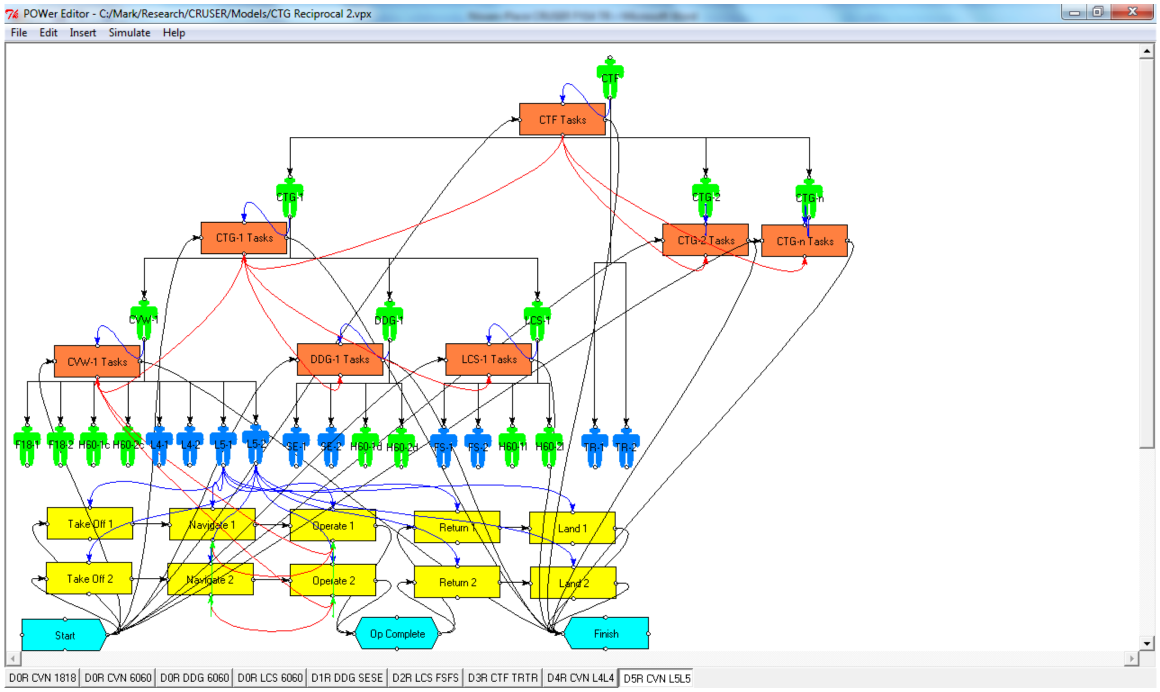

Figure 18. Model D5R – L5 UAVs

H. INTEGRATED INTERDEPENDENCE COMPUTATIONAL MODELS

As with reciprocal interdependence above, our examination of integrated interdependence reveals much also. We continue by characterizing variations across the matrix of experiment conditions pertaining to integrated interdependence. As above, this takes us from Degree 0 through Degree 5 autonomy. Also as above, here in the main body of the report we keep our discussion at a relatively high level. Detailed model specifications are included for reference in Appendix A.

1. D0I Model

Continuing with the format used to describe the models above, here we characterize Degree 0 autonomy models with integrated interdependence (D0I). Recall from above that integrated interdependence subsumes its reciprocal counterpart; that is, multiple aircraft fly together in common airspace. The key difference is that such integrated interdependence missions include *both manned and unmanned* aircraft flying together in common airspace. Recall further, however, that the definition of Degree 0 autonomy (e.g., continuous local control of flight and sensor operation) excludes unmanned aircraft, hence there is no model for D0I; that is, Degree 0 autonomy is limited to manned aircraft only. Hence we skip ahead immediately to D1I, in which a Degree 0 manned aircraft flies with a Degree 1 unmanned counterpart.

2. D1I Model

Continuing with the format used to describe the models above, here we characterize Degree 1 autonomy models with integrated interdependence (D1I). As above, we have only one model to represent D1I: one MH-60 and one ScanEagle operate in common airspace from one or more DDG platforms (“D1I DDG 60SE”). Clearly such integrated interdependence missions include *both manned and unmanned* aircraft flying together in common airspace. Consider, for instance, one *unmanned* aircraft (e.g., ScanEagle) operating as Wingman for a *manned* aircraft (e.g., MH-60) operating as Leader. Operating as such in common airspace exerts enormous C2 demands[15].

As with our models representing reciprocal interdependence, it also requires additional, ongoing communication, which is depicted in the model via (light/green) communication links between the Navigate and Operate tasks. Moreover, because integrated interdependence exerts enormous C2 demands, we include communication links between the manned and unmanned aircraft (i.e., MH-60, ScanEagle) and their ship platforms (i.e., DDGs), in addition to links between such ship platform organizations and the two echelons above (i.e., CTG, CTF). This represents a huge advance over the current state of the practice. We include a screenshot for this model in Figure 19.

[15] Such demands are likely to be organizational and cultural in addition to technical.

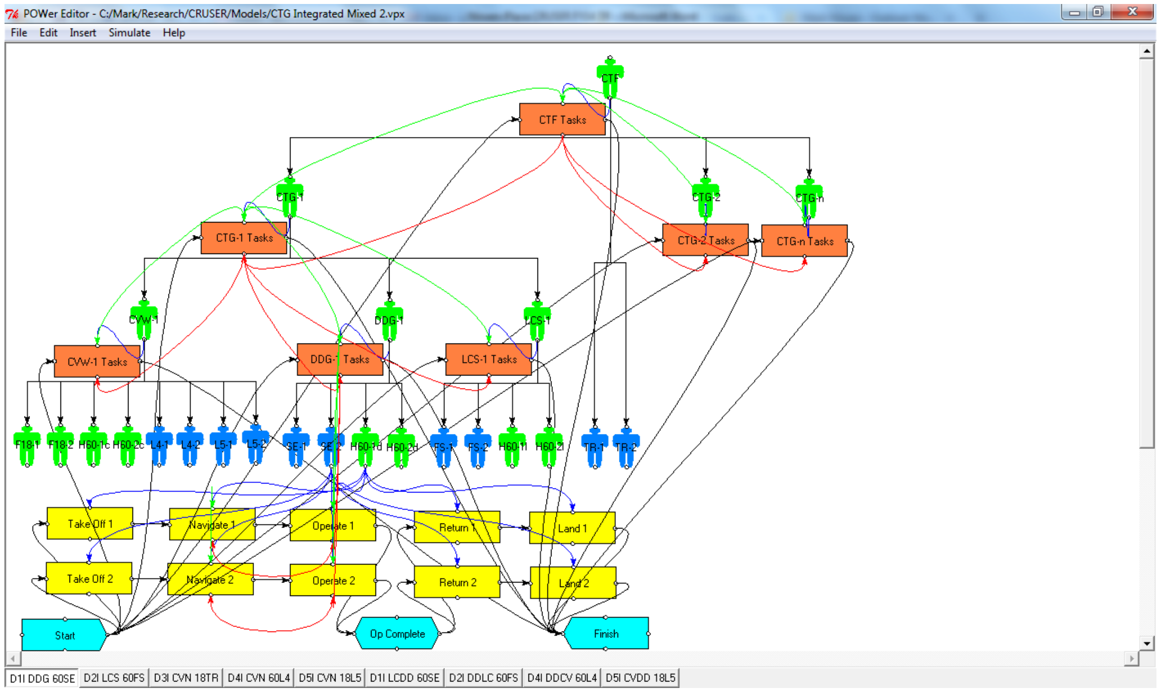

Figure 19. Model D1I – DDG MH-60 & ScanEagle

3. D2I Model

Continuing with this same format, here we characterize Degree 2 autonomy models with integrated interdependence (D2I). As above, we have only one model to represent D2I: one MH-60 and one FireScout operate in common airspace from one or more LCS platforms ("D2I LCS 60FS"). As above, operating as such in common airspace exerts enormous C2 demands[16], and it requires additional, ongoing communication, even between manned and unmanned aircraft, in addition to higher organization echelons. This represents a huge advance over the current state of the practice. We include a screenshot for this model in Figure 20.

[16] Such demands are likely to be organizational and cultural in addition to technical.

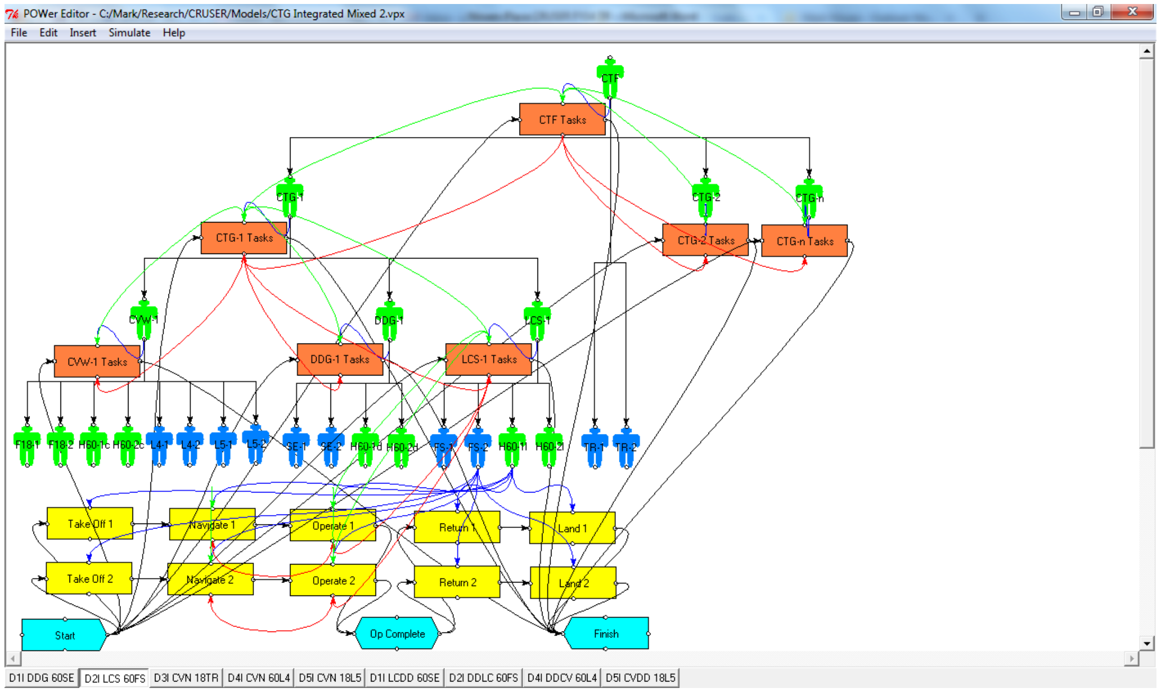

Figure 20. Model D2I – LCS MH-60 & FireScout

4. D3I Model

Continuing with this same format, here we characterize Degree 3 autonomy models with integrated interdependence (D3I). As above, we have only one model to represent D3I: one F/A-18 operates from the carrier, and one Triton operates from land in common airspace ("D3I CVN 18TR"). Here we presume that the CTF asserts authority over the Triton and that the CVW has authority over the F/A-18. As above, operating as such in common airspace exerts enormous C2 demands[17], and it requires additional, ongoing communication, even between manned and unmanned aircraft, in addition to higher organization echelons. This represents a huge advance over the current state of the practice. We include a screenshot for this model in Figure 21.

[17] Such demands are likely to be organizational and cultural in addition to technical.

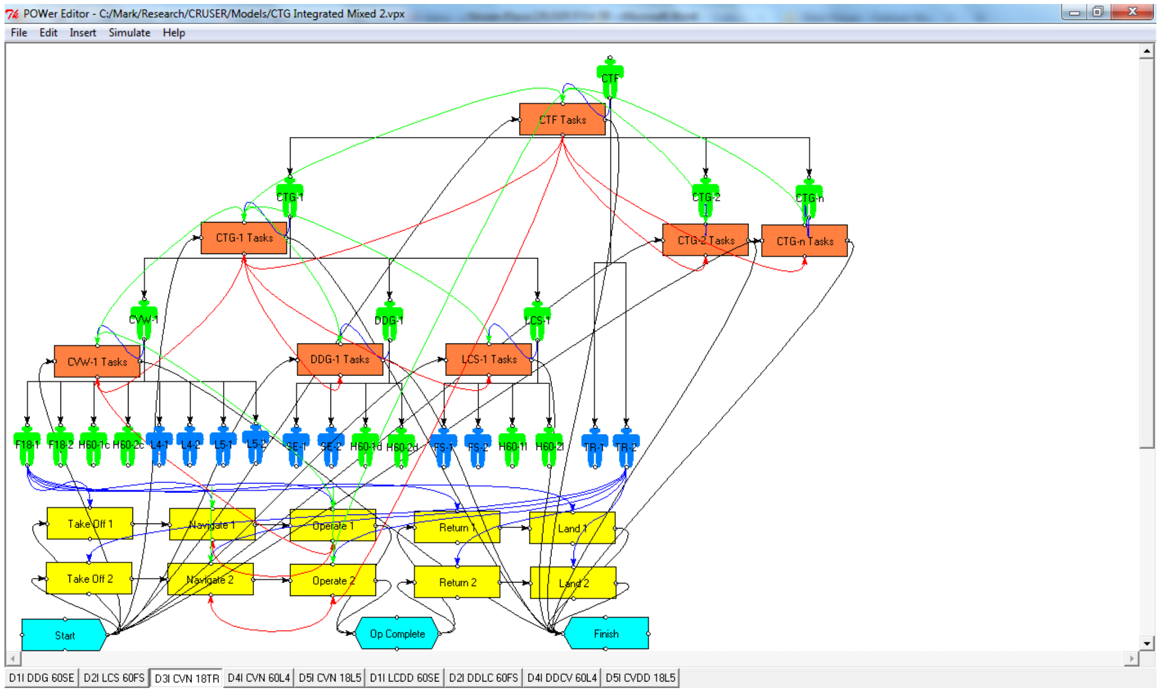

Figure 21. Model D3I – F/A-18 & Triton

5. D4I Model

Continuing with this same format, here we characterize Degree 4 autonomy models with integrated interdependence (D4I). As above, we have only one model to represent D4I: one MH-60 and one "Level 4" UAV operate in common airspace from the CVN ("D4I CVN 60L4"). As above, operating as such in common airspace exerts enormous C2 demands[18], and it requires additional, ongoing communication, even between manned and unmanned aircraft, in addition to higher organization echelons. This represents a huge advance over the current state of the practice. We include a screenshot for this model in Figure 22.

[18] Such demands are likely to be organizational and cultural in addition to technical.

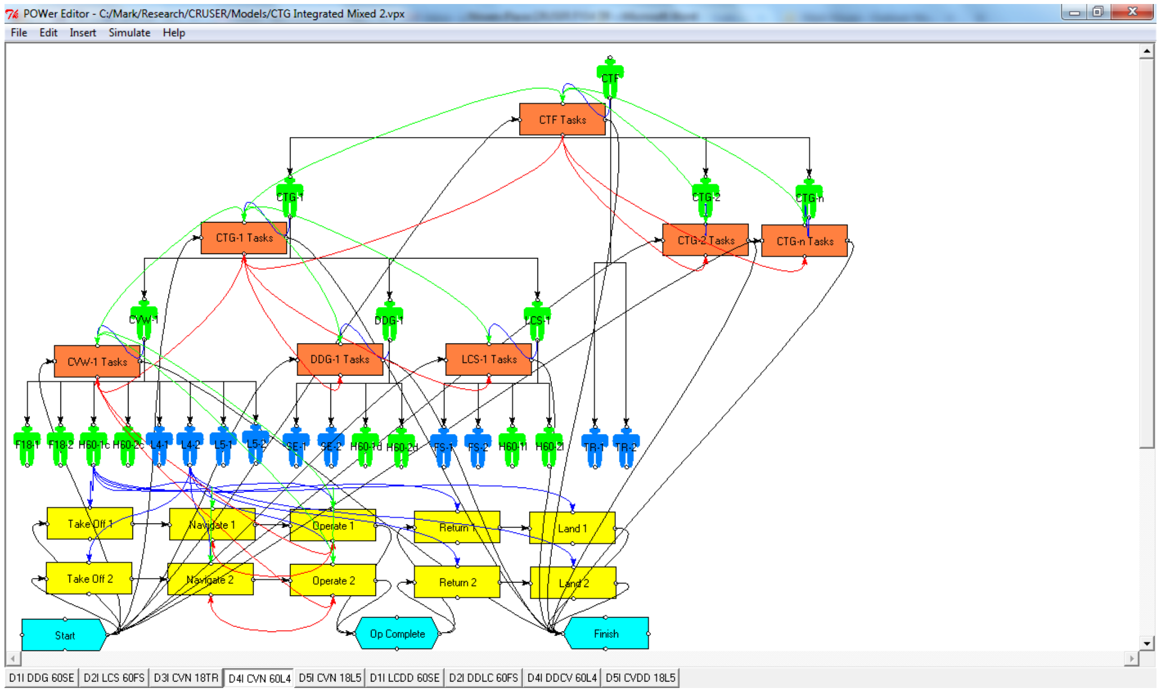

Figure 22. Model D4I – MH-60 & L4 UAV

6. D5I Model

Completing this format for the integrated interdependence models, here we characterize Degree 5 autonomy models (D5I). As above, we have only one model to represent D5I: one F/A-18 and one "Level 5" UAV operate in common airspace from the CVN ("D5I CVN 18L5"). As above, operating as such in common airspace exerts enormous C2 demands[19], and it requires additional, ongoing communication, even between manned and unmanned aircraft, in addition to higher organization echelons. This represents a huge advance over the current state of the practice. We include a screenshot for this model in Figure 23.

[19] Such demands are likely to be organizational and cultural in addition to technical.

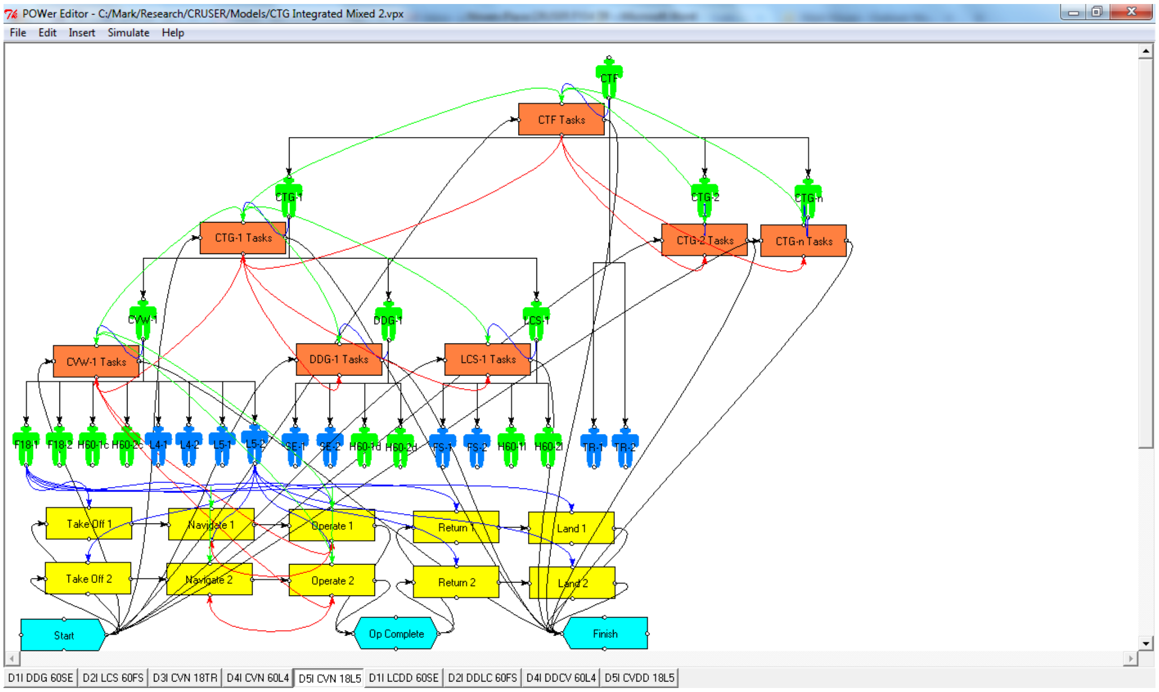

Figure 23. Model D5I – F/A-18 & L5 UAV

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IV. RESULTS

A. RESULTS OVERVIEW

In this section we present the key findings and results of our computational experiments. We first characterize results from our fieldwork and computational modeling effort. We then present findings and discuss results of our C2 computational experimentation.

B. FIELDWORK AND COMPUTATIONAL MODELING RESULTS

This study requires extensive fieldwork to understand both the manned and unmanned aircraft inventories available to and used by the Navy and other military services today. Through a nearly exhaustive investigation of diverse aircraft employed for ISR missions in general, we focus on those capable of and employed for ISR at sea.

Within this set, we focus on two manned aircraft, one fixed wing (i.e., F/A-18) and one rotary wing (i.e., MH-60), and we work to understand their essential ISR mission capabilities, uses, behaviors and performance characteristics. Because both of these aircraft types have been in use for considerable time, abundant data exist for specifying our computational models, and because both types reflect manned aircraft, their associated C2 and organization implications are relatively well-understood.

Within this set, we focus further on three unmanned aircraft reflecting diverse autonomy degrees, sizes, speeds, capacities, endurances and other characteristics: 1) ScanEagle, 2) FireScout and 3) Triton. Unlike their manned counterparts, however, these unmanned aircraft are relatively new to the Fleet at the time of this writing, and their associated C2 and organization implications are being discovered still.

Additionally, this study is forward looking and seeks to both anticipate and guide TASP C2 well into the future[20], so we focus on two UAV autonomy levels beyond those in the current unmanned aircraft inventory, to which we refer simply as Level 4 and Level 5 UAVs. Because these unmanned aircraft have yet to be deployed or developed, respectively, we must estimate their likely future capabilities, uses, behaviors and

[20] Indeed, we endeavor to maintain our research focus roughly 10 years ahead of emerging practice.

performance characteristics, and we must extrapolate through computational modeling their associated C2 and organization implications.

The extensive operational knowledge and detailed UAV understanding possessed by our research team elucidates the key information required to understand these seven diverse aircraft, and the extended fieldwork enables us to specify the computational models and establish a C2 organization experimentation capability that has never existed previously. This represents a substantial achievement through our research study.

As summarized in the preceding section, we develop and specify a set of computational models covering the whole matrix of 24 experiment conditions, and we partially replicate several such conditions by examining different variations within some cells. For instance, the cell D0P (autonomy degree 0, pooled interdependence) includes multiple different variations, in which we examine the ISR mission conducted by F/A-18s as well as MH-60s, operated from the CVN, DDG and LCS. In total we develop, specify, execute and analyze more than 36 different TASP C2 models to cover the 24 experiment conditions.

Table 6 summarizes this model set. The first column lists each of the six autonomy degrees (e.g., “D0” = Degree 0; “D5” = Degree 5), and the second column designates which ship platforms[21] the ISR aircraft operate from (e.g., “CVN” = carrier, “DDG” = destroyer, “LCS” = littoral combat ship, “LCDD” = littoral combat ship + destroyer[22]). The third column designates which two aircraft types conduct each ISR mission (e.g., “1818” = two F/A-18s, “6060” = two MH-60s, “60SE” = one MH-60 and one ScanEagle).

The remaining three columns are marked (x) to indicate where computational models have been developed. In all models where two aircraft of the same autonomy degree conduct a mission (e.g., two F/A-18s, two MH-60s, two ScanEagles), we examine all three interdependence levels (i.e., pooled, reciprocal, integrated[23]), but where a

[21] The Triton is land-based, and we presume that it comes under CTF control, hence the “CTF” designation.
[22] Where two different ship platforms are involved, we use only two letters for each, and we begin with the ship associated with the Leader aircraft. For instance, “LCDD” signifies that the Leader aircraft flies from an LCS and that the Wingman aircraft flies from a destroyer, whereas “DDLC” indicates that the Leader aircraft flies from a destroyer and that the Wingman aircraft flies from an LCS.
[23] Speaking technically, integrated interdependence does not apply to missions flown solely by two manned *or* two unmanned aircraft; that is, integrated interdependence applies only to missions flown by both manned *and* unmanned aircraft. Nonetheless, several model parameter settings differ between reciprocal

combination of manned and unmanned aircraft conduct a mission together (e.g., one MH-60 and one ScanEagle or FireScout, one F/A-18 and one Triton, one MH-60 or F/A-18 and one Level 4 or 5 UAV[24]), by definition only the integrated interdependence level applies, and hence only a single model is developed.

Table 6. Summary of TASP C2 Models

		Model Summary			
Level	Ship	Aircraft	Pool	Recip	Integ
D0	CVN	1818	x	x	x
	CVN	6060	x	x	x
	DDG	6060	x	x	x
	LCS	6060	x	x	x
D1	DDG	SESE	x	x	x
	DDG	60SE			x
	LCDD	60SE			x
D2	LCS	FSFS	x	x	x
	LCS	60FS			x
	DDLC	60FS			x
D3	CTF	TRTR	x	x	x
	CVCT	18TR			x
D4	CVN	L4L4	x	x	x
	CVN	60L4			x
	DDCV	60L4			x
D5	CVN	L5L5	x	x	x
	CVN	18L5			x
	CVDD	18L5			x

Each model is specified using aircraft performance data collected through our archival and field research. Appendix A – Section A summarizes aircraft performance data (e.g., endurance, crew size, sorties) for reference. Each model is specified using ISR mission and C2 tasks also (e.g., CTF/CTG/CVW command and staff work, aircraft navigation and ISR operation), the inputs for which derive from our archive and fieldwork too. Appendix A – Section B summarizes model task specifications for

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and integrated interdependence experiment conditions, and it is informative to examine even all-manned or all-unmanned aircraft missions through both such conditions.

[24] An implicit assumption is that the Level 4 UAV will be rotary wing helo, and hence tend to fly with the MH-60, and that the Level 5 UAV will be fixed wing jet, and hence tend to fly with the F/A-18. Nonetheless, *for C2 purposes*, we also examine some different combinations (e.g., Level 4 or 5 could be a vertical take-off and landing jet).

reference. Model staffing specifications (e.g., position, role, experience) derive similarly from our archival and field research also; they're summarized in Appendix A – Section C for reference. The set of parameters (e.g., centralization, formalization, communication probability) set to specify the baseline (i.e., D0P) model derive likewise from our archival and field research; they're summarized in Appendix A – Section D for reference.

Archival and field research inform us further regarding which parameters to vary systematically (e.g., team experience, matrix strength, noise probability) for our model manipulations across experiment conditions; they're summarized in Appendix A – Section E for reference. Model measures are inherent to the POWer computational environment, through which a huge number of parameters are available to serve as dependent variables. Our archival and field research guide us to focus on and employ only the set of model measures (e.g., duration, work cost, mission risk) appropriate for our context; they're summarized in Appendix A – Section F for reference.

As we specify and run these various models across the matrix of experiment conditions, it is important to note that the same tasks are performed by the same number of people, with the same skills, in the same organizations, across all of our experiment conditions. This gives us an extreme level of experiment control.

C. COMPUTATIONAL MODELING AND EXPERIMENTATION RESULTS

In this section we present findings and discuss results of our computational modeling and experimentation. We keep the data presentation at a relatively high level here in the body of this technical report, but we include great detail in Appendix B, in both numerical and graphical formats, for reference. Because we have so much data—through 36 different models [25], each simulated 50 times, across six autonomy degrees and four interdependence levels, assessed through eight performance dimensions—concise summarization is challenging. Leaving detailed summaries to Appendix B, here we focus on the most informative findings and results, and we organize the discussion in three parts: 1) Autonomy Degree, 2) Interdependence Level, and 3) C2 Implications.

[25] As noted above, in total we develop, specify, execute and analyze more than 36 different TASP C2 models to cover the 24 experiment conditions.

1. Autonomy Degree

Regarding autonomy degree, we can generalize to say that none of our performance measures varies linearly with increasing autonomy. Some—but not all—differences stem from the nature of the various aircraft types. Three relatively clear findings in this regard pertain to the measures *duration, functional risk* and *work cost*. Figure 24 delineates duration results across six autonomy degrees. For clarity—and to eliminate confounding from crossing interdependence levels—we show results for pooled interdependence only here, but the pattern holds for the other interdependence levels too. When discussing duration, it is important to recall from above that the simulated ISR mission has a *planned* duration[26] set at 24 hours, but actual time required to complete a mission successfully can vary clearly. In other words, this planned duration is constant across all experiment cells, but actual mission duration is a performance variable that we measure and compare through this computational experiment.

The vertical bars in the chart denote duration for each model (listed horizontally across the chart bottom). The four models to the left (i.e., one labeled "1818," and three labeled "6060") correspond to Degree 0 autonomy (i.e., manned aircraft) and all reflect relatively similar duration[27] results (e.g., roughly 30 hours). The next three models (i.e., labeled "SESE," "FSFS" and "TRTR") correspond to Degree 1 through 3 autonomy (i.e., unmanned aircraft in use today) and all reflect comparatively higher duration results (e.g., roughly 34 hours). The final two models (i.e., labeled "L4L4" and "L5L5") correspond to Degree 4 and 5 autonomy (i.e., future unmanned aircraft) and both reflect duration results similar to those of Degree 0 aircraft.

The similarities and differences stem in large part from the comparatively higher skill and culture experience that manned aircraft crews maintain over their (Degree 1 – 3)

[26] 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 these computational experiments.

[27] Keep in mind that duration (i.e., the time required for successful mission completion) is distinct from endurance (i.e., how long a particular aircraft type can fly). The F/A-18 aircraft, for instance, has endurance of roughly 1.5 hours, whereas endurance of the MH-60 is closer to 4.0 hours. To conduct a nominal 24 hour ISR mission, 16 F/A-18 sorties would be required, whereas only six would be required of the MH-60. This pertains to endurance. In terms of duration, however, both aircraft types are able to complete the ISR mission in roughly 30 hours.

unmanned counterparts. The higher skill in particular leads to fewer mistakes, hence lesser functional risk, and enables manned aircraft to complete missions in less time (duration). As UAVs (are expected to) become more advanced, this skill differential is anticipated to lessen (Degree 4 autonomy) and could even tip the other way (Degree 5 autonomy). Likewise with culture experience: as unmanned missions become increasingly integral—and perhaps even primary—to ISR, culture experience should increase and show negligible differential with respect to manned missions.

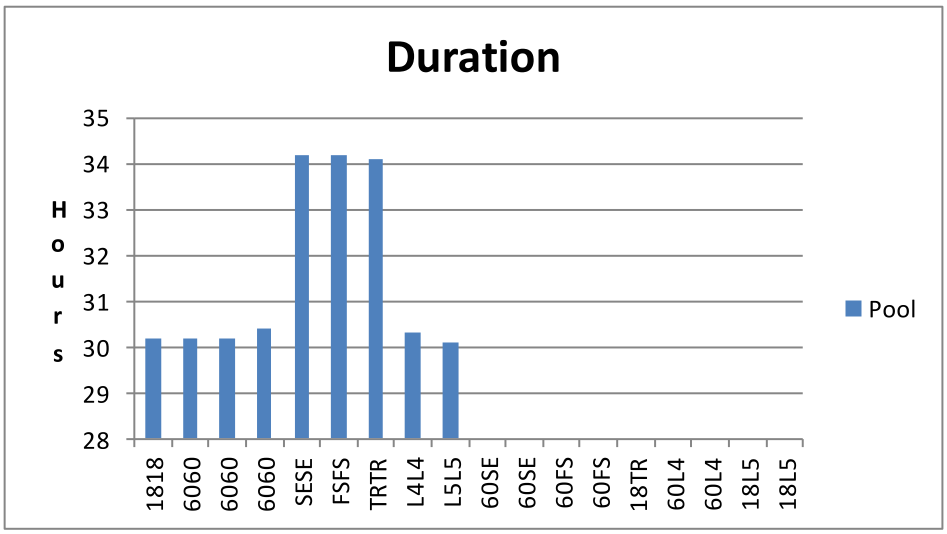

Figure 24. Duration – Pooled Interdependence

Figure 25 delineates functional risk results across the same six autonomy degrees and models. The pattern is very similar to and stems from the same factors that drive duration results. Note, for instance, the difference between results for the MH-60 (Degree 0) and FireScout (Degree 2) aircraft. In many organizations, the same crew members who fly the MH-60 helicopters also pilot and operate sensors for the FireScout. However, even such crewmembers have likely spent *many, many* more hours training on and operating the MH-60 than the FireScout, hence the skill difference. Moreover, such crewmembers are embedded deeply within the culture of manned aircraft—which has evolved through all the decades of manned aviation—whereas the culture of unmanned aircraft remains relatively nascent. Consider, for instance, the status differences at play in the Ward Room, Ready Room, ashore and other venues between aviators who fly manned aircraft versus those who control UAVs remotely, hence the culture difference.

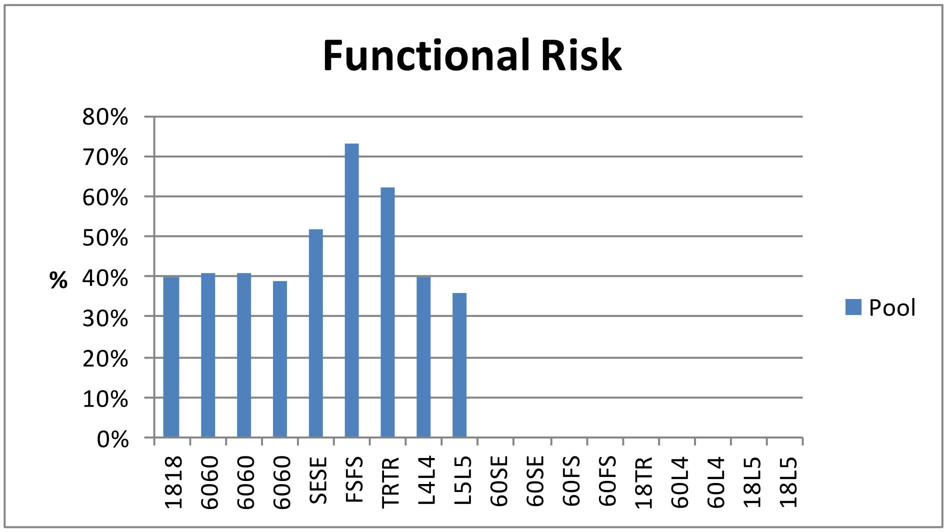

Figure 25. Functional Risk – Pooled Interdependence

Figure 26 delineates a very different pattern in terms of work cost across the six autonomy degrees. Although our cost parameters are *very rough and approximate*, they support the pattern delineated in this figure: different aircraft can incur dramatically different operating costs for performing the same, nominal, 24 hour ISR mission.

Succinctly, the F/A-18 appears to represent the most costly ISR platform, yet it also exhibits the greatest speed and mission flexibility (e.g., attack). The MH-60 costs roughly half as much to operate, is comparable to the FireScout, and has distinct capabilities (e.g., rescue operations). The Triton costs in turn about half as much as the FireScout, and the ScanEagle—along with the Degree 4 & 5 UAVs[28]—is expected to cost much less to operate. This finding holds across interdependence levels as well.

[28] Degree 4 & 5 UAVs represent future capabilities, and hence clearly have no operating cost data from which to draw. As summarized in Appendix A – Section A, we set costs for Degree 4 and 5 UAVs at the same levels as the ScanEagle. From the perspective of today's technology, this probably appears to be biased low, but given that we are forecasting *future capabilities* (e.g., processing power, miniaturization, integration, materials, nanotechnologies and like advances), any such bias may not be severe.

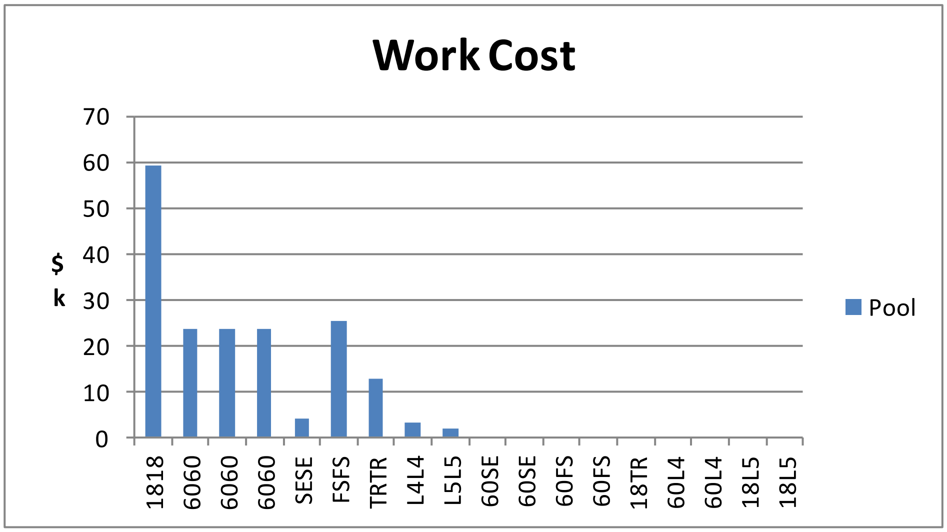

Figure 26. Work Cost – Pooled Interdependence

Other findings stem more from C2 considerations across autonomy degrees. Four explanatory findings in this regard pertain to the measures *coordination*, *wait*, *mission risk* and *maximum backlog*. Figure 27 delineates coordination results across six autonomy degrees. As above, we show results for pooled interdependence only here, but the pattern holds for the other interdependence levels too. Here we observe two different levels of coordination: 1) the manned aircraft and FireScout all reflect relatively higher levels (e.g., 13 – 15 person-hours), whereas 2) the other unmanned aircraft reflect lower levels (e.g., 3 – 4 person-hours).

Two factors appear to be playing parts: crew size and sorties. Generally, the higher the crew size and greater the number of sorties required to complete a nominal 24 hour ISR mission, the greater the coordination load. Although the F/A-18 has only a single pilot, this aircraft requires 16 sorties[29] to complete a nominal 24 hour mission, hence its comparatively higher coordination load. Alternatively, although the Triton has a (land-based) crew of three, it requires only a single sortie to conduct the nominal 24 hour mission, hence its comparatively lower coordination load. The ScanEagle has a

[29] Consider, for instance, how 16 pilots must be scheduled to fly their planes, at 16 different times; how such pilots must also be scheduled to rest, eat, plan the next mission and prepare for the subsequent flight; how each aircraft must be maintained and readied for flight at the right time; how the take off and navigation en route of each relieving flight must be coordinated, monitored and controlled with the return and landing of each flight that has been on station; and like factors.

(shipboard) crew of one, and along with the Level 4 and Level 5 UAVs, endurance is sufficient to complete the mission in a single sortie.

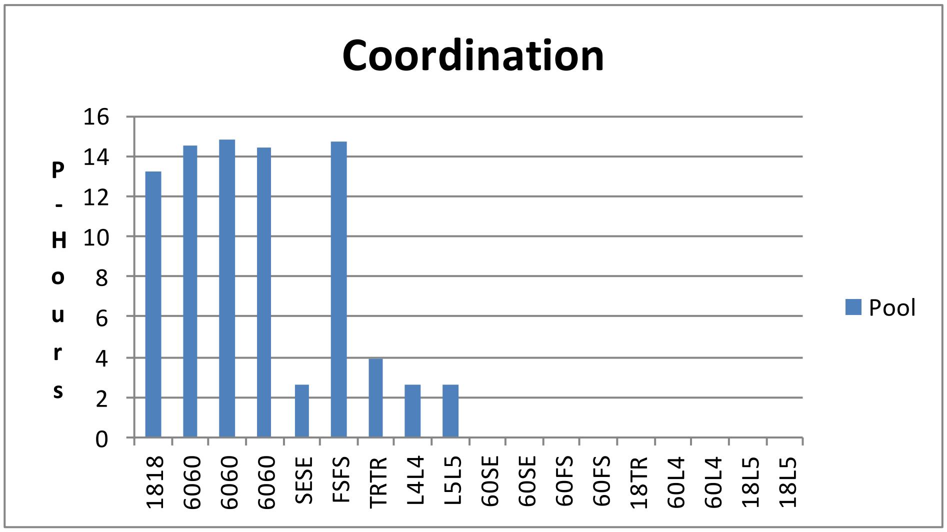

Figure 27. Coordination – Pooled Interdependence

Figure 28 delineates wait results across six autonomy degrees and reflects pooled interdependence. We observe the same pattern. With fewer people and fewer sorties to plan, coordinate, monitor and control, there is less time spent with people awaiting important information or decisions.

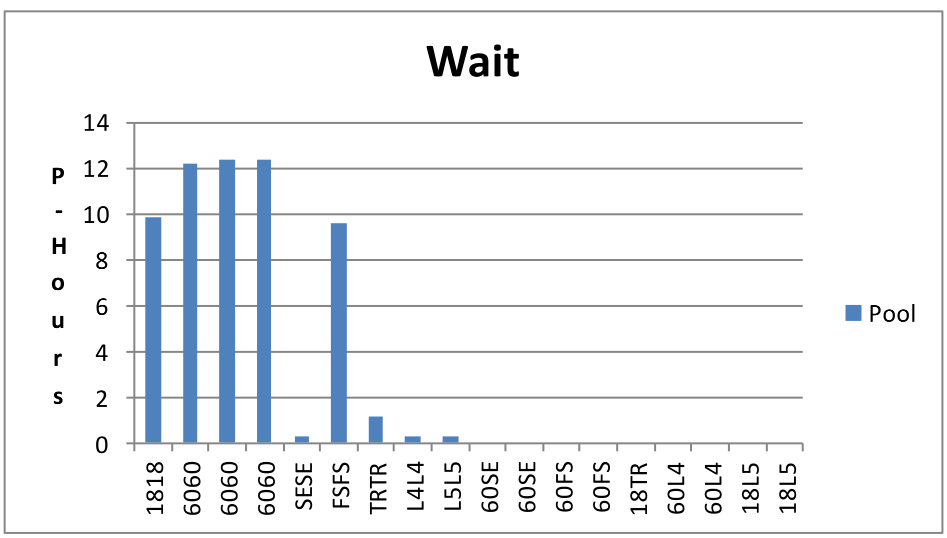

Figure 28. Wait – Pooled Interdependence

Figure 29 delineates mission risk results across six autonomy degrees and reflects pooled interdependence. Here a number of different factors tend to confound our ability to assign cause to the pattern. We have the same crew size and sortie issues as noted above, but mission risk is affected also by culture experience and skill in the POWer model, both of which are comparatively lower for the Autonomy 1 – 3 aircraft. This effect can cascade from making a greater number of mistakes, through differential rework levels, to higher fractions of residual, cross-functional errors that drive mission risk. The single C2 organization and approach specified across all autonomy degrees appears to have considerable limitations, which we discuss further below.

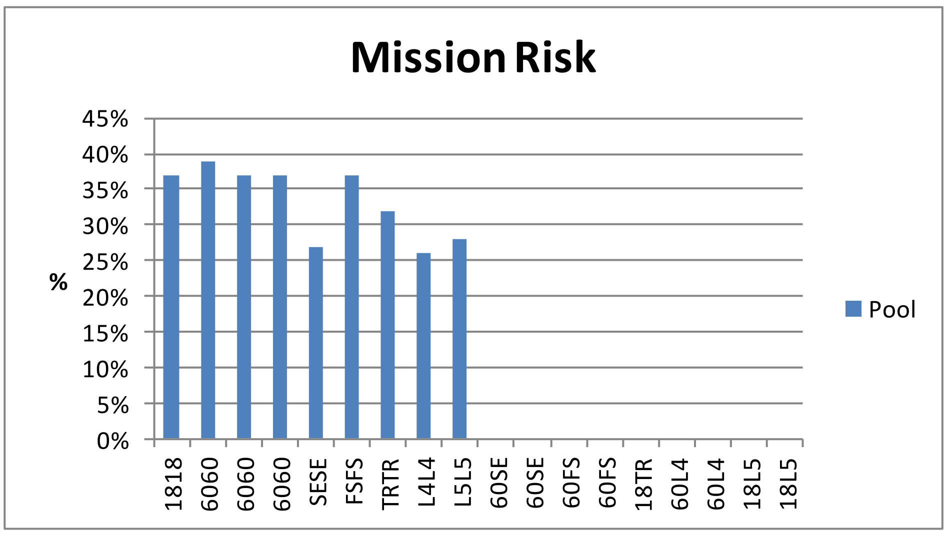

Figure 29. Mission Risk – Pooled Interdependence

Figure 30 delineates maximum backlog results across six autonomy degrees and reflects pooled interdependence. Here a number of different factors tend to confound our ability to assign cause to the pattern also, but all of the comments pertaining to mission risk in the POWer model above apply here too. In particular, the two future unmanned aircraft (i.e., Level 4 & 5 UAVs), with solitary crew size, long endurance, high culture experience and skill comparable to or exceeding that of manned counterparts experience the lowest backlogs.

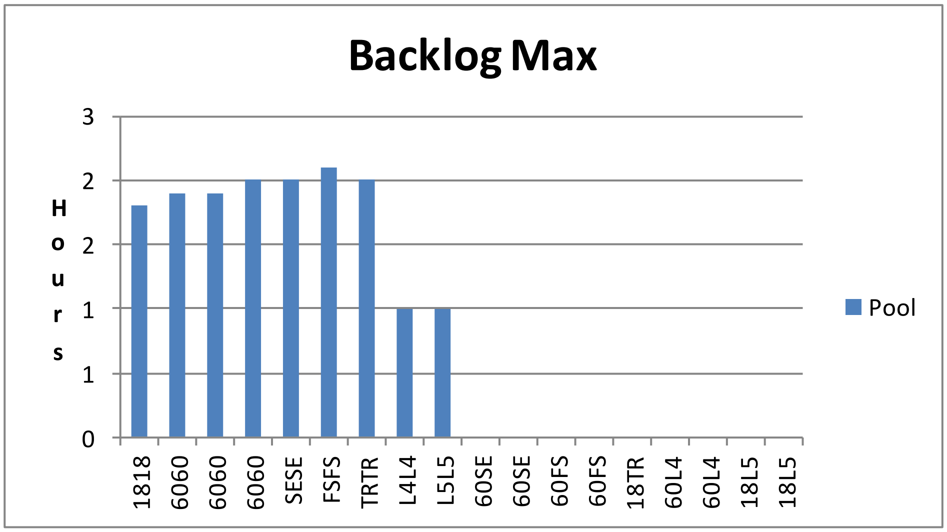

Figure 30. Maximum Backlog – Pooled Interdependence

2. Interdependence Level

In examining autonomy above, we hold interdependence level constant (pooled) to help isolate the effects. Here we isolate and examine interdependence effects, which are relatively clear: greater levels of interdependence correspond to higher values across almost all performance measures. It is important to note that higher does not necessarily imply either "better" or "worse," and some performance measures must be traded off against others (e.g., duration, rework, mission risk). Nonetheless, increasing interdependence makes almost all measures go up. This is clearly understandable in our TASP C2 context: as we pass through higher interdependence levels, the interactions between aircraft increase in frequency and intensity, and having multiple aircraft operating together in common airspace complicates their planning, operating, tracking, monitoring and intervening.

For instance, Figure 31 delineates the interdependence effect in terms of duration. Notice immediately how every experiment condition (shown horizontally across the chart bottom) reflects a monotonic duration increase with greater interdependence levels. Graphically, the (blue) vertical bars representing pooled interdependence are shorter than the corresponding (red) bars representing reciprocal interdependence. Missions take longer to complete with increasing interdependence levels. This is evident in particular with the transition from reciprocal to integrated interdependence. Recall that integrated interdependence subsumes its reciprocal counterpart but adds interorganizational interaction as well; that is, not only must multiple aircraft operate together in common airspace, teams of manned and unmanned aircraft must do so with integrated interdependence. This constitutes a qualitative difference[30].

[30] For instance, manned aircraft fly together in common airspace routinely. Pilots can see other aircraft aloft, they can communicate with one another; they hail generally from the same squadrons, and hence they know one another; plus, they probably fly together often. Alternatively, it is relatively rare for unmanned aircraft today to fly together in common airspace, for such aircraft (crews) generally are unable to sense one another in flight. Asking human pilots to fly with unmanned aircraft, and vice versa, invites great challenge and is a likely source of considerable controversy.

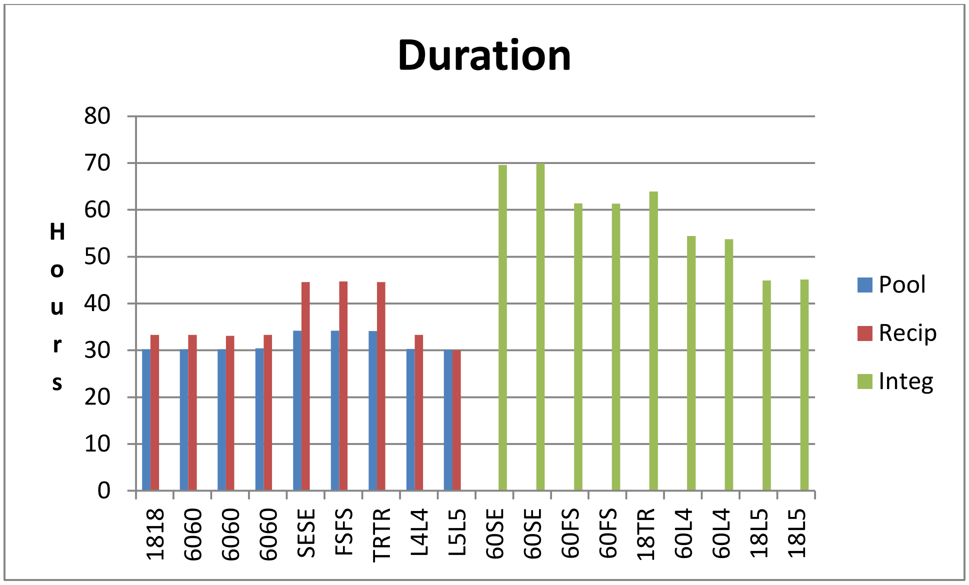

Figure 31. Duration – Interdependence Effect

Figure 32 delineates an even more extreme effect in terms of coordination, but this same effect attenuates somewhat in terms of work cost (not shown). Coordinating multiple aircraft flying in common airspace has a major impact in terms of C2. This is the case in particular for the manned aircraft and FireScout.

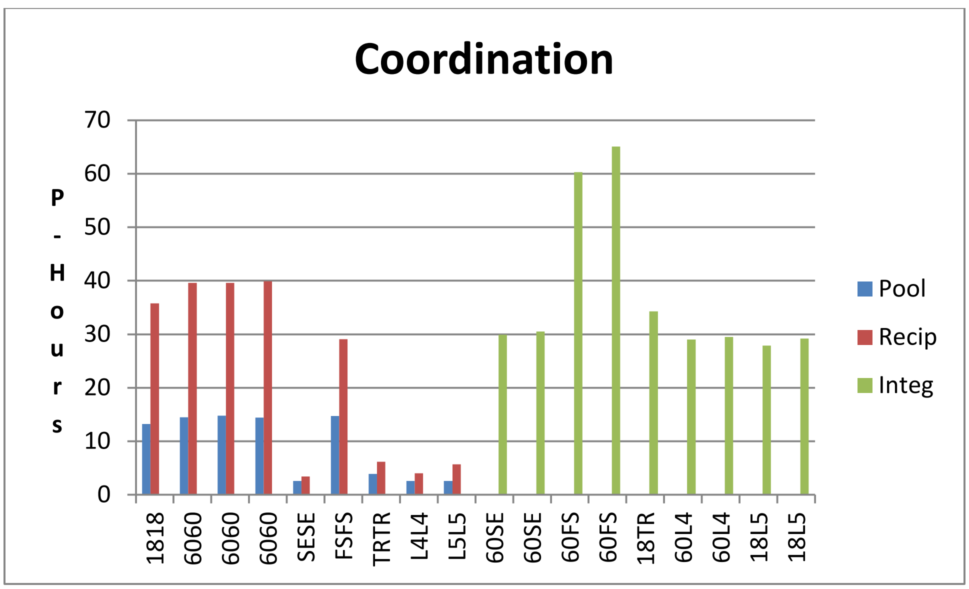

Figure 32. Coordination – Interdependence Effect

Conversely, Figure 33 delineates how interdependence appears to exert negligible influence over *functional* risk. Because functional risk, by definition, is limited to mistakes within functions and is driven largely by skill and experience, increasing interdependence levels should not be expected to affect it substantially. Simulation results confirm this expectation.

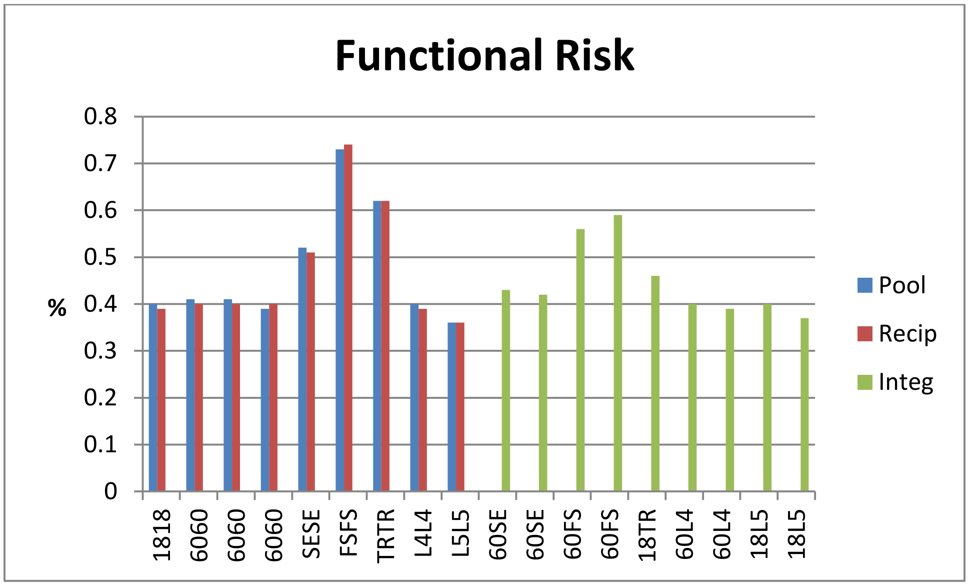

Figure 33. Functional Risk – Interdependence Effect

Figure 34 delineates a dramatically different story, however, as integrated interdependence exposes the ISR mission to roughly double the mission risk. With mission risk for integrated manned-unmanned sorties exceeding 70%, C2 for integrated interdependence appears clearly to have critical issues, which we discuss in considerable depth below. Maximum backlog (not shown) tells a similar story and contributes to its explanation.

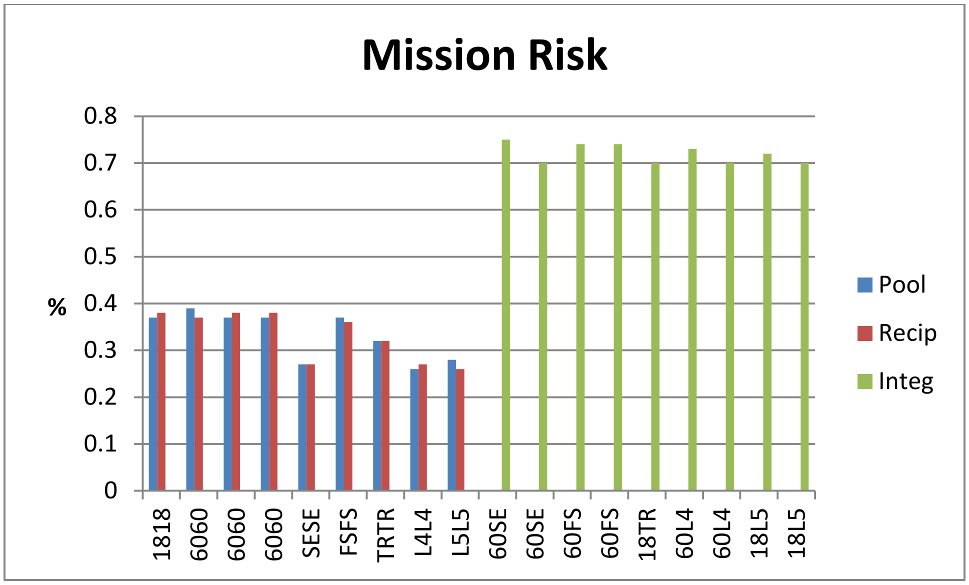

Figure 34. Mission Risk – Interdependence Effect

3. C2 Implications

Here we draw from our findings above to consider the C2 implications of the computational experiment. We begin by highlighting, recapitulating and elaborating on some of the key findings and results above that signal issues in terms of current or future TASP C2. This aids us in terms of identifying likely causes of such issues, and it enables us to conceive one or more promising alternate approaches to C2 organization.

Starting with current aircraft in operational use today, there is little cause for concern regarding Autonomy 0 (e.g., F/A-18, MH-60) with pooled interdependence (e.g., operating in separate airspaces). This is something that the Navy knows how to do well. There are no C2 implications per se here. This is business as usual.

Nonetheless, even though C2 appears to function acceptably well at present, several aspects of the extant and ubiquitous C2 organization and approach suggest that problems will emerge with continued advances in and integration of AS technology. For instance, the C2 organization reflects a tall, functional hierarchy, with considerable centralization, substantial formalization and frequent staff rotation. This makes for relatively long information flows and decision chains, coupled with perennial battles against knowledge loss from personnel turnover and challenges with cross-functional (and even more so with joint and coalition) interaction.

Recall from Figure 7 (reshown for reference here as Figure 35), for example, how even the operation of two manned aircraft (MH-60) involves the commanders, staffs, crews and operators from more than just a single ship platform (DDG and LCS in this case). This does not present any problems in terms of missions reflecting pooled interdependence (D0P), but even with manned aircraft, the situation complicates immediately with a transition to reciprocal interdependence (D0R): we find two aircraft being manned, flown and coordinated from different ships. Looking at the organization structure delineated in the figure, the lowest level role in the organization with authority over *both aircraft* is the CTG. Many organization experts would argue that the correspondingly long decision chains, information flows and staffing filters militate against efficient—or even effective—C2.

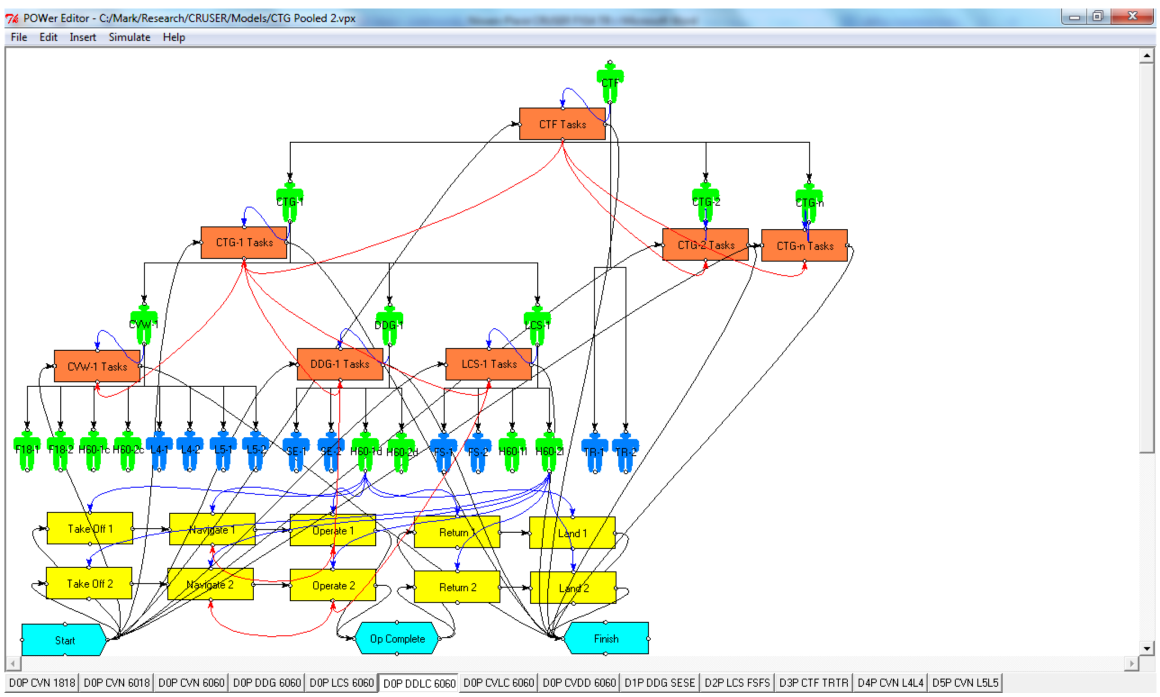

Figure 35. Baseline Model (D0P) – DDG MH-60 & LCS MH-60

Further, the formalization inherent within this C2 organization reflects a strong dependence upon written standards, rules and procedures (e.g., SOPs, TTPs, PPRs, work standards, job qualifications, organization interactions). Such standards, rules and procedures can be effective in organizations such as this that experience continuous personnel rotation, for the “business” of C2 and other activities is written down in explicit form to a large extent. For current missions involving manned aircraft, there is little issue, for the organization and its personnel have abundant experience in such context.

The introduction and integration of unmanned aircraft, however, represent much, much more recent phenomena, which are requiring even longtime and familiar standards, rules and procedures to be rewritten, and the pace at which UAVs and other AS are being introduced and integrated appears to be accelerating. This suggests that formalization through written documents may have a hard time keeping up with rapid and local changes onboard various ships and among diverse aircrews. Instead, local knowledge develops in each command, on each ship and among each aircrew, but such knowledge remains largely tacit, inherent in the experiences of individual people and the teams on which they interact. Such local knowledge is unlikely to be standard across different commands, ships and aircrews, so people will not be able to rotate so fluidly as they do at present. As with the long decision chains, information flows and staffing filters noted above, many organization experts would argue here that the correspondingly high dependence upon standardization and written documentation militate against efficient—or even effective—C2.

Indeed, when we move into Autonomy 1 – 3 (e.g., ScanEagle, FireScout, Triton), our results reveal several difficulties that arise. For instance, recall from above that unmanned aircraft take longer (duration) to complete the ISR mission than their manned counterparts do and that they experience greater functional risk. This stems in large part from the comparatively higher skill and culture experience that manned aircraft crews maintain over their (Degree 1 – 3) unmanned counterparts. The higher skill in particular leads to fewer mistakes, and hence lesser functional risk, and enables manned aircraft to complete missions in less time (duration).

In terms of C2—and perhaps somewhat counter intuitively—our results imply that unmanned (ISR) missions require *more* planning, monitoring, intervening and like control activities than their manned counterparts. Greater numbers of C2 staff—or more skilled and experienced staff members—will be required for unmanned than for manned missions, and such missions will take more time, suffer from more mistakes, and generally tax the C2 organization more. Long decision chains, information flows and staffing filters, combined with strong dependence upon written standards, rules and procedures, remain inherently at odds against the proliferation of unmanned aircraft in the context of constant personnel rotation and evolving local knowledge.

Alternatively and eventually, as UAVs (are expected to) become more advanced, this skill differential is anticipated to lessen (Degree 4 autonomy) and could even tip the other way (Degree 5 autonomy). Likewise with culture experience: as unmanned missions become increasingly integral—and perhaps even primary—to ISR, culture experience should increase and show negligible differential with respect to manned missions. These increases in skill and experience will help to mitigate the C2 tax imposed by unmanned missions, but it will likely be quite some time before the corresponding, future UAVs become operational, so we must continue to address and endure the higher C2 load for now. This suggests strongly that we should consider redesigning our familiar C2 organization to address the imminent shortcomings noted above.

Recall further from above how increasing levels of interdependence correspond with monotonically longer mission durations. Parallel to the shift from manned to unmanned aircraft missions discussed above (e.g., in which durations extend from Autonomy 0 to Autonomy 1 – 3 aircraft), durations extend also as missions become increasingly interdependent. Two aircraft—whether manned or unmanned—impose greater C2 demands when flying together in common airspace than alone in separate airspaces, and when both manned and unmanned aircraft fly together in common airspace this effect gets exacerbated. Hence the duration effect amplifies through the interaction of increasing autonomy and interdependence.

As above, greater numbers of C2 staff—or more skilled and experienced staff members—will be required for reciprocal than for pooled interdependence missions, and such missions will take more time, suffer from more mistakes, and generally tax the C2 organization more. Such C2 tax becomes even more severe with integrated interdependence, for which leaders, managers and policy makers must begin planning now. In particular, required C2 skills and experiences may not be uniform across manned and unmanned missions, and the Military’s current C2 organization and approach appear inadequate.

Indeed, the effects of accumulated experience and specialization suggest that we may find one set of C2 personnel (e.g., planners, controllers, watch standers) that is proficient principally in terms of manned missions, whereas a different cadre of personnel becomes proficient principally in terms of unmanned missions. One may think—initially and perhaps naïvely—that "C2 is C2," and "ISR missions are ISR missions." However, our results suggest otherwise.

Given our current C2 organization and approach, this will limit the degree of flexibility available in terms of assigning *suitably experienced personnel* to different jobs, and many organizations will need to staff themselves with seemingly redundant personnel: some possessing skill and experience with manned operations and others possessing similar yet distinct skill and experience with their unmanned counterparts. As task interdependence continues its shift toward integrated manned-unmanned missions, such similar yet distinct skill and experience will likely break down and become ineffective for C2. Alternatively, as noted below, other approaches to organizing and conducting C2 offer potential to mitigate these detrimental effects.

Further, we find additional C2 insights that emerge from the measures *coordination, wait, mission risk* and *maximum backlog*. Coordination requirements increase substantially under reciprocal interdependence, as aircrews and others must interact much more closely during mission execution than under pooled interdependence, and an increase in mission exceptions and mistakes seems inevitable, particularly as multiple aircraft fly together from different ship platforms. This is the case even for manned aircraft missions.

When we shift further to integrated manned-unmanned missions, moreover, computational results show that C2 will complicate still more through decreases in team and application experience (e.g., manned and unmanned aircrews will have less experience working with one another than with themselves), increases in communication requirements (e.g., coordinating unmanned aircraft from land [e.g., Triton] with shipboard manned or unmanned aircraft will tax commanders, staff members and aircrews alike), amplified noise (e.g., many more distractions and interruptions[31] will

[31] Recall, for instance, how unmanned aircraft (and crews) are generally unable to sense other aircraft aloft. Whereas two manned aircraft pilots can see one another's aircraft and coordinate their mutual actions

impact C2 work), and lower level roles (e.g., commanders, staff members and aircrews will need to establish, change and refine procedures to accommodate rotating personnel and local mission demands).

Results indicate further that wait times will lengthen, and mistakes will accumulate, as commanders and staff members become increasingly backlogged by exceptions, information requests and decision demands, which can cascade into progressively ever longer wait times, accumulations of mistakes and greater backlogs. Together these complications suggest that—with extant C2 organizations and approaches—we will make more mistakes; experience increasing time pressure; require greater effort, more time and higher cost to conduct missions; and operate under conditions of substantially higher mission risk. Again, as noted below, other approaches to organizing and conducting C2 offer potential to mitigate these detrimental effects.

Additionally, the analysis in this study centers on only *two aircraft* conducting *ISR missions*. Yet we find evident and compelling issues with the TASP C2 even in this simple case. Consider further the C2 implications in terms of scaling to large numbers of (manned and) unmanned aircraft flying in common airspace. Swarming, counterswarming and like tactics are being researched and developed now. If our C2 organization and approach appear fragile with aircraft operating reciprocally (or integrally) only in pairs today, then one can imagine easily how such organization and approach could break under the load of tens or even hundreds (or possibly thousands) of aircraft operating simultaneously and reciprocally (or integrally). Imagine further the exacerbation stemming from a shift to strike and other missions that diverge from the ISR context of this study.

Although clearly a significant amount of effort is on-going to develop the guidance necessary to mitigate risks associated with the lack of current standards and policy for unmanned systems, as noted above, written standards, rules and procedures may not be able to keep pace with continuing AS advances and mission integrations for much longer. Moreover, we note further how the continuous rotation of personnel may necessitate the development and refinement of intensely local knowledge within each

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directly, even "simple" maneuvers such as flying on a leader's wing become complicated with integrated interdependence.

different command, onboard each different ship, and among each different aircrew. Organizations will need to learn how to learn more quickly, and the current approach to education and training—with a heavy emphasis upon failure-prone, on-the-job training (OJT) and perishable, just-in-case training (JIC)—will likely fail.

Other, more advanced approaches to accelerating knowledge flows through C2 organizations will likely become mandatory—so that people, teams and organizations can learn more quickly and with fewer mistakes—and people will need ways to learn just in time (JIT), knowing what to do and how to do it well in the local context (e.g., when and where such knowing is needed). The Military's extant C2 organization and approach appear to be unprepared to meet these organization learning demands.

We understand increasingly well how C2 should focus on four, fundamental and inextricable elements: *people, process, organization* and *technology* (Nissen, 2013). People (esp. in terms of culture, trust and experience) are notoriously slow to change, and process (e.g., standards, procedures, formalizations) can lag well behind local experience, but organization in our military context remains all but immutable. These conditions conflict violently with technology, which is advancing very rapidly in terms of AS, and suggest that considerable, thoughtful and informed redesign will need to focus on the C2 organization. Our current C2 organization and approach may operate well across many conditions and circumstances at present, but teams of autonomous systems and people—especially as manifest through integrated manned-unmanned aircraft missions—appear to fall way beyond this set of current conditions and circumstances.

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V. CONCLUSION

The technological capabilities of autonomous systems continue to accelerate. Although AS are *replacing* people in many skilled mission domains and demanding environmental circumstances, people and machines have complementary capabilities, and *integrated* performance by AS and people *working together* can be superior to that of either AS or people working alone. We refer to this increasingly important phenomenon as Teams of Autonomous Systems and People, and we identify a plethora of open, command and control 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)? 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 of people and AS into combined units (e.g., integrated or composite squadrons; see CFFC, 2013)? For a third, how can researchers, policy makers and leaders develop confidence that their chosen C2 organization and 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) 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.

Computational experimentation offers unmatched yet largely unexplored potential to address C2 questions along these lines. Once computational models have been developed and validated, they can become virtual prototype C2 organizations to be examined empirically and under controlled conditions through efficient computational experiments. 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. The central problem is, this kind of C2 organization experimentation capability has yet to be developed and demonstrated in the TASP domain.

This is where our ongoing research project begins to make an important contribution. Building upon a half century of research and practice in modeling and simulation in general, and two decades of *organization* modeling and simulation work in particular, we have access to computational modeling and simulation technology representing the current state of the art. Agent-based organization models developed through this technology have also been validated dozens of times to represent faithfully the structure, behavior and performance of counterpart real-world organizations. Plus, we have adapted the same computational modeling and simulation technology over several years to the military domain to examine joint task forces, distributed operations, computer network operations, and other missions that reflect increasingly common Navy, joint and coalition endeavors.

In this technical report, we provide an overview of the POWer computational environment used to model and simulate TASP C2 organizations and phenomena. We explain how qualitative and quantitative models can be integrated and executed to examine dynamic properties and behaviors of diverse C2 organizations and approaches. We explain further how POWer reflects an information processing view of organizations, and we elaborate its ontological, computational and validational implications.

We summarize in turn the research method of computational experimentation. Like laboratory or field experimentation, computational experiments are designed in advance and conducted with precise controls and theoretically driven manipulations, but they further 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.

In short, we employ POWer to develop a computational model that represents our TASP C2 organization, technology and environment, and we analyze AS operations at sea to specify such model. This model and the associated operations focus on the CTG, with a CVN and one or more DDGs, LCSs and other ship platforms employed for both manned and unmanned aircraft ISR missions, with particular emphasis on TASP C2 implications.

We then identify a set of manipulations to represent six different autonomy degrees (Degree 0 – 5) and four increasing interdependence levels (Pooled, Sequential, Reciprocal, Integrated), and we specify a robust battery of eight dependent measures to gauge comparative performance across 24 computational experiment conditions. A unique computational model is developed for each experiment, simulated 50 times, and examined across our array of performance measures, which produce empirical results for analysis. Detailed model specifications—including experiment controls, manipulations and measures—are presented in Appendix A, and detailed results are presented in Appendix B, for reference.

Key results follow, beginning with findings from our extensive fieldwork. Through a nearly exhaustive investigation of diverse aircraft employed for ISR missions in general, we focus on those capable of and employed for ISR at sea, and we decide to focus on two manned aircraft and three unmanned aircraft in operation today. To support our forward looking study, we also focus on two additional UAV autonomy levels beyond those in the current unmanned aircraft inventory. The extensive operational knowledge and detailed UAV understanding possessed by our research team elucidates the key information required to understand these seven diverse aircraft, and the extended fieldwork enables us to specify the computational models to establish a C2 organization experimentation capability that has never existed previously. This represents a substantial achievement through our research study.

We include key results pertaining to our computational modeling effort too, developing and specifying a set of computational models covering the whole matrix of 24 experiment conditions. We further partially replicate several such conditions by examining different variations within some cells: developing, specifying, executing and analyzing more than 36 different TASP C2 models to cover the 24 experiment conditions.

Highly insightful findings emerge from our campaign of C2 computational modeling and experimentation, which we organize in three parts: 1) Autonomy Degree, 2) Interdependence Level, and 3) C2 Implications. Regarding autonomy degree, we can generalize to say that none of our performance measures varies linearly with increasing autonomy. Nonetheless, autonomy degree is a very impactful variable, and we find major C2 performance differences across the various manned and unmanned aircraft types, particularly in terms of the measures *duration, functional risk* and *work cost*. Specifically, the UAVs in our current inventory (Autonomy 1 – 3) take considerably longer to complete the ISR mission than either the manned (Autonomy 0) or future unmanned (Autonomy 4 & 5) aircraft. These same, current inventory UAVs also present greater functional risk. Both of these results stem from the lesser skill and experience levels associated with the corresponding UAV aircrews, with an accumulation of mistakes and required rework affecting mission duration and functional risk levels directly. This affects C2 substantially, as longer durations and greater functional risk levels must be accommodated explicitly through mission planning, execution, monitoring and intervention activities.

Work cost results affect C2 substantially also, as different aircraft can incur dramatically different operating costs for performing the same, nominal 24 hour ISR mission. Succinctly, the F/A-18 appears to represent the most costly ISR platform, yet it also exhibits the greatest speed and mission flexibility (e.g., attack). The MH-60 costs roughly half as much to operate, is comparable to the FireScout, and has distinct capabilities (e.g., rescue operations). The Triton costs in turn about half as much as the FireScout, and the ScanEagle—along with the Level 4 & 5 UAVs—is expected to cost much less to operate. All other considerations aside, the operating cost of an ISR mission could become an important C2 consideration.

Regarding interdependence level, we isolate and examine interdependence effects, which are relatively clear: greater levels of interdependence correspond to higher values (but not necessarily "better" or "worse") across almost all performance measures. This is clearly understandable in our TASP C2 context, for interactions between aircraft increase in frequency and intensity, and having multiple aircraft operating together in common airspace complicates their planning, operating, tracking, monitoring and intervening.

For instance, we find that missions take longer to complete with increasing interdependence levels. This is evident in particular with the transition from reciprocal to integrated interdependence. As another instance, we see clearly an even more extreme effect in terms of coordination. Coordinating multiple aircraft flying in common airspace has a major impact in terms of C2. A third instance centers on mission risk, which nearly doubles as we transition from reciprocal to integrated interdependence. C2 for integrated interdependence appears to have critical issues.

Regarding C2 implications, we begin by summarizing findings pertaining to current aircraft in operational use today: there is little cause for concern regarding Autonomy 0 (e.g., F/A-18, MH-60) with pooled interdependence (e.g., operating in separate airspaces). This is something that the Navy knows how to do well. There are no C2 implications per se here. This is business as usual.

Nonetheless, even though C2 appears to function acceptably well at present, several aspects of the extant and ubiquitous, military C2 organization and approach suggest that problems will emerge with continued advances in and integration of AS technology. For instance, the C2 organization reflects a tall, functional hierarchy, with considerable centralization, substantial formalization and frequent staff rotation. This makes for relatively long information flows and decision chains, coupled with perennial battles against knowledge loss from personnel turnover and challenges with cross-functional (and even more so with joint and coalition) interaction. As another instance, the formalization inherent within this C2 organization reflects a strong dependence upon written standards, rules and procedures, but the pace at which UAVs and other AS are being introduced and integrated appears to be accelerating, and such formalization through written documents may have a hard time keeping up with rapid and local changes onboard various ships and among diverse aircrews. Many organization experts would argue that both instances militate against efficient—or even effective—C2.

Indeed, these study results imply—somewhat counter intuitively—that unmanned (ISR) missions require *more* planning, monitoring, intervening and like control activities than their manned counterparts. Given our current C2 organization and approach, greater numbers of C2 staff—or more skilled and experienced staff members—will be required for unmanned than for manned missions, and such missions will take more time, suffer from more mistakes, and generally tax the C2 organization more. Although the capabilities of future UAVs may mitigate these effects to some extent, we must continue to address and endure the higher C2 load for now, and we should consider redesigning our familiar, military C2 organization to address the imminent shortcomings noted above.

Further, required C2 skills and experiences may not be uniform across manned and unmanned missions. Indeed, we may find one set of C2 personnel (e.g., planners, controllers, watch standers) that is proficient principally in terms of manned missions, whereas a different cadre of personnel becomes proficient principally in terms of unmanned missions. *Given our current C2 organization and approach,* this will limit the degree of flexibility available in terms of assigning *suitably experienced personnel* to different jobs, and many organizations will need to staff themselves with seemingly redundant personnel: some possessing skill and experience with manned operations and others possessing similar yet distinct skill and experience with their unmanned counterparts. Results reveal that as task interdependence continues its shift toward integrated manned-unmanned missions, such similar yet distinct skill and experience will likely break down and become ineffective for C2. Alternatively, as noted below, other approaches to organizing and conducting C2 offer potential to mitigate these detrimental effects.

Results reveal further that C2 organizations will make more mistakes; experience increasing time pressure; require greater effort, more time and higher cost to conduct missions; and operate under conditions of substantially higher mission risk. Moreover, if our C2 organization and approach appear fragile with aircraft operating reciprocally (or integrally) only in pairs today, then one can easily imagine how such organization and approach could break under the load of tens or even hundreds (or possibly thousands) of aircraft operating simultaneously and reciprocally (or integrally). Imagine further the exacerbation stemming from a shift to strike and other missions that diverge from the ISR context of this study.

Organizations will need to learn how to learn more quickly, and the current approach to education and training will likely fail. Other, more advanced approaches to accelerating knowledge flows through C2 organizations will likely become mandatory—so that people, teams and organizations can learn more quickly and with fewer mistakes—and people will need ways to learn just in time (JIT), knowing what to do and how to do it well in the local context (e.g., when and where such awareness is needed). Our extant military C2 organization and approach appear to be unprepared to meet these organization learning demands.

We understand increasingly well how C2 should focus on four, fundamental and inextricable elements: *people, process, organization* and *technology*. Our current C2 organization and approach operate well across many conditions and circumstances at present, but teams of autonomous systems and people—especially as manifested through integrated manned-unmanned aircraft missions—appear to fall way beyond this set of current conditions and circumstances.

We do not have all of the answers in the present study, but C2 organization (re)design lies at the center—particularly to promote rapid organization learning and to accelerate knowledge flows—and we may experience the compelling need to shift away from our familiar, hierarchical, archetypical C2 organization and toward higher maturity, agile, edge-like archetypes (e.g., *Collaborative*; see Alberts & Nissen, 2009).

Moreover, this elucidates an organization challenge for TASP C2 in general and the CTG in particular: mission efficacy may require shifting from one C2 approach and organization to another depending upon the context; that is, the same CTG (or other C2 organization) may need to employ different C2 approaches and organizations across the range of diverse TASP contexts, even within the same ISR mission set. Some nominal mission (e.g., "Mission-1") may be approached best by the traditional hierarchy, for instance, but then the next nominal mission (e.g., "Mission-2") may require Self-Synchronization or other, different C2 organization and approach. This will require not only understanding *which* C2 organization and approach is most appropriate for each particular mission, but also knowing *how* to transition from one C2 organization and approach to another. As such *we're defining the state of the art with our research*, and such C2 organization selection and transition is *way beyond current practice*.

We need to understand more about future AS, and we need to examine both current and future, manned and unmanned, aircraft missions through alternate C2 organizations and approaches (e.g., Hierarchy, Collaborative, Self-Synchronization). This represents the research trajectory on which this present study falls, and we welcome other researchers, leaders and policy makers to join our effort to develop good answers and to provide effective guidance. C2 represents the single, most important determinant of military efficacy (Nissen, 2013), and although we have been learning and mastering C2 over many millennia, we're witnessing quantum change in terms of AS at present, and the military that masters the associated C2 most quickly may very well win the next encounter involving TASP.

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APPENDIX A

In this appendix we include detailed model specifications for reference. Details pertain in sequence to A) aircraft performance characteristics, B) model task specifications, C) model staffing specifications, D) baseline model parameters, and E) model manipulations. 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, taking into account, 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
DDGs	Duration	120d	Air	Medium	Medium	Medium	0.10
LCSs	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) and littoral combat ship (LCS) 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[32]), 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[33] 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

[32] 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.

[33] 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	2	PM	Medium	Medium	1	0	A(M)
LCS	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) and littoral combat ship (LCS) 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 TASP C2 in this model, we include the three highest operational levels[34] of command and staff work (i.e., CTF at Level 4; CTG at Level 3; and CVW, DDG and LCS 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

[34] 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[35] 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.

[35] 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 – 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 TASP C2 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.

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

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 awareness; as with centralization and formalization, the Medium setting strikes a balance within this TASP C2 organization model[36]. Each of these model parameters ranges from Low to High.

[36] 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.

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.

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.

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**

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).

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 TASP C2 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. Model Measures

Measure	**Description**
Duration (hours)	Total clock or calendar time required to complete a mission
Rework (person-hours)	Amount of effort expended 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.

VII. APPENDIX B

In this appendix we include detailed model results for reference. Details pertain in sequence to A) numerical results and B) graphical results.

A. NUMERICAL RESULTS

We begin by summarizing numerical results from the computational experiments. Results in terms of each of the model measures are summarized in turn.

1. Duration

Table 13 summarizes results for duration. The first column of the table is labeled "Level" and refers to autonomy degree. "D0" in the first row, for instance, corresponds to autonomy degree 0 (i.e., manned aircraft). All autonomy levels 0 – 5 are included. The second column of the table is labeled "Ship" and refers to the ship platform that the manned and/or unmanned aircraft operate from. The three ship platforms (i.e., CVN, DDG, LCS) are all shown on separate rows—corresponding to separate POWer models—within the D0 section, for instance. The third column of the table is labeled "Aircraft" and refers to the aircraft flown to perform the ISR mission. Two aircraft are involved with every mission within this study, and each is designated by a two-digit label. "1818" corresponds to a mission conducted by two F/A-18 aircraft, for instance, with "6060" corresponding to a mission conducted by two MH-60 aircraft This same labeling continues down the table through all six autonomy degrees.

Table 13. Simulation Results – Duration

		Duration		(hrs x 10)	
Level	Ship	Aircraft	Pool	Recip	Integ
D0	CVN	1818	302	333	456
	CVN	6060	302	333	455
	DDG	6060	302	331	454
	LCS	6060	304	333	456
D1	DDG	SESE	342	446	624
	DDG	60SE			696
	LCDD	60SE			699
D2	LCS	FSFS	342	447	620
	LCS	60FS			614
	DDLC	60FS			613
D3	CTF	TRTR	341	446	622
	CVCT	18TR			639
D4	CVN	L4L4	303	333	460
	CVN	60L4			544
	DDCV	60L4			537
D5	CVN	L5L5	301	300	329
	CVN	18L5			449
	CVDD	18L5			451

The fourth column of the table is labeled “Pool” and refers to duration measured (hours x 10) under the pooled interdependence experiment condition. For instance in the first row (i.e., D0 CVN 1818), the result shown is 302, which is 30.2 hours; that is, the ISR mission required just over 30 hours to complete in this experiment condition (i.e., conducted by two F/A-18s operated in separate airspace from the CVN). The other three D0 results (i.e., D0 CVN 6060, D0 DDG 6060, D0 LCS 6060) are very close[37] in terms of mission duration (i.e., 302, 302, 304, respectively).

The fifth column in the table is labeled “Recip” and refers to duration measured (hours x 10) under the reciprocal interdependence experiment condition. For instance in the first row (i.e., D0 CVN 1818), the result shown is 333, which is 33.3 hours; that is, the ISR mission required just over 33 hours to complete in this experiment condition (i.e., conducted by two F/A-18s operated in separate airspace from the CVN). The other three

[37] There are myriad reasons why the same mission conducted by different aircraft operating from different ship platforms and controlled by different C2 organizations may reflect differing performance levels. Alternatively, where all things remain the same—*ceteris paribus*—one would expect the results to be very close if not exact. We discuss reasons for variation in the Results section.

D0 results (i.e., D0 CVN 6060, D0 DDG 6060, D0 LCS 6060) are very close in terms of mission duration (i.e., 333, 331, 333, respectively).

The sixth column in the table is labeled "Integ" and refers to duration measured (hours x 10) under the integrated interdependence experiment condition[38]. For instance in the first row (i.e., D0 CVN 1818), the result shown is 456, which is 45.6 hours; that is, the ISR mission required over 45 hours to complete in this experiment condition (i.e., conducted by two F/A-18s operated in separate airspace from the CVN). The other three D0 results (i.e., D0 CVN 6060, D0 DDG 6060, D0 LCS 6060) are very close in terms of mission duration (i.e., 455, 454, 456, respectively).

The same scheme follows for the other autonomy levels. In the autonomy degree 1 ("D1") section (see Column 1), for instance, we find three entries—corresponding to three different models—with the corresponding ship platforms (e.g., "DDG") and aircraft (e.g., "SESE") listed. Using our labeling system discussed above, "DDG" refers to one or more destroyers (DDGs) serving as the ship platform for the ISR mission conducted by both aircraft, and "LCDD" refers to one or more Littoral Combat Ships (LCSs) and destroyers serving together as ship platforms for the ISR mission conducted by the two aircraft. Likewise, "SESE" signifies that two ScanEagles are involved, and "60SE" signifies that one MH-60 and one ScanEagle are involved. This pattern and scheme continues through all autonomy degrees.

2. Rework

Table 14 summarizes results for rework. The layout of the table is identical to the one above. The values in the first row (i.e., " D0 CVN 1818") are 566, 549 and 400 (person-hours x 10), respectively, for the pooled, reciprocal and integrated interdependence conditions. More specifically, the ISR mission required 56.6 person-hours of rework in the pooled condition, 54.9 person-hours in the reciprocal condition, and 40.0 person-hours in the integrated condition.

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[38] Speaking technically, integrated interdependence does not apply to missions flown solely by two manned *or* two unmanned aircraft; that is, integrated interdependence applies only to missions flown by both manned *and* unmanned aircraft. Nonetheless, several model parameter settings differ between reciprocal and integrated interdependence experiment conditions, and it is informative to examine even all-manned or all-unmanned aircraft missions through both such conditions.

Table 14. Simulation Results – Rework

		Rework		(p-hrs x 10)	
Level	Ship	Aircraft	Pool	Recip	Integ
D0	CVN	1818	566	549	400
	CVN	6060	623	608	442
	DDG	6060	632	596	437
	LCS	6060	643	596	428
D1	DDG	SESE	124	126	73
	DDG	60SE			256
	LCDD	60SE			258
D2	LCS	FSFS	459	454	269
	LCS	60FS			362
	DDLC	60FS			347
D3	CTF	TRTR	150	153	95
	CVCT	18TR			238
D4	CVN	L4L4	134	136	82
	CVN	60L4			262
	DDCV	60L4			258
D5	CVN	L5L5	134	133	80
	CVN	18L5			241
	CVDD	18L5			258

3. Coordination

Table 15 summarizes results for coordination. The layout of the table is identical to those above. The values in the first row (i.e., " D0 CVN 1818") are 132, 358 and 454 (person-hours x 10), respectively, for the pooled, reciprocal and integrated interdependence conditions. More specifically, the ISR mission required 13.2 person-hours of coordination in the pooled condition, 35.8 person-hours in the reciprocal condition, and 45.4 person-hours in the integrated condition.

Table 15. Simulation Results – Coordination

		Coordination		(p-hrs x 10)	
Level	Ship	Aircraft	Pool	Recip	Integ
D0	CVN	1818	132	358	454
	CVN	6060	145	396	481
	DDG	6060	148	396	480
	LCS	6060	144	399	486
D1	DDG	SESE	26	34	140
	DDG	60SE			299
	LCDD	60SE			305
D2	LCS	FSFS	147	291	480
	LCS	60FS			603
	DDLC	60FS			651
D3	CTF	TRTR	39	62	203
	CVCT	18TR			343
D4	CVN	L4L4	26	40	138
	CVN	60L4			290
	DDCV	60L4			295
D5	CVN	L5L5	26	57	137
	CVN	18L5			279
	CVDD	18L5			292

4. Wait

Table 16 summarizes results for wait. The layout of the table is identical to those above. The values in the first row (i.e., “ D0 CVN 1818”) are 98, 37 and 149 (person-hours x 10), respectively, for the pooled, reciprocal and integrated interdependence conditions. More specifically, the ISR mission required 9.8 person-hours of wait in the pooled condition, 3.7 person-hours in the reciprocal condition, and 14.9 person-hours in the integrated condition.

Table 16. Simulation Results – Wait

		Wait		(p-hrs x 10)	
Level	Ship	Aircraft	Pool	Recip	Integ
D0	CVN	1818	98	37	149
	CVN	6060	122	46	147
	DDG	6060	124	36	138
	LCS	6060	124	38	156
D1	DDG	SESE	3	1	3
	DDG	60SE			98
	LCDD	60SE			104
D2	LCS	FSFS	96	41	162
	LCS	60FS			146
	DDLC	60FS			145
D3	CTF	TRTR	12	5	16
	CVCT	18TR			73
D4	CVN	L4L4	3	1	3
	CVN	60L4			105
	DDCV	60L4			106
D5	CVN	L5L5	3	1	2
	CVN	18L5			72
	CVDD	18L5			84

5. Work Cost

Table 17 summarizes results for work cost. The layout of the table is identical to those above. The values in the first row (i.e., " D0 CVN 1818") are 591, 768 and 1097 ($k x 10), respectively, for the pooled, reciprocal and integrated interdependence conditions. More specifically, work cost for the ISR mission was $59.1k in the pooled condition, $76.8k in the reciprocal condition, and $109.7k in the integrated condition.

Table 17. Simulation Results – Work Cost

		Work Cost		($k x 10)	
Level	Ship	Aircraft	Pool	Recip	Integ
D0	CVN	1818	591	768	1097
	CVN	6060	236	307	439
	DDG	6060	236	307	439
	LCS	6060	236	307	439
D1	DDG	SESE	42	55	78
	DDG	60SE			259
	LCDD	60SE			259
D2	LCS	FSFS	253	324	470
	LCS	60FS			455
	DDLC	60FS			455
D3	CTF	TRTR	127	165	235
	CVCT	18TR			667
D4	CVN	L4L4	30	38	55
	CVN	60L4			247
	DDCV	60L4			247
D5	CVN	L5L5	20	26	37
	CVN	18L5			567
	CVDD	18L5			567

6. Functional Risk

Table 18 summarizes results for functional risk. The layout of the table is identical to those above. The values in the first row (i.e., “ D0 CVN 1818”) are 0.40, 0.39 and 0.40 (% / 100), respectively, for the pooled, reciprocal and integrated interdependence conditions. More specifically, the ISR mission experienced 40% functional risk in the pooled condition, 39% in the reciprocal condition, and 40% in the integrated condition.

Table 18. Simulation Results – Functional Risk

		Functional Risk		(% / 100)	
Level	Ship	Aircraft	Pool	Recip	Integ
D0	CVN	1818	0.40	0.39	0.40
	CVN	6060	0.41	0.40	0.39
	DDG	6060	0.41	0.40	0.42
	LCS	6060	0.39	0.40	0.42
D1	DDG	SESE	0.52	0.51	0.52
	DDG	60SE			0.43
	LCDD	60SE			0.42
D2	LCS	FSFS	0.73	0.74	0.74
	LCS	60FS			0.56
	DDLC	60FS			0.59
D3	CTF	TRTR	0.62	0.62	0.61
	CVCT	18TR			0.46
D4	CVN	L4L4	0.40	0.39	0.40
	CVN	60L4			0.40
	DDCV	60L4			0.39
D5	CVN	L5L5	0.36	0.36	0.36
	CVN	18L5			0.40
	CVDD	18L5			0.37

7. Mission Risk

Table 19 summarizes results for mission risk. The layout of the table is identical to those above. The values in the first row (i.e., " D0 CVN 1818") are 0.37, 0.38 and 0.74 (% / 100), respectively, for the pooled, reciprocal and integrated interdependence conditions. More specifically, the ISR mission experienced 37% mission risk in the pooled condition, 38% in the reciprocal condition, and 74% in the integrated condition.

Table 19. Simulation Results – Mission Risk

		Mission Risk		(% / 100)	
Level	Ship	Aircraft	Pool	Recip	Integ
D0	CVN	1818	0.37	0.38	0.74
	CVN	6060	0.39	0.37	0.74
	DDG	6060	0.37	0.38	0.72
	LCS	6060	0.37	0.38	0.75
D1	DDG	SESE	0.27	0.27	0.53
	DDG	60SE			0.75
	LCDD	60SE			0.70
D2	LCS	FSFS	0.37	0.36	0.74
	LCS	60FS			0.74
	DDLC	60FS			0.74
D3	CTF	TRTR	0.32	0.32	0.60
	CVCT	18TR			0.70
D4	CVN	L4L4	0.26	0.27	0.54
	CVN	60L4			0.73
	DDCV	60L4			0.70
D5	CVN	L5L5	0.28	0.26	0.54
	CVN	18L5			0.72
	CVDD	18L5			0.70

8. Maximum Backlog

Table 20 summarizes results for maximum backlog. The layout of the table is identical to those above. The values in the first row (i.e., “ D0 CVN 1818”) are 18, 17 and 181 (hours x 10), respectively, for the pooled, reciprocal and integrated interdependence conditions. More specifically, the ISR mission experienced 1.8 hours maximum backlog in the pooled condition, 1.7 hours in the reciprocal condition, and 18.1 hours in the integrated condition.

Table 20. Simulation Results – Maximum Backlog

		Backlog Max		(hrs x 10)	
Level	Ship	Aircraft	Pool	Recip	Integ
D0	CVN	1818	18	17	181
	CVN	6060	19	17	218
	DDG	6060	19	17	215
	LCS	6060	20	16	221
D1	DDG	SESE	20	64	138
	DDG	60SE			272
	LCDD	60SE			274
D2	LCS	FSFS	21	64	136
	LCS	60FS			165
	DDLC	60FS			139
D3	CTF	TRTR	20	64	138
	CVCT	18TR			167
D4	CVN	L4L4	10	17	68
	CVN	60L4			190
	DDCV	60L4			195
D5	CVN	L5L5	10	10	39
	CVN	18L5			105
	CVDD	18L5			104

B. GRAPHICAL RESULTS

We continue by summarizing graphical results from the computational experiments. Results in terms of each of the model measures are summarized in turn.

1. Duration

Figure 36 summarizes duration results graphically. This is the same figure presented in the body of this report as Figure 31 and is included here among details for reference. These graphical values match the numerical results presented in Table 13 above. The graph delineates duration (hours) for each experiment condition. The different experiment conditions are listed horizontally along the bottom of the graph, and vertical bars for each reflect its duration value. The three interdependence conditions are depicted in different colors shown by the key at the right side of the graph.

For instance, the first experiment condition shown (far left) is labeled “1818,” reflecting two F/A-18 aircraft operated from a carrier. This corresponds to the row “D0 CVN 1818” in Table 13. The leftmost (blue) vertical bar represents the pooled interdependence result (30.2 hours), and the center (red) vertical bar represents the reciprocal interdependence result (33.3 hours). We omit a (green) vertical bar to represent the integrated interdependence result (45.6 hours) presented in the corresponding table above.

Likewise, the second experiment condition shown is labeled "6060," reflecting two MH-60 aircraft operated from a carrier. This corresponds to the row "D0 CVN 6060" in Table 13. As above the leftmost (blue) vertical bar represents the pooled interdependence result (30.2 hours), the center (red) vertical bar represents the reciprocal interdependence result (33.3 hours), and we omit a (green) vertical bar to represent the integrated interdependence result (45.5 hours).

This layout continues for the other two Autonomy 0 results, both labeled "6060" as well, which correspond, respectively, to the rows "D0 DDG 6060" (i.e., two MH-60 aircraft operated from the DDG; 30.2 hours, 33.1 hours) and "D0 LCS 6060" (i.e., two MH-60 aircraft operated from the LCS; 30.4 hours, 33.3 hours) in Table 13.

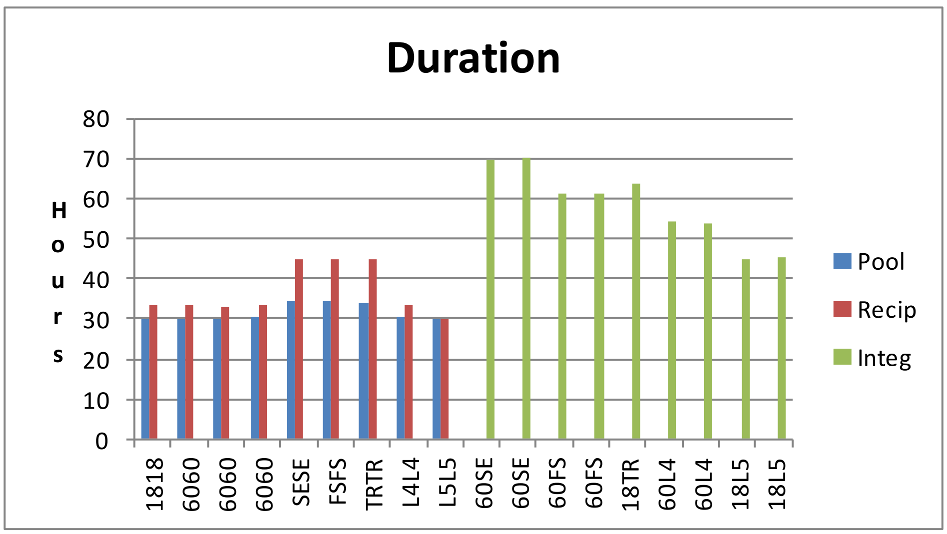

Figure 36. Graphical Summary – Duration

The pattern continues with Autonomy 1 results, labeled “SESE” in the figure, corresponding to the row “D1 DDG SESE” (i.e., two ScanEagle aircraft operated from the DDG; 34.2 hours, 44.6 hours) in Table 13. Likewise, the Autonomy 2 results, labeled “FSFS” in the figure, correspond to the row “D2 LCS FSFS” (i.e., two FireScout aircraft operated from the LCS; 34.2 hours, 44.7 hours). The Autonomy 3 results, labeled “TRTR” in the figure, correspond to the row “D3 CTF TRTR” (i.e., two Triton aircraft under authority of the CTF; 34.1 hours, 44.6 hours).

Continuing, the Autonomy 4 results, labeled “L4L4” in the figure, correspond to the row “D4 CVN L4L4” (i.e., two Level 4 UAV aircraft operated from the CVN; 30.3 hours, 33.3 hours); and the Autonomy 5 results, labeled “L5L5” in the figure, correspond to the row “D5 CVN L5L5” (i.e., two Level 5 UAV aircraft operated from the CVN; 30.1 hours, 30.0 hours) in Table 13. Notice that each of these Autonomy 1 – 5 experiment conditions includes two unmanned aircraft flying and does not include any instances of manned and unmanned aircraft performing the same missions. We include these for comparison on the left side of the graph with the corresponding pooled and reciprocal experiment conditions.

Alternatively, the next set of results on the right side of the graph all pertain to integrated interdependence, and they all reflect results of manned and unmanned aircraft flying and conducting missions *together*. Notice, for instance, how only a single (green) vertical bar is used to represent each result. The first one of this set reflects autonomy degree 1, with an MH-60 and a ScanEagle operated from the DDG; it is labeled “60SE” in the figure and corresponds to the row “D1 DDG 60SE” (69.6 hours) in Table 13. The next one reflects autonomy degree 1 also, with an MH-60 and a ScanEagle as well, and it has the same “60SE” label in the figure, but it corresponds instead to the row “D1 LCDD 60SE” (69.9 hours), as the MH-60 is operated from the LCS, and the ScanEagle is operated from the DDG.

This pattern continues for two Autonomy 2 results, both labeled “60FS” in the figure, that correspond, respectively, to the rows “D2 LCS 60FS” (i.e., one MH-60 operated from the LCS and one FireScout operated from the LCS; 61.4 hours) and “D2 DDLC 60FS” (i.e., one MH-60 operated from the DDG and one FireScout operated from the LCS; 61.3 hours) in the table. One Autonomy 3 result, labeled “18TR” in the figure, appears among this set and corresponds to the row “D3 CVCT 18TR” (i.e., one F/A-18 operated from the CVN and one Triton under authority of the CTF; 63.9 hours). This is followed by two Autonomy 4 results, both labeled “60L4” in the figure, corresponding, respectively, to the rows “D4 CVN 60L4” (i.e., one MH-60 operated from the CVN and one Level 4 UAV operated from the CVN; 54.4 hours) and “D4 DDCV 60L4” (i.e., one MH-60 operated from the DDG and one Level 4 UAV operated from the CVN; 53.7 hours). Finally, we see two Autonomy 5 results, both labeled “18L5” in the figure, corresponding, respectively, to the rows “D5 CVN 18L5” (i.e., one F/A-18 operated from the CVN and one Level 5 UAV operated from the CVN; 44.9 hours) and “D5 CVDD 18L5” (i.e., one F/A-18 operated from the CVN and one Level 5 UAV operated from the DDG; 45.1 hours) in Table 13.

Figure 37 provides a different perspective on the duration measure through a Radar chart depicting results for different ship platforms. Each radial line in the chart corresponds to a different ship platform, with distance from the center delineating increasing duration in hours. For instance, the radial line extending to the top of this figure is labeled “CVN 1818” and corresponds to the row “D0 CVN 1818” in Table 13. Each colored band corresponds with one of the three interdependence conditions. As in the charts above, blue is for pooled, and red is for reciprocal. In this first instance, one can see how each colored band extends outward along the (CVN 1818) radial to delineate the duration; that is, the blue band extends out to 30.2 hours duration for pooled interdependence, and the red band extends out to 33.3 hours duration for reciprocal interdependence.

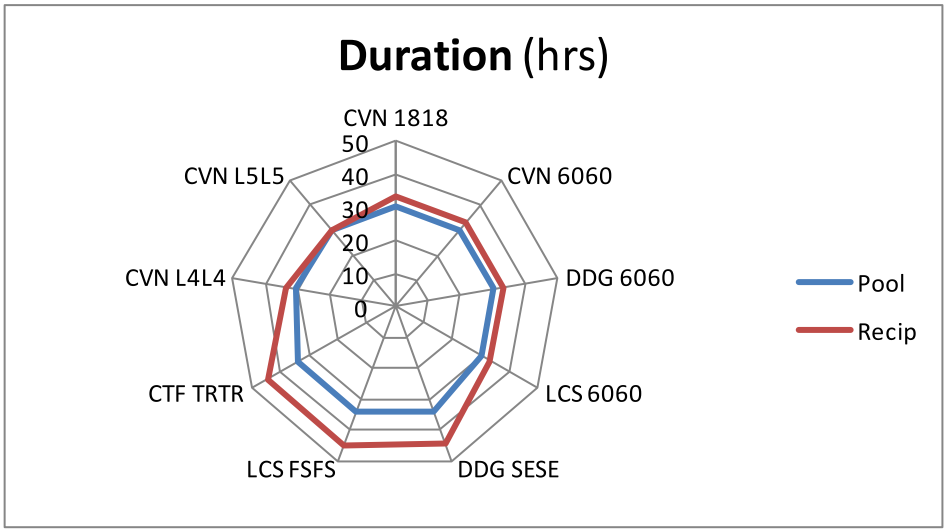

Figure 37. Combined Radar View – Duration

As another instance, moving clockwise around the figure, the next radial line is labeled “CVN 6060” and corresponds to the row “D0 CVN 6060” in Table 13. As above, each colored band corresponds with one of the three interdependence conditions: blue is for pooled (30.2 hours), and red is for reciprocal (33.3 hours). The other radial lines and duration values follow the same format.

Figure 38 provides this same perspective to the integrated missions conducted together by manned and unmanned aircraft, and it follows this same format also. As with the corresponding charts above, only integrated interdependence missions are depicted in this figure, hence only the single (green) band is included to depict duration values.

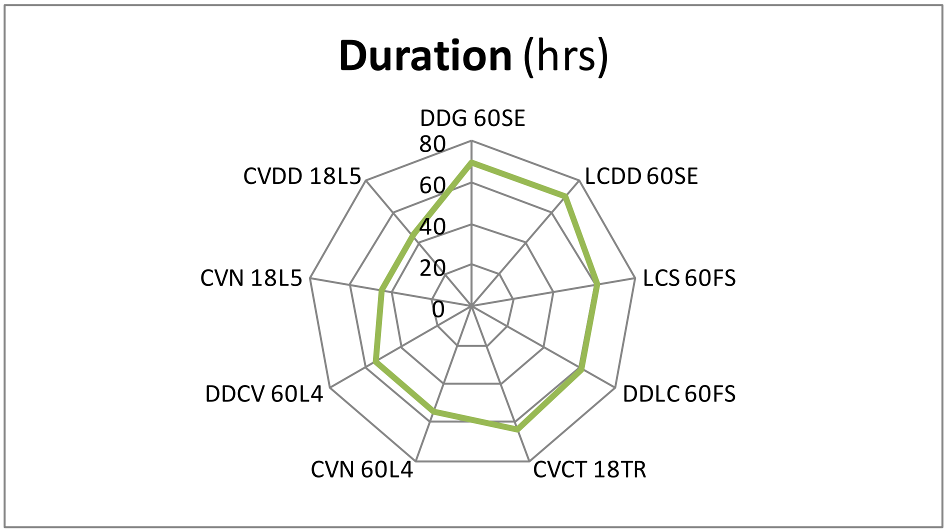

Figure 38. Mixed Radar View – Duration

2. Rework

Figure 39 summarizes rework results graphically. These graphical values (person-hours) match those presented in Table 14 above and follow the same layout as described previously.

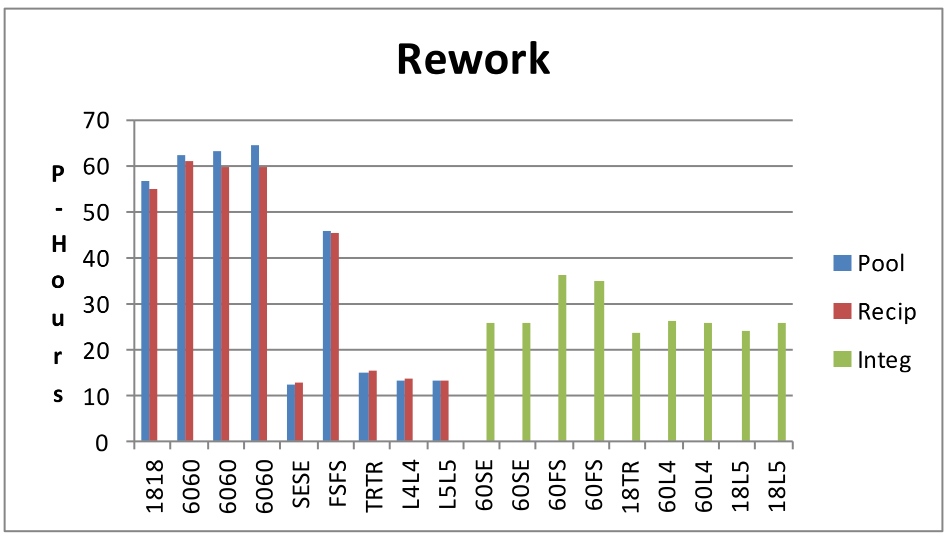

Figure 39. Graphical Summary – Rework

Figure 40 and Figure 41 provide a different perspective on the rework measure through Radar charts depicting results for different ship platforms. These charts follow the same format as their counterparts discussed above.

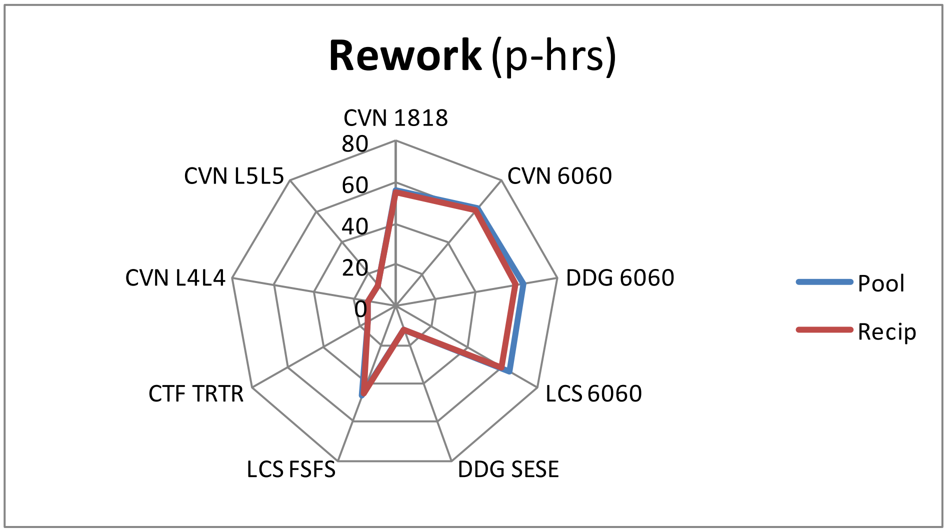

Figure 40. Combined Radar View – Rework

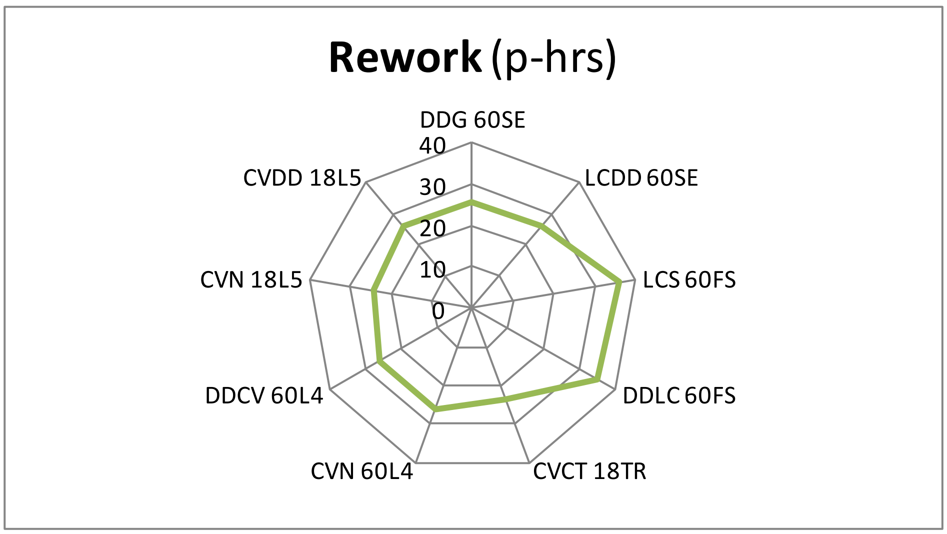

Figure 41. Mixed Radar View – Rework

3. Coordination

Figure 42 summarizes coordination results graphically. These graphical values (person-hours) match those presented in Table 15 above and follow the same layout as described previously.

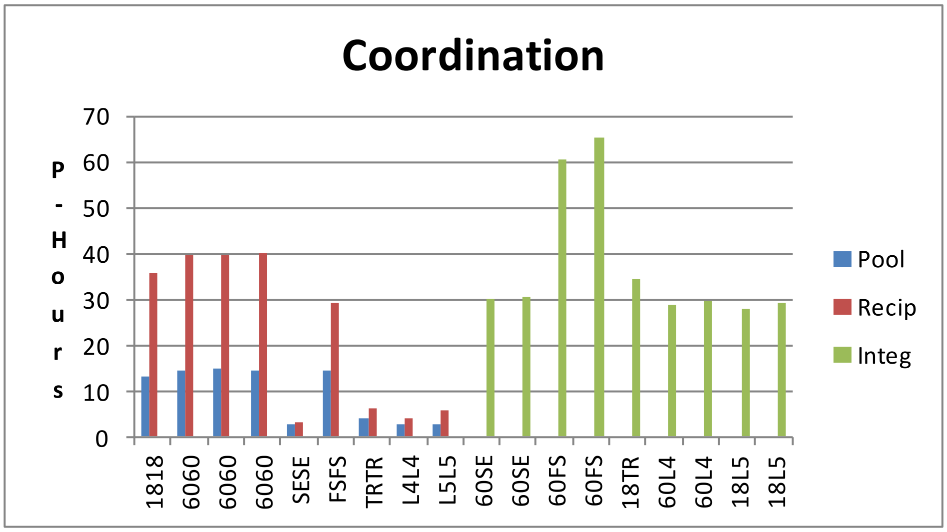

Figure 42. Graphical Summary – Coordination

Figure 43 and Figure 44 provide a different perspective on the coordination measure through Radar charts depicting results for different ship platforms. These charts follow the same format as their counterparts discussed above.

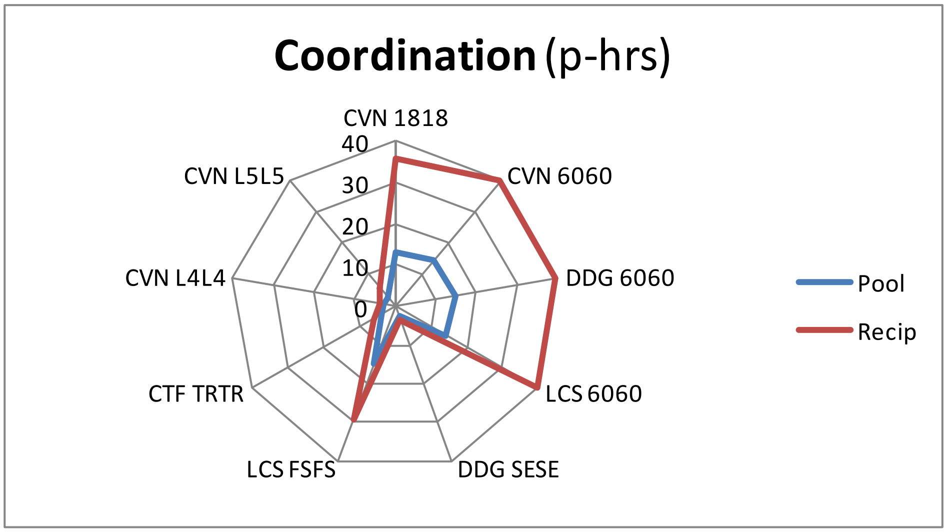

Figure 43. Combined Radar View – Coordination

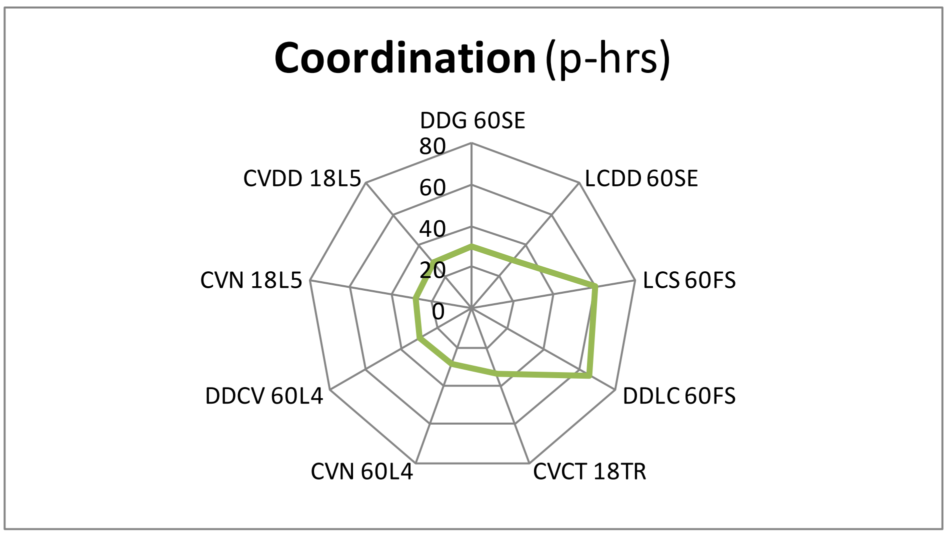

Figure 44. Mixed Radar View – Coordination

4. Wait

Figure 45 summarizes wait results graphically. These graphical values (person-hours) match those presented in Table 16 above and follow the same layout as described previously.

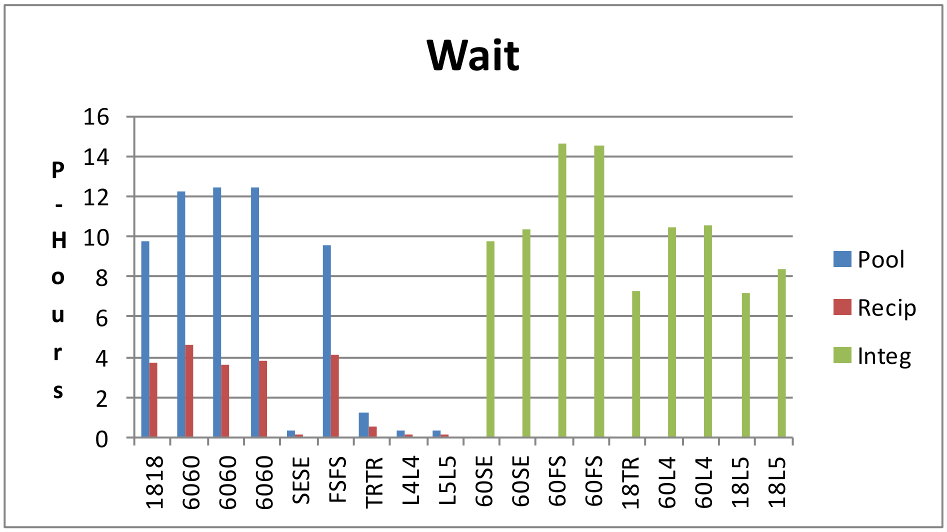

Figure 45. Graphical Summary – Wait

Figure 46 and Figure 47 provide a different perspective on the wait measure through Radar charts depicting results for different ship platforms. These charts follow the same format as their counterparts discussed above.

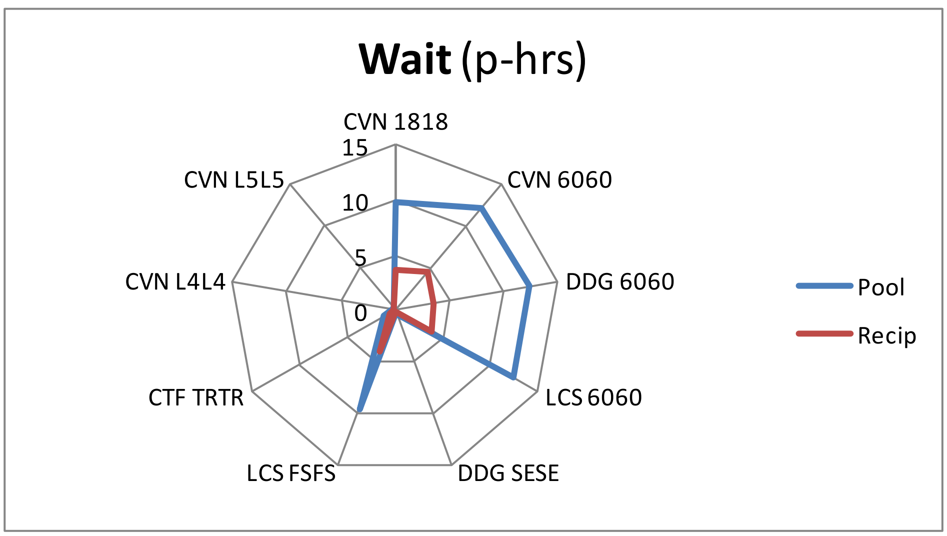

Figure 46. Combined Radar View – Wait

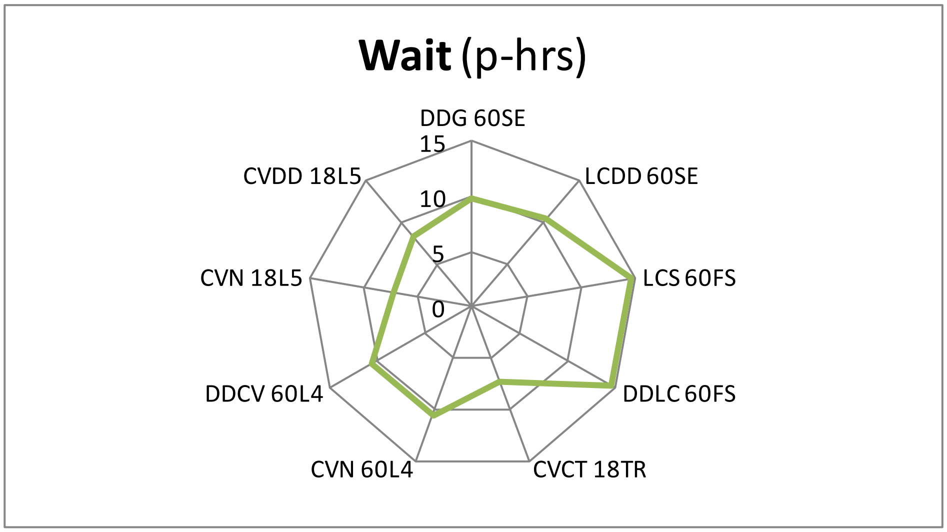

Figure 47. Mixed Radar View – Wait

5. Work Cost

Figure 48 summarizes work cost results graphically. These graphical values ($k) match those presented in Table 17 above and follow the same layout as described previously.

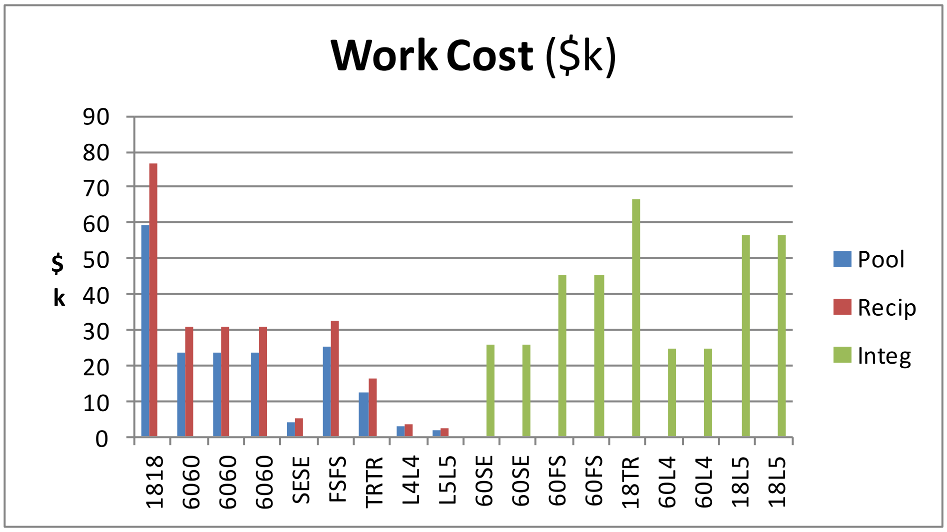

Figure 48. Graphical Summary – Work Cost

Figure 49 and Figure 50 provide a different perspective on the work cost measure through Radar charts depicting results for different ship platforms. These charts follow the same format as their counterparts discussed above.

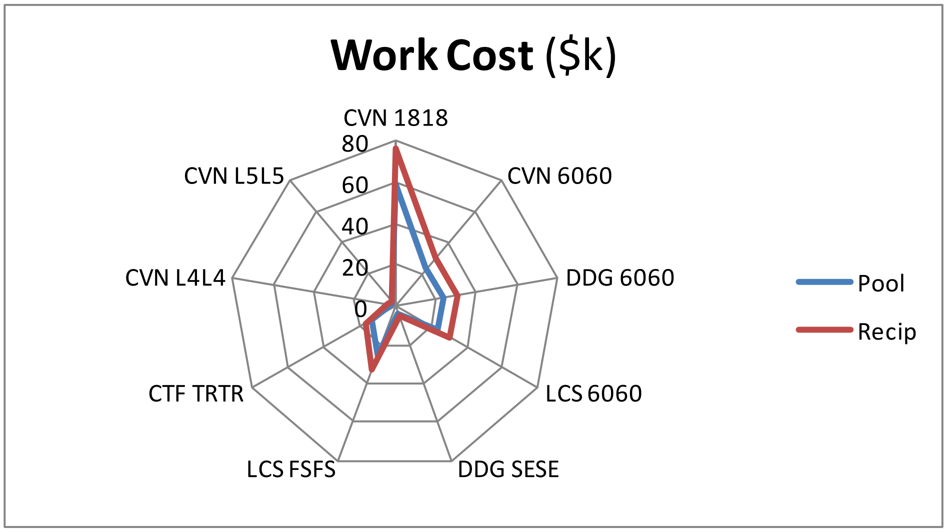

Figure 49. Combined Radar View – Work Cost

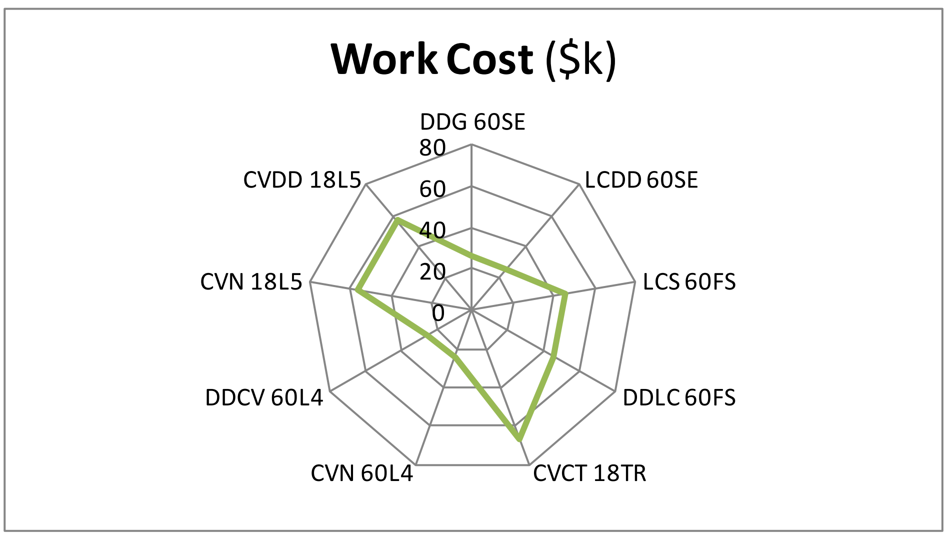

Figure 50. Mixed Radar View – Work Cost

6. Functional Risk

Figure 51 summarizes functional risk results graphically. These graphical values (%) match those presented in Table 18 above and follow the same layout as described previously.

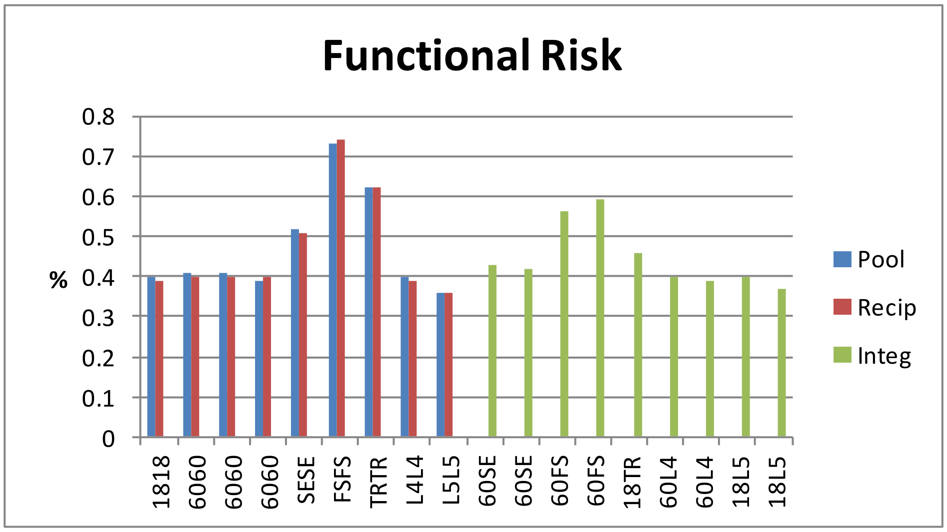

Figure 51. Graphical Summary – Functional Risk

Figure 52 and Figure 53 provide a different perspective on the functional risk measure through Radar charts depicting results for different ship platforms. These charts follow the same format as their counterparts discussed above.

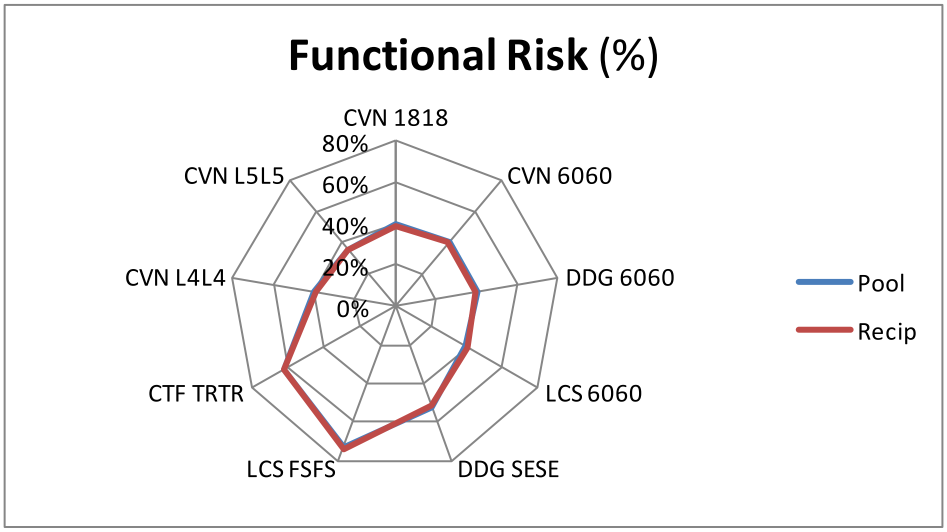

Figure 52. Combined Radar View – Functional Risk

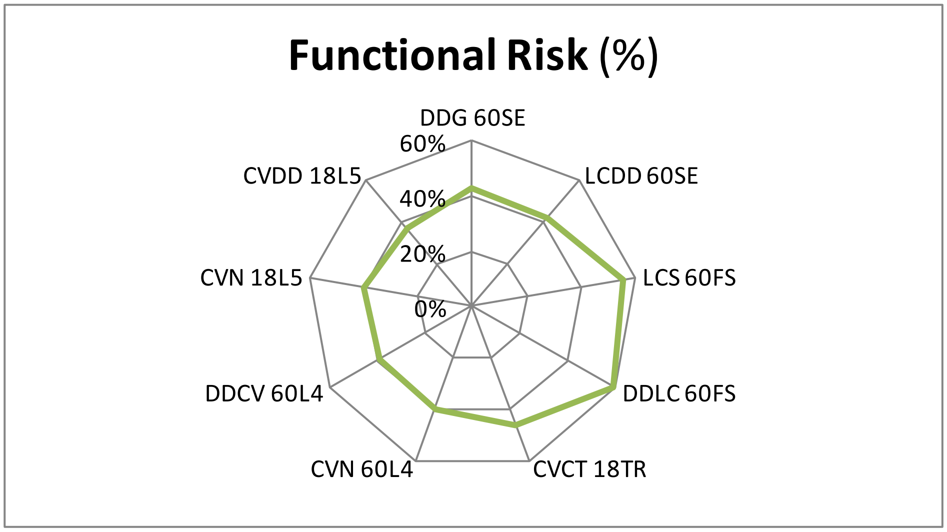

Figure 53. Mixed Radar View – Functional Risk

7. Mission Risk

Figure 54 summarizes mission risk results graphically. These graphical values (%) match those presented in Table 19 above and follow the same layout as described previously.

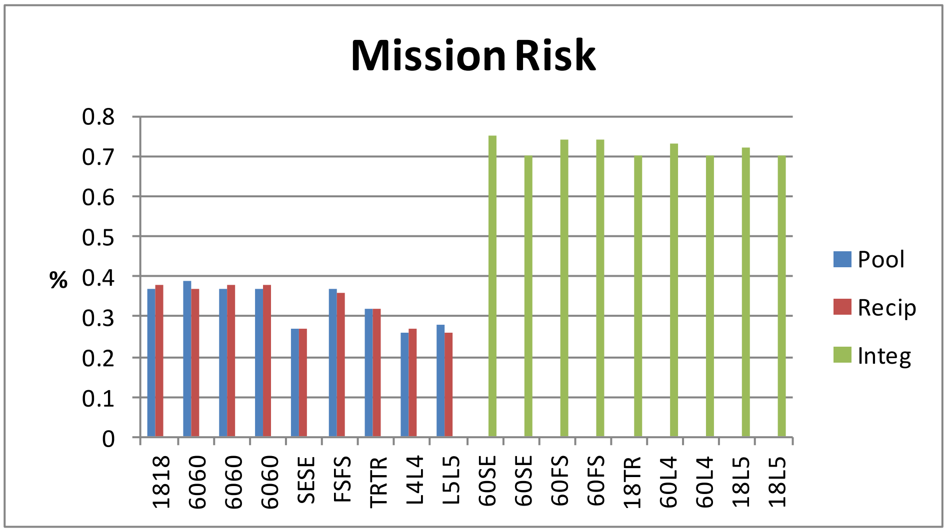

Figure 54. Graphical Summary – Mission Risk

Figure 55 and Figure 56 provide a different perspective on the mission risk measure through Radar charts depicting results for different ship platforms. These charts follow the same format as their counterparts discussed above.

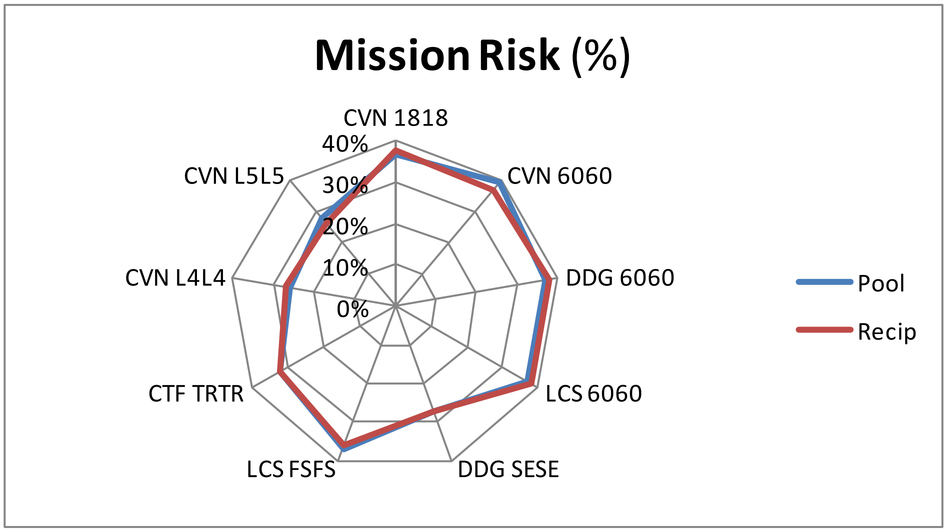

Figure 55. Combined Radar View – Mission Risk

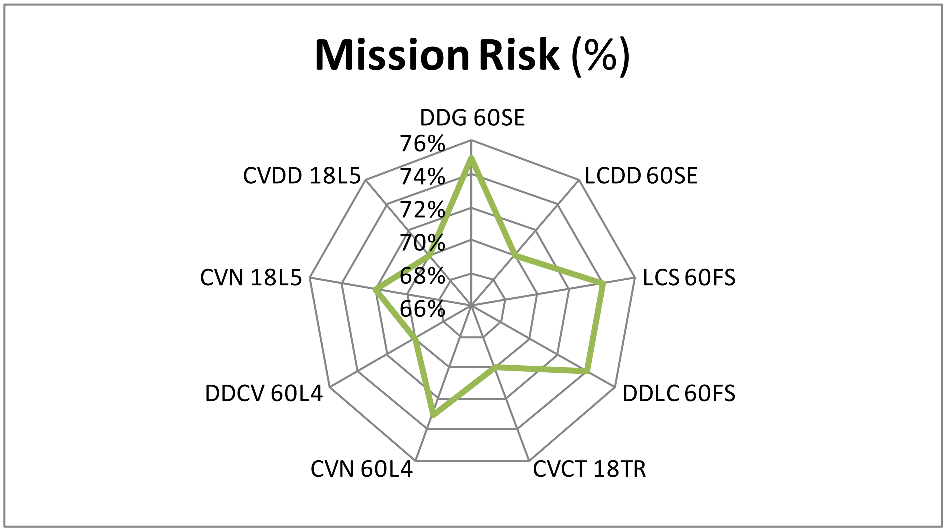

Figure 56. Mixed Radar View – Mission Risk

8. Maximum Backlog

Figure 57 summarizes maximum backlog results graphically. These graphical values (hours) match those presented in Table 20 above and follow the same layout as described previously.

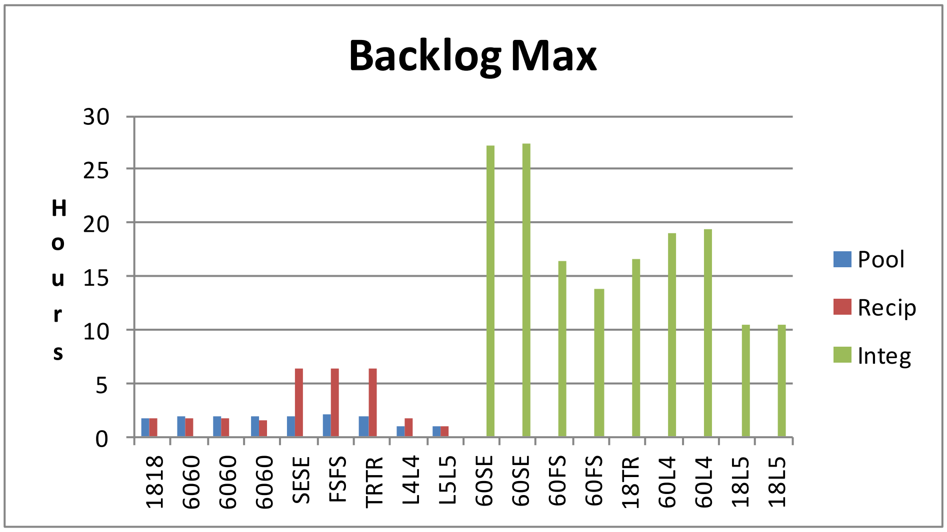

Figure 57. Graphical Summary – Maximum Backlog

Figure 58 and Figure 59 provide a different perspective on the maximum backlog measure through Radar charts depicting results for different ship platforms. These charts follow the same format as their counterparts discussed above.

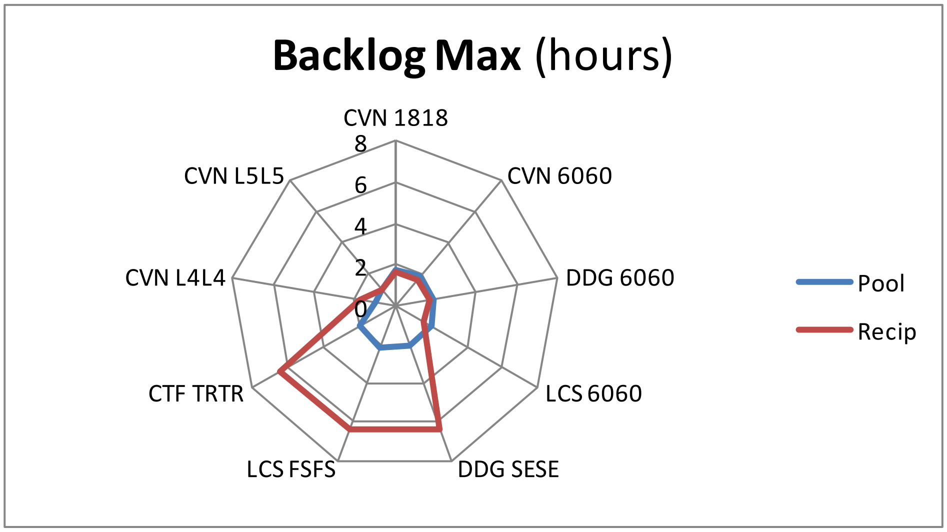

Figure 58. Combined Radar View – Maximum Backlog

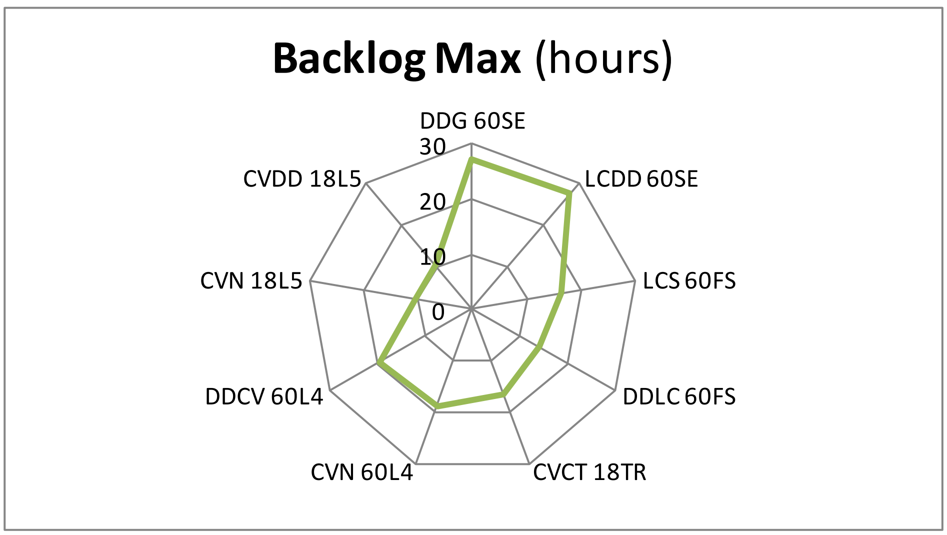

Figure 59. Mixed Radar View – Maximum Backlog

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